Extraction and Analysis of Baseline Data for Protected Area Management Using Geographic Information Systems, Remote Sensing and Ecological Niche Modeling

Case Study:

Armando Bermúdez National Park in the Cordillera Central of the Dominican Republic

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To My Parents

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List of Abbreviations

ABNP	Armando Bermúdez National Park
a.s.l.	Above sea level
COP	Conference of the Parties
DEM	Digital Elevation Model
DPI	Dots per Inch
ENM	Ecological niche models
GCP	Ground Control Point
GIS	Geographical Information System
ICM	Instituto Cartográfico Militar (National Cartographic Institute in Santo Domingo)
INDRHI	National Institute for Water Resources of the Dominican Republic
IUCN	International Union for the Conservation of Nature and Natural Resources
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NIR	Near-Infrared
PP	Principal Point
RGB	Red, Green, Blue
RMSE	Root Mean Square Error
SDM	Species distribution models
S-SDM	Stacked species distribution modeling
SRTM	Shuttle Radar Topography Mission
UTM	Universal Transverse Mercator
WCMC	World Conservation Monitoring Centre
WCPA	IUCN World Commission on Protected Areas
WDPA	World Database on Protected Areas

I. Introduction

I.1 GENERAL INTRODUCTION

Tropical mountain (or montane) forests occur in tropical temperate to cold altitudinal belts and range from evergreen species-rich broadleaf forests to species poor open woodlands (RICHTER 2008). In total 3.3 Mio km^2 are covered worldwide with tropical mountain forests, representing 21% of all tropical forests (SCATENA et al. 2010).

Tree species composition, distribution and structure of tropical montane forests depend on altitude, climate, soil type, edaphic conditions, geologic history and topographic heterogeneity (HOMEIER 2008; RICHTER 2008). Besides being hotspots of biodiversity[1] (BARTHLOTT et al. 2005) and centers of endemism (KESSLER & KLUGE 2008), tropical mountain forests provide important ecosystem services such as freshwater production, hydropower generation, soil stabilization and provision of food, fodder, timber and non-timber forest products (HÖLSCHER 2008). During the last years, human pressure has increased considerably on montane ecosystems, putting in danger the continued generation of the ecosystem services (GRADSTEIN et al. 2008; HÖLSCHER 2008). In many parts of the world, tropical montane forests are severely threatened as they occur on soil conditions suitable for agriculture and pasture (KAPPELLE & BROWN 2001 in MULLIGAN 2010). Conversion of natural forests to agriculture and pasture land is the most important threat to tropical mountain forests (SCATENA et al. 2010) and results in loss of vegetation cover and decrease of air and soil humidity and stability (KAPPAS 1999).

Protected areas are an important means to manage and reduce human impact in tropical mountain forests (MOSANDL & GÜNTER 2008). According to RODRÍGUEZ-RODRÍGUEZ et al. (2011), 32.4% of the world's terrestrial protected areas outside Antarctica are designated for mountain protection.[2] However, not all of them are effectively managed so that they cannot cope with the human induced threats they are facing (HOCKINGS 2004; WIENS et al. 2009).

Sustainable management and effective conservation planning of protected areas are only possible if detailed, site-specific baseline data are available, if the data are scientifically analyzed and the results used in the management process (HARMON 1994; MARGULES & PRESSEY 2000; OLDELAND et al. 2010).

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[1] Biodiversity shall be understood here as the "variability among living organisms from all sources including, inter alia, marine and other aquatic ecosystems and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems" (Article 2 of the Convention on Biological Diversity).

[2] RODRÍGUEZ-RODRÍGUEZ et al. (2011) used in their study the nationally designated protected areas from the World Database on Protected Areas of 2010.

Baseline data are also of high importance for *monitoring* and *evaluation* of the actual pressures of a site, of the conservation status and of the effectiveness of management. Furthermore they enable to assess progress towards global goals like the Strategic Plan for Biodiversity 2011-2020 of the Convention on Biological Diversity and the biodiversity conservation target of the Seventh Millenium Development Goal ("Environmental Sustainability").

Especially in developing countries, baseline data of protected areas and their scientific analysis are missing (NAUGHTON-TREVES 2005; STOLL-KLEEMANN 2010). Only East Asia and Europe delivered adequate data about protected forests for the Global Forest Resources Assessment (FRA) 2010 (FOOD AND AGRICULTURE ORGANIZATION 2010). Only 4% of all developing countries provided for the FRA 2000 information about protected forests based on detailed mapping (1:25,000-1:50,000) and nationwide field sampling (SAKET 2002). In tropical mountain forests data gathering is hampered by rugged terrain and limited infrastructure to and inside of protected areas.

Baseline data of protected areas and their surroundings comprise ecological data e.g. data on natural vegetation patterns or floristic compositions, and socio-economic data, e.g. data on human impact. They are analyzed to improve the understanding of the patterns and processes in a site and to determine the prevalent socio-economic pressures and their impacts on vegetation.

In the following baseline data and their analysis for sustainable management of montane protected areas are described in detail.

Changes in the spatial pattern of *land cover* and *land use*[3] entail negative consequences for the biological and physical processes inside a mountain forest (TOWNSEND et al. 2009). Forest conversion to agriculture or pasture land has severe consequences for biodiversity, hydrology, soil characteristics and local climate (NAIR et al. 2010). Thus, analysis of actual land cover and land use is important for conservation planning and monitoring purposes (HELMER et al. 2002).

Furthermore effective conservation plans require best estimates of the *spatial distributions* of *species* and of *patterns* of *biodiversity* and *endemism* (HERNÁNDEZ et al. 2006). Spatial explicit data about species occurrences are still scarce in most of the important conservation regions worldwide (BONN & GASTON 2005).

As tropical mountain forests vary considerably around the globe (RICHTER 2008), site-specific data about *species composition*, *vegetation-environment relationships* and *spatial distributions* of the main *vegetation types* must be analyzed to derive adequate management strategies

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[3] While land cover is related to the different feature types on the Earth's surface, land use refers to the human activity or economic function of a piece of land (LILLESAND & KIEFER 2008).

or conduct vegetation type-specific sensitivity analysis to environmental change (e.g. climate change or land conversion) (GUISAN et al. 2006).

For the extraction of *land cover* and *land use* information in mountainous areas with difficult access, remote sensing images represent adequate data (WIENS et al. 2009). On georeferenced images the exact location of each land cover/land use unit can be determined and measurements of size and distances be made. The spatial, spectral and temporal resolution of the data source has to be defined according to the purpose of the study. Land use units inside montane protected areas are mainly of small size so that medium resolution images do not deliver the desired results due to the mixed pixels (GLEITSMANN & KAPPAS 2005). High spatial resolution satellite images like GeoEye-1 or WorldView-2 would be appropriate for this task (WANG et al. 2010), but they are extreme costly for nature conservation institutions, especially in developing countries.

Digital aerial photographs represent an alternative due to their high spatial resolution (MADDEN et al. 1999; WELCH et al. 2002). Extensive aerial photograph archives exist in many countries around the world, also historical ones for retrospective studies (MILLER 1999; FENSHAM & FAIRFAX 2002; NUSKE & NIESCHULZE 2005). Extraction of land cover and land use based on aerial photography interpretation in combination with field work has been carried out for several mountain protected areas (BAKER et al. 1995; WELCH et al. 2002; MADDEN et al. 2004). The spatial analysis is undertaken by using Geographic Information Systems (GIS). GIS store large databases with geo-referenced location and permit analysis and mapping of spatial explicit information (SWENSON 2008). Its use in geographical and also biological research has increased considerably during the last years (SWENSON 2008). CASTRO & KAPPELLE (2000:12) stated that "The future success of decision-making in endemic species preservation, ecosystem restoration, (...) in tropical mountain forests strongly depends on the availability of a monitoring and evaluation GIS tool, integrating ecological and geographical information."

Differences in compositions of *vegetation types* and *vegetation-environment relationships* are assessed by statistical analysis of botanical data, for instance by ordination techniques (MCCUNE & GRACE 2002). The botanical data is sampled in the field and stored in databases or can be obtained from herbaria of Botanical Gardens.

Ecological niche modeling (ENM) allows the prediction of the potential *spatial distribution* of a *species* or *vegetation type*. ENM relates known occurrences of individual species or assemblages of species to environmental factors to predict suitable or unsuitable areas. Especially mountain areas cannot be sampled entirely, so that ENM is an adequate methodology to extrapolate ecological plot based data to a larger space. Ecological niche models represent a useful tool for conservation and reserve planning (ARAÚJO & WILLIAMS 2000), for modeling the distribution of single species (MCPHERSON & JETZ 2007; BUERMANN et al. 2008; BRADLEY & FLEISHMAN 2008), of species richness (SAATCHI et al. 2008; DUBUIS et al. 2011; GUISAN & RAHBEK 2011), of endemism (ESCALANTE et al. 2009) and for mapping the sensitivity of species to environmental change (for example: climate change, THUILLER et al. 2005), amongst other applications.

I.2 THIS THESIS

The major objective of the study is to generate and analyze ecological and environmental data that can be used to improve the management of Armando Bermúdez National Park, situated in the Cordillera Central of the Dominican Republic in the Caribbean[4]. Armando Bermúdez National Park is one of seven protected mountain forests in the Dominican Republic and holds the highest hydrological and a very important ecological value for the country.

In particular the main objectives of the thesis are:

- to generate an orthorectified aerial photograph mosaic to derive and analyze land cover and land use information;
- to analyze the floristic composition of the main natural mountain forest types and determine the vegetation-environment relationships;
- to develop a predictive model to map the spatial potential distribution of the main natural mountain forest types and analyze the potential distributions;
- to develop a predictive model to map the spatial potential distribution of selected woody species and analyze the potential distributions;
- to map and analyze the patterns of woody species richness and endemism and
- to give some recommendations for management.

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[4] MYERS et al. (2000) listed the Caribbean (Bahamas, Greater and Lesser Antilles) in the third place of the most important global biodiversity hotspots and in the fifth regarding endemism. In total, 13,000 plant species are known and 6,500 are endemics to single islands (SMITH et al. 2005). Only 10% of the original vegetation of the Caribbean hotspot remains in a natural state. 13% of the land area (30,000 km^2) are protected under different categories. However, many sites are far from pristine and urgently need better management and monitoring (SMITH et al. 2005). According to SMITH et al. (2005) montane forests are underrepresented in the protected area system in the Caribbean, thus requiring high conservation priority for the existing ones.

I.3 OUTLINE

Chapter II presents the history of protection of Armando Bermúdez National Park and unfolds relevant physical and socio-economic geographic aspects. Moreover management needs of the site are determined.

In Chapter III the photogrammetric steps to process an aerial photograph mosaic of 295 aerial photographs is described. Then land cover and land use information is extracted and analyzed from the mosaic.

