ASSESSING THE IMPACTS OF LAND USE CHANGE AND CLIMATE CHANGE ON AMPHIBIANS TO IMPROVE CONSERVATION STRATEGIES FOR BIODIVERSITY AND LIVELIHOODS IN THE SIERRA NEVADA DE SANTA MARTA, COLOMBIA

A Dissertation

by

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ABSTRACT

Land use and climate change are major anthropogenic threats to biodiversity. In the tropics, over 70% of land is in some form of agricultural matrix. Amphibians are the most threatened vertebrate class. Colombia, a megadiverse country, is second in amphibian species and the world's third largest coffee producer. Here, montane regions are impacted by agriculture and contain high levels of biodiversity and endemism. The Sierra Nevada de Santa Marta (SNSM) has high amphibian diversity and endemism and is the fourth largest coffee growing region in Colombia, making it a globally important biological and cultural region. The SNSM rises from the sea to 5,775 m in just 42 km, with overlap between coffee and amphibian habitat between 600 – 1,800 m. I examined three important themes related to amphibian conservation; 1) land cover impacts on amphibian community structure; 2) vulnerability of amphibian species to climate change; and 3) coffee farming community (*cafeteros*) perceptions and knowledge of biodiversity, climate change, and sustainability. We conducted amphibian visual encounter surveys from September 2017 to July 2018 at 35 transects across five major land cover types: forest, ecotone, páramo, pasture, and shade coffee. We modeled scenarios of climate change using multiple global climate models and two emissions scenarios and also conducted focal group surveys with five coffee growing communities in 2017 and 2018. Nineteen species of amphibians were recorded on surveys including 16 endemic. Land cover was the main determinant of amphibian community structure. The climate vulnerability assessment identified seven high priority species. Finally, we found that while coffee farmers have an inherent appreciation for the landscape and conservation; they require economic support to achieve sustainability goals. Regional conservation should be collaborative and include private

landowners, non-governmental organizations, government agencies, and academics. Actions should prioritize protecting extant natural habitat, restoring degraded habitats, increasing the heterogeneity of production systems, and improving landscape connectivity and watershed health. Preserving and restoring forest and ecotone land cover types will help retain amphibian habitat, improve watershed quality, and reduce climate impacts. Local communities must be involved in conservation action, to increase equitable and sustainability practices that can contribute to long-lasting positive conservation achievements in the SNSM.

DEDICATION

This dissertation is dedicated to all the women who have been told you are not good enough or cannot do it.

Yes, yes you can.

And to the local communities in the Sierra Nevada de Santa Marta.

Vamos a seguir luchando juntos para proteger la tierra del corazón del mundo.

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Contributors

This work was supervised by a dissertation committee consisting of Professors Thomas E. Lacher Jr. and Michelle Lawing of the Department of Ecology and Conservation Biology, Christian Brannstrom of the Department of Geography, and Don Church of Global Wildlife Conservation and Adjunct Professor of Ecology and Conservation Biology.

The data analyzed for Chapter 1 was analyzed in collaboration with Professor Nicolas Urbina-Cardona (Pontifica Universidad Javeriana, Bogotá Colombia) which was published in Global Ecology and Conservation 2020 (https://doi.org/10.1016/j.gecco.2020.e00968). The data analyzed for Chapter 2 was analyzed with Dr. Adrian Castellanos (Cary Institute). All other work conducted for this dissertation was completed by N. Roach independently.

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NOMENCLATURE

AOH	Area of Habitat
AC	Adaptive Capacity
AOO	Area of Occupancy
AR5	Fifth Assessment Report
CCVA	Climate Change Vulnerability Assessment
CENV	Current Climate Envelope
EOO	Extent of Occurrence
FNC	Federación Nacional de Cafeteros
GBIF	Global Biodiversity Information Facility
IUCN	International Union for Conservation of Nature
IUCN RL	IUCN Red List
NGO	Non-Governmental Organizations
PCA	Principal Component Analysis
PERMANOVA	Permutational Multivariate Analysis of Variance
RCP	Representative Concentration Pathways
SNSM	Sierra Nevada de Santa Marta

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CHAPTER I

INTRODUCTION

Global biodiversity is threatened from land use change, agricultural intensification, and climate impacts (Bellard et al., 2012; Newbold, 2018; Parmesan and Yohe, 2003; Urban, 2015). We have entered an epoch called the Anthropocene which is characterized by species extinctions, declines of populations, extensive habitat loss, and increases in invasive species and diseases (Lacher and Roach, 2018; Pachauri and Meyers, 2014). Across the globe there is tangible evidence that anthropogenic induced climate change is altering biodiversity (Bodmer et al., 2017; Moritz et al., 2008; Parmesan and Yohe, 2003). Unfortunately, the climate movement has been politicized, hindering global responses to mitigation and adaptation measures. Scientists predict increasing losses of biodiversity as temperatures soar past 1.5° C of warming (IPCC 2019). Many agencies lack the political will and/or tools to address climate change impacts on biodiversity. Strong and swift global policy action is needed to address expected biodiversity losses.

Over one-fifth of vertebrate species are threatened with extinction (Hoffmann et al., 2010). Climate change has impacts on organisms, populations, ecological networks, ecosystems, and biomes (Bellard et al., 2012; Hannah, 2008; Parmesan, 2006; Parmesan and Yohe, 2003). Responses to climate change have ranged from organismal (morphological and physiological changes) to altered phenology (breeding and migration), behavior (mating and plasticity), and distribution and range shifts (Parmesan and Yohe, 2003). Compounding factors between land use and climate change can have detrimental effects on biodiversity (Newbold, 2018; Newbold et al., 2019). Local and regional studies have found that endemic species with limited dispersal are at high risk for extinction (Menéndez- Guerrero et al., 2019a; Moritz et al., 2008; Prieto-Torres et al., 2020).

The goal of this research was to see how land use and climate change impact amphibians in a globally important biodiverse area. Amphibians are the world's most threatened vertebrate group (Stuart et al., 2004) and important environmental indicators. Their life history strategies, behavior, and physiology render them vulnerable to a number of major threats including habitat loss, disease, pollution, and climate change (Gascon, 2007; Heyer et al., 1994; Mendelson, 2006; Semlitsch, 2003). Amphibians are generally small in body size, limited dispersers, and have diverse life history strategies (Semlitsch, 2003). Recent waves of the disease *Chytridiomycosis*, a deadly fungal pathogen, has led to the extinctions and severe population reduction of several amphibians across the America's (Flechas et al., 2017; Lips et al., 2004a, 2008). Over 3,000 species of amphibians occur across montane regions (Rahbek et al., 2019). Neotropical amphibians are particularly diverse in their life history strategies and regional and local studies are necessary to uncover the conservation actions needed to mitigate impacts from land use and climate change. Many are endemic species and highly vulnerable to small alterations in available microhabitat or microclimates.

Colombia is a megadiverse country, ranked first in avian, second in amphibian, and fourth in mammalian diversity (SiB 2020). Nestled between two oceans and containing three cordilleras of the Andean mountain chain, Colombia harbors some of the highest numbers of endemic species in the world. Amphibians inhabit the Andean chain, with small niche spaces of ~ 500 m in elevation (Bernal and Lynch, 2008). Deforestation, agricultural intensification, tourism, and climate change threaten vulnerable species and livelihoods throughout Colombia (Aide and Cavelier, 1994; Andrade and Zapata, 2019; Avelino et al., 2015; Cavelier et al., 1999).

Large portions of amphibian habitat have been converted to agricultural landscapes (Etter et al., 2006). In montane landscapes these combined impacts from agricultural production and climate change makes species with specialized niches more vulnerable to climate impacts (Peters et al., 2019). Since the 2016 peace agreement, and the subsequent failings of the new government to uphold the agreement, opportunities for conservation action as well as new threats have surfaced. Many Colombian institutions are seeking ways to increase sustainable production across the country, especially in the coffee sector.

Colombia is the third largest global coffee producer (ICO 2019). Known for its mild Arabica blends (*Coffea arabica*), the crop is grown widely throughout the country (Kwan 2014) mostly above 500 m asl. Coffee systems and associated watersheds are highly affected by rising temperatures and erratic weather patterns (Hannah et al., 2017; Ovalle-Rivera et al., 2015). Agricultural practices that rely on water can be damaging to the environment. Climate change predictions show a shift in precipitation levels across parts of the country that could be detrimental to the crop and production levels (Pham et al., 2019; Santos et al., 2015). Colombia's coffee producing regions overlap with numerous key biodiversity areas. The development of sustainable management approaches with private land owners may aid in the conservation of some of the countries most threatened fauna.

One of Colombia's most biodiverse regions is the isolated Caribbean mountain range, the Sierra Nevada de Santa Marta (SNSM). The SNSM is the world's tallest tropical coastal mountain range, rising from the sea to 5,775 m asl in just 42 km. In 2013, the SNSM was ranked the world's most irreplaceable site for threatened species based on a high concentration of endemic amphibians (Le Saout et al., 2013). It has also been identified as a critically endangered ecosystem in Latin America (Ferrer-Paris et al., 2019). The region is home to four indigenous groups, a UNESCO Biosphere Reserve, two National Parks (Sierra Nevada de Santa Marta National Park and Tayrona National Park), Important Bird Area, Alliance for Zero Extinction Site, and recently designated a Key Biodiversity Area (Aide and Cavelier, 1994; Cavelier et al., 1998; González-Maya et al., 2011). The agricultural sector in the SNSM is diverse and includes palm oil, banana plantations, coffee and cattle. In fact, the SNSM is the fourth largest coffee growing region in Colombia, with over 20,000 ha dedicated to coffee production.

My dissertation was divided into three components: land use change, climate change, and perceptions of conservation and land use management of local coffee farming communities. All three components influence amphibian communities and local conservation opportunities. Chapter one is dedicated to understanding how elevation and land cover type influence the distribution and community structure of amphibians. For this analysis, I hypothesized that elevation and distance between landscapes would be more important in determining amphibian community structure than land cover (Lynch et al., 1997; Lynch and Suárez-Mayorga, 2002) and that species richness would be greatest across mid elevations (1,200 – 2,000 m; Janzen 1967; Cadavid et al. 2005). Lastly, I hypothesized that certain local environmental variables, specifically an increase in canopy cover and woody understory density would have a positive influence amphibian assembly structure along the entire altitudinal gradient (Mendenhall et al. 2014a; Evans 2019).

Chapter two takes a closer look at how climate change impacts amphibian vulnerability. I created a climate change vulnerability assessment (CCVA) based on correlative and trait based data. I aimed to prioritize amphibian vulnerability (by species) to climate change and offer potential conservation actions to reduce species extinction risk. I used occurrence data collected in the field and supplemented with GBIF records to examine 17 general circulation models under two RCP scenarios (4.5 – mild, and 8.5 – extreme). I used a number of potential spatial indicators of habitat use of amphibian species and life history traits including: 1) Area of Habitat (AOH; Brooks et al., 2019) for each species of interest; 2) climate niche overlap under two RCP scenarios (4.5 and 8.5); and 3) trait data on focal amphibian species. Using these three metrics, I assessed vulnerability to climate change and ranked species from low – high risk of species extinction under climate scenarios. I hypothesized that the endemic, aquatic breeders, habitat specialists, and species with restricted climatic environmental niche space would be more vulnerable to climate impacts, and that suitability of breeding sites would likely decrease because of altered precipitation patterns and elevated temperatures.

My third and final chapter is aimed at understanding how local land users, in this case coffee farmers, perceive biodiversity, climate change, and sustainable management practices. Globally, 125 million people depend on coffee for income. This number includes over 25 million coffee growers, mainly small share-holders, from 52 nations (Pelupessy, 2003). Ninety-five percent of coffee grown in the SNSM is shade coffee (FNC 2020), which has been demonstrated to have beneficial effects on some components of biodiversity (Perfecto et al., 1996; Perfecto and Vandermeer, 2008). Pollution from current wastewater management practices represent a concern for local communities as wastewater is deposited onto land or into local water sources post processing (Mekonnen and Hoekstra, 2010). It has been shown that pesticide use and coffee processing techniques are contaminating watersheds (Robinson and Mansingh, 1999), which can be critical breeding habitat for threatened amphibians. By obtaining data on the perceptions and management practices of local communities I aimed to identify how I could implement future sustainable projects to improve economic security of livelihoods and safeguard biodiversity.

Ultimately, I hope this research provides the groundwork for collaborative conservation initiatives. By using locally collected data, global models, and local community knowledge, I hoped to paint a holistic view of the conservation needs in the SNSM as they pertain to amphibians and coffee farmers. Recognizing the threats to biodiversity and livelihoods, addressing species' vulnerabilities, and working across networks of institutions, actors, and organizations is essential to offset future damage caused by habitat loss and climate change. Through my dissertation research, I aim to provide information that helps bridge the gap between academic institutions and governmental organizations and NGO's to implement conservation measures in a critical biodiverse area – the Sierra Nevada de Santa Marta, Colombia.

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CHAPTER II

LAND COVER DRIVES AMPHIBIAN DIVERSITY ACROSS STEEP ELEVATIONAL GRADIENTS IN AN ISOLATED NEOTROPICAL MOUNTAIN RANGE: IMPLICATIONS FOR COMMUNITY CONSERVATION[1]

2.1 Overview

Over 70% of land in the tropics is in some form of agricultural matrix which poses a threat to biodiversity. In Colombia, montane regions are dominated by varying intensities of agriculture and high levels of biodiversity and endemism. Globally, Colombia has the second largest number of amphibian species and is also the third largest coffee producer. Our study region, the Sierra Nevada de Santa Marta (SNSM), has high levels of amphibian endemism (38% and 10 threatened endemics) and is the fourth largest coffee growing region in Colombia. The SNSM rises from the sea to 5,775 m in just 42 km, with a direct overlap between coffee and amphibian habitat occurring across 600 – 1,800 m. We examined how land cover and elevation (from 800 to 3,700 m asl) influenced amphibian community structure, species richness, and abundance. We conducted surveys from September 2017 to July 2018 at 35 transects across five major land cover types: forest, ecotone, páramo, pasture, and shade coffee. In total, we recorded 19 species (366 individuals; 16 endemic species). Land cover was the main determinant of amphibian community structure, while the interaction between elevation and land cover was the main determinant of species richness and abundance. Forest and ecotone contained 73% of

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overall richness (14 species) with one species found exclusively in ecotone and three exclusively in forest. Pasture and coffee supported 42% (8 species) of species with only two species found exclusively at these land cover types. Shade coffee had low species richness and abundance and we detected just one endemic species in this land cover. The preservation of ecotone, transitional degraded habitat that occurs between two or more types of contiguous land cover types, represents an opportunity to safeguard microhabitats and microclimates. Conservation in the region should be collaborative and include private landowners, NGO's, government agencies, and academics. Conservation actions should prioritize protecting extant natural habitat, restoring degraded habitats, increasing the heterogeneity of production systems, and improving landscape connectivity and watershed health. To achieve those actions, local communities will require economic incentives to maintain forest cover and reduce the contamination of streams through agricultural runoff.

2.2 Introduction

Agriculture is one of the largest drivers of land use change (Fischer and Lindenmayer, 2007; Newbold et al., 2015). Both agricultural expansion and intensification pose a threat to biodiversity (Jenkins, 2003; Kehoe et al., 2015; Lacher and Roach, 2018). In the tropics over 70% of land has been converted to some type of mixed-managed landscape (McNeely and Scherr, 2003). Pending management practices, small scale agricultural production is often less detrimental to biodiversity (Perfecto and Vandermeer, 2010). In regions that are highly fragmented, agricultural matrices may help maintain community metapopulation structures (Gascon et al., 2000; Perfecto and Vandermeer, 2008; Watling et al., 2011). In Latin America, agricultural impact on biodiversity has increased rapidly (Laurance et al., 2014). The extremely diverse Colombian Andean region is experiencing direct threats from agriculture and climate change (Etter et al., 2006; Guzmán et al., 2016; Menéndez- Guerrero et al., 2019b; Ocampo-Peñuela and Pimm, 2014), yet the impacts of agricultural intensification on amphibian species in the Neotropics remains understudied.

Amphibians are indicator species and are particularly sensitive to environmental change. Their life history strategies, behavior, and physiology render them vulnerable to a number of major threats including habitat loss, disease, invasive species, overexploitation, pollution, and climate change (Gascon, 2007; Heyer et al., 1994; Mendelson, 2006; Nowakowski et al., 2018; Semlitsch, 2003). The 2004 IUCN Red List assessments identified amphibians as the world's most threatened vertebrate group (Stuart et al., 2004) and the 2019 global amphibian assessment update has thus far identified 31.5% of amphibians as threatened with extinction (IUCN 2019).

Neotropical amphibian life history strategies are particularly diverse. Many species are direct developers and do not rely on aquatic breeding sites (Haddad and Prado, 2005; Kühnel et al., 2010), making conservation efforts more complex. Amphibians occur in intact and degraded landscapes and have been reported to use agricultural matrices (Gascon et al., 1999). However, some researchers have observed that the dissimilarity in amphibian community composition between undisturbed and converted landscapes is especially pronounced (Greenberg et al., 2018; Nowakowski et al., 2018). Even in regions where amphibian habitat is intact, amphibians are still vulnerable to threats, such as the deadly *Chytridiomycosis*, which is responsible for dramatic declines of Neotropical amphibians in Central and South America (Flechas et al., 2017; Lips et al., 2008). Notably, agroforestry landscapes may act as a barrier to disease transmission, where the risk of transmission is higher in natural habitats (Becker and Zamudio, 2011). High diversity of Neotropical amphibians and the number of emerging threats emphasizes the importance of conserving a variety of microhabitats to protect amphibian communities, which are particularly sensitive to land-use conversion (Becker et al., 2010).

The maintenance of microclimates and microhabitats is of critical importance to amphibian persistence (Olson et al., 2007). Remnant landscapes in agroforestry matrices may contain important microhabitat variables that sustain amphibian populations (Cortes-Gómez et al., 2013; Mendenhall et al., 2014; Soto-Sandoval et al., 2017). Structurally diverse agroecosystems can provide a higher-quality matrix, improve connectivity across protected areas (Narango et al., 2019; Perfecto and Vandermeer, 2015) and buffer edge-matrix effects on amphibian populations (Santos-Barrera and Urbina-Cardona, 2011). Furthermore, riparian elements within agroforestry can increase diversity of amphibians in degraded landscapes (Ribeiro et al., 2018) and provide corridors to boost reproduction and dispersal (de Lima and Gascon, 1999).

In the Neotropics, over 5 million hectares have been converted from native forest to coffee (FAO 2017). Colombia's montane regions are dominated by high levels of biodiversity and endemism and varying degrees of agriculture (Etter et al., 2006). Ninety-five percent of Colombian coffee is shade-grown and is presumed to be a less detrimental form of habitat modification (Díaz-Bohórquez et al., 2014; Jha et al., 2014; Perfecto et al., 1996). Shade coffee provides a more heterogeneous vegetative structure, improves connectivity between forest patches, and increases biodiversity across landscapes (De Beenhouwer et al., 2013; Perfecto and Vandermeer, 2015). Research effort on the impact of coffee plantations on biodiversity has primarily been aimed at avian diversity (Anand et al., 2008; Hernandez-Aguilera et al., 2019; Narango et al., 2019). Recently, more attention has been drawn to the study on the effects of coffee plantations on Neotropical amphibians (Cruz-Elizalde et al., 2016; Macip-Ríos and Casas-

Andreu, 2008; Mendenhall et al., 2014; Monroe et al., 2017; Murrieta-Galindo et al., 2013a; Pineda et al., 2005; Santos-Barrera and Urbina-Cardona, 2011). However, there have been few studies on how agricultural landscapes influence Colombia's endemic and threatened amphibian communities (Restrepo et al., 2017).

Globally, Colombia is ranked second in amphibian species richness and endemism (836 species total and 372 endemics; Acosta-Galvis 2019, IUCN 2019). The Colombian Andes maintain remarkably diverse communities of anurans with narrow elevation ranges, less than 500 m for some species (Bernal and Lynch, 2008; Lynch et al., 1997; Navas, 2006). Amphibian diversity is particularly high at our study site, the Sierra Nevada de Santa Marta (SNSM). The SNSM is an isolated mountain range on the Caribbean coast and in 2013 was ranked the world's most irreplaceable site for threatened species based primarily on amphibian endemism (Le Saout et al., 2013).

In addition, Colombia is also the third largest global coffee producer. In 2018, Colombia produced 8.4% of the world's coffee across 900,000 hectares and 60 municipalities (Federación Nacional de Cafeteros de Colombia, 2018). In the department of Magdalena, where this study took place, approximately 20,000 hectares of land are devoted to growing coffee (Comité de Cafeteros del Magdalena, 2019; https://magdalena.federaciondecafeteros.org). Coffee has been grown in this region since the 1800's and is the most abundant crop grown from 600 – 2,000 m (Fundación ProSierra, 2019). Maintenance of high quality coffee requires access to clean watersheds, the same watershed habitats that are occupied by endemic amphibians and provide clean drinking water for millions of Colombians (González G. and Serna G., 2018). The majority of coffee grown is shade coffee and reportedly 50% of farms are considered organic (Arcila P et al., 2007), although this is debatable as enforcement of certifications is virtually non-existent.

Thus, gaining an understanding of the impact of coffee agroforestry on amphibians and their habitats is a high priority in the SNSM.

The goal of our study was to understand how amphibian community structure was impacted by land cover types and elevation in the SNSM. We hypothesized that elevation and distance between landscapes would be more important in determining amphibian community structure (Lynch et al., 1997; Lynch and Suárez-Mayorga, 2002) than land cover type and that species richness would be greatest across mid elevations (1,200 – 2,000 m; Cadavid et al., 2005; Janzen, 1967). Lastly, we hypothesized that an increase in canopy cover and woody understory density would have a positive influence on amphibian assembly structure along the entire altitudinal gradient (Evans, 2019; Mendenhall et al., 2014). Understanding how land cover and associated environmental parameters impact species communities allows conservation practitioners and policy makers to create strategic conservation plans.

2.2.1 Study Site and Selection

This study took place on the western slope of the SNSM, in the Department of Magdalena, Colombia (Fig. 1). The Sierra Nevada de Santa Marta (SNSM) is located on the Caribbean coast of Colombia, spanning three departments: Magdalena, La Guajira, and Cesar. The topography of the region has made it difficult to access and deforestation has been mostly small-scale agricultural conversion, leaving parts of the mountain patchy and fragmented. Increasing tourism demand coupled with agricultural intensification has heightened the anthropogenic impacts on the region. There are 47 described amphibian species, including 18 endemics. Recent expeditions in the SNSM have produced both new populations and species descriptions (González-Maya et al., 2011; Pérez González et al., 2017; Rada et al., 2019). High levels of elevational zonation have led to elevated biodiversity and endemism across this mountain range and it has been designated a UNESCO Biosphere Reserve, Important Bird Area, Alliance for Zero Extinction Site, Key Biodiversity Area, and is the site of two National Parks (Sierra Nevada de Santa Marta and Tayrona; Aide and Cavelier, 1994; Cavelier et al., 1998). While deforestation has fallen in the region since 2016, the SNSM continues to be threatened by land use change, primarily from agricultural enterprises, cattle ranching, tourism, natural resource extraction, and illicit crop cultivation (IDEAM 2018).

Surveys took place across three elevational bands, 1) Low (L): 800 – 1,200 m; 2) Mid (M): 1,200 – 2,000 m; and 3) High (H): 2,000 – 3,700 m. We surveyed a subset of the amphibian community in the SNSM and our study design was limited by road accessibility. Thirty-five permanent transects were placed in 10 landscapes. We used the definition of landscape found in Driscoll et al., (2013) 'as a spatial area whose diameter exceeded dispersal distances of focal species' for this study. Landscapes consisted of one to five land cover types: forest, ecotone, páramo, pasture, and shade coffee and were separated by a minimum of 5 km. Although landscapes appear linearly close together on the map, they were distinct in topography, occurring across varied slopes and aspects in the mountain. An individual landscape could include multiple elevational bands, land cover types, and transects (Table A1). The ten landscapes provided replication of the sampled land-cover in the SNSM.

Transects were 30 m long and separated by a minimum of 50 m, the estimated dispersal distances of our focal species (Luger et al., 2009; Pittman et al., 2014). Each elevational band had a minimum of three transects/land cover replicates (forest, ecotone, páramo, pasture or shade coffee) with the exception of páramo habitat where we were only able to survey two transects. Shade coffee only occurs in the SNSM across low and mid elevations, while pasture only occurred across mid and high elevations. Therefore, shade coffee was not included in analyses of high elevation land cover nor pasture in analyses of low elevation land cover.

Land cover types were defined as follows: 1) forest (beyond 50 m of any disturbed habitat or edge with other vegetation type); 2) ecotone defined here operationally as transitional degraded habitat that occurs near edges between two or more types of contiguous land cover type i.e. forest or agriculture or pasture), 3) páramo (high elevation natural grassland type habitat within 50 m of any major disturbance from land cover type or edge effects); 4) pasture; and 5) shade coffee (Fig. 2). Surveys were conducted in land cover categories clearly definable based upon our five mutually exclusive classifications. After evaluation of steep terrain at sites, transects of 30 m were placed in designated land covers. Given the difficult terrain of the region, forest interior transects were located 50 m from an edge to avoid edge effects on mountain amphibians (Santos-Barrera and Urbina-Cardona, 2011) while shade coffee and ecotone were located 10 m from an edge. Across each elevational band, there was at least one permanent body of water (stream, waterfall, river) within each land cover type, with the exception of pasture. We mainly avoided placing transects alongside roads, however if a non-forested transect fell along the road it was set 10 – 20 m away from the road. Most sites are difficult to access and transects can be very steep (45 + degrees). In addition, most principal roads were narrow dirt roads with minimal accessibility and very low frequency of vehicles. Shorter distances from roads were deemed acceptable for this study since the abrupt changes in topography and vegetation cover occurred dramatically within 10 m of roads.

2.3 Methods

2.3.1 Environmental Variables

We collected data on relevant environmental variables on each transect including: elevation, slope of the transect (at the beginning, middle, and end of the transect i.e. 0, 15, 30 m, using a clinometer), canopy cover at two points (10 m and 20 m using a densiometer and standard methods), understory density (separated into woody & grassy, measured 6 x, every 5 m, on alternating sides of the transect), and leaf litter cover and leaf litter depth (both leaf litter cover and leaf litter depth were measured 6x every 5 m from 5 to 30 m). To measure understory density, we used a 1.5 m rod (5 cm wide) to count the number of 1) woody stems or 2) grassy vegetation that touched the rod (Urbina-Cardona et al., 2006). Leaf litter cover was assigned a categorical variable based on percentage of estimated cover per 1 x 1 m quadrat, 1 = 0 – 25%, 2 = 25 – 50%, 3 = 50 – 75%, and 4 = 75 – 100%. Leaf litter depth (within a 1 x 1 m circle, divided into quadrats) was measured every 5 m at five points, taken at the middle of the quadrat and at the center most point within each of the four subquadrats (Heyer et al., 1994; Santos-Barrera and Urbina-Cardona, 2011; Soto-Sandoval et al., 2017; Urbina-Cardona et al., 2006).

2.3.2 Amphibian Surveys

We conducted visual encounter amphibian surveys during three temporal periods, two wet and one dry: September – October 2017 (wet), January – February 2018 (dry), and June 2018 (wet). Surveys were done at night, by a minimum of two people, 30 min after sunset to 03:00, avoiding moments of excessive rain and wind (> 25 km/hour). Visual encounter surveys for amphibians were conducted up to 1.5 m on each side of the 30 m transect. At each point where an amphibian was first observed a photograph was taken as a record of all captures and for confirmation of species identification (Ferreira et al., 2016; Heyer et al., 1994; Rödel and Ernst, 2004). This project was conducted under permission from the Corporación Autonoma Nacional de Magdalena and in conjunction with the lab of Luis Alberto Rueda Solano at the Universidad de Magdalena (14-000034461-DCP-2500).

2.3.3 Data Analyses

To assess sampling completeness for each land cover type per elevation range, we calculated the percentage that the number of species recorded represented of the corresponding estimated species richness using Bootstrap and Chao 1 and 2 (Anderson et al., 2008; Chao and Chiu, 2014). We also calculated the completeness of the richness estimates at all sites. The percentage of amphibian similarity between land cover and the taxa responsible for any variability were determined with Bray-Curtis similarity percentage analysis (SIMPER subroutine of Primer v7; Clarke et al., 2014). To test for spatial autocorrelation, we ran a Mantel test (Spearman Rank, correlation) using transect locations to look for any spatial autocorrelation among transects and the three measures of amphibian community structure and diversity: richness, abundance, and Bray-Curtis dissimilarity.

To visualize how land cover and elevation influenced amphibian community diversity we conducted a two-way permutational multivariate analysis of variance (PERMANOVA; Anderson, 2001) based on a Bray-Curtis similarity matrix (for community structure) and Euclidean distances (for total abundance and richness), type I partial sum of squares and 9,999 permutations of residuals under a reduced model. The sequential sum of squares is ideal for designs, including covariates, in which each factor is fitted after taking into account all previous terms in the model, and the sum of the individual SS will add up to the total SS (Anderson et al., 2008). PERMANOVA draws statistical inferences in a distribution-free process based upon geometric partitioning of distance measures (Anderson, 2017).

The experimental design had two factors: elevation (fixed with three levels: low, medium, high) and land cover (fixed with five levels: forest, ecotone, páramo, pasture, and shade coffee); landscapes (ten levels) were included into the model as a covariable without interactions with the two fixed factors. We compared the levels within significant factors and their interactions using *a posteriori* pair-wise comparison with PERMANOVA t-statistic and 9,999 permutations of residuals under a reduced model (Anderson et al., 2008). We ran principal coordinate analyses to visualize the variation in amphibian community structure related to land cover and elevation and we created a box plot for the total abundance and species richness.

Finally, to examine the level of association of land cover and elevation on amphibian community structure, we generated a heat map (Somerfield and Clarke, 2013) that represented the association index (Whittaker, 1952) of the species by elevation-habitat based on a Bray Curtis similarity matrix. The classification of species and land cover – elevation was evaluated to inspect for significant multivariate structure diversity, using a similarity profile routine (SIMPROF with 9,999 Monte Carlo simulations) detecting the degree of deviation of the observed profile relative to the null distribution of the permuted profiles (Clarke et al., 2008).

We used Pearson correlation coefficients to inspect for a relationship between environmental variables and to identify collinear variables ($R > 0.7$) to be excluded from further analyses. To test our hypotheses about the relationship between environmental parameters on amphibian community structure among sites, we examined the best fitted model by running a distance-based linear model (DistLM), applying a corrected Akaike's Information Criterion ($AIC_{c;}$ McArdle and Anderson, 2001) for small sample size. Additionally, we carried out an ordination and visualization of the best model with a distance based redundancy analysis (dbRDA) to estimate the percentage of variation explained by each environmental variable among landscapes. All the statistical analyses were conducted on Primer v7 and the Permanova+ add on (Clarke and Gorley, 2015).

2.4 Results

We recorded 19 species (16 endemics) and collected data from 366 individuals during 150 person/hours of sampling effort from September 2017 – July 2018. The species accumulation curves validated the survey effort (hours) needed to identify all species in a given area were met with more than 70% of mean completeness of inventory (Table 1). Chao 1 consistently generated the lowest estimates (with 100% completeness) but is often considered a lower bound estimator; Chao 2 and Jackknife 2 are both sample based estimators and are similar in performance, both generating the highest richness estimates (Colwell and Coddington, 1994). Results from the Mantel test found no significant correlation between site locations (latitude/longitude) and community variables (Spearman rank, *rho*, were non-significant for a) species richness = 0.19, b) abundance = 0.028, and c) Bray-Curtis = 0.155).

Species abundance was highest in forest, followed by ecotone, pasture, shade coffee, and páramo (Fig. 3; Table 2). Species richness was highest in forest, followed by ecotone, pasture, shade coffee, and páramo (Fig. 4). The forest was dominated by *Pristimantis megalops, Pristimantis sanctaemartae* and *Ikakogi tayrona* (SIMPER, percentage of contribution to similarity of 38.3, 30.9, and 10.4%, respectively), the ecotone was dominated by *Cryptobatrachus boulengeri* and *Colosthetus ruthveni* (SIMPER, percentage of contribution to similarity of 54.5 and 25%, respectively), and the pasture was dominated by *Pristimantis tayrona* and *Atelopus laetissimus* (SIMPER, percentage of contribution to similarity of 54.5 and 25%, respectively). The páramo was dominated by *Atelopus carrikeri* (SIMPER, percentage of contribution to similarity of 100). On the other hand, *A. carrikeri* was an important discriminatory species between the páramo and forest, ecotone, shade coffee and pasture habitats (SIMPER, percentage of contribution to dissimilarity of 37, 41, 89, 49% respectively). *Pristimantis tayrona* was an important discriminatory species between the pasture and forest, shade coffee, and ecotone habitats (SIMPER, percentage of contribution to dissimilarity of 16.4, 40.8, and 17%, respectively). *Pristimantis megalops* was also an important discriminatory species between forest and shade coffee and forest and ecotone habitats (SIMPER, percentage of contribution to dissimilarity of 19 and 15%, respectively).

Our study included ten threatened endemic species (IUCN 2019; Table 2) which largely occurred in forest and ecotone. However, in pasture, we found five endemic and/or threatened species: *Pristimantis tayrona* (n=4), *Pristimantis cristinae* (n=1), *Pristimantis delicatus* (n=5), *Pristimantis ruthveni* (n=2), and *Atelopus laetissimus* (n=2). Amphibian community structure was different between elevations ($F = 10{,}011$; p-perm = 0.0001), land cover ($F = 10{,}878$; p-perm = 0.0001), and in the interaction between land cover and elevation ($F = 59{,}775$; p-perm = 0.0001; Table 3). The factors with the highest estimated component of variation for community composition were land cover and the interaction between land cover and elevation (estimate of 495.11 and 473.19, respectively, Table 3). A similar pattern was observed for components of variation for species richness and total abundance (Table 3). Based upon *a posteriori* pairwise comparisons, at high elevations (2,000 m +), forest was different from páramo ($t = 3.73$; p-perm = 0.0001; 24.4 % of average similarity between transects/within land cover type), pasture ($t = 2.99$; p-perm = 0.0001; 28.2 % of average similarity between transects/within land cover type) and ecotone ($t = 2.69$; p-perm = 0.0004; 34.4 % of average similarity between transects/within land cover type). There were no differences between ecotone with pasture and páramo, nor between pasture and páramo. At mid elevations (1,200 – 2,000 m), all the land cover types were different except for the contrast between shade coffee and pasture ($t = 1.53$; p-perm = 0.133; 82.5 % of average similarity between transects/within land cover type). Finally, at low elevations (800 – 1,200 m), forest was different from shade coffee ($t = 2.18$; p-perm = 0.0013; 84.2 % of average similarity between transects/ within land cover type) and ecotone ($t = 2.89$; p-perm = 0.0043; 54.8 % of average similarity between transects/ within land cover type); and ecotone was different from shade coffee ($t = 2.9$; p-perm = 0.0024; 52.9 % of average similarity between transects/within land cover type).

Land cover had the largest influence on community structure (Fig. 5). Some species showed strong affiliations with land cover types; endemic species *Colostethus ruthveni* and *Cryptobatrachus boulengeri* were closely associated with ecotone community structure, while other endemics, *Pristimantis sanctaemartae* and *Pristimantis megalops*, were closely associated with forest community structure (Fig. 5). Our results demonstrate that there are seven largely distinct clusters representing species communities in the Sierra Nevada de Santa Marta, Colombia based upon land covers across elevational bands (Fig. 6). The four largest clusters included between two and seven species across multiple families. Three species (*Pristimantis ruthveni*, *Pristimantis tayrona*, and *Atelopus carrikeri*) each correspond to a single cluster exhibiting patterns of distribution deviating from the patterns of those four communities. Amphibian community clusters were also associated with clusters of land cover types, generating the strong diagonal gradient in the plot. High elevation pasture and high elevation páramo/ecotone occupy the two extremes of the diagonal, with a low-medium cluster of coffee and ecotone, a medium-high forest cluster, and a small group of high elevation ecotone and pasture species.

Forest dependent species included the families Craugastoridae (5) and Bufonide (2), while species from Leptodactylidae (1), Hylidae (1), and Dendrobatidae (2) occurred in more disturbed land covers. *Pristimantis* species (8; all endemic) were found across all land cover types except for coffee. However, *Pristimantis* species were not dispersed evenly across land cover types and there were demonstrable preferences amongst species in the genus.

None of the seven environmental covariates were strongly correlated (R^2 value < 0.7) and they were all included in the following analyses (Table 4). Three of the environmental covariates included in the analysis were found to be significant explaining changes in amphibian community structure (elevation, p = 0.02; grassy understory, p = 0.003; canopy cover, p = 0.002). The candidate models account for 36 – 53% of the variance in community structure at each land cover type including elevation and total average of canopy cover in the top models. Based on the best fitting distance based linear model (DistLM), the first two dbRDA axes explained 38.6 % of the variation in the amphibian community structure along samples (AICc = 256.39; R2 = 0.48; Table 5). The dbRDA results further demonstrate that canopy cover appears to distinguish forest and ecotone from more degraded agricultural land cover such as pasture and shade coffee (Fig. 7).

2.5 Discussion

Forest dependent species are increasingly vulnerable to land use change (De Beenhouwer et al., 2013; Philpott et al., 2008; Sekercioglu et al., 2008). The SNSM is an irreplaceable site for endemic species and an important ecoregion of global amphibian diversity (Loyola et al., 2008). Our results demonstrate that amphibian community structure is largely driven by land cover in the SNSM. There were clearly defined clusters of species associated with ecotone at low and mid elevations, other clusters were restricted to forest at various elevations, while others were found in open formations like pasture and páramo. The majority of species in this study were found inside protected areas, with the highest species richness (n=11) found in a private reserve (El Dorado Reserve). However, connectivity amongst protected areas in the region is limited, and most protected areas are surrounded by private lands.

Shade coffee was the least suitable habitat for amphibians. We found three species (15.7%) in coffee plantations and just one endemic (*Colostethus ruthveni*) was documented using shade coffee plantations. While not recorded directly in shade coffee during our study, two endemic species, *Ikakogi tayrona* and *Cryptobatrachus boulengeri,* occurred in riparian forest elements within < 30 m of shade coffee. Further anecdotal observations have found both species in waterways on coffee plantations. These species may demonstrate an ability to withstand some form of habitat transformation or degradation which also emphasizes the importance of conserving riparian areas within coffee plantations. The endemic species *Ikakogi tayrona* was also observed near transects where water flow output was strongest, usually near waterfalls or rushing streams, potentially indicating that this species requires consistent water flow rates during critical life history periods.

Previous agroforestry studies have documented mixed effects on amphibian community structure, abundance, and species richness (Macip-Ríos and Casas-Andreu, 2008; Murrieta-Galindo et al., 2013b, 2013a; Pineda et al., 2005; Rathod and Rathod, 2013). Other taxa, such as birds, are capable of dispersing more easily across shade coffee landscapes. For amphibians, it is necessary to maintain microhabitats and microclimates. The intensity of coffee management determines the suitability of the habitat (Philpott et al., 2008) and lower management intensity is preferred (Faria et al., 2007; Gardner et al., 2009; Stork et al., 2009). Shade coffee appears to be inhospitable habitat for most amphibian species in our study. This is likely given the overlap of harsh management practices during critical amphibian reproductive periods (N. Roach unpublished data) that alter microhabitats. It is possible that the current management practices in the SNSM may not be providing suitable habitat for amphibians.

Our study had species with mixed life-history strategies (non-direct vs. direct developers). All *Pristimantis* species are direct developers, which means they are not heavily dependent on aquatic habitats like *Atelopus* species, for example. In fact, direct developers may even be more susceptible to disease transmission (Mesquita et al., 2017) underscoring the importance of maintaining a complex array of microhabitats. However, *Pristimantis* species in the SNSM are greatly understudied and not much is known about their distribution or habitat use beyond this study. Changes to soil moisture and composition, forest structure and connectivity, and watershed health play important roles in the persistence of *Pristimantis* species in the region. The three *Atelopus* in our study are currently threatened with extinction which underlines the value of maintaining high quality stream habitat where reproduction occurs.

Ecotone (usually represented in our study as degraded forest or in several cases by riparian buffers between two contiguous land cover types) can increase landscape complexity and connectivity as long as movement across land cover types is possible. Ecotone habitat may help buffer landscapes against large-scale environmental changes such as climate change (Tscharntke et al., 2012). Conservation and restoration of the transitional habitats between agriculture and forested areas (i.e. ecotone) are important in the maintenance of microhabitats and microclimates for amphibians. This may represent an opportunity to conduct collaborative conservation with private landowners. In the absence of high intensity land management there may be opportunities to buffer agroforestry matrices that can alleviate losses of biodiversity. This confers the added benefit of improving microclimates for forest dependent species of amphibians.

Partnerships with private landowners could improve the management of healthy amphibian populations in coffee plantations by retaining and restoring the agricultural matrix through activities like reforestation, buffering riparian corridors, increasing connectivity between forest patches, improving stream water quality, and reducing the use of agrochemicals in farming practices (de Lima and Gascon, 1999; Maisonneuve and Rioux, 2001; Olson et al., 2007; Paoletti et al., 2018; Semlitsch and Bodie, 2003). Sustainable management of coffee plantations can even benefit local communities by increasing the coffee prices for specialty coffee buyers and providing additional rationale and support for conservation (Anand et al., 2008; Narango et al., 2019; Solano et al., 2017; Tscharntke et al., 2015).

We recognize the economic and livelihood importance of agriculture for local communities, and recommend cross-disciplinary and collaborative conservation action. Given the difficulty in establishing new protected areas, as well as the challenges in the prevention of degazetting of established protected areas (Mascia et al., 2014), strong arguments have been made to redirect conservation efforts toward private lands (Bradbury et al., 2010; Brockerhoff et al., 2008; Engel et al., 2008; Mitchell et al., 2018; Perfecto and Vandermeer, 2008; Rissman et al., 2007). In addition to agricultural intensification, climate change and rapid growth in tourism and development all pose an increased threat to biodiversity (Aukema et al., 2017; Ramirez-Villegas et al., 2012). Local land owners should be included in the conversation of potential conservation action on their lands and adjacent landscapes. The farmers in the SNSM already have a high level of respect for conservation and the environment (N. Roach unpublished data). Involvement of local people is likely to increase the likelihood of achieving conservation goals.

Promotion of sustainable development practices aimed at conserving appropriate amphibian habitat across the SNSM is a necessity. Academics, NGOs, and government agencies must share data and resources and partner with local communities to implement effective conservation actions. Specific actions should be aimed at protecting extant habitat, restoring degraded habitats, and improving forest connectivity and watershed health. Finally, it is important to provide meaningful economic incentives to local communities, reduce agricultural runoff and wastewater contamination, and protect extant forest habitat. Participatory conservation actions originating at the community level will help safeguard biodiversity and mitigate compounding anthropogenic impacts.

2.6 Figures

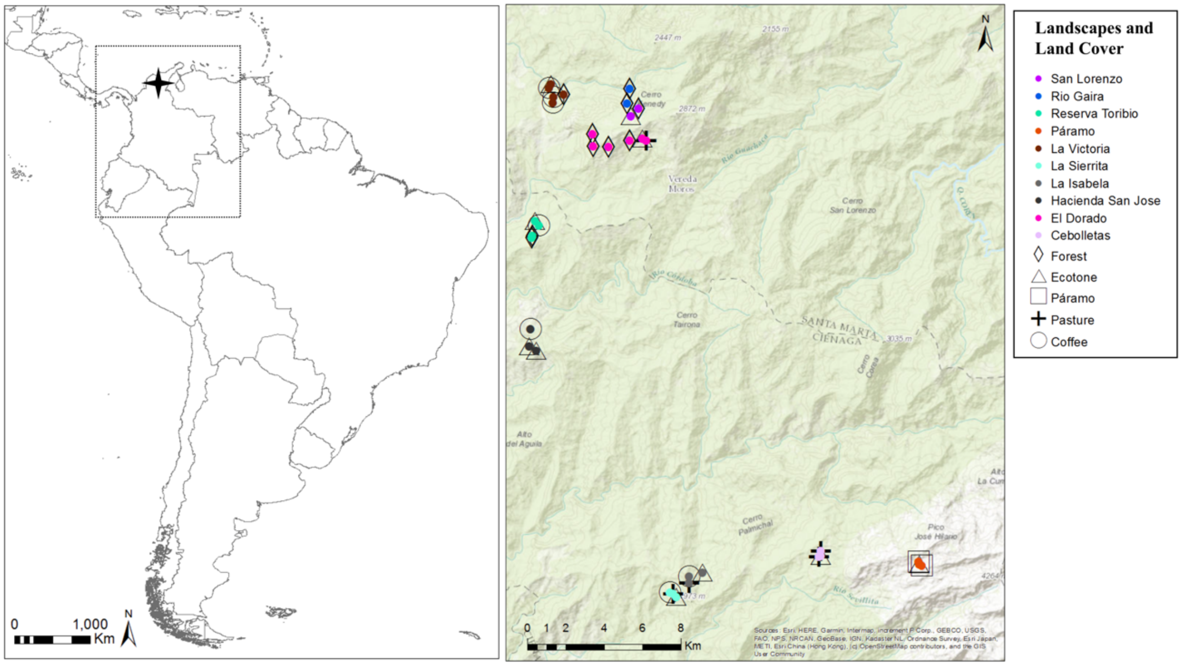

Figure 1. Study sites in the Sierra Nevada de Santa Marta, Colombia. The ten landscapes are represented by colors, where the five land cover types are represented by geometric shapes. Forest habitat was unevenly distributed throughout our study design and found mostly in the northern portion of this map.

Figure 2. Photos of land cover types (excluding pasture, which looks like a generic grassland pasture). An example of ecotone is shown in box C where the ecotone transect is the degraded forest remnant that occurs adjacent to agriculture landscapes (in this instance coffee situated directly above the road from the ecotone).

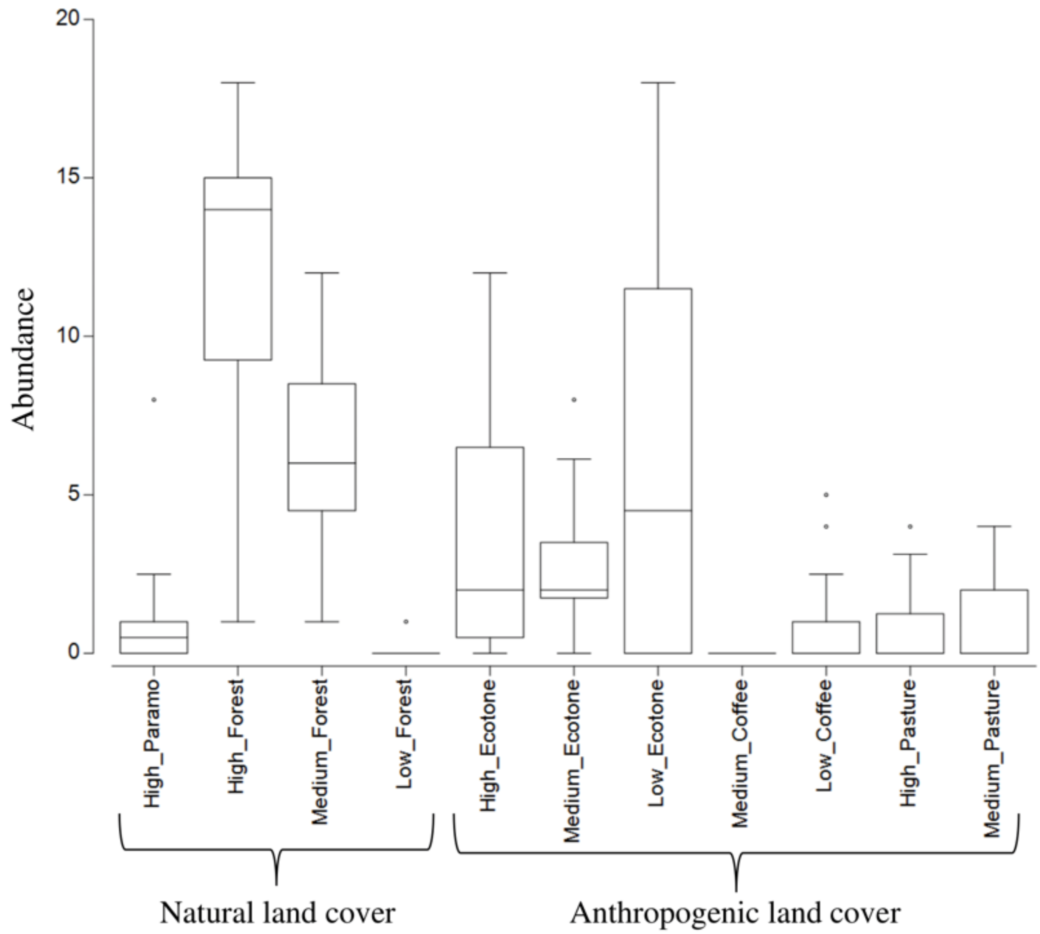

Figure 3. Amphibian abundance plotted by land cover type. Abundance was highest in high and medium forests followed by high and low ecotone.

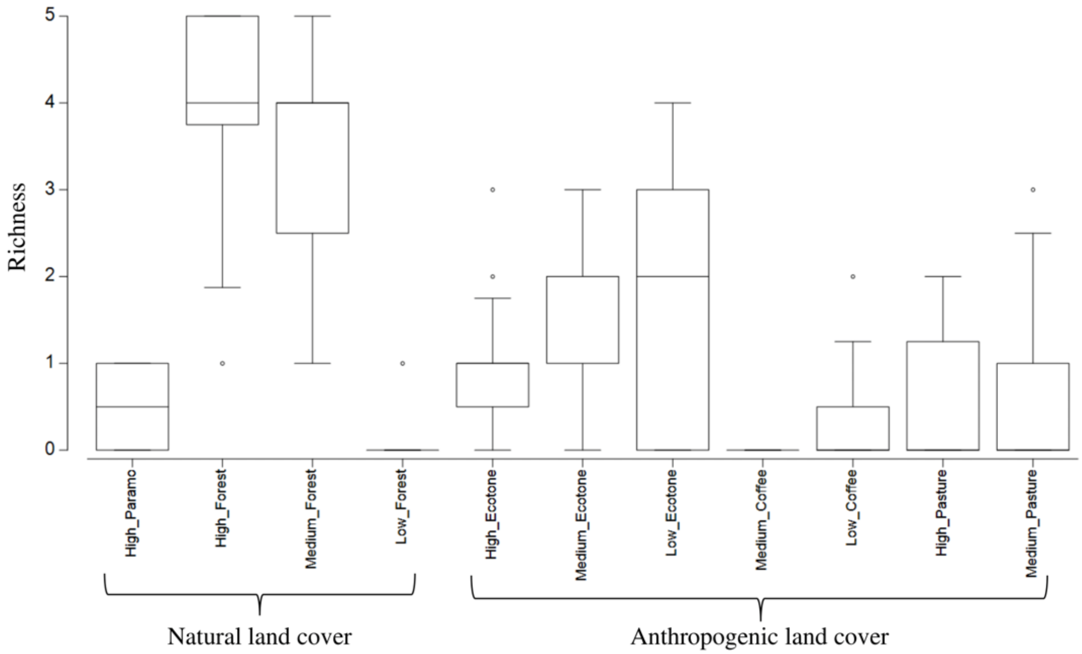

Figure 4. Species richness plotted by land cover type. Species richness is higher in high and medium elevational forests and low and medium ecotone.