Chapter IV illuminates the floristic compositions of the natural mountain forest types along the altitudinal gradient. The relationship between the occurrence of the natural mountain forest types in Armando Bermúdez National Park and environmental parameters is determined. Ecological niche models are built on the most significant environmental variables for the spatial prediction of the main forest types.

Chapter V investigates on the spatial distributions of selected woody species and analyzes the patterns of biodiversity and endemism.

Each chapter is finalized with an implication for management and possible further use of the results. Chapter VI provides an overall discussion and outlook, followed by a German and English summary.

II. The study area: Armando Bermúdez National Park

II.1 GEOGRAPHIC LOCATION

The Dominican Republic is located on the eastern part of Hispaniola in the Caribbean, between 17˚30' and 20˚ Geographic North and 68˚ and 72˚ Geographic West (Figure II.1). The western part of the island is occupied by the Republic of Haiti. The relief of the Dominican Republic is determined by the WNW-ESE trending mountain ranges and the in between lying valleys (Figure II.1). The oldest mountain system is the Cordillera Central, ranging from the Massif du Nord in Haiti to the Sierra de Ocoa in the plains of San Cristóbal and Baní in the south of the Dominican Republic (Bolay 1997). Its extension is of 300 km east-west and of 60 km north-south (Weyl 1966). The study area, Armando Bermúdez National Park, is situated between 19˚05' and 19˚25' Geographic North and 70˚80' and 71˚40' Geographic West in the center of the Cordillera Central at 495-3,087 m a.s.l. (Loma La Pelona) (Figure II.1). Here the main rivers of the country originate. Numerous plants and animals have their habitats. The national park is one of 28 national parks of 120 Dominican protected areas and with 790 km^2 the eight largest conservation area.

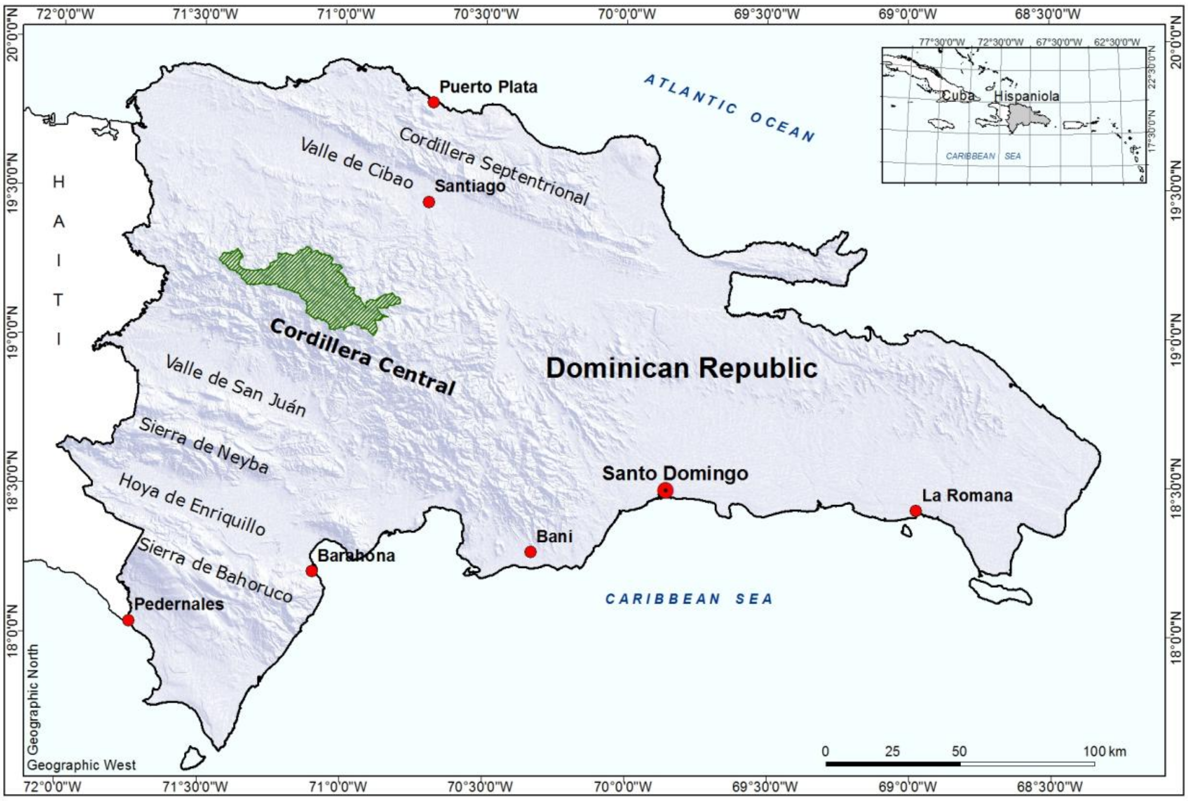

FIGURE II.1. Topography of the Dominican Republic and location of Armando Bermúdez National Park (Source: Boundaries of ABNP from Law 64-00; Cities from topographic maps 1:50,000, ICM 1983/1984; Hillshade from SRTM-3, NASA 2000; Country limits from ESRI World shapefile)

To the north of the national park extends the Valle de Cibao, to the east the Valle de Manabao with Yaque del Norte River, to the south José del Carmen Ramírez National Park and to the west Loma Nalga de Maco National Park.

II.2 HISTORY OF PROTECTION

When Columbus arrived in Hispaniola in 1492 the island was almost entirely forested. The earliest Amerindian settlers on Hispaniola and later the Tainos[5] had only little impact on the natural resources as population density was low. From 1510 on Africans were brought to Hispaniola to work as slaves. Between 1630 and 1880 the lowland forests were gradually converted to sugar cane plantations or cleared for grazing (BOLAY 1997). At the end of the 19th century the deterioration of the lowland forests (especially of *Swietenia mahagoni*) was already very advanced while the natural forests of the mountainous Cordillera Central were still intact. Interest in the forests of the Cordillera Central and in the endemic Creolan Pine (*Pinus occidentalis*) arose at the beginning of the 20th century when the lowland resources had almost entirely vanished. In 1920 the exploitation of the mountain forests had reached the remotest areas of the Cordillera Central (DARROW & ZANONI 1993). In order to stop the serious deforestation and minimize the negative effects on soils and biodiversity, the Private Reserve *Vedado del Yaque* was declared on February 27th, 1928 in the Cordillera Central. The Vedado del Yaque was established to protect the water basin of the Yaque del Norte River. However, the expected positive effects were minimal. Trujillo set up sawmills all over the mountains during his dictatorship between 1930 and 1961 and deforestation went on (DOTZAUER 1993). On October 22nd, 1951 the *Scientific Reserve for Nature Protection, Armando Bermúdez National Park*, was declared as the first real Dominican protected area with the objective to conserve the water basins of the rivers Amina, Mao and Guayubín (CONGRESO NACIONAL 1951). On February 19th, 1956 the Scientific Reserve was replaced by the *Forest Reserve Armando Bermúdez National Park* and protection was extended to the watersheds of the Yaque del Norte, Jagua and Bao Rivers (CONGRESO NACIONAL 1956). Since then, deforestation of the pine and broadleaf forests was restrained. In 2000 the limits of 1956 were ratified and in 2004 slightly modified (CONGRESO NACIONAL 2004). The actual limits of Armando Bermúdez National Park in the Cordillera Central are displayed in Figure II.2.

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[5] The Taínos (means "good", "noble") belonged to the Arawak Indians of the Amazonian region. They settled in Hispaniola around 800 B. C. (SCHOENHALS 1990). At the arrival of Columbus in 1492 about 1,000,000 Taínos lived on Hispaniola in five kingdoms (Cacicazgos). They lived on farming (yucca, maize), fishing and hunting. The Spanish conquerors forced them to labour in mines and on plantations. In 1514 only around 22,000 Taínos were still alive. They died in the following years by introduced diseases or were killed (BOLAY 1997).

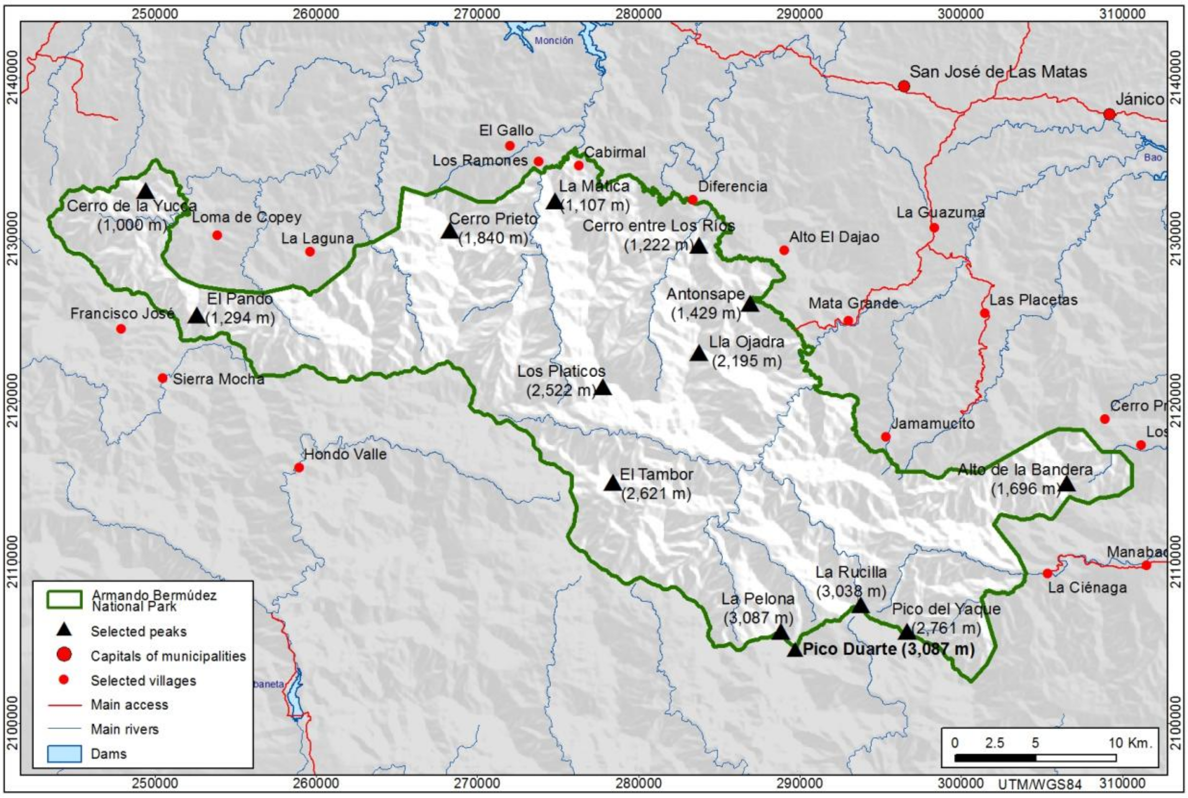


FIGURE II.2. Topography of Armando Bermúdez National Park with selected peaks (Source: Boundaries of ABNP from Law 64-00; Villages, roads, peaks, rivers, dams from topographic maps 1:50,000, ICM 1983/1984 and field work; Hillshade from SRTM-3, NASA 2000)

The Dominican national system of protected areas embarks 11,965.15 km^2 or 25% of the land surface (SECRETARÍA DE ESTADO DE MEDIO AMBIENTE Y RECURSOS NATURALES 2011). The IUCN-management categories are represented as follows: 12 Areas of Strict Protection (Category I), 28 National Parks (Category II), 30 Natural Monuments (Category III), 19 Habitat/Species Management Area (Category IV), 16 Protected Landscapes (Category V) and 15 Nature Reserves (Category VI). 4,770 km² of forests are protected in the system, 65 % of the remaining cloud, 58 % of the coniferous, 30 % of the humid broadleaf and 19 % of the dry forests (SECRETARÍA DE ESTADO DE MEDIO AMBIENTE Y RECURSOS NATURALES 2002). The system shows few ecological gaps (KEEL 2006).