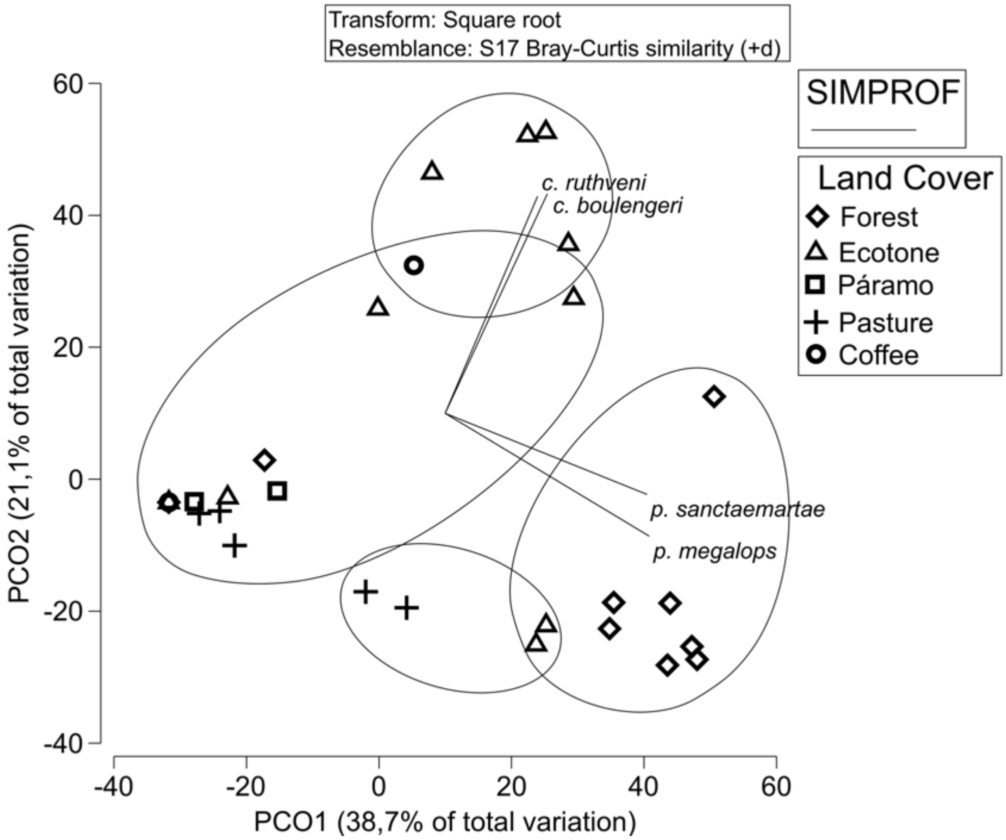

Figure 5. A principal coordinates analysis based on a Bray-Curtis resemblance similarity structure for species abundance represented by land cover type and elevation range. Circles represent statistically different SIMPROF classified groups. In the SNSM, amphibian community structure is associated with land cover, which is particularly noticeable for ecotone and forest land cover. Both *Colostethus ruthveni* and *Cryptobatrachus boulengeri* are associated with ecotone species communities, while *Pristimantis sanctamartae* and *Pristimantis megalops* are associated with forest dwelling species.

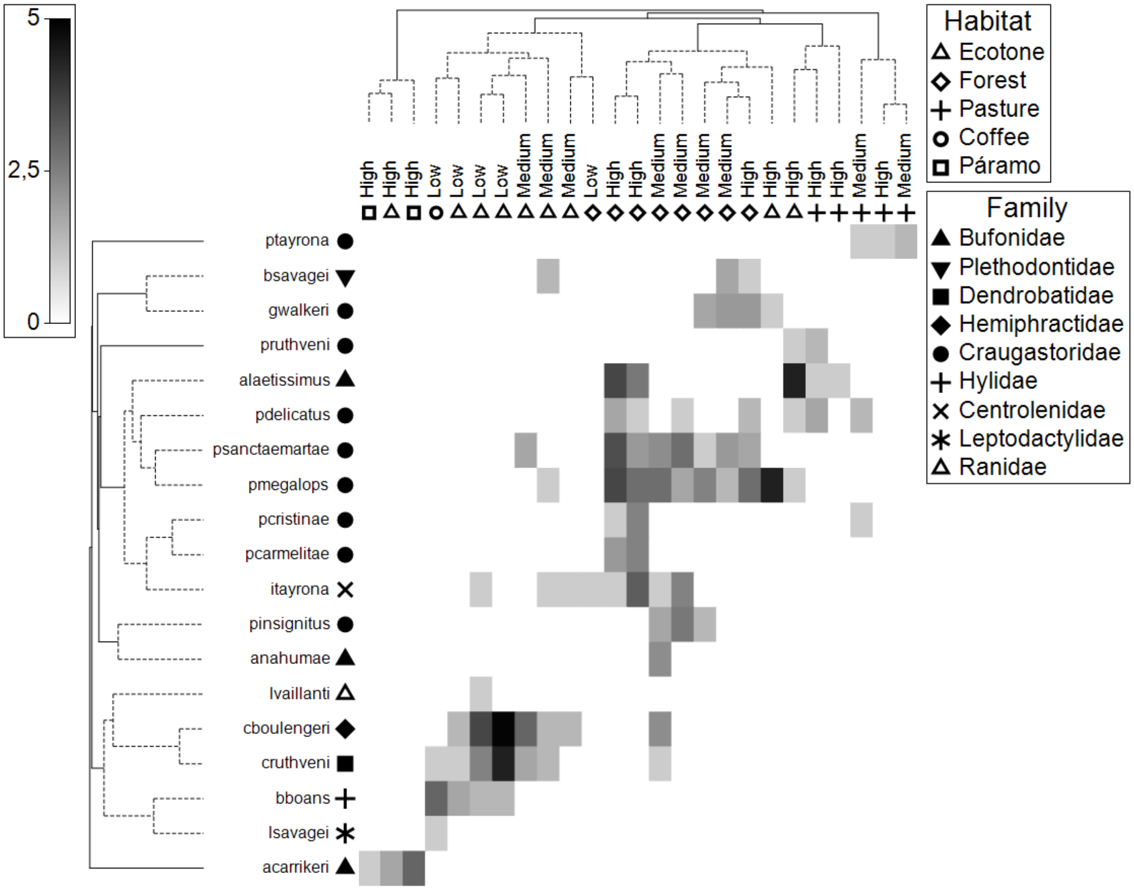

Figure 6. A species heat map of the entire amphibian community (19 species) encountered during this study at all occupied sites (24). For each species (left tree) their association degree with land cover type along the altitudinal range is represented (Whittaker index) with a grey scale; darker tones equate to higher abundance. There are strong species clusters associated with land covers, represented by the diagonal pattern across the heat map.

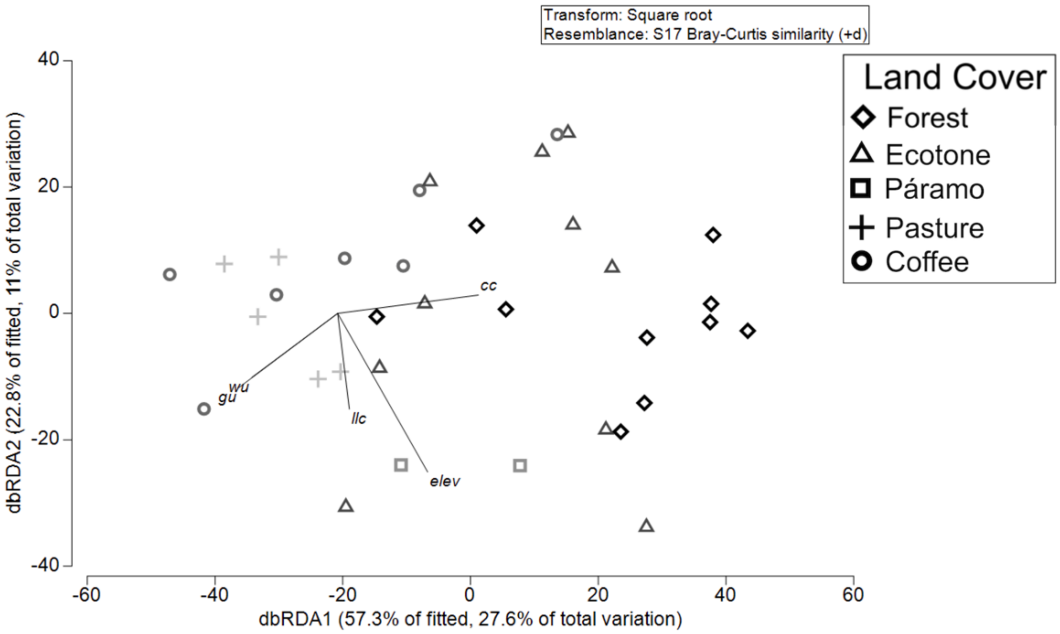

Figure 7. Distance based redundancy analysis demonstrates that the environmental variables explained changes in amphibian community structure along two axes of variation. Sites with more canopy cover (forest and ecotone) are grouped together on the upper right hand side and sites with more understory and lower canopy covers (agricultural sites) are grouped on the lower left hand side of this graph. High elevation páramo and ecotone sites align across the bottom. Microhabitat variable codes are as follows: elev = elevation; cc = canopy cover; gu = grassy understory density; wu = woody understory density; llc = leaf litter cover.

2.7 Tables

Table 1. Estimators of species completeness, by land cover type x elevation, including Chao, jackknife and bootstrap estimators. Completeness is estimated by (Index Estimate/S_{obs}) * 100. Community representation equals S_{obs}/19, and represents the contribution of each land cover type of the total species pool.

Land Cover	S_{obs}	Chao1	Chao2	Jackknife1	Jackknife2	Bootstrap	Mean Completeness	Range Completeness	Community Representation
Forest (H)	9	9	9.5	9.89	9.99	9.53	94.1	90.1 - 100	47.37
Forest (M)	10	10	12.25	12.75	13.73	11.32	84.2	72.8 - 100	52.63
Forest (L)	1	1	1	1.89	2.67	1.35	72.9	37.5 - 100	5.26
Ecotone (H)	6	6	10.5	8.75	10.49	7.21	73.2	57.1 - 100	31.58
Ecotone (L)	5	5	5	6.83	8.5	5.71	83.9	58.5 - 100	26.32
Ecotone (M)	1	1	1	1.89	2.67	1.35	72.9	37.5 - 100	5.26
Páramo (H)	1	1	1	1	1	1.02	99.6	98 - 100	5.26
Pasture (H)	4	4.25	5	5.78	5.97	4.9	78.4	67 - 94.1	21.05
Pasture (M)	3	3.5	5	4.67	5.47	3.76	68.9	54.8 - 85.7	15.79
Coffee (M)	0	0	0	0	0	0	0.0	0	0
Coffee (L)	3	3	5	4.83	5.74	3.82	70.6	52.3 - 100	15.79
all samples	**19**	**19**	**23.5**	**21.97**	**23.94**	**20.34**	88.0	**79.4 - 100**	**100**

Table 2. Abundance of individual species by land cover type and elevational range, and IUCN Red List status from 2019. Endemic species are denoted by *. Land covers: E = ecotone, F = forest; C = coffee, Pa = pasture; Pár = páramo.

Land Cover Type		**E**			**F**			**C**		**Pa**		**Pár**	**Total**
Species	**IUCN Status**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**M**	**H**	**H**	**--**
Atelopus carrikeri	EN*	0	0	3	0	0	0	0	0	0	0	10	13
Atelopus laetissimus	EN*	0	0	19	0	0	20	0	0	0	2	0	41
Atelopus nahumae	EN*	0	0	0	0	5	0	0	0	0	0	0	5
Bolitoglossa savagei	NT	0	2	0	0	3	1	0	0	0	0	0	6
Colostethus-ruthveni	NT*	26	5	0	0	1	0	1	0	0	0	0	33
Cryptobatr-achus boulengeri	VU*	39	13	0	0	5	0	0	0	0	0	0	57
Geobatrach-us walkeri	EN*	0	0	1	0	7	4	0	0	0	0	0	12
Boana boans	LC	7	0	0	0	0	0	9	0	0	0	0	16
Ikakogi tayrona	VU*	1	2	0	1	7	11	0	0	0	0	0	22
Leptodactylus savagei	LC	0	0	0	0	0	0	1	0	0	0	0	1
Lithobates vaillanti	LC	1	0	0	0	0	0	0	0	0	0	0	1
Pristimantis carmelitae	EN*	0	0	0	0	0	10	0	0	0	0	0	10
Pristimantis cristinae	EN*	0	0	0	0	0	7	0	0	1	0	0	8
Pristimantis delicatus	EN*	0	0	1	0	1	6	0	0	2	3	0	13
Pristimantis insignitus	NT*	0	0	0	0	12	0	0	0	0	0	0	12
Pristimantis megalops	NT*	0	1	20	0	19	29	0	0	0	0	0	69
Pristimantis ruthveni	EN*	0	0	1	0	0	0	0	0	0	2	0	3
Pristimantis sanctamartae	NT*	0	3	0	0	18	19	0	0	0	0	0	40
Pristimantis tayrona	NT*	0	0	0	0	0	0	0	0	3	1	0	4
Total Abundance													**366**

Table 3. Results from the two-way PERMANOVA analysis of amphibian community structure, richness, and total abundance that included landscape as covariable, and elevation and land cover type as factors.

							Estimated component of variance	
	Source	**DF**	**SS**	**MS**	**Pseudo-F**	**P(perm)**	**Estimate**	**Sq. Root**
Community composition	Landscape	1	3210.300	3210.300	35375.000	0.001	21931.000	46831.000
	Elevation	2	18170.000	9085.200	10 011.000	0.000	240.580	15511.000
	Land Cover	4	39486.000	9871.600	10878.000	0.000	495.110	22251.000
	Elevation X Land Cover**	4	21698.000	5424.600	59775.000	0.000	473.190	21753.000
	Residuals	93	84397.000	907.500			907.500	30125.000
	Total	104	167000.000					
Species richness	Landscape	1	0.032	0.032	0.034	0.855	0.009	0.094
	Elevation	2	16.477	8.238	8.623	0.001	0.214	0.463
	Land Cover	4	85.157	21.289	22.282	0.000	1.123	1.060
	Elevation X Land Cover**	4	71.441	17.860	18.693	0.000	1.771	1.331
	Residuals	93	88.855	0.955			0.955	0.977
	Total	104	261.960					
Total abundance	Landscape	1	49.358	49.358	4.428	0.037	0.364	0.603
	Elevation	2	124.060	62.032	5.565	0.005	1.497	1.224
	Land Cover	4	526.710	131.680	11.812	0.000	6.657	2.580
	Elevation X Land Cover**	4	631.380	157.840	14.160	0.000	15.368	3.920
	Residuals	93	1036.700	11.148			11.148	3.339
	Total	104	2368.200					

Table 4. Pearson's correlation matrix of all environmental variables in analyses.

Variable	Elevation	Slope	Leaf Litter Depth	Leaf Litter Cover	Woody Understory	Grassy Understory
Slope	0.08					
Leaf Litter Depth	-0.41	-0.21				
Leaf Litter Cover	-0.23	0.10	0.35			
Woody Understory	0.21	-0.31	-0.12	-0.12		
Grassy Understory	0.31	-0.23	0.10	-0.29	-0.20	
Canopy Cover	-0.62	0.11	-0.05	0.39	0.03	-0.63

Table 5. AICc results of the best-adjusted models that explained the variation in the distribution of amphibian structure based upon environmental variables. We report the best model per number of variables (from 1 to 7 variables) and the models are ranked based upon AIC_c values. 1 = Elevation; 2= Slope Average; 3 = Leaf Litter Depth Average; 4 = Leaf Litter Cover Average; 5 = Woody Understory Average; 6 = Grass Understory Average; 7 = Canopy Cover Average.

AICc	R^2	RSS	No.Vars	Selections
256.29	0.48075	40942	5	1,4-7
256.98	0.42182	45589	4	1,5-7
257.41	0.36494	50073	3	1,5,7
257.45	0.51101	38556	6	1,3-7
259.11	0.27963	56800	2	1,7
259.73	0.5276	37248	7	All
263.22	0.12723	68816	1	7

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CHAPTER III

VULNERABILITY OF GLOBALLY THREATENED ENDEMIC AMPHIBIANS TO CLIMATE CHANGE IN AN ISOLATED MONTANE ECOSYSTEM

3.1 Overview

Climate change and habitat loss or fragmentation play a significant role in biodiversity loss. Neotropical montane amphibians are particularly sensitive to these threats. Colombia, a megadiverse country, is home to the world's second largest number of amphibians. The Sierra Nevada de Santa Marta (SNSM), an isolated mountain range, is home to 48 amphibian species and 17 are endemic. We aimed to address climate vulnerability of the amphibian community in the SNSM from 800 – 3,600 m. Our goal was to prioritize amphibian species at risk and conservation actions in this globally important biodiversity area. We conducted three visual encounter surveys from September 2017 – July 2018. In order to assess species vulnerability, we conducted two independent spatial analyses. First, we calculated species' Area of Habitat, or the habitat available to a species'. Area of Habitat was refined (from the original IUCN EOO values) for the majority of amphibian species, averaging a reduction in available suitable habitat by 71%.

We then examined climatic niches of 16 species and the subsequent predicted change in available climate niche space for species under two RCP scenarios 4.5 and 8.5 for 2050. The overlap of climate niche space amongst our focal species, revealed a large reduction in current climate space for species under both RCP 4.5 and 8.5 scenarios (2050). We used these two analyses alongside trait data, obtained from previous research, to create a combined (correlative-trait) climate change vulnerability assessment (CCVA) for 19 focal species (16 endemic). Our vulnerability assessment identified seven high priority species, including all three *Atelopus spp* and four within the *Pristimantis* complex. Given its isolation, the SNSM and endemic species are particularly susceptible to changing climates. The information provided from the CCVA offers a platform to develop climate change adaptation and conservation strategies in the region.

3.2 Introduction

Globally, over one-fifth of vertebrate species are threatened with extinction (Hoffmann et al., 2010). Climate change, habitat loss or fragmentation, pollution, and species exploitation all play a significant role in biodiversity loss (Bellard et al., 2012; Lacher and Roach, 2018; Parmesan et al., 2011; Urban, 2015). Climate change may have particularly detrimental impacts on montane species (Anderson, 2013; Elsen and Tingley, 2015; La Sorte and Jetz, 2010), including loss of habitat and species homogenization (Jantz et al., 2015; Menéndez- Guerrero et al., 2019; Nowakowski et al., 2018) and reduction in adaptive divergence along steep elevational gradients (Bachmann et al., 2020). In order to assess species vulnerability to climate change, researchers may employ a number of methods and modeling types (Elith et al., 2010; Harris et al., 2014; Peterson et al., 2015). Species vulnerability assessments are a good tool used to understand species vulnerability to climate change scenarios and prioritize actions (Foden et al., 2019; Foden and Young, 2016; Pacifici et al., 2015).

In 2016, the International Union for Conservation of Nature (IUCN) Climate Change Specialist Group produced the climate change vulnerability assessments (CCVAs) guidelines; a useful conservation tool applied to understand the threats and subsequent vulnerability to extinction risk that species will experience under various climate change scenarios (Foden and Young, 2016; Pacifici et al., 2015). Vulnerability is defined as the net effects of species sensitivity (S; intrinsic factors such as genetic diversity and dispersal capability) and exposure (E; extrinsic factors i.e. habitat loss, disease, invasive species) minus adaptive capacity (AC; the ability of a species to cope with or adjust to a given change and includes both behavioral and ecological plasticity and evolutionary adaptation; expressed as S+E – (AC) (Foden et al., 2019; IPCC, 2014).

There are four common methodological approaches to vulnerability assessments: correlative, mechanistic, trait-based, and combined approaches (Foden et al., 2019; Foden and Young, 2016). Correlative models are frequently used in CCVAs because there is more widespread availability of data on associations of species occurrence with environmental information. Mechanistic modeling approaches reduce uncertainty but are limited because physiological data can be difficult to obtain for many species (Peterson et al., 2015). The spatial scale at which data is collected is of critical importance to reducing model and predictive uncertainty (Austin and Van Niel, 2011; Trivedi et al., 2008). Trait-based assessments can be useful tools for prioritizing conservation action, but again, trait data are not widely available for all species (Böhm et al., 2016). Combined approaches use one or more of the aforementioned modeling techniques to assess vulnerability. Rare and dispersal-limited species, such as amphibians, pose a challenge to CCVAs given the lack of data and verifiable modeling techniques, which have not been refined for small range species with minimal locality data. Yet, local species assessments are important for conservation efforts and directly feed back into conservation action plans.

Amphibians are the world's most threatened vertebrate class and 31% of species are currently threatened with extinction (Stuart et al. 2004; IUCN 2019). Limited dispersal, small range sizes, and life history strategies often make amphibians more susceptible to climate change impacts (Agudelo-Hz et al., 2019; Bernal and Lynch, 2008; Cheza et al., 2020; Prieto-Torres et al., 2020). Over 3,300 species of amphibians can be found exclusively in mountain ranges

(Rahbek et al., 2019). Montane amphibians are threatened with habitat loss, climate change, pollution, and disease (Lips et al., 2008; Scheele et al., 2019; Whitfield et al., 2016). In the tropics, species experience smaller seasonal variation and have narrow physiological tolerances, specific thermal niches, and small population sizes (Janzen 1967; Deutsch et al. 2008). Most amphibians prefer cool, damp, and stable microclimates (Semlitsch, 2003) and small shifts in microhabitat or microclimate conditions can impact physiology, population dynamics, and habitat use (Rivera-Ordonez et al., 2019). Endemic species, with contracted ranges and limited dispersal, can be particularly difficult to assess given mismatches between data collection and resolution and modeling techniques. Yet, endemic species are some of the most vulnerable to habitat loss and climate change (Lowrey et al., 2016; Mayani-Parás et al., 2019). It is important to identify direct and indirect threats and provide strategies to reduce species extinction risk.

Colombia is the country with the second highest amphibian diversity (838 described species; https://www.batrachia.com/; Galvis Acosta 2019). There are 366 endemic species and 174 are threatened with extinction (IUCN Red List 2019; Table 8a). The Colombian Andes are an amphibian diversity hotspot and encompass a number of key conservation areas (Bernal and Lynch, 2008; Etter et al., 2006; Navas, 2006, 2003). Our study region, the Sierra Nevada de Santa Marta (SNSM), while isolated from the Andean chain, is an important hotspot of global amphibian endemism with 17 endemics, including 10 threatened with extinction (IUCN Red List 2019).

Our objective was to assess amphibian vulnerability to climate change in the SNSM. Previous studies in the region demonstrated that climate change would lead to shifts and contractions in amphibian ranges and an increase in unsuitable land within these new ranges (Forero-Medina et al., 2011). In order to provide guidance for amphibian conservation initiatives we conducted two independent analyses. First, we examined current species ranges on the IUCN RL (Extent of Occurrences, EOO) and refined these ranges through environmental filtering (Ocampo-Peñuela et al., 2016) to create an Area of Habitat (AOH) for each species. Second, we identified the current available climatic niche space for our focal species and modeled future niche space under two climate scenarios (RCP 4.5 and RCP 8.5). Finally, we used trait data from previous literature and amphibiaweb (https://amphibiaweb.org/) to inform our CCVA. These three methods were used to produce a CCVA and prioritize species for conservation action. We hypothesized that endemic, aquatic breeders, would be more vulnerable to climate impacts as suitability of breeding sites would likely decrease through altered precipitation patterns and elevated temperatures. In addition, range restricted species with little protected area coverage would be exposed to elevated risk. Finally, we suggest action steps to mitigate the impact of climate change for particularly vulnerable species.

3.3 Methods

3.3.1 Study Site

The SNSM is one of the world's tallest coastal mountain ranges, rising from sea level to 5,775 m asl in 42 km. The region is categorized by high levels of elevational zonation and biodiversity. Le Saout et al. (2013) ranked the SNSM the most irreplaceable site on earth, based on the mountain's isolation and high levels of amphibian endemism. The SNSM is also a UNESCO Biosphere Reserve, a National Park (Sierra Nevada de Santa Marta National Park and Tayrona National Park), an Important Bird Area, an Alliance for Zero Extinction Site, and a Key Biodiversity Area (González-Maya et al., 2011).

The isolation, caused partially by intense shifts in topography, of the SNSM has historically shielded it from extremely high levels of development. Land above 2,500 m is protected as a National Park and Indigenous territories. Below 2,500 m the majority of land is comprised of private lands (agriculture, tourism, nature reserves). Small-scale agriculture from the four indigenous cultures (Kogui, Arhuaco, Wiwa, and Kankuamo) and a thriving *campesino* (farmer) population impact habitat suitability for amphibians. Deforestation through small-scale agricultural enterprises have reduced connectivity in the region (Granados-Peña et al., 2014). Recent improvements to infrastructure have increased development and tourism also leading to the degradation of intact habitat. Resource extraction, agricultural intensification, and climate change are the biggest threats to amphibian species in the region (Aide and Cavelier, 1994; Roach et al., 2020).

3.3.2 Field Methods

Amphibian visual encounter surveys (Heyer et al. 1994) were conducted on the north-western slope of the SNSM, in the department of Magdalena (Fig. 8). Surveys were conducted at 35 transects across three elevational bands (Low: 800 – 1,200 m; Mid: 1,200 – 2,000 m; and High: 2,000 – 3,700 m), and five land cover types (Fig. 8). We also collected data on relevant environmental variables on each transect including: slope, elevation, canopy cover, leaf litter cover, leaf litter depth, woody understory density, grassy understory density. Methods of data collection are described in detail in Roach et al. (2020).

3.3.3 Statistical Methods; Area of Habitat

We used IUCN Red List (hereafter IUCN RL) Extent of Occurrence (EOO) polygons (IUCN 2017), to calculate Area of Habitat (AOH), defined as the "*habitat available to a species, that is, habitat within its range*" (Brooks et al. 2019; Table B1). EOO polygons are minimum convex polygons that represent the dispersion of risk for species to threats. They are often the only available spatial data for species on the Red List, especially when there are too few data points to calculate Area of Occupancy (AOO), the equivalent of range in IUCN terminology. None of the 19 species in the study had AOO estimates, common for rare endemics. Following the published methodology (Brooks et al. 2019), AOH was derived for 18 of the 19 species. We included two of our three non-endemic species: *Leptodactylus savagei* and *Lithobates vaillanti*, both of which have largely Central American distributions, but with disjunct populations in the SNSM. We did not include *Boana boans*, which is broadly distributed throughout the Amazon Basin and the northern Pacific coast of South America, but there is considerable taxonomic confusion on which *Boana* species occurs in the SNSM on amphibiaweb.org. In addition, all three non-endemic species are classified as Least Concern on the RL and not priority candidates for a vulnerability assessment. We filtered EOO polygons for all study species according to the published elevation range and land cover classifications taken from the most recent IUCN RL Assessments for each species (Table B1). We used elevation data from the Shuttle Radar Topography Mission digital elevation model version 4.1 (Jarvis et al. 2008) at a resolution of 250 m and land cover data from the 2018 European Space Agency Climate Change Initiative Land Cover product at a resolution of 300 m. Both raster layers were resampled to ~ 1 km resolution. The resulting polygons representing AOH for each species were validated using point data obtained from the Global Biodiversity Information Facility (GBIF; doi:10.15468/dl.ihs3es; doi:10.15468/dl.hcqkns), following the prescribed methodology (Brooks et al. 2019). Additionally, for each species, we calculated percent coverage of protected areas for all AOH estimates using the most recent shape files from www.protectedplanet.net available through the World Database on Protected Areas (WDPA; UNEP-WCMC 2019) of the IUCN World Commission on Protected Areas.

3.3.4 Climate Niche Ordination and Analysis

The assessment of the vulnerability of species to climate change is now a critical part of IUCN Red List Assessments, and studies range from coarse-scale global analyses (Foden et al., 2013; Pacifici et al., 2017), to species interactions (Gómez-Ruiz and Lacher, 2019) and detailed species-specific assessments (Vicenzi et al., 2017). There are multiple available modeling approaches, and species distribution models are most widely used, but they present limitations when assessing the risk for rare, range-restricted endemics with few presence data points due to model overfitting (Breiner et al., 2015). Several new approaches present alternatives focused on niche ordinations for studies of invasive species and climate change (Broennimann et al., 2012; Di Cola et al., 2017; Guisan et al., 2014).

To assess current and future climate space of the focal species within the SNSM, we examined the realized niches of species in current climate space and calculated how the availability of current suitable climate space shifts under two climate scenarios. We used species occurrence data from GBIF (doi:10.15468/dl.ihs3es, doi:10.15468/dl.hcqkns) to supplement the records collected from our visual encounter surveys and generate a minimum of five observations for all species (Proosdij et al., 2016). We removed duplicate localities, those with high georeferencing uncertainty, samples outside of a species' known elevation range, and samples with taxonomic uncertainty. We defined our geographic extent for analyses as the entire range of the SNSM, which would encompass all available habitats from sea level to 5,775 m for 14 of our focal montane species (out of 16 modeled) given their geographical restrictions, with a one-degree buffer around the SNSM to include potential low elevation, non-montane climates.

We used the ecospat package ecospat.grid.clim.dyn (for niche quantification) in R (Broennimann et al., 2017; Di Cola et al., 2017) to estimate the climatic niche for 16 of our focal species. The endemic species *Atelopus nahumae* and *Pristimantis carmelitae* did not have sufficient occurrence data to include in the analysis, and we excluded the broadly distributed *Boana boans* for reasons discussed earlier. For variables, we considered the 19 climatic variables from WorldClim version 1.4 (Hijmans et al., 2005, Table B2) at a spatial resolution of ~ 5 km to take into account the potential errors associated with the temporal heterogeneity of the date of collection of GBIF records and the recently collected occurrence records. We used a principal component analysis (PCA) of the climatic variables to conduct an ordination to project available climate space for the study region by selecting the first two PCA axes, representing 64.8% and 13.8% of the variation, respectively, and transforming them into a 100 x 100 cell grid. We then plotted the PCA scores (Table B3) of the species distributions onto the grid of cells in climate space. Rather than a minimum convex polygon, we applied a kernel density function (Broennimann et al. 2011, Di Cola et al. 2017) with smoothed occurrence densities for each species using standard smoothing parameters (see Silverman, 1986; Figs. B1 and B2) and the kernel threshold set to the default of 0. These were then converted to NA. We used these polygons to determine the climate space occupied by each species within the study extent (Tingley et al., 2016) defined as CENV (current climate envelope) for each species. By taking into account the scale of the study at 5 km (within an area of > 35,000 km^2), it should reduce any clustering of occurrence points without compromising the already small sample sizes of points.

To determine how climate change shifts the available climatic space for each species, and how this is reflected in geographic space, we considered two representative concentration pathways (RCPs) for 2050: 4.5 and 8.5. These were chosen to represent medium- and high-risk scenarios for the time period considered (Harris et al., 2014). We chose 17 general circulation models (GCMs, Table B4) used for both RCPs in the Fifth Assessment Report (AR5) of the

Intergovernmental Panel on Climate Change that are downscaled, interpolated, and calibrated to produce predictions of the 19 WorldClim bioclimatic variables (Hijmans et al. 2005; Table B2). Considering 17 GCMs and their respective predictions for our climate variables of interest provides a more comprehensive view of the climate uncertainty in this region for this 30 year time period (Beaumont et al., 2008).

For each GCM, RCP, and species combination, we calculated climatic space using a PCA of the 19 climate variables in both current and future scenarios for the study region. We produced 272 total rasters (17 GCMs x 16 species) for each RCP 4.5 and 8.5 scenario, respectively. By linking the PCA values relating to the future climate scenarios to each species, we can calculate and compare where a species is predicted to occupy in a shift from current to future climatic space. We then projected our model built in climatic space to geographic space using ecospat.grid.clim.dyn. We totaled the outputs of climate niche for each species for all 17 GCMs in each cell and the uncertainty for each climate prediction was calculated using a score of 1 when a gridded cell indicated the species is found across all 17 models, a score of 0 means it never occurred in a cell. The climate niche space was then calculated for each species with the mean and standard deviation to indicate the uncertainty in the climate niche estimate. The sum of species averages was used to determine the predicted species richness for each cell in 2050 at each RCP and produced an estimate of species overlap that took into account the uncertainty of the 17 models (Fig. B2). This also enabled the use of anomaly maps and explicitly indicates regions of major species loss.

3.3.5 Vulnerability Ranking

We compiled information on variables that represented exposure, sensitivity, and adaptive capacity of species to climate change. Exposure variables included current and future climate niche space and protected area coverage (World Database of Protected Areas: https://www.protectedplanet.net/). Sensitivity variables included land cover use from Roach et al. (2020) and available trait data (amphibiaweb.org; Stuart et al. 2008; Mendoza- Henao et al. 2019) which included feet webbing (indicator for water dependency), reproductive development modes (plasticity in habitat use) and endemism (dispersal capability). To assess adaptive capacity (AC) we used species' land cover usage (Roach et al. 2020), trait data, and information provided by previous studies on abundance, thermal tolerance, and epidemiology (Navas et al., 2013; Roach et al., 2020; Rueda Solano et al., 2016a; Rueda-Solano et al., 2016b).

To calculate a percentage of the total climate space (ENV) occupied by each species, the area of the kernel density surface, created for each species, was compared to the area of total climate space found in the study area. If space occupied under the two RCP scenarios was less than the current climate space, then the reported ENV would be smaller than CENV and can be expressed either in terms of the mean vales with standard deviations from the 17 GCM runs, or as a percent of mean of the current CENV. We similarly ranked ENV from 5 (occupying below 20% of the CENV for that species) to 1 (occupying above 80% of the CENV). To account for uncertainty in the projections, we calculated and present the mean and standard deviation of the estimated kernel density results. Protected areas were ranked by the percentage of total coverage 1 = 75 – 100%; 2 = 50 – 75; 3 = 25 – 50; 4 = 10 – 25; 5 = < 10.

To rank the AOH of our species, we used the range of the area of distribution sizes (IUCN RL) for all Colombian amphibians with distribution polygons available. We calculated the distribution area for each species that overlapped Colombia (setting the maximum distribution area allowed to the area of Colombia to reduce outliers caused by widespread species). We then determined the quintile cutoff thresholds considering all of these values to rank our species from 5 (small AOH comparable in size to the lowest 20% of Colombian amphibian distributions) to 1 (large AOH comparable in size to the top 20% of Colombian amphibian distributions). Land cover data was ranked from 1 – 3; 1 = agriculture habitat; 2 = mixed habitat use (natural and agricultural), and 3 = habitat specialists that only used natural habitat (forest or páramo – a high elevation natural grassland habitat). We ranked trait data as a 1 – 3 for feet webbing (higher score of 3 for complete dependency on water); 1 or 2 for reproductive development modes (1 = direct developer; 2 = non-direct developer); and 1 (non-endemic) or 2 for endemic species.

Trait and spatial data collected relevant to adaptive capacity of species was evaluated amongst co-authors when identifying species of low – high risk. If species were able to use mixed types of land cover (natural and anthropogenic), we assumed them to be more adaptable to environmental degradation. Previous literature supports findings that some species, like *Atelopus carrikeri*, may be resilient to changing temperatures (Rueda Solano et al., 2016), which would increase their AC. Yet, many of our focal species are dispersal limited, reducing their AC. Future studies on amphibian adaptive capacity would improve the predictions of at risk species (Beever et al., 2016).

We quantitatively ranked species based on the aforementioned information. We then discussed each species ranking individually amongst co-authors, taking into account expert opinion, adaptive capacity, and anecdotal evidence (e.g. importance of high flow streams for some species that was noted in the field but not specified in the data collection). Each species was given a ranking from low – high vulnerability (Table 6) and a justification for their subsequent ranking (Table B5).

3.4 Results

3.4.1 Area of Habitat

Filtering range polygons by elevation and habitat characteristics more accurately quantifies area suitable for species, but reduces the area of EOOs (Fig. 9). Reduction in suitable area of AOH (due to filtering by elevation and habitat limits), ranged from a minimum of 41% to a maximum of 97% of the EOO, with an average reduction in area by 71%. Many species had significant decreases in available habitat when AOH was calculated (Fig. B3). Ranges for *Atelopus laetissimus*, *Atelopus nahumae*, and *Pristimantis carmelitae* were reduced to less than 10% of their original EOO.

3.4.2 Climate Niche Overlap Analysis

Sixteen amphibian species found during our surveys had at least five records, enabling kernel density estimation via ecospat. These species varied in how much and what parts of climate space they occupied (Table 6). The total amount of climate space available for species ranged from 0.97% (*Pristimantis cristinae*) to 33.97% (*Leptodactylus savagei*) with an average of 8.67% (Table B6). The largest amount of overlap among the community in climate space occurred at mid-range values of PC1 and low values of PC2. PC1 is typically negatively associated with temperature and positively associated with precipitation, whereas lower PC2 scores are associated with higher isothermality (diurnal temperature fluctuates relative to annual averages) and higher precipitation (Table B3). When translated to geographic space, the hotspots of amphibian suitability are centered to the west and northwest of the mountain range, typically above 1,500 m (Fig. 10). With the exception of *Leptodactylus savagei* and *Lithobates vaillanti*, the environmental space occupied by most species is relegated to mid-elevation bands between 1,500 m and 3,000 m (Fig. 10).

The two climate scenarios examined (RCPs 4.5 and 8.5) show similar results (Fig. 10), with a decrease in regions suitable for multiple species and dissolution of an amphibian hotspot, with many species shifting eastward in the 4.5 models. This is due to available environmental space decreasing at the extremes, notably in the areas of increased precipitation as well as the lack of annual temperature fluctuation found in low values of PC2. The main difference among the two climate scenarios for 2050 is more environmental space is lost and the anomaly change for species richness is larger in the RCP 8.5 climate models. Means and standard deviation of climate space decrease from 4.5 to 8.5 for each species except *L. vaillanti*, a lowland species which gains elevation (Table 6). Additionally, there is a decrease in species overlap along the western end of the mountain range (Fig. 10).

3.4.3 Vulnerability Assessment

We ranked species from low to high vulnerability (Table 6). The majority of species have low AC as they are endemic, dispersal limited and usually occur in few locations of only 1 – 2 types of land cover. Additionally, the majority of species had a small AOH and occupy low climate envelopes for both RCP scenarios, and therefore trended toward moderate-high vulnerability. All three *Atelopus* species were ranked "high" for extinction risk. *Atelopus* are the most threatened amphibian genus in the world (Granda-Rodríguez et al. 2020; IUCN 2019). Unlike *Atelopus* populations in Central America, *Atelopus spp* in the SNSM have not been heavily affected by *Chytridiomycosis* (Flechas et al., 2017; Lips et al., 2004; Whitfield et al., 2016). The biggest threat to *Atelopus* in the SNSM is habitat loss or degradation and climate change. Most amphibian research attention in the SNSM has been focused on *Atelopus* life-history and population dynamics, including thermal ecology and epidemiology (Navas et al. 2013; Rueda-Solano et al. 2016a; Rueda Solano et al. 2016b; Granda-Rodríguez et al. 2020).

Further information on *Atelopus*' populations and distribution will be useful to improve predictions of extinction risk.

The *Pristimantis* species complex is of particular concern given all species are endemic, have small AOHs, and experience significant losses in climate niche space from 4.5 to 8.5. They are also some of the most understudied species in the SNSM. The only species that ranked low on the CCVA were the three non-endemic species (*B. boans*, *Lithobates vaillanti*, and *Leptodactylus savagei*). Two endemic species ranked low-medium (*Colostethus ruthveni* and *Pristimantis megalops*), largely based on their capability to persist in disturbed habitats and their relatively high levels of abundance (Roach et al., 2020). Species justifications for vulnerability rankings, including their associated threats, are highlighted in (Table B5).

3.5 Discussion

Previous CCVAs have yielded useful results to set spatially-explicit conservation priorities (Böhm et al., 2016; Gardali et al., 2012; von May et al., 2019). Although vulnerability assessments are not directly comparable (Foden et al., 2013), because they are site and species specific, they can be very useful at a local or regional scale. Currently, the National Parks Service in the SNSM does not have an amphibian conservation action plan. We employed various methods (AOH, climatic niche ordination, protected area coverage, and trait data) to create a CCVA that provides guidance about amphibian vulnerability under different warming scenarios in the hope that conservation practitioners can prioritize amphibian conservation in this globally important montane region of endemism.

Our results demonstrate decreased suitability in available climatic niche space for the majority of our study species. The high-risk species all occur above 1,500 m in elevation. Our results show a loss of low to mid elevation (0 – 2,500 m) habitat suitability where many species are currently living close to their upper thermal limits. The northwestern section of the SNSM is currently characterized by high precipitation. Both RCP models predict decreased precipitation in this northwestern section representing a significant threat to amphibian habitat. In addition, the possibility of local land users growing crops in previously undisturbed forested habitat due to altered temperature and precipitation levels may also reduce amphibian habitat and population sizes (Etter et al., 2006; Laurance et al., 2014). Our models for 2050 show new climate space that does not currently exist in the SNSM in regions above 3,000 m. Given the lack of data availability above 3,000 m, and the fact that this elevational range falls outside the limits for 14 of our focal species, our modeling approach does not allow us to make predictions above 3,000. The elevational transition from upper montane rain forest to sub-páramo also begins at 3,000 m, representing a major change in vegetation structure (Peyre et al., 2018). There is also uncertainty associated with the dispersal ability of our focal species and they may not be able to disperse to new habitats regardless of climate availability.

In Latin America, the impacts of climate change on montane amphibian species paint a glum narrative (Agudelo-Hz et al., 2019; McCain and Colwell, 2011; Menéndez- Guerrero et al., 2019). Seven of our focal species were ranked high on the vulnerability assessment; yet current conservation action in the region is primarily aimed at *Atelopus* species. Four *Pristimantis* species (*carmelitae, cristinae, delicatus, insignitus*) ranked high on the vulnerability assessment. Small-bodied direct-developers (such as *Pristimantis*) may be potentially more susceptible to thermal stressors than other species (von May et al., 2019). These species are forest dwellers, though some in the SNSM also tolerate ecotone and pasture. Studies from other Andean countries have shown a reduction in *Pristimantis* habitat under RCP 4.5 and 8.5 climate scenarios (Cheza et al., 2020), while other studies have found that direct developers, like

Pristimantis, may even be more susceptible to *Chytridiomycosis* (Mesquita et al., 2017). *Pristimantis spp.* are an important but overlooked research priority in the region. It will require data collection on the abundance, distribution, taxonomy, and threats to accurately assess the vulnerability of the *Pristimantis* complex. Currently, amphibian conservation action in the region includes data collection on known *Atelopus* populations and searches for new populations (Granda-Rodríguez et al., 2020) as well as education and engagement programs with local indigenous and *campesino* (rural farmer) communities.

In the SNSM, current land use practices and development may intensify habitat loss. For instance, the future availability of water and the protection of watersheds as microhabitats is of critical importance to safeguard amphibian habitat (Cortes-Gómez et al., 2013; Earl and Semlitsch, 2015; Nowakowski et al., 2017). Current agricultural practices often dump wastewater directly into streams and *microcuenas* (small watersheds), potentially increasing contaminant loads that may disrupt amphibian reproduction cycles (Boone et al., 2007). The predicted decreases in precipitation levels will likely result in reduced stream flow. Water-dependent breeders like *Atelopus* species are particularly vulnerable to reduction of water quality and volume and losses of breeding sites. Management and manipulation of water is a tool that has been successful in amphibian conservation, especially as drought frequency increases (Mathwin et al., 2020). Water scarcity is a critical impact of climate change and addressing water quality and availability has significance for biodiversity and human well-being (Mwenge Kahinda et al., 2019).

3.5.1 Challenges to Data Collection and Analysis

Most global models are on a scale that is too coarse to discern microhabitat features that are important to amphibian distribution and habitat use (Mendenhall et al., 2014). Using a variety of data sources and an assortment of analytical methods allowed us to build a more robust analysis of climate vulnerability in a region where reliable spatial data are scarce. Restricted data availability may limit our ability to robustly model species distributions across environmental space. The only local climate data station is at 2,500 m, at the San Lorenzo Biological Station. No local climate data stations exist above 2,500 m (on a mountain which reaches 5,775 m asl). Lack of fine-scale data from high elevation habitats makes it difficult to build reliable local climate models. Until we are able to reduce uncertainty, associated with lack of data for local climate models, we must continue to rely on global-scale models like WorldClim.

The majority of amphibian occurrence records in the SNSM come from the NW portion of the mountain range (near the city of Santa Marta). Other regions of the mountain, especially in the departments of Guajira and Cesar, remain largely understudied. The southern and eastern portion are not well explored and much of the land is indigenous territory. Researchers are not allowed to enter these regions without proper permits, which can take years to acquire. Difficult road accessibility, increasing conflict over land use, illicit activities, government corruption, and permitting issues remain barriers toward data collection and enforcement of conservation action.

3.5.2 Future Directions

As home to 85% of vertebrate species', mountains represent critical biodiverse regions that are particularly susceptible to land use and climate impacts (Newbold et al. 2015; Peters et al. 2019; Rahbek et al. 2019). Compounded local land use and local climate change also increase the threat of species extinction risk (Williams and Newbold, 2019). Slowing the impact of climate change will require collaborative conservation action. We must work across academic institutions, NGO's, government agencies, and private land owners to share data and resources to improve and reduce model uncertainty (Lacher et al., 2012). This type of collaborative action can improve model prediction and technologies that increase mitigation and adaptation schemes.

A recent example of local collaboration that led to a conservation success is the story of the "lost" amphibian species *Atelopus arsyecue.* After three years of collaboration with the Arhuaco Indigenous Sogrome community, a local NGO, Fundación Atelopus, was able to photograph the toad for the first time since the early 1990's (Mongabay 2019). This is an example of how local collaboration and expertise (biological and local ecological knowledge; Thornton & Scheer 2012; Petriello & Stronza 2020) and building community trust can lead toward the acquisition of new knowledge of an elusive species. Collaborative conservation initiatives with local schools, *campesinos*, and Indigenous groups will be important to engage diverse voices in the SNSM. Climate mitigation and adaptation targets must take place through a transparent and holistic understanding of shared conservation goals.

3.6 Figures

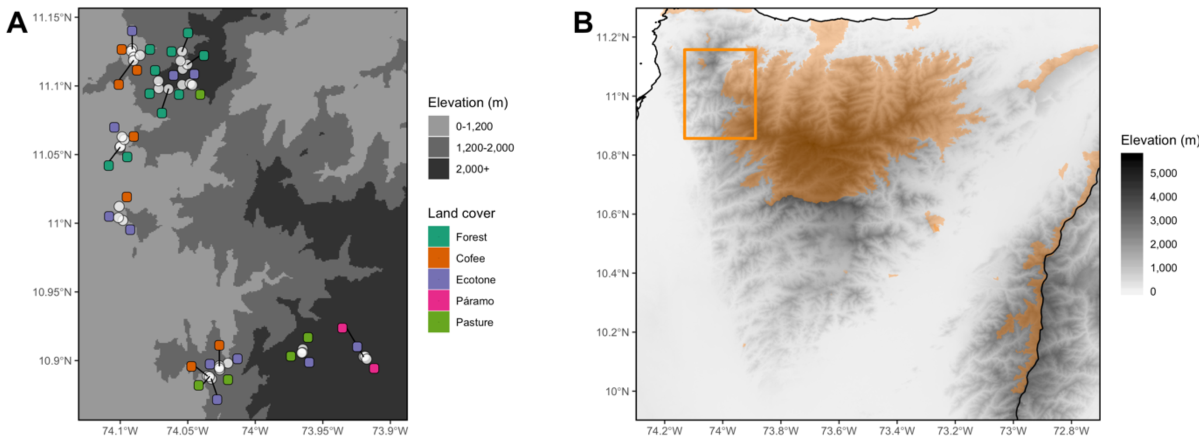

Figure 8. Elevation maps showing A) the sites chosen for amphibian surveys with colored boxes referencing the dominant land cover characteristics of the site and B) the extent of the Sierra Nevada de Santa Marta with protected regions highlighted in orange. The extent of panel A is depicted as an orange rectangle in panel B.

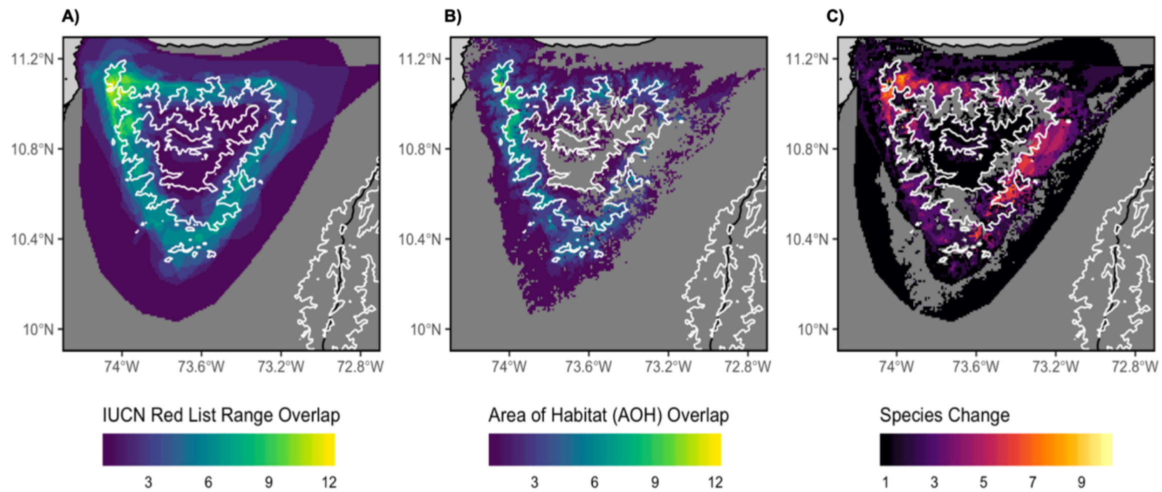

Figure 9. Maps showing the difference in species richness observed using A) IUCN Red List ranges (EOO) and B) Area of Habitat (AOH) polygons filtered for elevation range and available habitat, while C) an anomaly map shows where the change in species richness occurs. Contour lines delimit elevational ranges every 1,500 m.