Formal management plans have just been elaborated for 35 of the 120 protected areas. A national system plan for the portfolio does not exist. Although the IUCN requires buffer zones for the management categories I and II and recommends them for the categories III and IV, they have not been established up to now.

II.3 RELEVANT PHYSICAL GEOGRAPHIC ASPECTS

II.3.1 Geology, soils and hydrology

Geology

Hispaniola forms together with Jamaica and Puerto Rico the northern part of the Caribbean Plate which is surrounded by the North American, the South American and the Cocos and Nazca Plates. The center of the Cordillera Central is part of three Antillean submarine arcs, trending from Yucatán and Honduras to Cuba and Jamaica reaching the Dominican Republic, proceeding to Puerto Rico and the Lesser Antillean Islands. These arcs have their origin in volcanic activities and plate tectonic movements of the above mentioned plates after the rupture of Pangaea in the early cretaceous period (CUCURULLO 1952). The magmatic center of the Cordillera Central was surrounded during the cretaceous period by flat seas with high sedimentation activity of limestone. Acid intrusions took place between the late Cretaceous and early Eocene (LEWIS 1980). The material dissolved and was solidified to crystalline slate (WEYL 1966). Folding and elevation processes are dated to the Eocene/Oligocene and Pliocene/Pleistocene. Today crystalline slates, sediments and volcanics, peridotites and quartz diorites of the cretaceous period are found in the Cordillera Central. Besides the Cordillera Central and the Sierra del Seibo all other Dominican mountain ranges are composed of tertiary sediments (Figure II.3). The steep and narrow valleys of the Cordillera Central are witnesses of the tectonic activity of the humid tropics (KAPPAS & SCHÖGGL 2005). Along the southern border of Armando Bermúdez National Park the mountains are higher (for example Pico del Yaque 2,761 m a.s.l., Loma de la Viuda 2,801 m a.s.l., Loma La Rucilla 3,038 m a.s.l., Loma La Pelona 3,087 m a.s.l.) than in the north (Cerro de la Yucca 1,000 m a.s.l., Loma La Matica 1,107 m a.s.l., Cerro entre los Ríos 1,222 m a.s.l.) (Figure II.2). In the center, two high mountains are Loma del Tambor (2,621 m a.s.l.) and Loma de los Platicos (2,522 m a.s.l.). The altitudes in the western part of the national park are lower than in the east. Nearly all of Armando Bermúdez National Park is composed of magmatic rocks.

Glacial geomorphologic and sedimentary features near Loma de La Viuda and Alto de la Bandera like cirques, arêtes, glacial channels, roches moutonnêes, moraines, bog-filled depressions suggest the existence of glaciers and a snowline at 2,200-2,300 m a.s.l. during the Quaternary (SCHUBERT & MEDINA 1982).

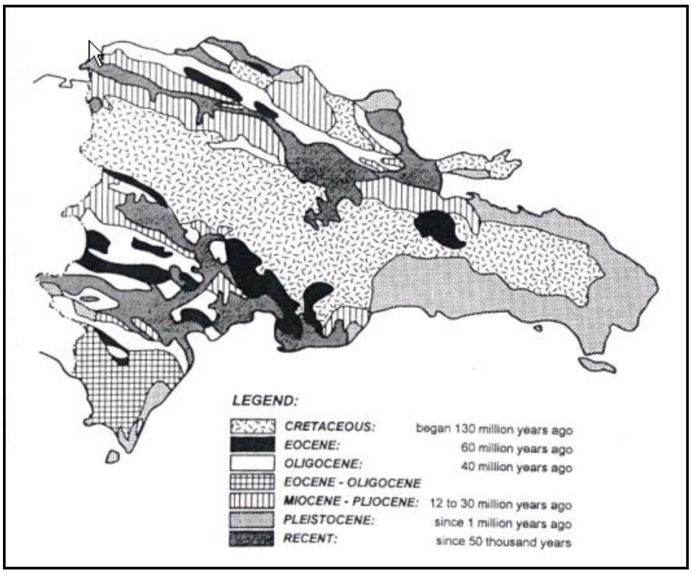


Figure II.3. Geological structure of the Dominican Republic (Source: Nuñez Molina (1980) in Bolay 1997:55)

Soils

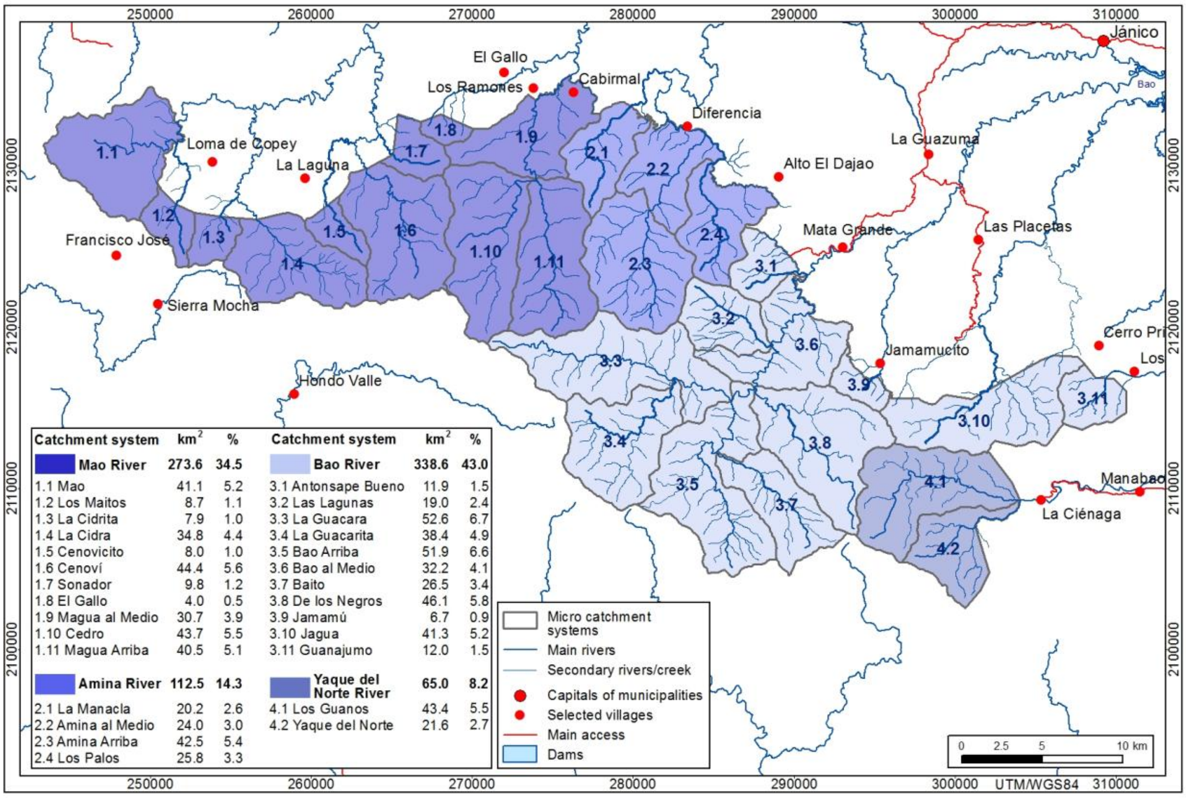
The soils of Armando Bermúdez National Park are of the acid and little profound Ferralsol type (IUSS Working Group WRB 2007). Ferralsols are intensively weathered soils in the tropical and subtropical forests that occur on siliceous rocks such as siliceous tuffs and quartz diorites. Their color ranges from yellow to red. On the peaks and along the steep slopes (> 60%) the soils are highly eroded**,** poor in nutrients and rich in aluminum. The texture is variable with fine components, water retention capacity and fertility are low (May 2007). These acid and weathered soils are just tolerated by a very specialized flora with a high amount of endemic plant species, sometimes of primitive character (Liogier 2000). Along the creeks and rivers the soils are less eroded and younger due to the transported mineral material of the fluvial sediments. They contain a higher proportion of nutrients, are less acid and their aluminum content is poor (May 2007). Soil color varies here between brown and black. A detailed soil map does not exist of the study area.

Hydrology

About 4,000 permanent and temporal streams run through the Dominican Republic. The surface water is used for energy generation, for industrial production, for irrigation and as drinking water. The Cordillera Central is the main water producer of the country. Therefore it is also called “Madre de las Aguas” (engl: mother of the waters). 709 rivers and creeks originate in the central mountain range, including Yaque del Norte River which rises in Armando Bermúdez National Park near Loma La Rucilla (SECRETARÍA DE ESTADO DE MEDIO AMBIENTE Y RECURSOS NATURALES 2004a). All of the rivers that originate in Armando Bermúdez National Park drain into Yaque del Norte River, mainly in the Valle de Cibao. Yaque del Norte River flows into the Atlantic ocean close to Monte Cristi and is with 201 km the longest river and the one with the largest catchment area. Due to the seasonal precipitation regime (see II.3.2 Climate), discharge volume varies throughout the year. For Yaque del Norte the maximum mean monthly discharge (1956-2001) measured at Pinar Quemado near Jarabacoa was of 14.6 m^3/sec in May and minimum of 7.1 m^3/sec in February (VICIOSO 2002 in GLEITSMANN 2005).

The catchment subsystem of Yaque del Norte River embarks 65 km^2 or 8.2% of the entire protected area (Figure II.4) and is divided in the two river systems Yaque del Norte and Los Guanos. Their confluence is near the village La Ciénaga at the eastern entrance of the national park. The catchment area of the subsystem of the Mao River in the extreme western part of Armando Bermúdez National Park has an extension of 273.6 km^2 (34.5%) (Figure II.4). It is composed of 11 rivers and creeks: Magua Arriba, Cedro, Magua al Medio, El Gallo, Sonador, Cenoví, Cenovicito, La Cidra, La Cidrita, Los Maitos and Mao. Mao River flows into Yaque del Norte River in the Valle de Cibao near the city of Valverde Mao.