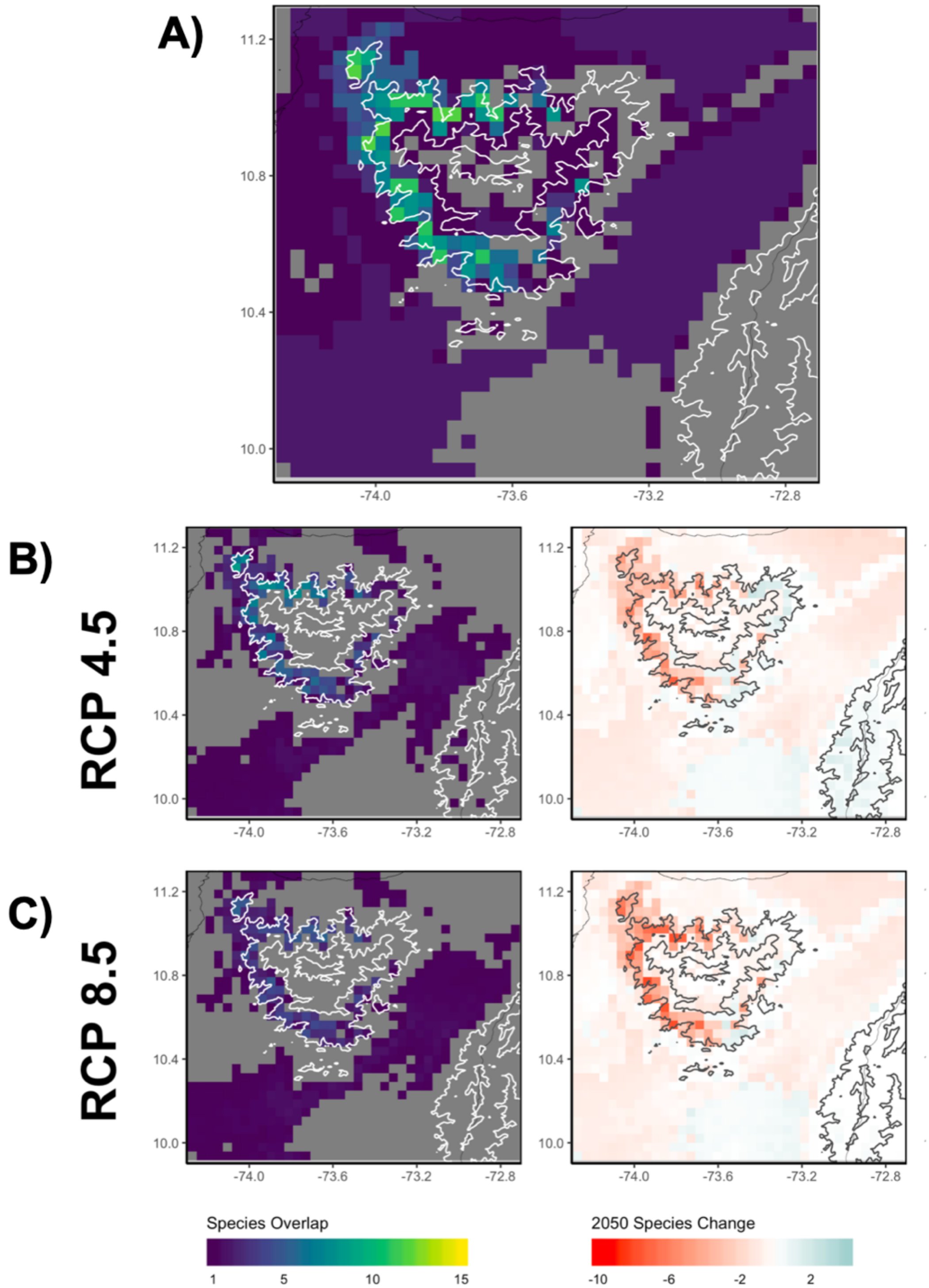

Figure 10. A) represents current species overlap. Below are the differences in B) RCP 4.5 and C) RCP 8.5 climate change scenarios, in regards to species overlap and anomaly maps of change in predicted species richness for each RCP scenario (2050 species change).

3.7 Tables

Table 6. Area-based and trait-based variables used in the regional climate change vulnerability assessment (CCVA) of amphibians in the Sierra Nevada de Santa Marta. AOH = Area of Habitat; CENV = current climate envelope as a percent of available climate space in the SNSM; ENV4.5 = projected climate envelope under RCP 4.5 as a percent of CENV; ENV8.5 = projected climate envelope under RCP 8.5 as a percent of CENV; PA% = protected area coverage in the AOH; E = endemic; FW = foot webbing; D = direct or non-direct development; Land Cover Types indicate the likely degree of habitat specificity; Vulnerability Assessments indicate our quantitative (Supplemental Material Table 10.1-10.5) and qualitative evaluation of the species vulnerability to climate change between now and 2050 based upon the available spatial and trait-based data.

SPECIES	AOH	CENV	ENV 4.5	ENV 8.5	PA %	E	FW	D	Land Cover	CCVA
Atelopus carrikeri	360.3	11.78	0.32	0.31	97.7	Yes	Very extensive	ND	Ecotone, Páramo	High
Atelopus laetissimus	24.3	6.57	0.35	0.28	87.07	Yes	Very extensive	ND	Ecotone, Forest, Pasture	High
Atelopus nahumae	182.3	NA	NA	NA	89.26	Yes	Very extensive	ND	Forest	High
Bolitoglossa savagei	1,705.2	1.47	0.51	0.33	53.03	Yes	Extensive	DD	Ecotone, Forest	Medium
Colostethus ruthveni	2,782.4	6.82	0.35	0.27	16.73	Yes	Reduced feet only	ND	Ecotone, Forest, Coffee	Low-Medium
Cryptobatrachus boulengeri	5,253.7	7.97	0.42	0.38	13.94	Yes	Absent	DD	Ecotone, Forest	Medium
Geobatrachus walkeri	467.7	15.06	0.36	0.31	61.9	Yes	Absent	DD	Ecotone, Forest	Medium
Boana boans	5,458,062.7	NA	NA	NA	"large"	No	Very extensive	ND	Ecotone, Coffee	Low
Ikakogi tayrona	3,028.0	7.35	0.6	0.49	26.35	Yes	Absent	ND	Ecotone, Forest	Medium
Leptodactylus savagei	199,864.0	33.97	0.54	0.52	37.73	No	Absent	ND	Coffee	Low
Lithobates vaillanti	379,236.3	15.08	0.85	1.08	"large"	No	Very extensive	ND	Ecotone	Low
Pristimantis carmelitae	8.4	NA	NA	NA	5	Yes	Absent	DD	Forest	High
Pristimantis cristinae	191.4	0.97	0.49	0.32	53.93	Yes	Absent	DD	Forest, Pasture	High
Pristimantis delicatus	10.9	3.05	0.4	0.28	0	Yes	Absent	DD	Ecotone, Forest, Pasture	High
Pristimantis insignitus	277.0	1.81	0.48	0.31	64.72	Yes	Absent	DD	Forest	High
Pristimantis megalops	1,138.2	6.28	0.42	0.36	37.24	Yes	Absent	DD	Ecotone, Pasture	Low-Medium
Pristimantis ruthveni	301.4	5.26	0.36	0.28	61.75	Yes	Absent	DD	Pasture, Páramo	Medium - High
Pristimantis sanctaemartae	2,762.3	6.18	0.38	0.28	34.91	Yes	Absent	DD	Ecotone, Forest	Medium
Pristimantis tayrona	1,842.1	9.13	0.38	0.31	47.11	Yes	Absent	DD	Pasture	Medium

3.8 References

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CHAPTER IV

UNDERSTANDING THE PERCEPTIONS AND MANAGEMENT STRATEGIES OF COFFEE FARMERS TO SUSTAIN LIVELIHOODS AND BIODIVERSITY IN AN ISOLATED COLOMBIAN MONTANE REGION

4.1 Overview

Understanding the perceptions of local land users is critical to the creation of effective conservation programs. Colombia is the third largest global producer of coffee. In Colombia *cafeteros* (rural coffee farmers) produce the majority of the coffee, which is 95% shade grown. The Sierra Nevada de Santa Marta (SNSM) Colombia is an isolated mountain on the Caribbean coast and one of the world's most biodiverse regions where coffee growing subsists alongside high levels of endemic fauna. Our goal was to understand *cafetero* perceptions about biodiversity and wildlife, climate change, sustainability, limitations to their livelihoods, and coffee management practices to inform future conservation action plans. We selected coffee communities that were close to concurrent amphibian research sites. Working with the local extension agents from the Federación Nacional de Cafeteros in Santa Marta, we conducted focus groups in five coffee farming communities. Both conservation and development themes emerged from the five focus groups, specifically conservation program design and livelihood constraints. These were broken down into generic categories and subcategories ranging from *cafetero* knowledge of biodiversity and climate change to how understanding how corruption and socio-economic constraints impact the lives of coffee farmers. We found that while coffee farmers have an inherent appreciation for the landscape and conservation, they require economic support in order to achieve sustainability goals. We recommend three steps to improve sustainability and equitable practices in the SNSM: 1) alleviate the economic strain on local coffee growers through social and economic government programs, 2) improve distribution of updated technology and coffee processing methods and to farmers; and 3) connect local farmers directly with buyers.

4.2 Introduction

Long-term conservation implementation is rarely successful without the support and engagement of local communities (Bennett et al., 2017b). One barrier to enacting conservation action is a lack of understanding of local community perceptions on conservation issues (Bennett, 2016). Globally, land users participate in the extraction or alteration of natural resources on small scales. Of the estimated 570 million worldwide farms, small shareholders (< 2 ha) make up approximately 87% (Lowder et al., 2016; Nagayets, 2005). Across the tropics, agriculture has contributed to habitat loss and homogenization of biodiversity (Gallmetzer and Schulze, 2015; Menéndez- Guerrero et al., 2019; Nowakowski et al., 2018). However, dependent upon management practices, small shareholders can have lower environmental impacts (Perfecto et al., 2019). Understanding the local land user's perception of biodiversity and conservation and how perceptions integrates with management practices improves collaborative conservation efforts (Bennett, 2016).

Campesinos, or rural farmers, are some of the most important agricultural land users in Latin America. *Campesinos* are characterized by being relatively poor and associated with rural landscapes tied to agriculture either as producers, laborers, or both (Loker, 1996). They are important contributors to global agricultural supply chains for products like coffee, cacao, bananas, and palm oil. *Campesinos* typically have small-scale farms of < 5 ha and are completely dependent on their land, making them vulnerable to climate impacts and the instability of global market prices (Andrade and Zapata, 2019; Hannah et al., 2017; Montgomery, 2019; Villarreal, 2018). Resource use and land use change are intertwined with territories, historical contexts, and geographic landscapes (Zimmerer, 2002), and *campesinos* can provide new knowledge to conservation as they intersect with wildlife on a frequent basis (Granados-Peña et al., 2014). Understanding *campesino* value systems, perspectives, and a landscapes history can inform management and help to enact appropriate conservation strategies (Bennett et al., 2017a; Sawchuk et al., 2015). Researchers can gather new knowledge from land users that will improve ecological studies, the understanding of multiuse landscapes, and associated local climate patterns (Mwenge Kahinda et al., 2019; Thornton and Scheer, 2012).

In Colombia, agricultural production occurs in mountain habitats across the Andean chain to the isolated Sierra Nevada de Santa Marta (SNSM). Both mountain ranges are global hotspots and support immense biodiversity and endemism (Agudelo-Hz et al., 2019; Myers et al., 2000; Ocampo-Peñuela and Pimm, 2014). Agricultural production, primarily coffee and cattle, dominate montane landscapes. Current agricultural practices threaten biodiversity through the degradation of landscapes and watersheds, overexploitation, deforestation, and forest fragmentation (Etter et al., 2006). Concerns for biodiversity conservation are driven by climate change and the impacts of habitat loss; specifically increases in agricultural intensification and shifts of production into previously undisturbed habitats. These threats are perverse in montane regions where many species are endemic and therefore dispersal and adaptation limited (McCain and Colwell, 2011; Menéndez- Guerrero et al., 2019).

Colombia is the third largest global exporter of coffee (ICO 2019). In Colombia, coffee growers call themselves *cafeteros*, a type of *campesino* that focuses on growing, harvesting, and exporting coffee from their lands. Coffee is primarily grown in montane regions overlapping areas with high species endemism and biodiversity (Bernal and Lynch, 2008; Hoyos-Hoyos et al., 2012; Roach et al., 2020). Ninety-five percent of Colombian coffee is from small-scale farms of less than 8 ha (FNC 2020). A decade of low global market prices and climate instability pose challenges for *cafeteros* in Colombia's montane regions. In 2019, coffee prices hit their lowest level in ten years (ICO 2020). Disease outbreaks (coffee leaf rust) and climate change have left Latin American coffee growers struggling to find market stability (Avelino et al., 2015; Hannah et al., 2017; Läderach et al., 2017). Climate change has presented threats to Colombia's biodiversity (Agudelo-Hz et al., 2019; Flechas et al., 2017; Menéndez- Guerrero et al., 2019), agriculture (Andrade and Zapata, 2019; Ramirez-Villegas et al., 2012), and livelihoods (Múnera and van Kerkhoff, 2019).

Previous research has demonstrated that sustainable agricultural practices can be less detrimental to biodiversity (Perfecto and Vandermeer, 2008), mitigate climate impacts (Andrade and Zapata, 2019), and benefit local community members (Solano et al., 2017; Tscharntke et al., 2015). An example of this is sustainably-grown shade coffee, which provides a more heterogeneous vegetative structure, offers increased habitat complexity, and is preferred over monoculture crops (Perfecto and Vandermeer, 2010). While shade coffee appears to benefit some species (Caudill and Rice, 2016; González et al., 2020; Guzmán et al., 2016; Murrieta-Galindo et al., 2013), results across taxa are mixed, and dependent on the vegetative structure and management practices of the shade coffee agroecosystem (Narango et al., 2019; Otero-Jiménez et al., 2018; Philpott et al., 2008; Roach et al., 2020). The intensity of land management appears to be the most important factor to sustaining biodiversity, with lower intensity management practices preferred (Haggar et al., 2011; Perfecto and Vandermeer, 2008).

In Colombia, the management of shade coffee has implications for biodiversity. Previous research in our study region demonstrated that amphibians do not use coffee plantations (Roach et al. 2020). Amphibians are environmental indicators and highly sensitive to changes in microhabitats and climates (Semlitsch, 2003). It was important for us to understand if farmer's noted amphibians on their landscapes. If they heard frogs calling it would mean an observed presence of amphibians. Local observations also provide important ecological knowledge about microclimates, amphibian population dynamics and habitat use, and local extirpations. We hypothesized that management practices of coffee may conflict with important life history periods for amphibians, the focal organism of our ecological research in the region (Roach et al. 2020). In order to implement effective amphibian conservation strategies, across the primary land-use in the region, it was important for us to understand the perspectives of *cafeteros* on biodiversity, climate change, and sustainable practices. We were interested broadly in questions relating to *cafeteros* knowledge of biodiversity and wildlife, what they valued about their landscape and livelihoods, and if climate change had impact their livelihoods. Finally, it was also important to integrate these insights with the history of coffee. Through the integration of the perspectives of *cafeteros* with amphibian conservation we hoped to gain insights in ways we could enact collaborative conservation plans that would sustain both biodiversity and the permanency of local livelihoods.

4.3. Study Area and Institutions

4.3.1 Site Selection

Our research took place in the Sierra Nevada de Santa Marta (SNSM), department of Magdalena, Colombia (Fig. 11). The SNSM is a globally important area for biodiversity (Le Saout et al., 2013) and the fourth largest coffee growing region in Colombia (Federación de

Cafeteros 2020; https://magdalena.federaciondecafeteros.org/). It has been designated a key biodiversity area, Alliance for Zero Extinction site, UNESCO Biosphere Reserve, and has two national parks (Sierra Nevada de Santa Marta and Tayrona). Deforestation has left the landscape patchy with reduced habitat connectivity (Granados-Peña et al., 2014). Land above 2,500 m is indigenous territory and a national park (SNSM NP), while land under 2,500 m is largely a mixed-agricultural matrix interspersed with private nature reserves and ecotourism development.

Culturally, the SNSM is made up of four indigenous groups (Arhuaco, Kogui, Wiwa, and Kanquamos) and an established *cafetero* population. Both the indigenous and *cafetero* populations engage in agricultural practices, mostly on a small scale (< 5 ha). Coffee is the main agricultural crop, grown from 600 – 2,000 m (Fig. 12). Local research has shown coffee between 600 – 800 m is most vulnerable to climate change (Dr. Santiago Giraldo, Director Fundación ProSierra, pers. comm). Cattle ranching becomes more prevalent over 1,000 m and is particularly extensive in the páramo, high elevation grassland habitat, where the indigenous communities maintain land control alongside the SNSM National Park authorities.

In the department of Magdalena, there are four coffee growing zones: Aracataca, Ciénaga, Fundación, and Santa Marta. The department of Magdalena contains 5,200 coffee farms and over 20,000 ha devoted to coffee production (FNC 2020). The largest coffee production in the region stems from Ciénaga. Coffee is grown along mountain ridges, where crops occur on steep slopes sometimes over 45 degrees. Over 95% is shade coffee grown on farms less than 8 ha (Farfán Valencia, 2014). The terrain is rugged and transportation limited and most coffee farmers use mules to transport their crops. The landscape in the SNSM is incredibly steep and it is impractical to grow coffee in some areas making it common to find patches of intact forest adjacent to coffee plantations. Colombian law dictates a 30-m natural vegetation buffer along major waterways (Decree 2811, 1974), however these laws are hardly enforced. Of the 5,200 farms in the region, half are considered organic (José Torres, extension agent, Federación Nacional de Cafeteros, pers. comm.) The reliability of organic information is questionable given the lack of enforcement of organic certification guidelines.

Management practices are varied and there is a mix of pesticide and fertilizer use among organic and non-organic farms. Colombian Decree 2667 (2012) states that environmental authorities can fine farmers who dump unprocessed wastewater on land or into waterbodies, but this law has yet to be enforced in the region. Currently, many coffee wastewater systems are drained back into the landscape without being processed. Given the lack of assistance from the environmental authorities, the responsibility to maintain clean watersheds falls largely on local communities. This leaves watersheds at risk of unregulated wastewater dumping and contamination from trash and septic tanks.

Coffee is a main source of income for small-scale *cafeteros* (3 – 8 ha coffee) in the region. Larger farms owners (> 20 ha) may also have a steady income and employment, apart from coffee, and live in larger nearby cities. Unlike other regions in Colombia, there is only one *cosecha* (coffee harvest) in the SNSM. Coffee is picked by hand during October – March. The length of *cosecha* is variable, dependent on the altitude of a farm, and the yearly precipitation and temperature patterns. During *cosecha*, the entire family assists with harvest, whether picking coffee, cooking for the workers, cleaning, or other tasks. Even local school schedules are altered to accommodate *cosescha*.

Over the last ten years, the region has seen increased tourism. The western facing slope of the SNSM (Santa Marta coffee zone) has become a hub for eco-tourism. Most tourism enterprises are owned and operated by foreigners and the local communities often do not have the opportunity to participate or benefit economically. Successful ecotourism ventures are limited or do not currently exist in the remaining coffee regions (Aracataca, Ciénaga, and Fundación).

We worked with extension agents from the Federación Nacional de Cafeteros (FNC), or the Colombian Coffee Growers Federation, to assist in the organization and moderation of focus groups. We selected coffee farming communities based on geographic proximity to concurrent amphibian field research sites (four out of five communities were adjacent to our sites on amphibian research from Roach et al. 2020), as well as where FNC extension agents offered their help with the organization of focus groups. We selected five coffee communities across two of the main coffee zones, Ciénaga and Santa Marta, to conduct focus groups. The five communities we surveyed were Palmor, Plan de las Ollas, San Javier, San Pedro, and Vista Nieve. The FNC coordinated the logistics of the focus groups. Specifically, extension agents contacted farmers to see if they would be willing to participate in the focus group and organized the location, time, and date for the focus group.

4.3.2 Federación Nacional de Cafeteros

The FNC (https://federaciondecafeteros.org/) is a private organization that was formed in 1927 with a mission to look after the welfare of coffee farmers through an effective trade union and democratic and representative organization. The FNC provides a number of services to farmers including, 1) guarantee of purchase – FNC will continue to buy coffee from farmers regardless of the year, or current market prices; 2) promotion of the consumption of Colombian coffee; 3) scientific research and technology through the Centro Nacional de Investigaciones de Café (Cenicafé); 4) extension agent services; 5) management of local, regional, and international alliances and projects; 6) guarantee the quality of Colombian coffee. Cenicafé is responsible for developing new technologies ranging from disease resistant and climate change tolerant plants and filtration systems to reduce contamination in coffee wastewater. The FNC utilizes the extension agent service to provide advances from Cenicafé to farmers. The FNC has a national sustainability development plan, including development objectives in four areas: economy, governance, environmental, and social (FNC 2020; https://federaciondecafeteros.org/wp/sostenibilidad/).

4.4 Methods

4.4.1 Focus Groups

Our approach to the examination of the communities, their perceptions, and actions related to biodiversity, combined narrative and case study approaches (Bennett, 2016; Marshall and Rossman, 1995; Moon et al., 2016). We chose to conduct focus groups which can be particularly useful in regions where there has been little to no research. For conservation studies, a focus group can provide researchers with baseline information that will help design future ethnographic studies and interviews. Focus groups are helpful to obtain data for pilot studies, such as ours, and allow researchers to engage in informal discussion with a small number of people focused on a particular set of issues (Krueger and Casey, 2000; Wilkinson, 2004). They are an economic and efficient way to obtain data rapidly (Krueger and Casey, 2000; Onwuegbuzie et al., 2009) while allowing participants to feel they are in a safe environment to share their thoughts (Vaughn et al., 1996). Focus groups allow for direct interaction with respondents, including the ability to ask follow up questions and note non-verbal behavior or interactions (Stewart et al., 2009). The open-ended questions allow researchers to obtain data that present the participant's wording and do not require inquiries about a participant's literacy abilities. In addition, focus groups allow for participants to build on each other's ideas, potentially providing new information to the moderators (Stewart et al., 2009). Finally, the results of focus groups are generally easy to understand for both researchers and decision makers.

While we felt a focus group approach would be best for our pilot study on *cafeteros* in the SNSM, there are limitations to the approach. Limitations include: small numbers of participants may constrain generalizing to larger populations, responses from members of the group are not independent and may be biased if one member of the group dominates the conversation, credibility of live respondents can be questionable in statistical summaries, and that data can be difficult to summarize and interpret (Stewart et al., 2009). We attempted to address these limitations by recording information on the number of participants that spoke during the focus group, and by having two independent moderators who assessed responses. Our goal was to obtain preliminary information that would be useful for future research design and implementation on similar topics.

We conducted five focus groups in the Ciénaga and Santa Marta coffee growing regions. Initially, in October 2017, we conducted a pilot focus group in the coffee-growing community of San Javier. This exploratory focus group allowed us to identify how group conversations were organized, how to structure the discussion, and how to expand or adjust our *a priori* questions (Table C1). We then made slight changes to the questions we asked the subsequent four focus groups and also created a *coffee calendar* with the remaining groups to identify key management practices during the calendar year.

In total, we had 50 participants across all five groups. Focus group size ranged from a minimum of 7 participants to a maximum of 17 per group (Table 7). Approximately two-thirds of the participants were coffee farm owners and managed their own landscapes, while the remaining one-third of participants were *administradores* and acted as land managers for the owners who lived elsewhere (usually in nearby cities of Santa Marta or Barranquilla). Each focus group had two moderators and one FNC extension agent whom were present during the interviews (with the exception of San Pedro where no extension agent was present). It is important to note that the presence of extension agents may have hindered the honesty of responses from participants. For instance, participants may have been less inclined to speak honestly about their relationship with the FNC and/or allied organizations if an extension member was present. Focus groups took place on one of the participant's farms or a neutral space, such as a *tienda* (local store) nearby. Focus groups lasted two to three hours and were conducted in Spanish and later translated to English with the help of local research assistants.

Focus groups took place in October 2017 (during *cosecha* or harvest season) and June – July 2018 (after *cosecha*). Participants were both male (38) and female (10) and adults (> 18 years). Some children were present during the interviews with their families, but did not participate in the discussion. We asked a series of pre-prepared, open-ended questions related to biodiversity and conservation, climate change, sustainability, history of the region, and the current and future challenges to coffee farmers (Table C1). We allowed for the conversation to flow and asked follow-up questions dependent on the answers given earlier in the focus groups (Patton, 2002). Finally, we had farmers from each community create a "coffee calendar" highlighting the various activities they were involved in during specific temporal periods. This calendar highlights periods of intensive land management practices and can be used to identify periods of conflict with species life history strategies and/or conservation opportunities.

After each focus group, the moderators gathered and answered a series of reflection questions and discussed any prevalent themes that emerged during the focus group. Data were reviewed and revised by two persons, one with fluency in Spanish. Here moderators reflected independently on what each focus group discussed and wrote down observations including how people interacted with each other to how much time they spent on a particular topic.