Amina River has a catchment area of 112.5 km^2 covering 14.3 % of Armando Bermúdez National Park. The main tributaries of Amina River are Los Palos, Amina Arriba, Amina al Medio and La Manacla (Figure II.4). Amina River also discharges into Yaque del Norte River close to Valverde Mao. The Bao catchment area is with 338.6 km^2 (43%) the largest subsystem in Armando Bermúdez National Park. Bao River is also the longest (57.8 km) within the national park (Figure II.4). The water basin is divided in 11 micro catchment systems formed by the rivers and creeks Guanajumo, Jagua, Jamamu, de los Negros, Baito, Bao al Medio, Bao Arriba, La Guacarita, La Guacara, Las Lagunas and Antonsape Bueno. Bao River flows near Jánico in the Reservoir of Bao and is unified with Yaque del Norte River at Boca de Bao south of Santiago de los Caballeros.



Catchment system	km²	%	Catchment system	km²	%
Mao River	**273.6**	**34.5**	**Bao River**	**338.6**	**43.0**
1.1 Mao	41.1	5.2	3.1 Antonsape Bueno	11.9	1.5
1.2 Los Maitos	8.7	1.1	3.2 Las Lagunas	19.0	2.4
1.3 La Cidrita	7.9	1.0	3.3 La Guacara	52.6	6.7
1.4 La Cidra	34.8	4.4	3.4 La Guacarita	38.4	4.9
1.5 Cenovicito	8.0	1.0	3.5 Bao Arriba	51.9	6.6
1.6 Cenoví	44.4	5.6	3.6 Bao al Medio	32.2	4.1
1.7 Sonador	9.8	1.2	3.7 Baito	26.5	3.4
1.8 El Gallo	4.0	0.5	3.8 De los Negros	46.1	5.8
1.9 Magua al Medio	30.7	3.9	3.9 Jamamú	6.7	0.9
1.10 Cedro	43.7	5.5	3.10 Jagua	41.3	5.2
1.11 Magua Arriba	40.5	5.1	3.11 Guanajumo	12.0	1.5
Amina River	**112.5**	**14.3**	**Yaque del Norte River**	**65.0**	**8.2**
2.1 La Manacla	20.2	2.6	4.1 Los Guanos	43.4	5.5
2.2 Amina al Medio	24.0	3.0	4.2 Yaque del Norte	21.6	2.7
2.3 Amina Arriba	42.5	5.4			
2.4 Los Palos	25.8	3.3			

FIGURE II.4. Hydrology in Armando Bermúdez National Park (Source: Boundaries of ABNP from Law 64-00; Catchment systems, villages, roads, rivers, dams from topographic maps 1:50,000, ICM 1983/1984 and field work)

II.3.2 Climate

The Dominican Republic lies at the interface between the seasonally shifting tropical rainy climates and the dry tropical doldrums. The country is influenced all throughout the year by the north easterly trade winds that have their origin at the Intertropical Convergence Zone (ITCZ) near the equator (HORST 1992). At the ITCZ warm air masses rise and flow pole wards to compensate for the energy differences prevailing between the low and high latitudes (HEYER 1972). These air masses sink at 30° Geographic North and South and head from the subtropical anticyclone belt back towards the ITCZ. With decreasing distance from the ITCZ their vertical expansion is reduced, providing space for the higher air layers to sink. Thus, the trade wind inversion is formed, separating humid air masses on the ground from dry air masses of the middle and high troposphere. In the Dominican Republic the north easterly trade winds are forced to rise at the Cordillera Central. Considerable orographic rainfall occurs in summer along the north eastern slopes (luv) while the south western slopes are much drier (lee). The stable conditions of the TWI are weakened in the Caribbean in summer with the shifting northwards of the North-Atlantic subtropical anticyclone belt. Therefore a “rain season” between May and October and a drier season between December and March is formed (WEISCHET 1996). Mean annual mean precipitation varies between 500 mm in Azua in the dry south-west and 2,500 mm in Maimon in the center (1961-1990) (INSTITUTO NACIONAL DE RECURSOS HIDRÁULICOS 2009). Mean annual temperature at sea level is 23˚C in January and 28˚C in July (BOLAY 1997).

Annual precipitation in Armando Bermúdez National Park ranges from 1,500-2,500 mm according to the location of the site (INSTITUTO NACIONAL DE RECURSOS HIDRÁULICOS 2009). Maximum precipitation amounts are expected below the base of the trade wind inversion which is at approximately 2,150 m a.s.l. (SCHUBERT et al. 1995). Above the base of the trade wind inversion conditions become drier. Due to the northwest-southeast direction of the massif, the amount of orographic precipitation from the trade winds on the south-western slopes (José del Carmen Ramírez National Park) is about half of the amount along the north-eastern slopes (WEISCHET 1996; KAPPAS 1999).

January, February and March are the driest months while May, June and October are the wettest (BOLAY 1997). Temperature decreases from north to south in Armando Bermúdez National park due to increasing terrain heights. On the highest peaks annual mean temperature varies between 9-13˚C. 21˚C of annual mean temperature were registered at the station of Mata Grande at 1,000 m a.s.l. on the northern border (1990-2008, Figure II.4 and Figure II.5). Annual mean precipitation summed up to 1,861 mm at this station (Figure II.5). Inside of Armando Bermúdez National Park climate stations do not exist so that the precipitation pattern is difficult to assess (FEIDEN 2004). According to SCHUBERT & MEDINA (1982) the average minimum temperature of 0˚C is reached at 2,800 m a.s.l.. During winter invasions of cold air masses from the north can already cause frost in altitudes above 2,000 m a.s.l. (BOLAY 1997).

Mata Grande (1,000 m a.s.l.)		1,861.1 mm
	Geographic West: 70°59'15"	21.2°C
	Geographic North: 19°12'03"	

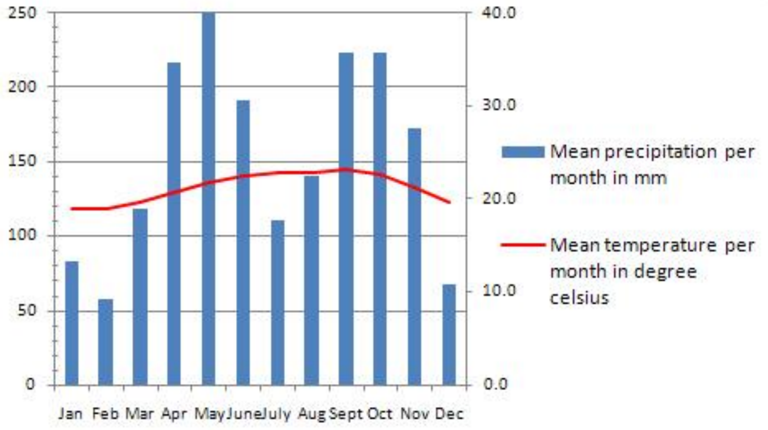


FIGURE II.5. Mean monthly precipitation and mean monthly temperature, Mata Grande (1990-2008) (Source: Instituto Nacional de Recursos Hidráulicos (2009), own presentation)

II.3.3 Vegetation

The flora of Hispaniola belongs to the Neotropical Floristic Kingdom, at regional level to the flora of the Caribbean. 5,600 vascular plant species (5,000 spermatophytes and 600 pteridophytes) are known of 185 families and 1,102 genera (ACEVEDO-RODRÍGUEZ & STRONG 2008). According to LIOGIER (2000), five components can be distinguished in the Hispaniolan flora: a cosmopolitan, an Antillean, an endemic, a continental and an introduced/exotic element.

The cosmopolitan component consists of pan-tropical and pan-Caribbean species, principally composed by sea shore plants and tropical shrubs. Elements of the Antillean flora present in the flora of the Dominican Republic and also in Armando Bermúdez National Park, are for example: *Clusia rosea*, *Cyrilla racemiflora*, *Brunellia comocladifolia*, *Prunus occidentalis*, *Weinmannia pinnata* and *Ocotea coriacea*. Regarding the endemic component Hispaniola has an endemism of vascular plants of 36% and occupies the second place in the Caribbean after Cuba with 51% (BORHIDI 1996). In Armando Bermúdez National Park more than 750 different vascular plant species have been identified, 186 of them are endemic (PEGUERO et al. 2007; SECRETARÍA DE ESTADO DE MEDIO AMBIENTE Y RECURSOS NATURALES 2003a). The woody species, *Omphalea ekmanii*, for instance is a locally endemic plant in Armando Bermúdez National Park. The continental element of the Hispaniolan flora is composed by species of North-, Central-and South-America. The affinities of the Hispaniolan flora with the South-American are stronger than with the Central-American (LIOGIER 2000). Holarctic elements of temperate habitats are represented by *Pinus* and *Juglans jamaicensis* in the Dominican Republic and also Armando Bermúdez National Park. In the eastern part of the Cordillera

Central, the species of the genus *Magnolia* are frequent. It is still being discussed whether colonization occurred primarily through dispersal or along temporary land bridges between the Caribbean islands and the continent (ACEVEDO-RODRÍGUEZ & STRONG 2008). The introduced or exotic elements consist mainly of shrubs from the old continent introduced to Hispaniola after 1492.

Due to the variability of the topography, soils and the climate of the Dominican Republic very different vegetation types have evolved (KAPPAS & SCHÖGGL 2005) ranging from halophytic, dry, semi-deciduous, evergreen and pine to freshwater vegetation (HAGER & ZANONI 1993). Classification schemes for the Dominican natural forests and vegetation types were developed by DURLAND (1922), CIFERRI (1936), CHARDON (1941), TASAICO (1967)/HOLDRIDGE (1947) and HAGER & ZANONI (1993).

Holdridge established a life zone system to predict vegetation types in the tropics based on biotemperature and mean annual precipitation. Evapotranspiration and elevation are included as secondary environmental parameters in the model. TASAICO (1967) applied the HOLDRIDGE (1947) life zone system to the Dominican Republic. According to the system, the mountain forests in Armando Bermúdez National Park are classified (Table II.1) as subtropical moist forest (16-24˚C; 1,000-2,000 mm)[6], subtropical wet forest (16-24˚C; 2,000-4,000 mm), lower montane or warm temperate moist forest (12-16˚C; 1,000-2,000 mm), lower montane or warm temperate wet forest (12-16˚C; 2,000-4,000 mm) and montane or cool temperate wet forest (8-12˚C; 1,000-2,000 mm) (TASAICO 1967; HOLDRIDGE 1947; HOLDRIDGE 1967). HOLDRIDGE's system is a theoretic model that does not take into account edaphic factors, soil types, exposure or relief.