To analyze responses from focus groups, we conducted a qualitative content analysis (QCA) to examine themes that emerged across focus groups (Krippendorff, 1980; Schreier, 2012). QCA is a flexible tool that allows researchers to decide how to organize data through a coding framework. Each analysis is different pending researchers insights, skills, and analytical abilities (Elo and Kyngäs, 2008; Hsieh and Shannon, 2005). We developed a categorization matrix to code data into different categories. We used deductive structure to analyze the data as we had pre-identified questions of interest that were used to group responses into categories. Looking at the participants responses we created subcategories, generic categories, and main categories (Elo and Kyngäs, 2008). The main categories represent major themes that were prevalent across all five focus groups. Using this information, we make recommendations for engaging in conservation and sustainable projects in the region that are derived from the perspectives of the coffee farmers.

4.5 Results

Two main categories, or themes, emerged from the QCA: conservation program design and livelihood constraints (Fig. 13). Themes can help guide local conservation decisions in conjunction with coffee farmers. The interplay between the cross-cutting themes and the site-specific conditions determines the kinds of conservation interventions that are possible, and influences the likelihood of the implementation (Table A9).

Below we present the generic categories for conservation program design (natural resources and land use management) and livelihood constraints (infrastructure and socio-economic constraints; Fig. 13). These generic categories contain topics that emerged from the focal group results and were present in some aspect in all communities. Included within the generic categories are descriptions of four subcategories related to the natural resources (biodiversity, wildlife, value of landscapes, and climate change), two subcategories related to land use management (certifications and coffee calendar), three subcategories related to infrastructure (waste management, limited network service, and bad roads), and lastly four subcategories related to socio-economic constraints (low coffee prices, no government assistance, children leaving for university, and corruption). The responses and attention to specific subcategories varied among focal groups.

4.5.1 Natural Resources

4.5.1.1 Defining Biodiversity

Across all focus groups, the majority of participants were able to define biodiversity as relating to wildlife and plants. Some common responses included: "biodiversity was everything in the ecosystem", "everything found in the land or environment", and "all the species of flora and fauna". They often included pastures and farms in their definition of biodiversity as well.

4.5.1.2 Wildlife

Participants were particularly knowledgeable about wildlife on their land. The most commonly discussed species across all focal groups were mammals and birds. Some respondents commented on animal behavior, particularly those from Plan de las Ollas. They observed that frogs were found mostly near streams and could be heard calling at night and provided descriptions of specific frogs, including *Ikakogi tayrona*, an endemic species. Participants from Plan de las Ollas even noted the specific behavior of certain animals, including breeding seasons, the food the animals ate, and interspecific interactions amongst bird species.

The primary mammal species mentioned included: agouti (*Dasyprocta punctata*), howler monkey (*Alouatta seniculus*), deer (*Mazama* spp.), cats (mostly jaguar *Panthera onca* but also puma *Puma concolor*), and armadillos (*Dasypus novemcinctus*). Lesser mentioned mammals included: foxes (*Cerdocyon thous*), *tigrillo/oncilla* (*Leopardus tigrinus*), squirrels (*Sciurus granatensis*), and pigs (*Sus scrofa*). Common bird species mentioned were Toucan's (*Ramphastos sulfuratus*) and Macaws (*Ara* spp.), Sickle-winged Guan (*Chamaepetes goudotii*.), Black-chested Jay (*Cyanocorax affinis*), and the Crested oropendula (*Psarocolius decumanus)*.

The only amphibian that was exclusively discussed was the *rana platanera* (*Boana boans*), a common species typically found in agricultural zones. Other participants described frogs by their color and calls. Some participants were familiar with the *rana cristal* (*Ikakogi tayrona*) and *Colostethus ruthveni*, a small species with golden stripes down the side of their body, which calls throughout the day and is found commonly in degraded habitats and in surrounding streams and forests on coffee plantations (Roach et al., 2020). Respondents were more likely to note the presence of reptiles, specifically snakes, including the fer de lance (*Bothrops asper*) and coral snake (*Micrurus* spp). It is common to find snakes while harvesting coffee. A few respondents stated that they killed venomous snakes but not others, like the boa (*Boa constrictor*). However, we did not obtain information on their ability to correctly identify venomous vs. non-venomous snakes.

4.5.1.3 Value of Landscapes

Participants commented on the global importance of the SNSM, particularly its uniqueness. Four of five groups stated the most important thing in the SNSM is water, including the maintenance of watersheds and "*microcuencas*" (small watersheds or streams). The Palmor group placed value on coffee and future growing viability. The group from Plan de las Ollas also placed value on the tranquility of the SNSM. The San Pedro group stated that "doing conservation and taking care of the land" was the most important thing they could do and they desired technologies that were less detrimental to the environment. The Vista Nieve group was particularly interested in conservation and restoration of habitat and the reduction of contamination. All groups also indicated that people worked to conserve watersheds and understood the importance of the SNSM. Finally, all groups placed value on their own land stating that coffee was the most important aspect to them.

4.5.1.4 Climate Change

Each focus group observed changes in the climate over the last 10 – 30 years. Participants in the Palmor group observed a decrease in water and ice, as well as less rain overall but higher storm intensity; "in just one day we will get all the water that used to fall in one week". They also observed hotter temperatures locally, and that cooler temperatures were observed at higher elevations than previously. They even stated their coffee was now able to be grown at a higher altitude than before (1,700 m vs. 1,200 m).

The group from Plan de las Ollas observed that, 25 – 30 years ago, the closest town used to be cold and "people wore jackets, hats, and had blankets. Now it is hot and people use fans". They also noted changes in precipitation patterns, commenting that in previous years, it rained during two periods throughout the day, and now rains just once a day. The changes in climate have affected their coffee and participants mentioned coffee must now be planted at specific times of the year that are different from previous temporal periods.

In San Javier, participants noted that there were more frequent and intense rain events causing the coffee fruits to fall off early, resulting in economic losses for the farmers. They also noted that summers (dry periods) were shorter, which made it difficult for coffee to mature. In

San Pedro, participants observed some avian species had moved up higher in elevation. They also observed lower water availability and drier streams. As a result, some farmers discussed changing crop types to avocado and mango (traditionally grown at lower, warmer elevations). Similarly, participants from Vista Nieve observed changes in precipitation patterns and an increase in temperatures. They also observed birds that had moved higher in altitude and were aggressive with other species such as the Bi-colored wren (*Campylorhynchus griseus*) and Great-tailed grackle (*Quiscalus mexicanus)*. They also stated their coffee production was irregular because there was often too much sun or rain.

4.5.2 Land Use Management

4.5.2.1 Certifications

Around half of the participants had at least one type of certification. Organic certifications ranged from Colombian specific certifications like EcolRed and ColCafé to globally recognized programs like Rainforest Alliance. Organic certifications prohibit the use of chemical fertilizers and pesticides. Participants noted it can take up to three years to prepare a farm to become organic, which is economically costly and labor intensive, and a reason some farmers chose not to transition. They also discussed that organic farms can be at a disadvantage to plagues and disease since they are unable to apply insecticides or pesticides.

Once coffee is harvested and processed it is brought to cooperatives that then buy the coffee directly from the farmers. During years when the coffee market is low, FNC provides security to farmers by ensuring the purchase of coffee. Once the coffee is in the cooperative it is either locally roasted or exported to US and European markets, where it is sold to consumers at seven times the price (ICO 2019).

4.5.2.2 Coffee Calendar

Four communities participated in the coffee calendar: Palmor, Plan de Las Ollas, San Pedro, and Vista Nieve. The coffee calendar highlights the main land management practices during the 12-month calendar year (Fig. 14). The temporal period of activities across communities varied slightly, most likely due to differences in elevation, topography, and precipitation. Notably, land management practices intensify during the rainy season, a critical reproductive time period for amphibians. While, amphibians do not directly use shade coffee in the SNSM, they use adjacent landscapes and waterbodies that are directly impacted by management practices (Roach et al. 2020). The lack of amphibians in coffee plantations is potentially because of the mismatch between land management practices that reduce or eliminate understory vegetation and leaf litter and the alterations to soils (Rao et al., 2020; Robinson and Mansingh, 1999). The washing of coffee can impact streams through organic run-off and increase in heavy metal content (Siu et al., 2007; Zayas Pérez et al., 2007). Amphibians that use surrounding watersheds may be negatively impacted by changes in environmental conditions.

4.5.2.3 Infrastructure

Across all groups, one of the main concerns was road accessibility. Most roads are unpaved and during the rainy season can be impassable for periods of a time. Landslides are common and it can be difficult to get supplies and coffee up and down the mountain. Every focus group emphasized they wanted better transport and road systems, network service (i.e. phone connectivity; many farmers go without cellphone signal for days), and to improve their homes and *beneficiadero* (coffee processing system) infrastructure. Additionally, participants in Palmor discussed that roads could not be improved due to the *resguardos indígenas* (indigenous private property, as decreed in the Colombian constitution). This land is not allowed to be developed and the *campesinos* in Palmor commented that there was no future in the SNSM because of lack of development allowed. Finally, due to limited road access, trash removal is a problem for many residents and it is common to burn and bury trash.

4.5.2.4 Socio-economic Constraints

Low coffee prices are the largest concern for coffee farmers in the SNSM. Every group stated their primary concern was the low price of coffee. At the time of this study, global coffee prices in Colombia were $1.25 USD/LB (2017) and $1.13 USD/LB (2018) (International Coffee Organization 2020; http://www.ico.org/coffee_prices.asp), although each farmer reported receiving slightly higher prices ranging from ~ $2 – 2.50 USD/LB of coffee. Organic growers can sell coffee at slightly higher prices, and farmers reported an increase of about 30 cents more/pound. This margin of 12 to 15% increase is only viable if losses to pests are less than this and there is no significant loss of productivity due to reliance on organic fertilization.

The producers want to sell coffee for higher prices; and some groups mentioned they wished to sell directly to buyers instead of going through filters of organizations and cooperatives. Farmers wanted access to other types of economic gains. Mostly farmers want economic support that will allow them to spend less of their own money on maintenance of their farms and machinery. The majority of small-shareholder coffee farmers live through the year with their earnings from *cosecha* and they usually cannot afford to invest in programs like organics or new equipment.

Participants in Palmor and Plan de las Ollas mentioned their interest in ecotourism as a way to increase their income. Coffee farmers in Plan de las Ollas and Vista Nieve were concerned about the future of oversight on their farms. Often the children leave for nearby cities, such as Santa Marta or Barranquilla, to attend University. Others become motorcycle drivers (transporting tourists and local people up and down the mountain) which provides more money than harvesting coffee. Regardless of the activity, participants were concerned with the lack of generational interest in the practice of growing coffee. However, participants did note that even if their children did not want to grow coffee there would always be people to come harvest. Colombians from other regions and Venezuelans commonly work *cosecha*.

Finally, most of the participants complained about lack of government support, specifically mentioning the local environmental authority, which has not fulfilled many of its duties. In Vista Nieve, the environmental authority said they would send a vehicle to collect trash. The vehicle never arrived. This left community members frustrated, angry, and distrustful of people who promise to assist them. Participants in Vista Nieve also stated that some community members accept bribes. Corruption across governmental agencies, such as the local environmental authority, and mistrust of researchers were brought up by Vista Nieve and San Pedro (respectively). Both San Pedro and Vista Nieve mentioned biologists who had conducted studies in the region such as camera trapping and amphibian surveys. In both situations, the communities never saw the results of the research and the people never came back, leaving communities feeling frustrated and lowering trust of outsiders. In San Javier, participants spent time discussing the history of the armed conflict and how it affected their livelihoods, including illegal land seizures, increased homicides, and lack of safety in the region. Detailed information on responses from communities can be found in (Table C2-C6).

In summary, the results highlighted livelihood barriers for *cafeteros* that hinder consistent sustainable management of coffee farms and surrounding landscapes. Without addressing these barriers there will be little success enacting conservation plans across their landscapes. Perceptions of local land users are critical to understanding how decisions regarding future land use are made. Our two main themes derived from this study demonstrate that knowledge of local wildlife and climate, as well as socio-economics and corruption, interact in the decision-making process and contribute to coffee management decisions. Interestingly, we found a link between *cafeteros*, amphibians, and their value and dependence on water. Water could be the resource that links both *cafeteros* and amphibians to achieve conservation goals in the region.

4.6 Discussion

Historically, conservation programs have neglected livelihood constraints or see them as "outside" issues (Wilkie et al., 2006). However, livelihood constraints do influence how land users manage their landscape, which impacts ongoing conservation initiatives (Hwang et al., 2020; Iverson et al., 2019). We suggest that both main themes – conservation program design and livelihood constraints – must be addressed when creating a conservation program in the SNSM.

In the SNSM, we found that *cafeteros* have conservation-leaning perceptions of biodiversity, land values, and climate change. Coffee farmers place an inherent value on their land (coffee) and the surrounding landscapes (water and conservation). The connection between *cafeteros,* amphibians, and water represents a conservation opportunity. Water is an important natural resource and is used heavily during coffee processing, with up to 140 L of water used to process one cup of coffee (Chapagain and Hoekstra, 2003). Streams and moist soils also provide important breeding habitat for many of the threatened amphibian species found in this region. While current land management practices are deemed sustainable to some extent, farmers would like to improve their sustainable practices and technology. New technologies that reduce water consumption during coffee processing are available, but often farmers with small land holdings cannot afford them.

Though shade coffee has been promoted as biodiversity friendly (Solano et al., 2017; Tscharntke et al., 2015), current management practices as a whole may be at odds with amphibian conservation. Results from the coffee calendar (Fig. 14) demonstrate a mismatch between management practices and life history strategies of amphibians. Management practices intensify during the reproductive season of amphibians. In addition, non-organic farmers use fertilizers and herbicides and fire to control vegetation and understory growth. The use of fertilizers may lead to disruptions in endocrinology and sexual differentiation of amphibians (Boone et al., 2007; Mann et al., 2009) and the clearing of understory eliminates important microhabitat reducing connectivity across the agroforestry matrix. Dispersal limited species, like amphibians, that rely on microclimates and microhabitats may be more vulnerable to these intensive land practices at a local scale (Otero-Jiménez et al., 2018; Roach et al., 2020).

Another limitation impeding improvement of sustainable practices, is the length of time (up to three years) to transition to an organic farm. During focus groups, *cafeteros* noted they would be more likely to transition to organic farming if they had economic support, including new technology, new coffee plants, and improved coffee processing infrastructure. Organic farms are also more susceptible to disease, like *broca*, the coffee berry borer (*Hypothenemus hampei*), that has decimated plants across the globe (Damon, 2000). Organic farmers may lose money as their crop is destroyed, which influences the decision to participate in organic farming. In the SNSM, the variable oversight by certification organizations exacerbates the inconsistencies in organic coffee quality and reduces accountability of the conservation of the surrounding forest and watershed landscapes (Roach unpublished data).

Economic limitations remain the largest barrier to the lack of implementation of sustainable technologies in the region. Price and market demand fluctuations most strongly influence decision-making regarding land-use and investment among coffee farmers in the SNSM. *Cafeteros* express inherent value for their land and the surrounding ecosystem, noting importance of the SNSM as a unique ecosystem, that "can only be found here"; however, farmers are unlikely to alter management practices unless provided with assistance or economic incentives. Coffee is a billion-dollar business and one of the top beverages consumed globally (FAO 2017; ICO 2019), yet farmers barely break even (Montgomery, 2019; SCAA, 2013). The biggest barrier coffee farmers face in the SNSM is the lack of economic support and instability in the marketplace. Low coffee prices compounded with local corruption increase inequality and often have negative effects on the confidence and trust of local communities while hindering the efficacy of conservation policies (Lucas, 2016; Sundström, 2016). Accountability and enforcement of laws is necessary to ensure that use of illegal fertilizers and wastewater contamination is reduced. Finally, national government support through economic and social programs is necessary to ensure the future of coffee and coffee growers in Colombia.

Across Latin America, farmers are experiencing negative impacts of changing climate on coffee, including secondary impacts like increased exposure and susceptibility to disease, and land becoming increasingly unsuitable for coffee (Andrade and Zapata, 2019; Coltri et al., 2019; Solano et al., 2017; Villarreal, 2018). Climate change presents a long-term concern for the global coffee markets and the 100 million farmers that rely on income from coffee (Hannah et al., 2017; Jaramillo et al., 2013; Ovalle-Rivera et al., 2015; Schroth et al., 2015). In the SNSM all five communities clearly perceive the effects of climate change on the landscape and on their livelihoods. A similar level of perception of climate change impacts on livelihoods was documented in agricultural regions in the Himalayas in India and Nepal (Macchi et al., 2015) and in the coffee producing region of Manizales in the central Colombian Andes (Barrucand et al., 2017). Unpredictable temperature and precipitation patterns are a planning challenge for farmers that can also directly damage coffee plants (Santos et al., 2015). While agroforestry in the form of shade trees can mitigate the short-term climate impacts for coffee (Gomes et al., 2020), other research suggests that coffee may need to move into new areas, increasing deforestation (Schroth et al., 2015). This places economic and social constraints on the ability of communities to respond without significant government engagement (e.g. land reform) and investment.

Ultimately, farmers are more likely to make land use decisions based on their economic wellbeing. In regions where inequality and poverty are rampant, it can be difficult to gain community trust and build momentum for conservation action (Brooks et al., 2012). Engagement in conservation programs can be stymied by corruption, mistrust, and bureaucratic barriers (Rodriguez Solorzano and Fleischman, 2018). For example, the decision of coffee farmers in Puerto Rico to participate in conservation programs were heavily influenced by financial considerations, the kinds of incentives offered, and a general distrust of government programs (Gladkikh et al., 2020). We recommend conservation researchers who plan to implement a conservation program employ focus groups, a community workshop, or a similar approach to build community trust and engagement early on, which will help researchers better understand the complexities of the surrounding region and assist in addressing any design or implementation issues. Specifically, in the SNSM, in order to improve sustainability and equitable practices and bolster conservation efforts, we recommend three steps: 1) alleviate the economic strain on local coffee growers through social and economic government programs, 2) improve technology and coffee processing methods and their distribution to farmers; and 3) connect local farmers directly with buyers.

Conflict arises when local people are left out of conservation decisions that take place on adjacent landscapes (Brockington and Wilkie, 2015; Sodik et al., 2020). Having local community support for conservation programs is critical to improve program implementation and accountability. When possible, conservation practitioners should utilize the willingness of local land users to participate in conservation or sustainable programs to engage them in the conservation process. There can often be a disconnect between the perceived need of information and technical support, and what *cafeteros*, in the case of the SNSM, actually receive from agencies or organizations (Barrucand et al., 2017). Therefore, it is important that both technological and economic support from programs directly benefits local participants.

The development of IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) places great emphasis on the links between services provided by natural systems and livelihoods in rural communities (Díaz et al., 2019, 2018). Maintaining sustainable livelihoods will provide a mutual benefit for these natural systems. Biodiversity conservation programs will be more effective when local land users have economic security that is based upon programs that respond to both local needs and perceptions. Conservation programs must further build upon the existing appreciation of the local environment and the pre-existing legacy of the land that communities find intrinsically meaningful to conserve.

4.7 Figures

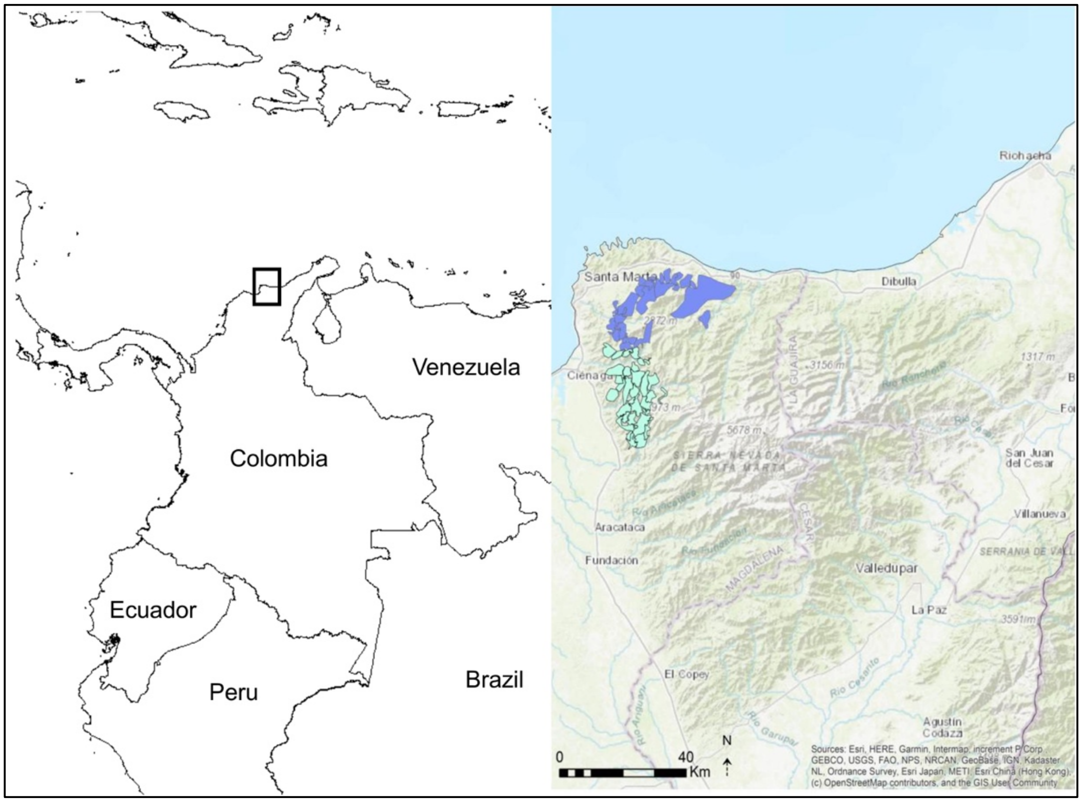

Figure 11. Site map of study region in Sierra Nevada de Santa Marta, Colombia. The dark blue is the Santa Marta coffee growing region and the light blue is the Ciénaga coffee growing region where focus groups were conducted.

Figure 12. Coffee habitat and processing in SNSM. A) San Pedro community and coffee below ridge; B) shade coffee farm; C) coffee drying on a farm in San Pedro; D) Coffee going through the de-pulping and washing process.

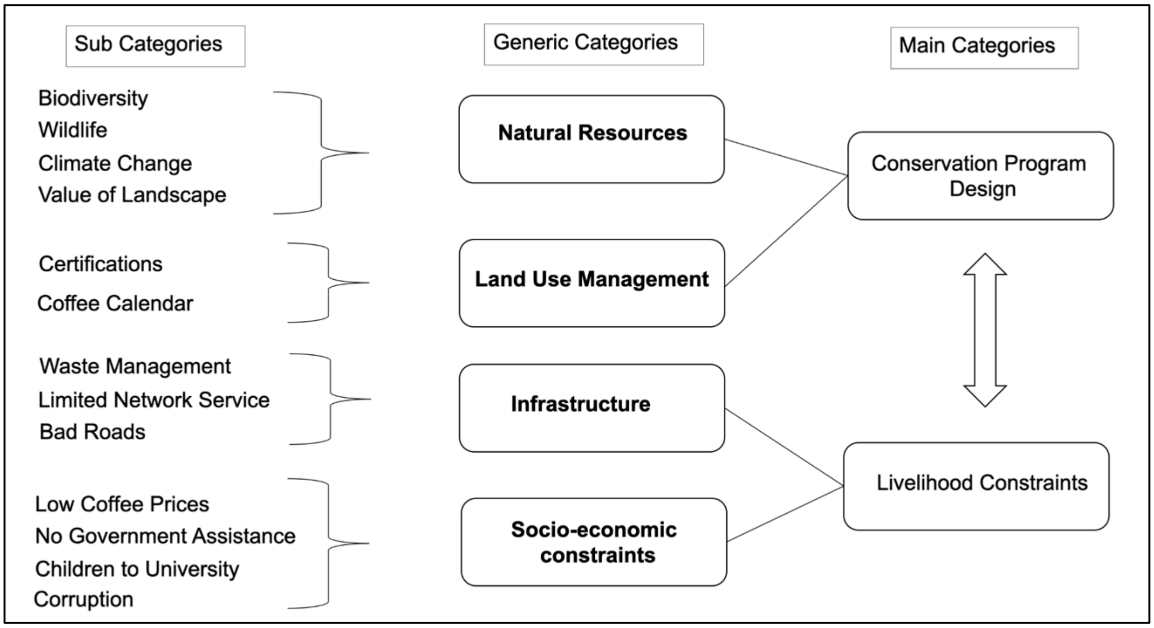

Figure 13. Flow chart of subcategories, generic categories, and main categories based on responses from focus groups.