HAGER & ZANONI (1993) set up a very detailed classification of the natural Dominican vegetation based on vegetation structure and composition. According to their system, the following vegetation types are present in Armando Bermúdez National Park (Table II.1): Evergreen broadleaf forests of seasonal precipitation of the *Sloanea ilicifolia* type (18-24˚C; 2,000 mm; 1,500 m a.s.l.)[7], riparian forests of the high mountains (2,000 mm; 600-1,600 m a.s.l.), cloud forests (15˚C; 1,700-2,000 mm; 1,600-2,200 m a.s.l.) and the pine forests of medium (800-2,200 m a.s.l.) and high elevation in the Cordillera Central (above 2,200 m a.s.l.).

In Table II.1 the vegetation classification schemes of TASAICO (1967)/HOLDRIDGE (1947), HAGER & ZANONI (1997) and PEGUERO et al. (2007) (see next chapter) are compared.

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[6] Temperature is presented as isotherm (˚C) and precipitation as annual mean precipitation (mm) for the Holdridge life zones.

[7] Temperature is presented as isotherm (˚C), precipitation as annual mean precipitation (mm) and elevation in meters above sea level for the classification of HAGER & ZANONI (1993).

Table II.1. Comparison between three classification systems of the natural forest types of Armando Bermúdez National Park (Tasaico 1967/Holdridge 1947; Hager & Zanoni 1993; Peguero et al. 2007)

Life Zones **Tasaico (1967)/Holdridge (1947)**	**Natural vegetation types** **Hager & Zanoni (1993)**	**Forest types** **Peguero et al. (2007)**
Montane/ Cool temperate wet forest	Pine forest of high elevations	Pine forest
	Pine forest of medium elevations	Pine forest (mixed forest)
Lower montane/ Warm temperate wet forest Lower montane/ Warm temperate moist forest	Cloud forests, Manaclares, *Schefflera tremula*	Cloud forest, Manaclares
Subtropical wet forest Subtropical moist forest	Evergreen forests with seasonal precipitation	Humid broadleaf forest, Manaclares
	Riparian forests of high elevations	Riparian/gallery forests, Manaclares

May (1997a) followed the classification of Hager & Zanoni (1993) for a brief description of the mountain forest types of the Dominican Republic, including Armando Bermúdez National Park.

Peguero et al. (2007) distinguished five forest types in Armando Bermúdez National Park: Humid broadleaf forests, riparian/gallery forests, cloud forests, manaclares, pine forests and mixed forests (Table II.1). The differentiation was based on floristic data collected on punctual field plots. A brief summary of each type is given below.

Extensive information about the spatial vegetation patterns of the entire area of the national park does not exist nor have been analyzed the environmental factors which determine them.

Humid broadleaf forest

Evergreen broadleaf forests are found in Armando Bermúdez National Park at the lower elevations. The most characteristic tree species are *Beilschmiedia pendula*, *Ocotea leucoxylon*, *Dendropanax arboreus*, *Inga vera*, *Prunus occidentalis*, *Ocotea coriacea*, *Guarea guidonea*, *Oreopanax capitatus* and *Prestoea montana*, among others. On the trees endemic epiphytes, Bromeliaceae of the genus *Tillandsia* and Orchidaceae occur. The shrub layer is dense with species such as *Piper* spp., *Palicourea* spp., *Psychotria berteriana* and *Bertiera guianensis* and tree ferns of the genus *Cyathea* and *Alsophila*. The herb layer is nearly non-existent due to the high density of the shrub and tree layers. On clear spots Poceae such as *Homolepis glutinosa*, *Lasiacis divaricata*, *Pharus lappulaceus* and species of the genera *Panicum* and *Paspalum* are present. Lianas are scarce.

Riparian/gallery forests

Riparian forests occur along the main valleys of Armando Bermúdez National Park. Depending on the altitude of the riparian forests in the water basin, riparian forests are floristically similar to humid broadleaf forests or to cloud forests. Mean tree height is about 18 m, some individuals surpass 20 m. The most frequent tree species are: *Guarea guidonea*, *Syzigium jambos*, *Dendropanax arboreus, Inga vera*, *Prunus occidentalis*, *Ocotea coriacea* and *Beilschmiedia pendula*. The shrub layer is composed of *Piper* spp., *Psychotria berteriana*, *Bertiera guianensis, Clusia minor* and *Poitea galegoides*. The most characteristic herb of the mean elevation riparian forests is *Gynerium sagittatum* growing up to five meters. Lianas are present (e.g. *Bomarea edulis*, *Trichostigma octandrum, Mikania cordifolia*) and the epiphytes species and genera are similar to the humid broadleaf forests.

Cloud forest

Cloud forests are present in Armando Bermúdez National Park at high elevations where mist and fog occurrence permit horizontal precipitation. Cloud forests are of distinctive floristic and structural form and are accompanied by mosses, ferns, orchids and other epiphytic plants on trees and in the understory (HAMILTON et al 1995). Cloud forests are supposed to disappear faster than any other forest ecosystem in the Caribbean and Central America (LABASTILLE & POOL 1978 in DOUMENGE et al. 1995). Tree heights vary between 5-20 m. Characteristic tree species are amongst others: *Sloanea ilicifolia*, *Schefflera tremula*, *Brunellia comocladifolia*, *Cyrilla racemiflora*, *Weinmannia pinnata*, *Ditta maestrensis* and *Haenianthus salicifolius* var. *obovatus*. In the shrub layer, the most common species are *Hediosmum domingense*, *Cordia lima*, *Budleja domingensis* and *Palicourea* spp.. In the herb layer *Ichnanthus pallens*, *Isachne rigidifolia*, *Oplismenus hirtellus* are recorded. Tree ferns of the genera *Alsophila* and *Cyathea* are frequent while lianas are not abundant, but can be found (e.g. *Odontadenia polyneura*, *Rhodopis lowdenii*, *Odontosoria uncinella*). The tallest trees are covered by epiphytes (e.g. *Tillandsia selleana*, *Catopsis floribunda*), orchids (e.g. *Jacquiniella* spp., *Lepanthes* spp.) and ferns (genera *Blechnum* and *Campyloneurum*).

Manaclar

Along the steep northern slopes and in mountain valleys the Sierran Palm Forest, the *manaclar*, occurs in Armando Bermúdez National Park (CIFERRI 1936). This forest type is dominated by *Prestoea montana*, representing more than 50% of all species of this vegetation type. The height varies between 10-13 m, but can also reach 20 m. The understory is mainly open.

The same tree species described for the humid broadleaf, riparian and cloud forests are associated with *Prestoea montana*, according to elevation. Due to the high degree of humidity the presence of epiphytes is elevated. Often tree ferns (*Cyathea* spp.) are observed in manaclares.

Pine forest

The natural pine forests of Armando Bermúdez National Park consist of the endemic Creolan Pine, *Pinus occidentalis* (ZANONI 1993). In reforested areas around the national park, *Pinus occidentalis* is associated to the introduced Caribbean Pine, *Pinus caribaea*.

Pinus occidentalis occurs naturally in a range of 150-3,000 m a.s.l. in the Dominican Republic (CHARDON 1941). Tree heights vary between 6-8 m at the highest elevations and 20 m between 1,900-2,500 m a.s.l.. The trunk is always straight and undivided. Branching begins at the upper portion of the tree and consists of stout, horizontal and spreading branches (HUDSON 1991). The understory of montane high elevation pine forests is composed of ferns and shrubs or of the bunch grass, *Danthonia domingensis* (ARECES-MALLEA et al. 1999). In elevations of 1,600-1,800 m a.s.l. pine branches are often covered by *Tillandsia usneoides* and *Usnea* spp. (DARROW et al. 1991). Amongst the shrubs in the understory at humid sites *Ilex* spp., *Weinmannia pinnata* and *Garrya fadyenii* are common. In drier environments, *Baccharis myrsinites, Myricia picardae, Cestrum tuerckheimii, Lyonia heptamera, Satureja alpestris* and *Eupatorium illitum* are associated with *Pinus occidentalis.*

Mixed forests

This forest type occurs only on areas affected by fire, landslides, hurricanes or humans (HAGER & ZANONI 1993). *Pinus occidentalis* is considered here as pioneer (MAY 1997a). Besides *Pinus occidentalis*, the tree species *Brunellia comocladifolia*, *Ocotea leucoxylon, Podocarpus aristulatus* and *Schefflera tremula* are found in mixed forests. The mixed forests have a rich epiphytic flora of mosses, lichens and other cryptograms.

II.3.4 Fauna

The fauna of Hispaniola is the most diverse of the West Indies. 70 species of fish (53% endemism), 60 species of amphibians (97% endemism), 141 species of reptiles (83% endemism), 34 species of mammals (12% endemism) and 254 species of birds (18% endemism) are known. The natural areas of the Dominican Republic serve as a habitat for 270 migratory bird species (SECRETARÍA DE ESTADO DE MEDIO AMBIENTE Y RECURSOS NATURALES 2004a).

47 species of reptiles and amphibians (90% endemism) have been identified in the Cordillera Central (SECRETARÍA DE ESTADO DE MEDIO AMBIENTE Y RECURSOS NATURALES 2003b). Most of them have been recorded in Armando Bermúdez National Park in altitudes below 2,500 m a.s.l. (HERNÁNDEZ 2007). The bird fauna is represented with 50 species in the national park, 17 species are endemic (ALMONTE 2007; LATTA et al. 2006). Important mammals are the Hispaniolan hutia (*Plagiodontia aedium*), the Hispaniolan solenodon (*Solenodon paradoxus*), the big brown bat (*Eptesicus fuscus*) and the wild boar (*Sus scropha*). Furthermore Armando Bermúdez National Park is the major habitat for the Hispaniolan daylight butterflies (BASTARDO LANDRAU 2007).

II.4 HUMAN IMPACTS ON THE NATURAL RESOURCES

60 communities are situated around Armando Bermúdez National Park mainly to the north, northeast and east. Over two third of them have a direct impact on the natural resources of the national park as a result of their location and economic activities of the inhabitants (MCPHERSON 2007). Standard of living in the villages in the *Sierra* is low and the generation of a reasonable income is difficult. The educational infrastructure and health care are poor and only a few communities count on electricity (Table II.2). Thus, migration out of the area to Santiago de Los Caballeros, Santo Domingo and even to the USA is high. Nearly all of the communities visited on the field trips have a negative migration rate for the time span between 1999 and 2011 (Table II.2). Positive numbers were just recorded in the villages Los Ramones and Arroyo Bonito/Los Montazos Abajo where intensively managed *Caturra* coffee (*Coffea arabica* var. *caturra*) plantations have been expanding during the last years. Mainly Haitian workers attend the plantations.