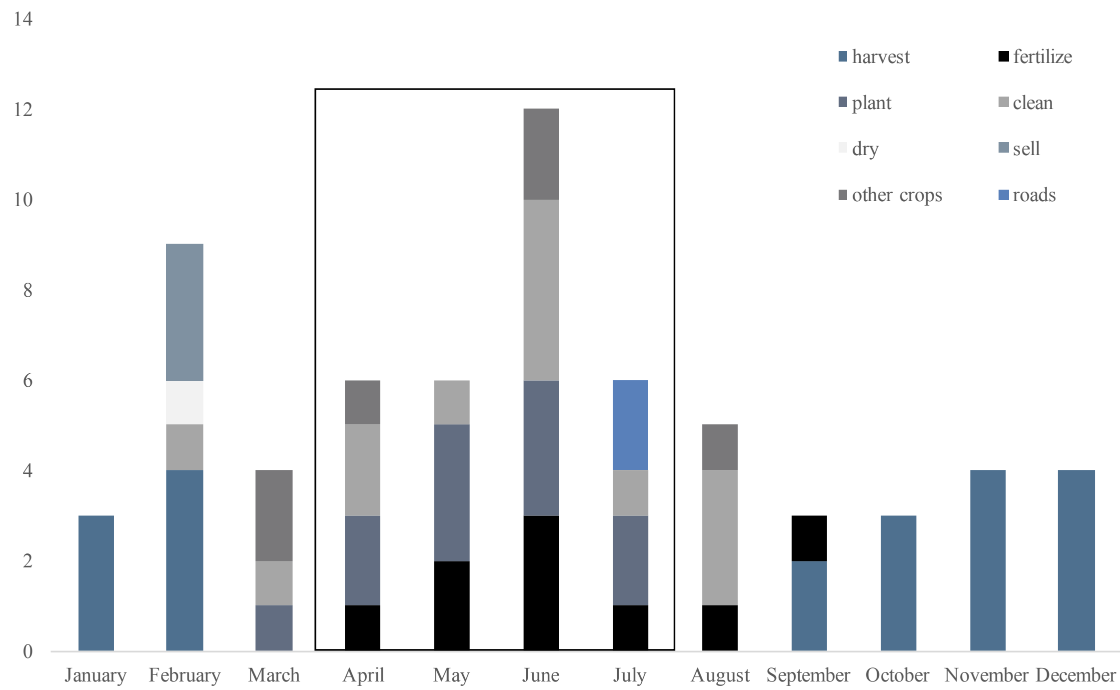

Figure 14. Coffee calendar from four communities (Palmor, San Javier, San Pedro, and Vista Nieve). Activities during the rainy season (amphibian reproduction season) are outlined in black box. Activities "dry, plant, harvest, clean, fertilize, and sell" relate to coffee plantations and crops. Where "other crops" relates to time periods planting or harvesting additional crops, and "roads" relates to road maintenance done by local community members.

4.8 Tables

Table 7. Information about focal group demographics and landscapes.

Municipality	Community	Elevation (m)	Participants (n)	Date of Focus Group
Ciénaga	Palmor	1076	17	June 2018
Santa Marta	Plan de las Ollas	950	8	June 2018
Ciénaga	San Javier	1530	7	October 2017
Ciénaga	San Pedro	1418	10	July 2018
Santa Marta	Vista Nieve	1087	8	July 2018

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CHAPTER V

CONCLUSIONS

Since the 1980's scientists have warned governments about the impact of climate change. Forty years later, major political leaders have defied the overwhelming science evidence with inaction. In 2019, the United States, the second largest global polluter, officially submitted their withdrawal notification from the world's largest climate accord to date – the Paris Climate Agreement (2016). Corruption and political agendas continue to dictate what happens to our societies, often at the expenses of our natural resources and most vulnerable populations.

Our world is changing rapidly. Today, we are experiencing a global pandemic, the first in 100 years, that has altered lives for nearly everyone on Earth. Economies have screeched to a halt, communities are shut indoors, and inequality has been exacerbated across the globe. Climate scientists have drawn parallels from human response to the Covid-19 pandemic to the climate emergency. Without immediate action aimed at reducing emissions to slow the warming of the planet, we will experience massive extinctions, increased conflict over dwindling resources, and loss of wildlife and human life.

The majority of biodiversity is found in the tropics, where often unstable governments and corruption lessen the efficacy of conservation action. My doctoral research highlights the impact of land cover and climate change on amphibians in a globally biodiverse area. Land-use activities affect amphibian communities. While some amphibians are found using pasture in the SNSM I found no species using coffee plantations. Higher species richness and abundance can be found in more natural land cover types such as forest and ecotone. The majority of focal study species are vulnerable to climate change. Seven species ranked high in extinction risk vulnerability. Reducing the intensity of agricultural production and shifting toward more sustainable crop production is necessary to mitigate biodiversity loss. The preservation of forest and ecotone, reforestation programs, and introduction of sustainable agricultural practices will also greatly reduce threats to amphibian survival.

As climate changes, both wildlife and livelihoods will be negatively impacted. Populations of amphibians in the northwestern corner of the SNSM are likely to face large losses of habitat due to changing temperature and precipitation regimes. Coffee farmers have already experienced the negative impacts of warming temperatures on their crops (drought or too much rain). Additionally, the majority of coffee farmers are poor. Their income does not necessarily offset the expenses for growing, which will worsen as climate impacts effect their livelihoods. The coffee supply chain is extremely inequitable and coffee farmers will continue to struggle until they are properly compensated.

The results of my dissertation demonstrate the importance of local scientific knowledge and traditional ecological knowledge to better understand conservation needs of a region. Coffee farmers would like to be sustainable, but often cannot afford the means to buy-in to organic crops and technologies needed. Coffee management also conflicts with the reproductive season of amphibians. This conflict could be detrimental for species that use watersheds adjacent to coffee farms or disperse through agroforestry patches. I found there was a connection between coffee farming, amphibian conservation, and water conservation. Water was a valued resource by the coffee farmers and is a critical natural resource for both human and amphibian survival. Focusing on watershed conservation may help preserve amphibian habitat while also serving as an option to improve sustainable management practices for coffee farmers.

Sustainable practices such as the reduction of chemical use and the protection and conservation of water associated with agricultural production will improve habitat quality and mitigate climate change impacts on farms and the surrounding landscapes. Coffee farmers in the SNSM have support through the Federación Nacional de Cafeteros (FNC). The FNC monitors crop production, provides disease-resistant crops, and assists in the implementation of sustainable practices. The *sistemas modulares de tratamientos aguasmieles* (SMTAs) is a coffee wastewater processing system found in the SNSM. All organic farms are required to use SMTAs. Colombia law even states agricultural wastewater cannot be dumped onto land or water, violators will be fined (Decree 2667; 2012).

The findings of my PhD research led to the creation of a new project called: *Filters for Frogs*. The project began in August 2019 and will run for one year. The goal of the research is to understand how the SMTA systems work and if they effectively reduce contaminant and organic component loads in coffee wastewater. Wastewater management is one of the leading issues for coffee growers. While current initiatives for sustainable coffee systems exist (Rainforest Alliance, Bird Friendly, Utz), few have focused on the interaction between coffee production and amphibians, the world's most threatened vertebrate group, in shared riparian zones. The project aims to provide short and long-term solutions to improve water quality and environmental sustainability, enhance conservation efforts for critically threatened species, and provide economic incentives for farmers who participate in the program.

We encountered difficulties throughout the field component of the project. We found that the majority of organic farms were not using the SMTA systems. Large farms were unable to process coffee with SMTAs because there was too much water that the three-tank system could not handle. Farmers lose time and product value if they try to use the SMTAs. We also encountered farms that were organic but were using pesticides on their land and in adjacent streams. Finally, some farms did not want us to sample on their properties due to their lack of cooperation with organic certification guidelines. I found that enforcement in the region is virtually non-existent and there are select individuals who own large farms and influence coffee distribution. It will take at least 6 months to get the results from this ongoing study to see if the filtration systems do in fact reduce wastewater contamination in the region. In the meantime, I continue to work closely with FNC and local collaborators to engage local farmers in sustainability and conservation projects to protect biodiversity.

I learned how valuable it is to conduct both quantitative and qualitative research from an ecological and socioeconomic perspective in a region. We can gather all the scientific data we want (or are allowed too), but without an understanding of the local communities, we will not be able to implement maintainable conservation programs. When there are low levels of enforcement, it can be critical to involve local community leaders in conservation projects, which can improve accountability and education surrounding the projects goals. The farmers liked learning about biodiversity and conservation and were willing to participate in sustainable practices, if they could (i.e. are not limited by finances or had some sort of assistance including training and access to technology and resources). Conservation programs may be more successful if they include community and species' needs into action plans. *Campesinos* in Latin America co-exist with nature in some of the world's most biodiverse regions and can be the main land users and resource extractors. More integration of conservation practitioners with local land users may assist in achieving both conservation and sustainable development goals.

The SNSM is a remarkable place, packed with biodiversity and kind, hardworking people. In order to work toward conserving the biodiversity and livelihoods I recommend 1) involvement of local land users in conservation practices, 2) increased research efforts in the region (academic, NGOs, National Park Service), and 3) improvements in data sharing and trust amongst stakeholders. The SNSM is a difficult place to work, based on its topography and the mistrust amongst communities of local institutions. Many local people are suspicious of researchers and the processes for approval of permits and can be slow. However, open communication and commitment to follow-through on conservation initiatives can positively influence livelihoods and the perceptions of conservation practitioners by the local communities in the region.

Since 2016, Colombia has faced a difficult transition from a long civil war to “peace”. The peace agreement has faltered under the new president. New criminal groups, paramilitaries, and other guerilla groups have seized control of evacuated FARC territories and violence has begun to surge in some of the most vulnerable regions in Colombia (Amazonas, Chocó, Nariño, and Santa Marta). Since the peace deal was signed, Colombia has seen a rise in deforestation (IDEAM 2019) and an increase in assassinations of environmental and social leaders (Front Line, 2019). These political and social factors are deeply embedded in the conservation landscape and can make it virtually impossible to conduct research, engage with communities, or enact conservation action.

The world’s most vulnerable populations, such as coffee farmers, will experience more climate induced suffering. Vulnerable populations lack economic stability and resources. Failed government programs, or lack thereof, make it harder for vulnerable populations to climb out of the shackles of inequality. The responsibility and reparations needed for climate vulnerable populations should fall to the richest countries (and largest polluters). Without support, conflict and violence will increase and corruption will dominate many societal structures.

Conservation is a complex enterprise. Political, economic, social, and ecological factors have a role in how conservation action is enacted. There are many incredible scientists in Colombia producing knowledge and sharing resources. The Humboldt Institute (Bogotá, Colombia) is one of South America's premiere research institutions. I am fortunate to have worked with many dedicated conservationists, including partners who have implemented jaguar-friendly coffee practices in the SNSM. Slowly, progress is being made, despite political and institutional barriers.

I am an optimist. I believe that humans can do the right thing to protect biodiversity and ensure the health of our planet and human life for future generations. But the future will be bleak if we continue to deplete the earth's natural resources and ignore the growing climate crisis. Fortunately, Generation Z and Millennials have pushed back against this history of climate inaction, through climate strikes, engagement with local, regional, and global leaders, and publishing resources on climate change (Sunrise Movement and Extinction Rebellion). The media views on climate change have shifted, and readers are more likely to see *climate emergency* or *climate crisis*, representing the state of urgency to address these issues. Finally, and arguably most importantly, it is essential for free nations to elect leaders who are willing to take on large corporations and capitalistic greed and endorse science.

Local conservation projects can have positive impacts on communities and habitats. I have seen that in my own work and my collaborators work. Still, without governmental leadership that prioritizes the welfare of biodiversity and human life, conservation actions will have little global impact. The Covid-19 pandemic is a wake-up call to all citizens. We are interconnected and the decisions made in one country have global consequences. We have the solutions to many of our climate-related problems. Investing in renewable energy sources, like wind and solar power, protecting extant habitat including reforestation programs, improving sustainable agricultural practices, and implementing carbon taxes are a just a handful of ideas that have been posited to reduce emissions.

Successful conservation programs are multi-layered. Scientists must understand the threats on an ecosystem or species, figure out how to address those threats through actions and policies, and work toward building equitable systems that have longevity. Participatory involvement from multiple stakeholders is critical to making conservation programs successful. Scientists and governments have the tools necessary to enable quick and effective conservation action. Small actions lead to big changes. However, we are now within a limited time frame to act on climate change before it is too late. We need global leaders to get aggressively behind the science in order to see sweeping change. The science and solutions are available, they must be enacted, for it is our future at stake.

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5.1 References

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APPENDIX A

SUPPLEMENTAL INFORMATION FOR CHAPTER II

Table A1. Characteristics of the 10 landscapes surveyed in this study. Modified with permission from Roach et al., 2020.

Landscape	Land Cover Types	Elevation (L, M, H)	# Transects
La Victoria	Coffee, Ecotone, Forest	L, M	5
Hacienda San Jose	Coffee, Ecotone	L	3
La Isabela	Coffee, Ecotone, Pasture	M	4
La Sierrita	Coffee, Ecotone, Pasture	M	3
Cebolletas	Ecotone, Pasture	H	3
Reserva Toribio	Coffee, Ecotone, Forest	L	4
El Dorado Reserve	Ecotone, Forest, Pasture	M, H	6
San Lorenzo Biological Reserve	Ecotone, Forest	H	2
Rio Gaira	Forest	M	2
Páramo	Ecotone, Páramo	H	3
Total			**35**

APPENDIX B

SUPPLEMENTAL INFORMATION FOR CHAPTER III

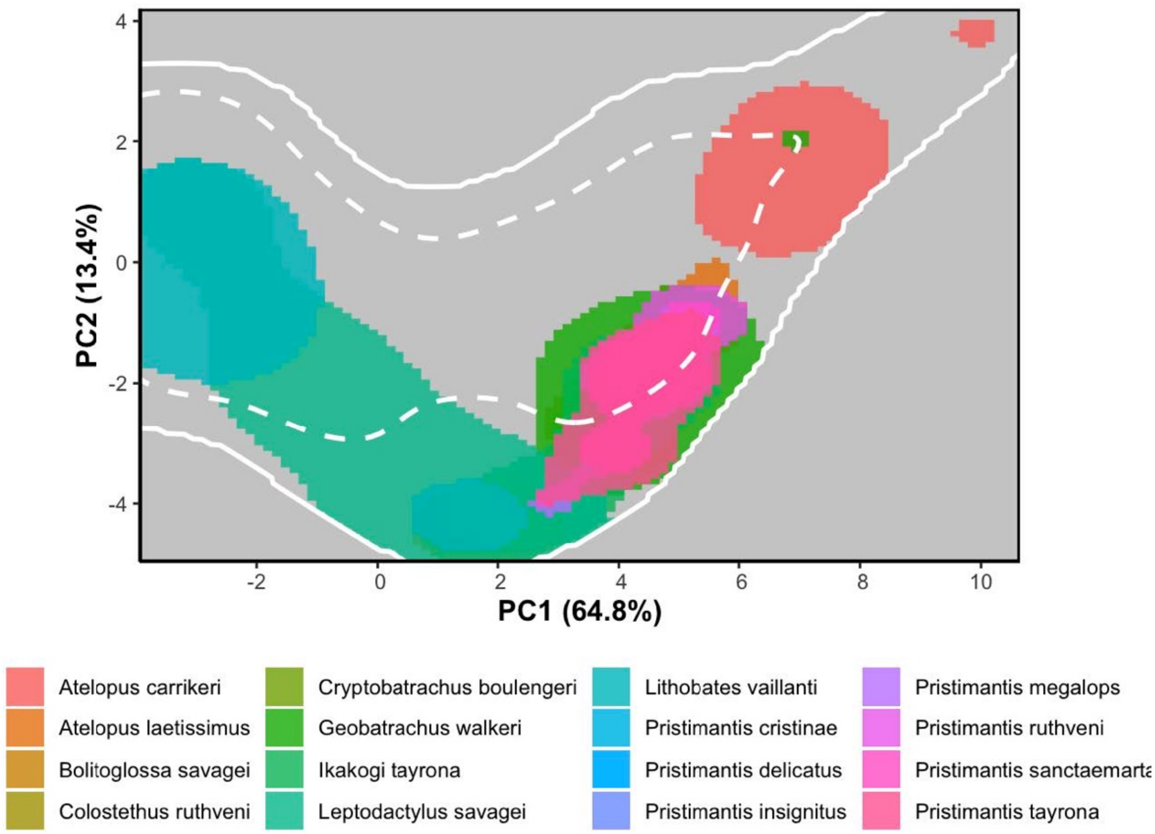

Figure B1. Plots of the polygons of the 16-focal species within the available climate envelope (solid white line) as defined by the PC1 and PC2 axes. Most species cluster in a relatively restricted climate space as described in the results.

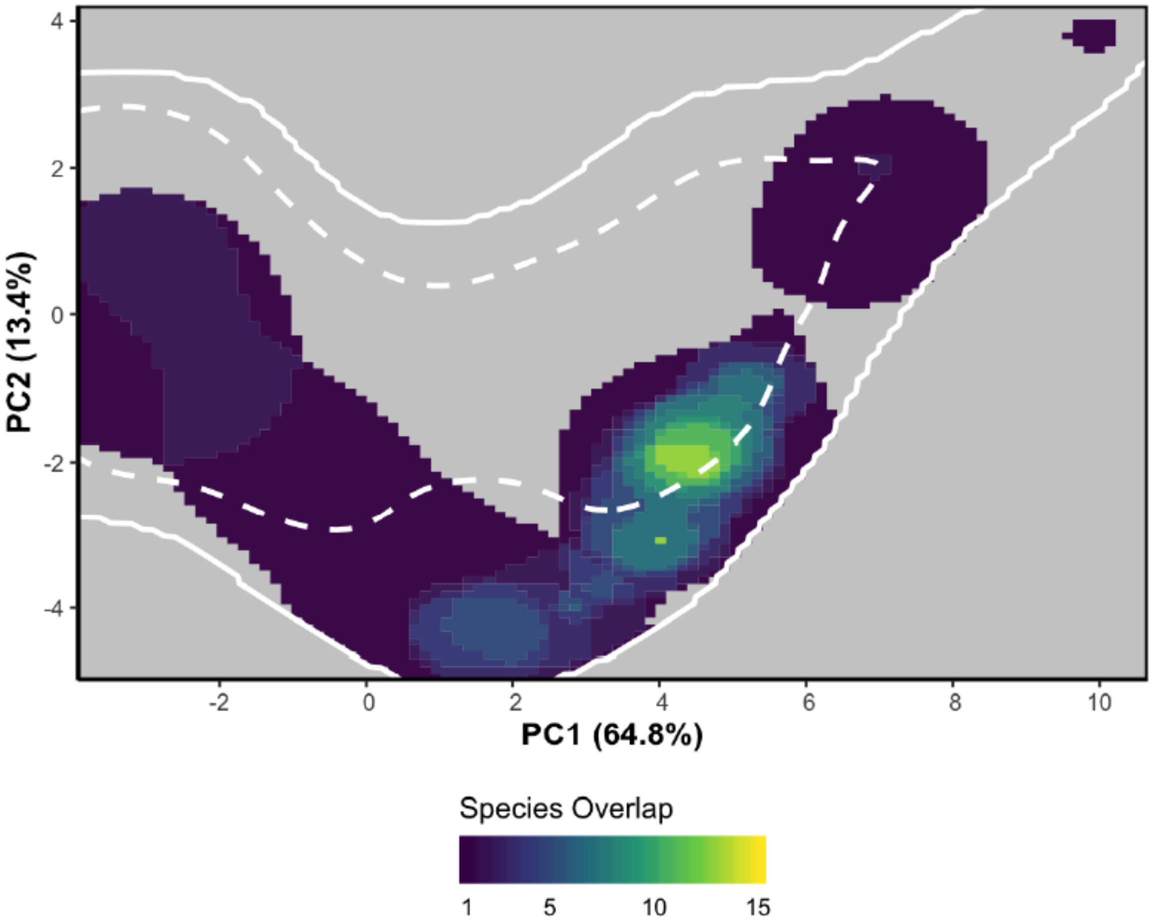

Figure B2. Visualization of the climate niche kernel densities for the 16 species, showing the overlap in species density in a relatively constrained climate space. Standard smoothing parameters (Gaussian kernel with a standard bandwidth, which corresponds to 0.9 times the minimum of the standard deviation and the inter-quartile range of the data divided by 1.34 times the sample size to the negative one-fifth power) from Silverman (1986) and Broennimann et al. (2012).

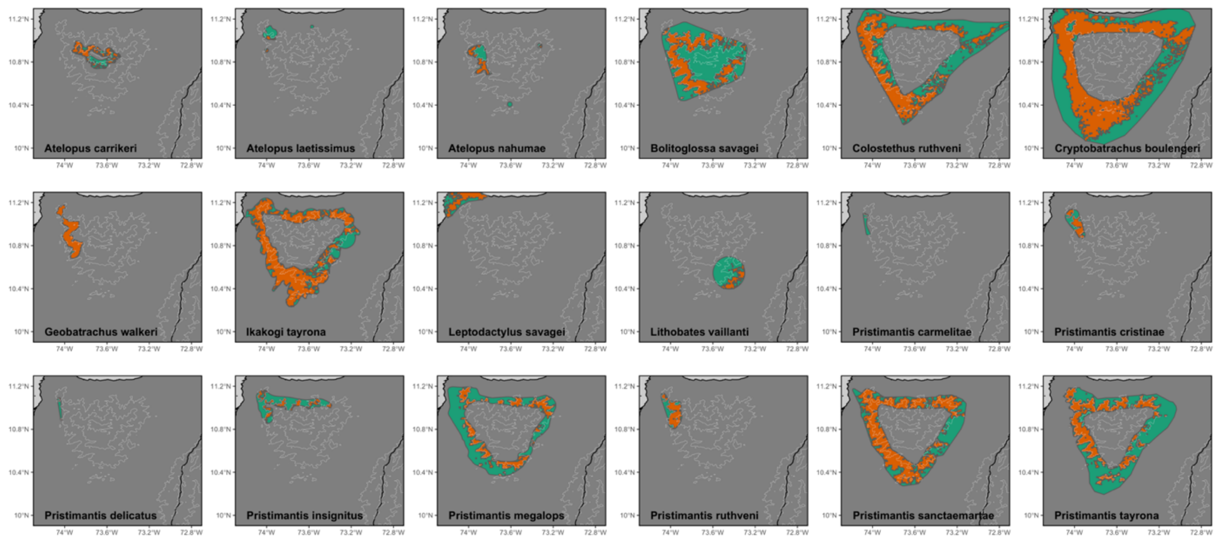

Figure B3. Maps showing the EOO as defined by the IUCN Red List range polygons (green) and the AOH (orange) as we defined it for 18 of our study species. By definition, AOH polygons are a subset of the EOO.

Table B1. Elevation and habitat/land cover data used in the derivation of AOH from EOO for the 18 species used in the CCVA.

Species	Elevational Range (m)	Habitat/ Land Cover	Citation
Atelopus carrikeri	2,350 – 4,800	Sub- Páramo, páramo, and super- Páramo, some modified habitat (pasture).	IUCN SSC Amphibian Specialist Group. 2017. *Atelopus carrikeri*. *The IUCN Red List of Threatened Species* 2017: e.T54496A49534770. https://dx.doi.org/10.2305/IUCN.UK.2017-3.RLTS.T54496A49534770.en
Atelopus laetissimus	1,900 – 2,880	Sub-Andean forests, closed-canopy secondary forest, riparian forest. more abundant in intact habitat.	IUCN SSC Amphibian Specialist Group . 2014. *Atelopus laetissimus*. *The IUCN Red List of Threatened Species* 2014: e.T54519A3015811. https://dx.doi.org/10.2305/IUCN.UK.2014-3.RLTS.T54519A3015811.en.
Atelopus nahumae	1,900 – 2,800	Sub-Andean forests, closed-canopy secondary forest, riparian forest. more abundant in intact habitat.	IUCN SSC Amphibian Specialist Group . 2014. *Atelopus nahumae*. *The IUCN Red List of Threatened Species* 2014: e.T54531A3015954. https://dx.doi.org/10.2305/IUCN.UK.2014-3.RLTS.T54531A3015954.en.
Bolitoglossa savagei	1,400 – 2,800	Montane forest, in bromeliads and dried ferns, in decaying logs and stumps and under decaying leaves.	IUCN SSC Amphibian Specialist Group. 2017. *Bolitoglossa savagei*. *The IUCN Red List of Threatened Species* 2017: e.T59204A49345792. https://dx.doi.org/10.2305/IUCN.UK.2017-2.RLTS.T59204A49345792.en.
Colostethus ruthveni	600 – 2,000	Along streams in cloud forest, grassland and dry tropical forests, tolerates some degree of habitat alteration	IUCN SSC Amphibian Specialist Group . 2018. *Colostethus ruthveni*. *The IUCN Red List of Threatened Species* 2018: e.T55144A85891000. https://dx.doi.org/10.2305/IUCN.UK.2018-1.RLTS.T55144A85891000.en.
Cryptobatrachus boulengeri	250 – 1.790	On rocks within fast-flowing streams near waterfalls in primary montane forests and in secondary forests and possibly coffee plantations	IUCN SSC Amphibian Specialist Group. 2017. *Cryptobatrachus boulengeri*. *The IUCN Red List of Threatened Species* 2017: e.T55304A85897264. https://dx.doi.org/10.2305/IUCN.UK.2017-2.RLTS.T55304A85897264.en.
Geobatrachus walkeri	1,400 – 3,900	cloud forest habitats, where wet montane habitats are surrounded by dry forests in adjacent lowlands, found also in the *páramo* habitat, dominated by rocky and shrub vegetation.	IUCN SSC Amphibian Specialist Group. 2017. *Geobatrachus walkeri*. *The IUCN Red List of Threatened Species* 2017: e.T57081A85890786. https://dx.doi.org/10.2305/IUCN.UK.2017-2.RLTS.T57081A85890786.en.
Ikakogi tayrona	700 – 2,500	Riparian gallery forests	IUCN SSC Amphibian Specialist Group . 2017. *Ikakogi tayrona*. *The IUCN Red List of Threatened Species* 2017: e.T54941A85879089. https://dx.doi.org/10.2305/IUCN.UK.2017-2.RLTS.T54941A85879089.en.
Leptodactylus savagei	0 – 660	Wide variety of habitats including primary and secondary lowland to premontane tropical moist forests, forest edges and severely deforested areas.	IUCN SSC Amphibian Specialist Group. 2020. *Leptodactylus savagei*. *The IUCN Red List of Threatened Species* 2020: e.T136079A54357258. https://dx.doi.org/10.2305/IUCN.UK.2020-1.RLTS.T136079A54357258.en.