Due to the low monetary resources and precarious health system in the Sierra, plants are frequently used to cure diseases. 93 plants of the area are reported to have a medical use or value (PEGUERO 2007). The most important medical plants are: *Cymbopogon citratus*, *Chenopodium ambrosioides*, *Mentha spicata*, *Citrus aurantium*, *Ocimum sanctum*, *Tetragastris balsamifera*, *Ambrosia artemisifolia* and *Ocotea foeniculacea*.

The main impacts on the natural resources of Armando Bermúdez National Park are caused by agriculture, extensive livestock-grazing, felling of trees, hunting, wild fires, hurricanes and visitation.

Small scale agriculture and the cultivation of coffee have a long tradition in the Sierra. The main agricultural products are sweet potatoes (*Ipomoea batatas*), beans (*Phaseolus* spp.), maize (*Zea mays*), manioc *(Manihot esculenta)*, tannia (*Xanthosoma sagittifolium*) and pumpkin (*Cucurbita spp*.). The traditional coffee (*Coffea arabica* var. *tipica*) is managed under shade trees in the Sierra such as the mountain immortelle (*Erythrina poeppigiana*), the Spanish oak (*Inga vera*) or orange tree (*Citrus sinensis*) in association with banana bushes (*Musa* spp.) (SECRETARÍA DE ESTADO DE MEDIO AMBIENTE Y RECURSOS NATURALES 2004b). Before the establishment of the national park all of these products were grown on *conucos* in areas which belong today to Armando Bermúdez National Park. Besides the traditional Arabic coffee the improved *Caturra* coffee is cultivated for exportation. Caturra is mainly grown without shade trees and with a high input of agro-chemicals, contaminating the rivers and soils.

A constant threat for the conservation of protected areas is the agriculture of the shifting cultivation type. Besides the loss of diversity provoked by the slash and burn agriculture, erosive processes are favored leading to reduced soil fertility and increased sedimentation (KAPPAS & SCHÖGGL 2005) of the water reservoirs. MARTIN et al. (2004) found out that life-form diversity was higher on old growth forest than on secondary forests in Armando Bermúdez National Park.

Extensive livestock grazing is also a problem in Armando Bermúdez National Park. Near La Ciénaga, La Diferencia and Los Ramones grazing cattle and goats were observed during field work. The main problem of cattle grazing inside the national park is the possible introduction of exotic and invasive alien (plant) species (IAS). IAS are non-indigenous species that could spread out rapidly and aggressively when introduced beyond their normal range and displace the indigenous species of the protected site (TU 2009). Worldwide IAS are recognized as a threat to biodiversity as they can cause habitat loss and fragmentation. The existence of *Psidium guajava* – although not an IAS - in the national park is a result of extensive grazing. Furthermore erosive processes are favored.

Illegal felling of trees went on until the last sawmills were closed in the 1990s. Today the bad practice is not wide-spread, but still exists. On a field trip to El Piquito close to La Diferencia recently precipitated trunks were detected of *Pera bumeliifolia* and *Podocarpus hispaniolensis* (Photo II.1). Other trunks of *Pera bumeliifolia* with considerable diameters had already been marked for future felling. Logging of species such as *Podocarpus* can cause substantial changes to forest structure (DOUMENGE et al. 1995). Besides illegal felling, illegal hunting is difficult to control by the park management. *Sus scropha* and *Solenodon paradoxus* are hunted for their meat and birds are captured to be sold as pets on the markets in Navarette, Villa de los Almácigos and Santiago de los Caballeros (mainly *Buteo jamaicensis, Melanerpes striatus* and *Amazona ventralis*).

TABLE II.2. Number of families and infrastructure in villages around Armando Bermúdez National Park

Communities	**1999***	**2006****	**2011****	**Distance to ABNP (m)**	**Infrastructure****		
	Number of families				**Electricity**	**School**	**Health care**
“Central Zone”							
Los Tablones	10	10	10	200	no	no	no
El Arraiján	22	22	18	1640	no	yes	no
Boca de los Ríos	50	50	49	100	no	no	no
La Ciénaga	61	95	50	1300	no	yes	yes
La Cotorra	19	12	10	300	no	no	no
El Derrumbado/ Jolla Ramón	48	39	29	1170	no	yes	no
El Higo	13	0	0	-	no	no	no
“Northern Zone”							
Arroyo Bonito	17	24	30	7424	no	yes	no
Montazo Abajo	53	76	85	-	no	no	no
Montazo al Medio	16	9	8	1376	no	yes	no
Montazo Arriba	48			1400	no	no	no
Cerro Prieto	23	22	21	1486	no	no	no
La Lomita	25	0	0	984	no	no	no
El Cerrazo	10	0	0	1456	no	no	no
Loma de los Ríos	30	2	2	1964	no	no	no
Donajá	14	22	20	2915	no	no	no
Las Lagunas Abajo	115	63	62	2340	no	no	no
Las Lagunas Arriba	23	26	24	921	no	no	no
Los Pérez (inside park)	9	0	0	-	no	no	no
Alto El Dajao	55	2	2	1000	no	no	no
Mata Grande	119	100	98	2780	yes	yes	no
La Sierrecita	25	1	1	934	no	no	no
Sabaneta	n. a.	22	20	1726	no	no	no
Loma Prieta	20	18	16	728	no	yes	no
Jamamucito	42	16	10	728	no	yes	no
“Northeastern Zone”							
La Diferencia	78	65	63	141	yes	yes	yes
Manacla	n. a.	46	44	860	yes	yes	no
Cabirmal	20	10	8	-583	no	no	no
Los Ramones	80	85	100	538	yes	yes	no
El Gallo	n. a.	30	28	1769	no	no	no
Los Calimetes	2	2	2	-	no	no	no
Cenoví	n. a.	43	n. a.	-	no	no	no
Vallecito	70	59	n. a.	6483	no	yes	yes
Los Abuqueyes	22	15	12	5246	no	no	no
La Lomita de Cidra/ La Laguna	25	22	20	4019	no	no	no
La Cidrita/Arroyo los Puercos	13	5	0	3201	no	yes	no
Loma de Copey	15	11	10	2267	no	yes	no
Boca de Cana	13	6	1	-	no	no	no
Los Amaceyes	27	5	6	-	no	no	no
Coquí	19	17	6	3864	no	no	no
Francisco José	n. a.	15	16	2088	no	no	no

Source: *MCPHERSON (2007), ** Information collected on field trips from 2006-2011, n. a.: Data not available

PHOTO II.1. Felled *Pera bumeliifolia* and *Podocarpus hispaniolensis* inside of Armando Bermúdez National Park (El Piquito, La Diferencia, 1,123 m a.s.l.)

Fires are caused in Armando Bermúdez National Park by lightings or by humans to improve fodder for domestic animals or facilitate hunting. As the soils for agriculture are prepared during the dry season, locally intended fires can spread over to the dry natural vegetation and become difficult to control (Photo II.2). While mature pine trees are well adapted to fire and shrub taxa at high elevations have a high resprouting ability (HORN et al. 2001), cloud forests in the Cordillera Central are only poorly adapted to fire (MAY 2000a).

PHOTO II.2. Pine forest after wild fire (around Valle de Tetero, 1,900 m a.s.l)

Badly managed recreational activities in protected areas can lead to contamination of the water, extraction of the flora, introduction of invasive species, disturbance of the fauna and erosion of the trails. Annually between 3,000 and 4,000 national and international tourist visit Armando Bermúdez National Park (SECRETARÍA DE ESTADO DE MEDIO AMBIENTE Y RECURSOS NATURALES 2011). Knowledge about the impact of visitation on the natural resources of the national park does not exist.

II.5 ACTUAL MANAGEMENT AND INFORMATION NEEDS

The third management plan for Armando Bermúdez National Park was elaborated between 2003 and 2004 by a consortium of national and international institutions and agencies (SECRETARÍA DE ESTADO DE MEDIO AMBIENTE Y RECURSOS NATURALES 2004b). Besides a brief diagnostic part about the actual conditions of the national park, the plan includes a zoning plan and four management programs formulated to meet the main management objectives.

One of these four is the management program for the *natural resources* and for *biodiversity*. It is divided in two subprograms: the subprogram of *scientific investigation* and the subprogram for *monitoring* and *evaluation*.

Scientific investigation shall contribute to raise knowledge about the different species, ecosystems and about biodiversity (SECRETARÍA DE ESTADO DE MEDIO AMBIENTE Y RECURSOS NATURALES 2004b). The scientific information shall be used to improve decision making and implementation of adequate management strategies. In the second subprogram biodiversity and water resources shall be monitored and the effects of climate change assessed.

However, since the publication of the management plan in 2004 none of these subprograms has been worked on. This study aims to improve the situation. Ecological and environmental baseline data are generated and analyzed so that they can be used to improve the effectiveness of management of this unique and valuable national park.

The following questions are answered:

- What are the main land cover and land use types in Armando Bermúdez National Park?
- Where do the mayor infractions occur (regarding land use)? What dimension do they have?
- What are the characteristic woody species of the main natural mountain forest types?
- Which environmental factors determine the occurrence of the main natural mountain forest types?
- What is the predicted geographic potential distribution of the main natural mountain forest types?
- What is the geographic potential distribution of selected woody species?
- Where are the biodiversity hotspots and where are the centers of endemism (regarding woody species)?

III. Land cover and land use mapping on the basis of color aerial photograph interpretation

III.1 INTRODUCTION

Human induced land cover conversions affect ecosystem structure and functioning and lead to a consequent loss of ecosystem services (SALA et al. 2000). Tropical mountain forests are becoming increasingly affected by human interventions (GRADSTEIN et al. 2008). One means to keep land cover conversion low or even avoid it, consists in effective management of protected areas (BRUNER et al. 2001; SÁNCHEZ-AZOFEIFA et al. 2002; DEFRIES 2005; NAUGHTON-TREVES et al. 2005; DUDLEY et al. 2007; GASTON et al. 2008; NAGENDRA 2008). Effective management requires profound knowledge about the resources to be protected (KUHN 1999; WELCH et al. 2002; ROGAN & CHEN 2004; JENSEN 2007; GARDNER et al. 2008; TOWNSEND et al. 2009; GROSS et al. 2009). Land cover and land use maps are adequate tools to impart such knowledge that can be used in decision making in the protected area management process (AREENDRAN et al. 2010).

Up to now land cover/land use maps do not exist for Armando Bermúdez National Park. Consequently, a land cover and land use maps is elaborated here (WELCH et al. 2002; AMEND et al. 2002). Important questions before producing land cover/land use maps are related to the spectral and spatial resolution of the data and the interpretation methodology (GLEITSMANN & KAPPAS 2005; LUNETTA et al. 2006; WANG et al. 2010). The vegetation cover of Armando Bermúdez National Park consists of a mixture of broadleaf and pine forests, of shrub- and grassland and probably small land use units. As agricultural fields are small, medium resolution satellite data lead to unsatisfactory results due to mixed pixels (GLEITSMANN & KAPPAS 2005). High spatial resolution satellite images possess the appropriate resolution (GLEITSMANN & KAPPAS 2005), but the acquisition costs are too high to cover the entire area. Another possible source is represented by digital aerial photographs (MADDEN et al. 1999; ROGAN & CHEN 2004; LILLESAND et al. 2008). Vertical aerial photographs have been used in several studies to extract land cover/land use information and to undertake quantitative analysis in montane protected areas (MILLER 1999; WELCH et al. 2002; MADDEN et al. 2004; TATTONI et al. 2011).

Here digital color aerial photographs at a scale of 1:20,000 were processed. An obstacle related to the use of aerial photographs for the extraction of quantitative land cover/land use information in large areas with high relief is the time consuming digital photogrammetrical process that has to be gone through to geometrically correct and georeference the images (ABER et al. 2010). A modified photogrammetric procedure had to be developed to overcome problems related to the quality of the aerial photographs and land cover patterns inside the national park.

Image interpretation can be performed with various levels of complexity and its success depends on the training and experience of the interpreter (LILLESAND et al. 2008). There is no ideal classification scheme, it rather depends on the user's objectives (ANDERSON et al. 1976) and on the radiometric and spatial resolution and seasonality of the aerial photographs (LILLESAND et al. 2008). For monitoring purposes classification schemes should present equivalent cover classes in a hierarchical system in all images (ANDERSON 1976; GARDNER et al. 2008). Visual interpretation is one means of aerial photograph interpretation besides automatic, software driven approaches. Visual interpretation of the human interpreter is based on several image characteristics (Chapter III.2.4) (HILDEBRANDT 1996; JENSEN 2007). The interpreter takes these characteristics into account and delineates discrete areal units (here land cover/land use classes) on the geometrically accurate aerial photographs to derive quantitative information. These units, or polygons digitized on the image, are saved to Geographic Information Systems which are effective tools for storing and processing large sets of geospatial data (FOODY 2008) and for analyzing spatial relationships (MASON et al. 2003). In this study the aerial photographs were visually interpreted. An object-oriented classification approach could not be applied as similar objects had varying spectral properties in different parts of the aerial photographs due to bidirectional reflectance (TUOMINEN & PEKKARINEN 2005; FRANKEN & HOFFMAN 2010).

The specific objectives of this study are:

(i) to produce a controlled mosaic out of 295 large-scale digital color aerial photographs at a scale of 1:20,000 to be used as a base map for land cover/land use information extraction

(ii) to generate and analyze the different land covers and land uses on the base map with a special focus on determination of human infractions inside the national park.

III.2 Material and methods

III.2.1 Digital photogrammetry – Terminology and workflow

According to the definition of the American Society of Photogrammetry photogrammetry is the ”…art, science and technology of obtaining reliable information about physical objects and the environment through the process of recording, measuring, and interpreting photographic images and patterns of electromagnetic radiant imagery…” (Slama et al. 1980: 1). Digital photogrammetry is applied to digital or digitized images by using photogrammetric software installed on computers (Jensen 2007). The products of the digital photogrammetric process are digital elevation models, digital orthophotos and the thematic layers derived from them. Digital orthophotos are produced by transforming the geometry of a non-rectified digital aerial photograph with central perspective to a planimetric image with an orthographic projection and uniform scale (Jensen 2007) so that accurate measurements of geographic locations, area sizes, slopes, volumes or distances can be performed. Orthophoto production requires a *forward overlap* between adjacent aerial photos, the stereopairs, so that each terrain object has at least two photographic views. The apparent positional change of an object in adjacent aerial photographs due to the forward movement of the aircraft is called *stereoscopic parallax* and is the basis for three-dimensional *stereoscopic viewing* (Jensen 2007). Based on the differences of the parallaxes of various objects measurements of terrain/object heights and elimination of geometric displacements are possible. Geometric displacements and variation in scale are mainly caused by central perspective, relief and tilt of the camera axis (Wolf & Dewitt 2000). Figure III.1 gives an overview of the methodological steps performed to generate the orthophotos and the mosaic of the study site. The single procedures are described in the following chapters. For aerial photograph interpretation the workflow and methodology is displayed in Chapter III.2.4.

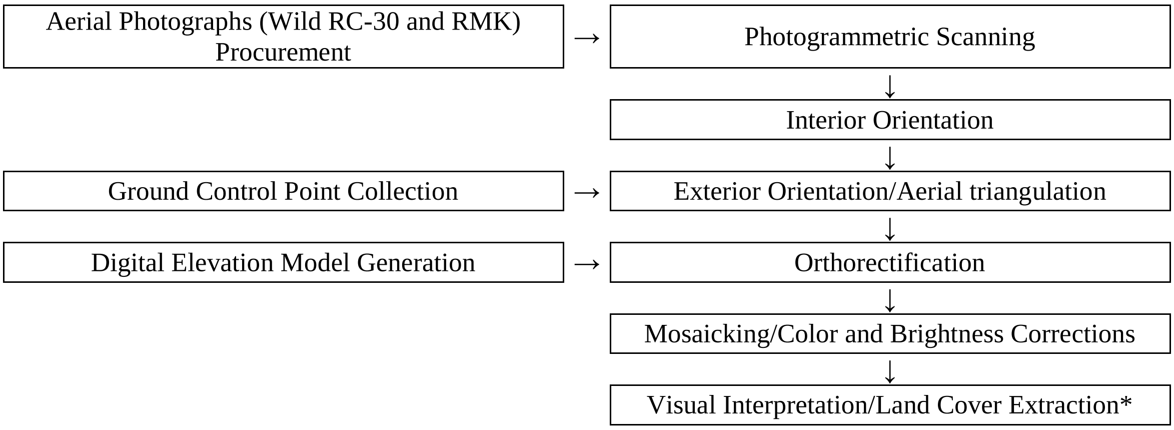

Figure III.1. Workflow of orthophoto generation and mosaicking applied in this study (*Detailed workflow for aerial photograph interpretation in Chapter III.2.4)

III.2.2 Aerial photographs used in this study and pre-processing

To cover Armando Bermúdez National Park and its surroundings 295 digital color aerial photographs at a scale of 1:20,000 were processed. The aerial photographs were taken in the frame of the Inter-American Development Bank-financed PROMASIR project for the National Institute of Hydraulic Resources (INDRHI) in Santo Domingo. The spectral resolution of the color aerial photographs was 0.4-0.7 µm, representing the reflection of blue, green and red light from the objects of the Earth's surface. 34 of the 295 aerial photographs were taken between 1999-2001 at an average flying height of 3,050 m above-ground-level (AGL) by a Wild RC-30 camera equipped with a Wild Universal Aviogon/4-S lens (focal length = 153.299 mm) (camera calibration certificate). The majority of the here used aerial photographs, 261 out of 295, were captured between 2002-2004 at the same average flying height by a RMK TOP 15 camera and a Pleagon A3 lens (focal length = 152.925 mm) (camera calibration certificate). The aerial photographs taken by the Wild RC-30 camera had a higher quality in colors and contrasts. Kodak S0846 films were used in both cameras. The flight lines of the study area were taken in direction northwest to southeast and vice versa (Figure III.2), parallel to the trending of the Cordillera Central with a stereoscopic overlap of 60% and a sidelap of 20%. Most of the flight lines were composed of aerial photographs of different dates, a fact that influenced the aerial triangulation procedure (to be discussed). Unfavorable atmospheric conditions had been the main cause for impeding a continuous capture of entire flight lines (pers. communication C. NEALE 2003, PROMASIR project coordinator from Utah State University). In Appendix III.A the flight lines, photo numbers and capture dates of the 295 aerial photographs are listed. All aerial photographs in the block were vertical photos.

The film transparencies were scanned at Tobin International, Houston/USA on a high resolution photogrammetric VEXCEL 4000 scanner with red, green and blue filters to create digital aerial photographs with a pixel resolution of 20 mµ (equals 1,270 dots per inch (dpi) [8]). This scanner delivered a high geometric and radiometric precision. For the generation of orthophotos a scan resolution between 15-30 µm (1,693-846 dpi) is appropriate (JENSEN 2007). Each image matrix consisted of approximately 11.000 x 11.000 pixels, resulting in a file size of 430-450 MB per digital aerial photograph. The ground resolution of one pixel was approximately 40 cm.[9]

Six aerial photographs had to be scanned at 1,200 dpi on a simple desktop scanner from the hardcopy aerial photographs as the digital datasets were corrupt (Figure III.2). The geometric

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[8] The equation for conversion from µm to dpi is: dpi = (2.54/µm)*10,000 and from dpi to µm: µm = (2.54/dpi)*10,000 (JENSEN 2007).

[9] The ground resolution pixel size in meters (PM) can be obtained by using the image scale (SI) and dpi: PM = (SI/dpi)/39.37 (JENSEN 2007).

accuracy of the desktop scanner was poor compared to the photogrammetric scanner generating problems during the photogrammetric processes (to be discussed).

Digital image data was served by INDRHI in a TIFF-format without terrestric control and without georeference (INSTITUTO NACIONAL DE RECURSOS HIDRÁULICOS 2004). All 295 digital aerial photographs were imported in ERDAS Imagine 9.2 (ERDAS Inc., Atlanta, USA) as image files. Then a block file was created with Leica Photogrammetry Suite 9.2 (Imagine LPS 9.2) (ERDAS Inc., Atlanta, USA) and all 295 digital aerial photographs were added to it. A block file is a file containing various adjacent overlapping images of one or more flight lines. Pyramid layers were calculated to speed up display of image data and the respective camera model was designated to each aerial photograph in the block.