Table B1. Continued

Species	**Elevational Range (m)**	**Habitat/ Land Cover**	**Citation**
Lithobates vaillanti	0 – 880	Very humid tropical forest and in dry forest, and disturbed habitats.	IUCN SSC Amphibian Specialist Group. 2020. *Lithobates vaillanti*. *The IUCN Red List of Threatened Species* 2020: e.T58744A53972044. https://dx.doi.org/10.2305/IUCN.UK.2020-1.RLTS.T58744A53972044.en.
Pristimantis carmelitae	1,520 – 2.200	Riparian forest under rocks along rivers in very humid areas.	IUCN SSC Amphibian Specialist Group. 2017. *Pristimantis carmelitae*. *The IUCN Red List of Threatened Species* 2017: e.T56494A85859561. https://dx.doi.org/10.2305/IUCN.UK.2017-3.RLTS.T56494A85859561.en.
Pristimantis cristinae	1,520 – 2,200	Montane forest and parámo habitats, along rivers in very humid areas.	IUCN SSC Amphibian Specialist Group. 2017. *Pristimantis cristinae*. *The IUCN Red List of Threatened Species* 2017: e.T56532A85857783. https://dx.doi.org/10.2305/IUCN.UK.2017-2.RLTS.T56532A85857783.en.
Pristimantis delicatus	1,500 – 2,600	Arboreal inhabitant of forested areas and in riparian forests.	IUCN SSC Amphibian Specialist Group. 2017. *Pristimantis delicatus*. *The IUCN Red List of Threatened Species* 2017: e.T56554A85865585. https://dx.doi.org/10.2305/IUCN.UK.2017-3.RLTS.T56554A85865585.en.
Pristimantis insignitus	1,530 – 2,130	Forests under logs or rocks on roadsides and in artificial microhabitats such as roof tiles.	IUCN SSC Amphibian Specialist Group. 2017. *Pristimantis insignitus*. *The IUCN Red List of Threatened Species* 2017: e.T56673A85871060. https://dx.doi.org/10.2305/IUCN.UK.2017-3.RLTS.T56673A85871060.en.
Pristimantis megalops	1,300 – 2.530	Cloud forest habitats, closed-canopy secondary forest, riparian forest, and pine plantations, plus some perturbed areas.	IUCN SSC Amphibian Specialist Group. 2017. *Pristimantis megalops*. *The IUCN Red List of Threatened Species* 2017: e.T56752A85868169. https://dx.doi.org/10.2305/IUCN.UK.2017-3.RLTS.T56752A85868169.en.
Pristimantis ruthveni	1,500 – 3,800	Moist forests and rocky high mountain habitats (*subpáramo* and *páramo*) often associated with streams.	IUCN SSC Amphibian Specialist Group. 2017. *Pristimantis ruthveni*. *The IUCN Red List of Threatened Species* 2017: e.T56939A85883275. https://dx.doi.org/10.2305/IUCN.UK.2017-3.RLTS.T56939A85883275.en.
Pristimantis sanctaemartae	900 – 2,600	Dense vegetation in forest interior habitats, does not tolerate degraded habitats.	IUCN SSC Amphibian Specialist Group. 2017. *Pristimantis sanctaemartae*. *The IUCN Red List of Threatened Species* 2017: e.T56945A85882673. https://dx.doi.org/10.2305/IUCN.UK.2017-3.RLTS.T56945A85882673.en
Pristimantis tayrona	1,300 – 2,700	Forest species very dependent on bromeliads	IUCN SSC Amphibian Specialist Group. 2017. *Pristimantis tayrona*. *The IUCN Red List of Threatened Species* 2017: e.T56997A85880400. https://dx.doi.org/10.2305/IUCN.UK.2017-3.RLTS.T56997A85880400.en.

Table B2. Bioclimate variables from WorldClim 2.0 used in niche overlap analyses.

Variable Number	Description
BIO1	Annual Mean Temperature
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO3	Isothermality (BIO2/BIO7) (×100)
BIO4	Temperature Seasonality (standard deviation ×100)
BIO5	Max Temperature of Warmest Month
BIO6	Min Temperature of Coldest Month
BIO7	Temperature Annual Range (BIO5-BIO6)
BIO8	Mean Temperature of Wettest Quarter
BIO9	Mean Temperature of Driest Quarter
BIO10	Mean Temperature of Warmest Quarter
BIO11	Mean Temperature of Coldest Quarter
BIO12	Annual Precipitation
BIO13	Precipitation of Wettest Month
BIO14	Precipitation of Driest Month
BIO15	Precipitation Seasonality (Coefficient of Variation)
BIO16	Precipitation of Wettest Quarter
BIO17	Precipitation of Driest Quarter
BIO18	Precipitation of Warmest Quarter
BIO19	Precipitation of Coldest Quarter

Table B3. PCA loadings for PC1 and PC2 axes. PCA with values from both rasterStacks. Without this, future and current climate can't be compared, we need them both in the same PCA. The row numbers of the PCs relate to which rasterStack they are from. We can use indexing to grab only the PC values relating to cells from 2050 and see where frog occurrence points relate to these cells. Bioclim numbers can be found in variables.

Variable	PC1	PC2
BIO1	-0.27780853	-0.09307307
BIO2	-0.21967542	0.08132114
BIO3	-0.07367967	-0.45715318
BIO4	0.10355352	0.32714242
BIO5	-0.27912486	-0.06680041
BIO6	-0.27662917	-0.10413441
BIO7	-0.20091723	0.25994619
BIO8	-0.27750022	-0.09489798
BIO9	-0.27832855	-0.09465288
BIO10	-0.27759144	-0.08781819
BIO11	-0.27780407	-0.09996648
BIO12	0.24416779	-0.22668996
BIO13	0.21583705	-0.33783486
BIO14	0.26043199	0.13905952
BIO15	-0.10305247	-0.32181200
BIO16	0.22518870	-0.30936164
BIO17	0.25777778	0.11207598
BIO18	0.19858260	-0.39146097
BIO19	-0.11688952	-0.01536506

Table B4. The 17 General Circulation Models (GCMs) used on the future climate niche projections. The models used are detailed here: (https://www.worldclim.org/data/v1.4/cmip5_2.5m.html)

ACCESS1-0 (ac)
BCC-CSM1-1 (bc)
CCSM4 (cc)
CNRM-CM5 (cn)
GFDL-CM3 (gf)
GISS-E2-R (gs)
HadGEM2-AO (hd)
HadGEM2-ES (he)
HadGEM2-CC (hg)
INMCM4 (in)
IPSL-CM5A-LR (ip)
MIROC-ESM (mr)
MIROC5 (mc)
MRI-CGCM3 (mg)
MIROC-ESM-CHEM (mi)
MPI-ESM-LR (mp)
NorESM1-M (no)

Table B5. Narrative justification of CCVA assessments as evaluated by co-authors based on species rankings, adaptive capacity, and anecdotal evidence from the field.

Species	CCVA Ranking	Vulnerability Assessment Justification
Atelopus carrikeri	High	This species has a small AOH and loses a lot of suitable environmental space under both scenarios. It is habitat specialist found at high elevations only, but it is well-protected because the entire range falls within a national park. The largest threats are climate change and habitat loss through burning and cattle grazing.
Atelopus laetissimus	High	Species has a small AOH and the environmental niche space decreases to one third of its current niche space as effects of climate change increase. It is well protected in San Lorenzo, is an endemic and dependent upon water as a non-direct developer. The major threats are climate change and habitat loss.
Atelopus nahumae	High	The assigned quantitative score was low because we do not have environmental data, however this species ranks high on all trait data, has a fairly high level of protection, but is known from only one site (1 breeding location) in the SNSM. Threats are climate change and habitat loss.
Bolitoglossa savagei	Medium	While *Bolitoglossa* has a small environmental niche space, this species is less dependent on water. Only half its range is protected, but it is found in a variety of habitats. It may be under-surveyed' contributing to the low available niche space. The primary threats is habitat loss.
Colostethus ruthveni	Low - Medium	This is a fairly abundant species, and it can be found across agricultural landscapes, and seems to tolerate higher temperatures. It has a low level of protected area coverage. In spite of a higher ranking of the coding, we consider it less vulnerable than other species. The environmental niche space estimate is small. Threats include habitat loss, but can it persist in degraded areas.
Cryptobatrachus boulengeri	Medium	This species is fairly abundant in fast-flowing streams, has low protection, but can withstand higher levels of degradation. Based upon its reproductive strategy, desiccation would impact development of offspring. Its major threats are habitat loss and reduction in stream flow.
Geobatrachus walkeri	Medium	*Geobatrachus* has a larger niche space than other species, perhaps because of its forest dwelling behavior resulting in low abundance or detectability. It is found at specific sites, has a reasonable amount of protection, and is not water dependent but forest dependent. Threats are forest loss.
Boana boans	Low	This species is Least Concern, is widely distributed, occupies a wide range of habitats, non-endemic, and can withstand low to medium levels of disturbance. It can also be found in agricultural areas.
Ikakogi tayrona	Medium	This species has a larger AOH, but anecdotal evidence suggests a dependence on high stream flow. Streams can be intermediate between natural forest and disturbed areas, and can sometimes be found on the edges of coffee farms. They occupy bromeliads, and likely depend on high precipitation levels. Threats include habitat loss and reduced precipitation/stream flow levels.
Leptodactylus savagei	Low	Occupies a large AOH and environmental niche space, is not endemic, and not tied to water sources. It has intermediate levels of protection, but the distribution is quite large.
Lithobates vaillanti	Low	A species with a large AOH and environmental niche space, not endemic, not tied to water sources. It has an intermediate level of protection and actually increases its niche space under RCP 8.5.
Pristimantis carmelitae	High	This *Pristimantis* has a very small AOH, is not abundant, is endemic, and a habitat specialist in forest. It also has minimal protected area coverage. Threat is primarily habitat loss and climate change.

Table B5. Continued

Species	CCVA Ranking	Vulnerability Assessment Justification
Pristimantis cristinae	High	An endemic species with a very small environmental niche space which is heavily impacted under the 8.5 scenario, thus presents a longer-term concern than some other species. Threats are habitat loss and climate change.
Pristimantis delicatus	High	This endemic species has a very small AOH, with big losses in available environmental niche space from RCP 4.5 to RCP 8.5. Zero percent of the estimated AOH has protected area coverage. More broadly distributed across the landscape than some other species in the genus, including in pasture. Primary threats are habitat loss and climate change.
Pristimantis insignitus	High	A species with a small AOH, where the environmental niche space decreases from RCP 4.5 to RCP 8.5. It is a forest dependent endemic species, with higher PA coverage (64%) than most others. Threats are habitat loss and climate change.
Pristimantis ruthveni	Medium-High	A higher elevation species, endemic, with intermediate coverage of protected areas. Threats are climate change, but because can it withstand some levels of degradation, being found in pasture, it might be somewhat less susceptible.
Pristimantis sanctaemartae	Medium	A species of this genus with a larger AOH, compared to other *Pristimantis* endemics. An abundant species that can be heard calling throughout forests during breeding seasons, found across various localities in the SNSM. It has low-to intermediate protection, and doesn't appear to occur in degraded habitats. Threat is primarily habitat loss.
Pristimantis tayrona	Medium	A medium sized AOH for the SNSM, about 50% under protected area coverage. It has the biggest environmental niche space of *Pristimantis*, occurring in pasture; it can persist in degraded habitats. It has low detectability, and may be common in pasture like habitat on or near coffee. Threat is likely climate change and not habitat loss.

Table B6. Results of the kernel density estimates of the ecospat analysis for the current time period (CENV in Table 1) and the mean and standard deviations of the 17 GCM model results of the area present in 2050 under RCP 4.5 and RCP 8.5. This gives an estimate of the error associated with the estimation of remaining climate space averaged over 17 GCMs.

Species	Environmental space use		
	Current	**RCP 4.5**	**RCP 8.5**
*Atelopus carrikeri**	11.78	3.73 (±3.43)	3.70 (±3.51)
*Atelopus laetissimus**	6.57	2.32 (±1.89)	1.82 (±1.70)
*Bolitoglossa savagei**	1.47	0.75 (±0.56)	0.48 (±0.51)
*Colostethus ruthveni**	6.82	2.42 (±1.67)	1.81 (±1.67)
*Cryptobatrachus boulengeri**	7.97	3.38 (±2.66)	3.03 (±3.20)
*Geobatrachus walkeri**	15.06	5.48 (±4.36)	4.73 (±4.14)
*Ikakogi tayrona**	7.35	4.44 (3.07)	3.58 (3.18)
Leptodactylus savagei	33.97	18.35 (±12.02)	17.74 (±12.79)
Lithobates vaillanti	15.08	12.75 (±6.29)	16.23 (±9.73)
*Pristimantis cristinae**	0.97	0.48 (±0.38)	0.31 (±0.34)
*Pristimantis delicatus**	3.05	1.22 (±0.96)	0.85 (±0.79)
*Pristimantis insignitus**	1.81	0.86 (±0.64)	0.56 (±0.58)
*Pristimantis megalops**	6.28	2.64 (±1.95)	2.27 (±2.02)
*Pristimantis ruthveni**	5.26	1.91 (±1.50)	1.47 (±1.34)
*Pristimantis sanctaemartae**	6.18	2.33 (±1.83)	1.75 (±1.63)
*Pristimantis tayrona**	9.13	3.45 (±2.75)	2.82 (±2.63)

APPENDIX C

SUPPLEMENTAL INFORMATION FOR CHAPTER IV

Table C1. Focal Groups questions which we used to guide discussions. We allowed for freedom of discussion to flow throughout focal group interviews depending on the groups interest of information of particularly topics. Documented in both English and Spanish. Focal Group discussion questions, Part 1 and 2.

Biodiversity	Sustainability	Governance
What types of animals do you see on your farm? *Que tipo de animals has visto en su tierra? En qué partes las ve?*	What do you do with the water and fruit after the coffee is processed? *Qué hacen con el agua y los frutos del café después de que el café es procesando?*	What's your relationship with FNC? *Cuál es su relación con Federación de Cafeteros?*
Do you have frogs on your land? Did you use to have frogs? If so where were/are they? *Hay ranas en tu tierra? Habían ranas antes? Si las habían dónde estaban?* What types of animals do you see on your farm? *Que tipo de animals has visto en su tierra? En qué partes las ve?*	Do you have certifications? What type of certifications do you have? Why did you choose this certification? Why do you choose no certification? Do you want to be certified? *Tiene certificados? Que tipos de certificados tienes? Porque eligió esa certificación? Porque no eligío un sistema de certificados? Quieres obtener alguno(s) tipos de certificados?*	Does the Colombian government support coffee farmers? Do you think this could be improved? How could this be improved? How could that be better for you? What would this help you do that you cannot do now? *Piensas que el gobierno de Colombia apoya a los cafeteros? Piensas que esto podría mejorar? Cómo podría ser mejorado? Cómo sería mejor para ti? Cómo te ayudaría esto a hacer algo que no puedes hacer ahora?*
Are you familiar with the term biodiversity? Si YES: What is the definition? *Estas familiarizado con la palabra biodiversidad? Si la conoces, podrías explicarme cuál es su definición?*	Would you be willing to engage in a program where you donated your coffee fruit/ casks to reduce waste? (if you were paid?) *Podrías participar en una programa que limpia el agua y elimina los frutos rojos?*	
What do you think about biodiversity? *Que piensas que es la biodiversidad?* Do you do you accommodate biodiversity on your land? How? *(For example maintain areas that are forested) Ud. hace algo para mantener animales en su tierra? Por ejemplo, mantener áreas forestadas?*		

Table C1 continued

Climate Change	Values	Background/History
Have you observed changes in the weather or climate? (If yes) Which changes have you notices? When did you observe these changes? Have these changes impacted you? In which way (productivity of coffee or your life)? *Has observado cambios en el clima? Si los has observado, qué tipo de cambios has observado? Cuándo observaste estos cambios? Estos cambios tuvieron algún impacto en ti? De que manera? (productividad de café, otro tipo de agricultura, o su vida?)*	What is the most important thing to you about 1) your land, 2) the SNSM? *Qué es lo más importantes de la 1) su tierra, 2) la sierra?*	How long have you been farming coffee? Did you grow up farming coffee? Did your parents farm coffee? Do you own the land on which you grow coffee? If yes, for how long? *Creciste cosechando café? Tus padres sembraban café? Eres el dueño de la tierra dónde cosechas el café? Si eres el dueño, desde hace cuándo posees la tierra? For those not owner of the land: O cuál es su título? Hace cuánto trabajas en esa finca o en la Sierra?*
Do you have any concerns about the future of coffee in this region? *Tienes alguna preocupación sobre el futuro del café en esta región?*	What do you think about the future of coffee in the SNSM? *Que piensas del futuro del café en la sierra?*	What other crops do you grow? *Cual son los otros tipos de agricultura que tienen?*
What would you do if you could not grow coffee in the same place you grow it now? Do you have any other options? (i.e. other crops or moving - I wanted to see if they have any adaptive capacity). *Qué harías si no puedes cosechar más café en el mismo lugar en el que lo haces ahora? Tienes alguna otra opción? (por ejemplo, otras cosechar o moverse de lugar? Si no puedes cosechar café en el mismo sector o lugar, que harías? Por ejemplo, tiene opciones de otros tipos de cultivos? O puedes mover sus plantas de café a otro lugar?*	Who will continue to work on the farms? (many young people aren't interested, tried not to ask this without guiding the question somewhere). *Quién va a continuar trabajando en las fincas ya que ahora los jóvenes no muestran mucho interés en continuar cosechando?*	What are the best and worst prices you've received for coffee? Is there an average price? *Cual son los mejores y peores pagos que reciben por su café? Los precios son estables o cambia mucho? Hay un precio promedio?* What is your main source of income? *Cual es su metódo principal de ingresos?*

Table C2. The community responses of Palmor presented here.

Subcategories	Palmor
Biodiversity & Wildlife	Farms, pastures, forest, trees, animals – the variety of everything. Birds: toucans, macaws, turkey hen; mammals (pigs and deer; pumas eat armadillos) and frogs, reptiles (snakes).
Climate Change	More water 10 years ago. Need to move higher to be cooler. Previously, cool at 1200 - 1250 m now it is 1700 – 2000 m. Storms are more intense – all water falls in one week; rains are less common but stronger. Mules tire frequently.
Value of Land	Water. Coffee production. The sierra has everything (expressed gratitude).
Coffee Certifications	Organics do not contaminate water, very strict rules (no chemicals, fumigation, burning), Inspectors visit homes and coffee plantations (enforce that no one under 18 works), difficult to obtain organic certification. Farmers make their own decisions, independent of certifications "if want to have a good farm you shouldn't use chemicals". Complaints about low market prices.
Socio-economic limitations	Coffee prices too low, limited government support for farmers.
Infrastructure	Improve roads.
Moderator observations from focal groups discussions	Coffee farmers are not as interested in biodiversity as they are in improving coffee profitability. Farmers require economic support (to transition to organics). Some farmers choose not to be organic, even if they show the intention to be. Low income is the biggest hardship.

Table C3. The community responses of Plan de las Ollas presented here.

Subcategories	**Plan de las Ollas**
Biodiversity & Wildlife	Biodiversity: everything in land/environment. Wildlife: Mammals (armadillos, monkeys, *tigrillo* eats armadillos), reptiles (snakes), birds (Crested oropendola), amphibians (Boana boans or *rana plantanero*). Farmers do not hunt wildlife. Avoid fumigating.
Climate Change	Temperatures have increased, precipitation levels have changed. There used to be snow in June in the peaks. 25 – 30 years ago it was another climate. Climate change affects their crops because they can't plant coffee.
Value of Land	Land: water, coffee, agriculture, and their home. Sierra: it's unique.
Coffee Certifications	Coffee certifications: Red Ecolsierra. Farmers join cooperatives because they provide income (higher prices and better markets) and assistance.
Socio-economic limitations	Low coffee prices. Sons leave for cities, over time they may sell their lands. Want alternative crops to coffee and also interested in ecotourism. Want to derive new economic strategies like incentives for farmers that participate in conservation programs.
Infrastructure	Improve roads.
Moderator observations from focal groups discussions	Farmers were happy to have the meeting stating its importance to learn about biodiversity and conservation. The farmers had lots of knowledge about animal behavior in birds and mammals.

Table C4. The community responses of San Javier presented here.

Subcategories	**San Javier**
Biodiversity & Wildlife	Biodiversity is the ecosystem; species of flora and fauna. Wildlife: mammals (Agoutis, monkeys, deer, squirrel, guartinaja (lowland paca), jaguar, armadillos, foxes), birds (turkey hen), amphibians (frogs and toads)
Climate Change	Changes in precipitation and length of dry season (shorter). Coffee fruits cannot grow fully and fruits fall off early.
Value of Land	Small watersheds and taking care of the ecosystem, Sierra is important.
Coffee Certifications	Collective certificates ensure that the purchased coffee is high quality and organic. The minimum price is 15 thousand COP/kilogram (~ 5 USD/2.2 lbs). Organic requirements include no chemicals and no burning, government provides money *prima organica* which lasts past cosescha.
Socio-economic limitations	History of conflict and land displacement, many people were killed or left but eventually came back when it was safe. Farmers want higher coffee prices. Current coffee prices are so low that the money farmers gain doesn't outweigh the money farmers spend on processing their coffee. Thank FNC for regulating prices.
Infrastructure	Better access, previously kids would walk 4 -5 hours a day to get to school.
Moderator observations from focal groups discussions	La junta de acción comunal (community leadership, elected by the community that oversees communities needs and mediate between government entities), forbids people who own forest from hunting. Participants do a clean-up with kids every other day to teach the importance of landscape and sense of belonging. FNC gives security to farmers through guarantees of coffee purchases. Topics differed by age of participants: older were more interested in discussing history of conflict and coffee while the younger were more interested in biodiversity, clean water and air.

Table C5. The community responses of San Pedro presented here.

Subcategories	San Pedro
Biodiversity & Wildlife	Biodiversity: plants, animals, and weather. Wildlife: mammals (deer, jaguar, oncilla); birds (black-chested jay, turkey hen, toucans eat coffee); reptiles (they kill venomous snakes but not others like boas), amphibians (listen to frogs & toads).
Climate Change	Coffee, plants, and animal ranges have shifted to higher elevations. Warmer temperatures and water. Farmers have had to change crops to cultivate avocado & mango; 90% of seeds are roya (coffee rust) resistant.
Value of Land	Conservation of the land and improve productivity of coffee landscapes.
Coffee Certifications	Most farmers have organic certifications/associations. Different associations have different rules. Can take up to three years of preparation to become organic. There are internal and external inspections. Red Ecolsierra does two visits/year, one in March and one in August, and also exports coffee. Organic associations receive better prices for the coffee, and a social bonus (prima social) to do improvements on their farms. Government gives coffee farmers credits in the bank but in general they don't provide support for cafeteros. Seem satisfied with prices of coffee for organics.
Socio-economic limitations	Previous projects on the landscape never returned results, farmers wanted recognition and knowledge of programs. Want other crops and express interest in ecotourism. Want to sell coffee directly to consumer avoiding filters of organizations or associations.
Infrastructure	Improve cellular network and roads. Better coffee technology, including filters for wastewater and transportation so that they don't harm the environment.
Moderator observations from focal groups discussions	Decisions farmers make are ultimately about coffee prices. Coffee farmers don't know what to do about jaguars – they want to conserve them but they are a nuisance that eat animals such as mules, dogs, and goats. Very interested in coffee filters for waste water and certifications. They would like to sell their coffee already processed and remove the middle man.

Table C6. The community responses of Vista Nieve presented here.

Subcategories	**Vista Nieve**
Biodiversity & Wildlife	Biodiversity is several species of animals and diversity of crops. All animals are found here: mammals (monkeys, foxes, puma, jaguar), birds (parrot, Santa Marta Parakeet), snakes (endemics 2-3 spp), amphibians (streams are where frogs are, find them more at night; different varieties - glass frogs and a red frog). CorpaMag (the environmental authority) brought invasive species.
Climate Change	Changes in temperature (increase) and precipitation levels, new climate conditions favor damaging beetle borer (*broca*). Changes in species interactions (specifically with two birds, *chupahuevo* and bi-colored wren). Coffee cannot produce as well as previously.
Value of Land	Water, conservation, rivers and streams. Reforestation and desire for no contamination (trash has not been removed in one year).
Coffee Certifications	Certificates: rain forest alliance (bird-friendly). Trainings through certification organizations which teach farmers to take care of the soil and streams and management of sewage water. 4 organic farms in focus group. Organics - no chemicals, burning, or fumigating (use machetes to clear understory). Government: supports them but they can't do anything to get higher prices. The committee of cafeteros supports them a lot (specifically, caficosta). Organics: want to take care of the environment and also have income bonus for higher coffee prices; non-organics can produce more coffee/year. Negative to non-organic is the soil becomes infertile rapidly. Coffee prices are low.
Socio-economic limitations	Government doesn't support farmers with higher prices, but FNC and caficosta (cooperative) is supportive. Worry about coffee prices and kids interest in coffee (moto taxis vs coffee growing). Very mad with CorpaMag who has not cleared trash in > 1 year. Local-level corruption (bribes with community leaders). They want to increase entities with more sense of belonging, support for children's education. Want help to reforest including incentives.
Infrastructure	Better cellular network and schools.
Moderator observations from focal groups discussions	Many complaints about the local environmental authority (CorpaMag). Don't want to be taken advantage of; interested in differences between organics and non-organics.