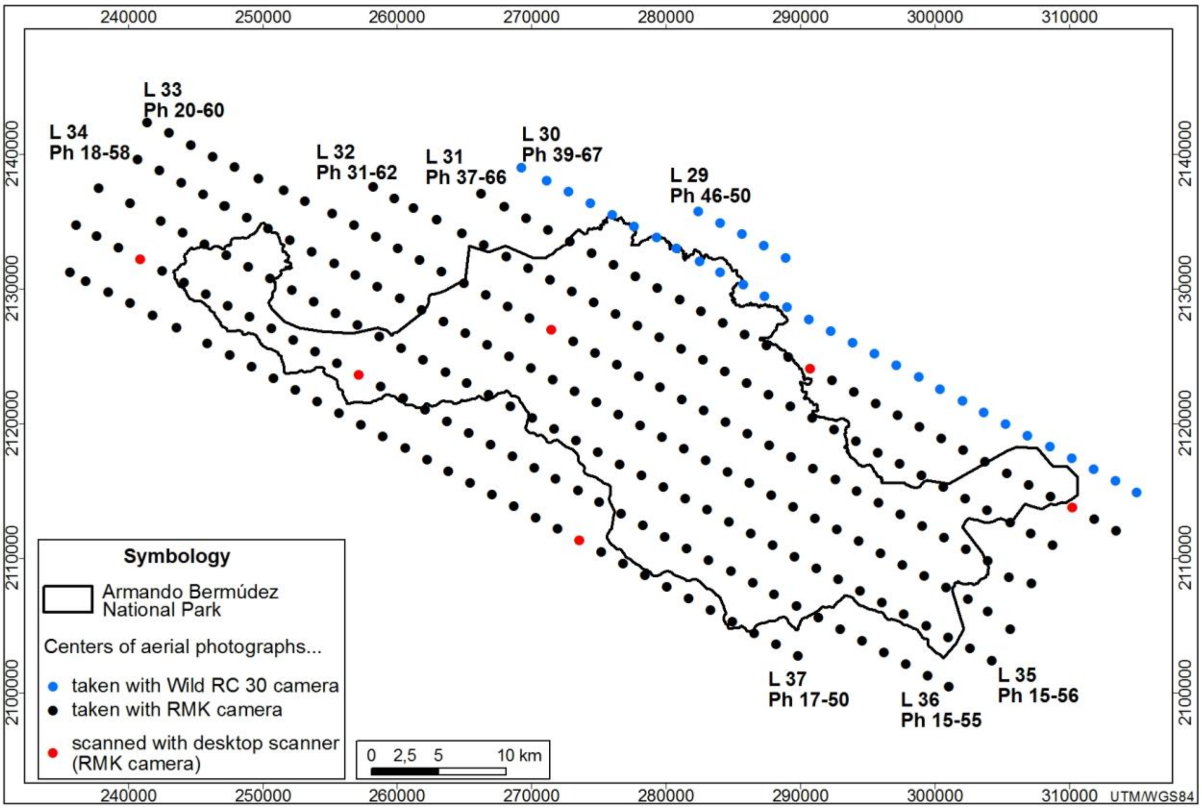

FIGURE III.2. Flight lines (L), photo numbers (Ph) and camera types of all aerial photographs used in this study (Source: Photocenters, Instituto Nacional de Recursos Hidráulicos 2004; Boundaries of ABNP from Law 64-00)

III.2.3 Photogrammetrical steps of orthophoto and mosaic generation

Interior Orientation

By means of the interior orientation the bundle of rays within the camera at the time of photographic exposure has to be reconstructed. The necessary calibrated parameters to set up the geometry of the paths within the camera are: principal point (PP), focal length (f), coordinates of the fiducial marks and radial symmetric lens distortion (HÖHLE 1996). The PP is the intersection of the optical axis with the image plane, close to the image center (ABER et al. 2010). The image position of the PP has to be calculated for each image separately by measuring the fiducial marks. A two dimensional affine transformation is used to relate the measured to the calibrated fiducials and to resample the scanned *pixel coordinate image* to a new matrix based on the *image coordinate system* of the fiducial marks. As a measure of correspondence between the pixel and the image coordinate systems the Root Mean Square (RMS) error is calculated.

Here the calibrated values of the parameters needed for interior orientation were taken from the camera calibration certificates of the Wild RC-30 and the RMK. Both cameras had eight fiducial marks on each image. They were measured (digitized) on each of the 295 aerial photographs according to the order specified in the camera calibration certificates. If the RMS error was larger than 0.5 pixels in one aerial photograph the measurement was revised. An overall RMS threshold was not defined as six of the 295 images had been scanned on a desktop scanner (Chapter III.2.1) and high RMS errors were expected for these images.

Exterior orientation and aerial triangulation

Exterior orientation reconstructs the bundle of rays at exposure in the object coordinate system with the six parameters: Projection center coordinates (X0, Y0, Z0) and the rotations of the camera around the three axes (omega, phi, and kappa) (ABER et al. 2010). The parameters are found with the help of ground control points (GCPs). GCPs are object points with known ground coordinates (XYZ) identifiable both in the terrain and in the aerial photographs used to establish the *absolute orientation* of the block. Theoretically at least three horizontal and four vertical points are needed to calculate the parameters for one stereopair (KRAUS 2004). Practically, however, less than three GCPs are sufficient when an entire block of images is oriented by means of aerial triangulation (ABER et al. 2010). Aerial triangulation establishes a mathematical relationship between the aerial photographs in a block, the camera and the ground by using the bundle-block adjustment technique with the statistical method of least squares adjustment (LEICA GEOSYSTEMS GEOSPATIAL IMAGING 2008). These methods determine or adjust the exterior orientation for each image at photographic exposure, minimize and distribute errors associated with the imagery and GCPs and estimate the ground coordinates of the tie points. A solution in aerial triangulation is obtained when the residuals related to the input data are minimized and a user-specified value is obtained (convergence value) (LEICA GEOSYSTEMS GEOSPATIAL IMAGING 2008). The results from block triangulation can then be used for DEM extraction and orthorectification. Tie points are identifiable points in the stereoscopic overlaps of two or more images that are required besides GCPs to determine the *relative orientation* of the images in the block. Their ground coordinates are unknown at first and are calculated later by aerial triangulation so that the final amount of GCPs is extended. Tie points are either identified manually or automatically based on image matching techniques such as feature based matching (FÖRSTNER & GÜLCH 1987 in LEICA GEOSYSTEMS GEOSPATIAL IMAGING 2008). The automatic tie point search algorithm requires at least two GCPs or two manually set tie points in the stereoscopic overlap (LEICA GEOSYSTEMS GEOSPATIAL IMAGING 2008). Their positional accuracy, image quality and the displacements due to the relief influence the success of the algorithm. The more tie points placed correctly in multiple images the more useful they are for aerial triangulation.

Prior to field work the GCP objects were marked on amplified aerial photograph windows at a scale of 1:500-1:3,000. Therefore 63 aerial photographs were broadly pre-rectified to UTM coordinates with a WGS84 datum based on the PP of each aerial photograph[10], the average flying height and an approximate kappa value (both from database of photocenter shapefile, Instituto Nacional de Recursos Hidráulicos 2004). UTM WGS84 was the projection system used by PROMASIR and also in this study. The spatial accuracy of the rapidly rectified aerial photographs ranged from 150-300 m (overlay with topographic maps in ArcGIS 9.1, (ESRI Inc., Redlands, USA) and did not make orthorectification redundant.

Due to the continuous tree cover in Armando Bermúdez National Park GCPs were limited to intersections and curves of trails, shelters, bridges, stand alone trees and rocks. Outside the national park GCP collection was easier as cultural objects existed. Objects at the edges of the block were also recorded to establish a stronger geometry in aerial triangulation (LEICA GEOSYSTEMS GEOSPATIAL IMAGING 2008). The field collection of GCPs with measured UTM WGS84 coordinates was realized between 2005 and 2006 in various field trips with a handheld Trimble GeoXM GPS, running TerraSync Standard Edition 2.50 (Trimble Navigation Limited, Westminster/USA). As differential GPS (DGPS) was not available to correct the X, Y and Z coordinates, the mean of 100 single measurements taken at an interval of five seconds was processed for each GCP in GPS Pathfinder Office Software 3.10 (Trimble Navigation Limited, Westminster/USA) (WELCH et al. 2002). Altogether 557 GCPs were collected (Figure III.3), digitized on the respective aerial photographs of the block and their ground coordinates entered.

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[10] Ground PP coordinates had been taken at exposure by an on-board GPS.

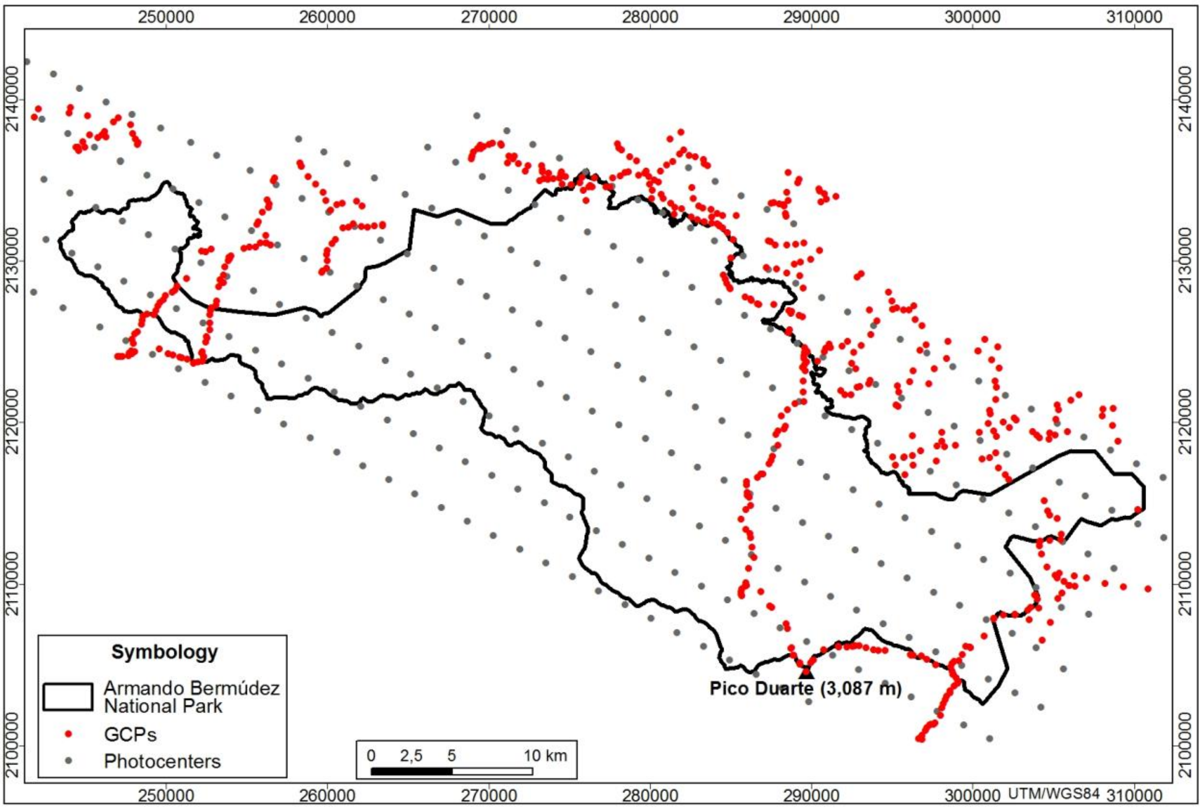


FIGURE III.3. Location of GCPs in relation to photocenters (Source: GCPs, GPS field work; Photocenters, INDRHI 2004; Boundaries of ABNP from Law 64-00)

Two students from the Department of Geography of the Gutenberg-University of Mainz helped to carry out the manual tie point search. Starting point for the manual tie point search were the aerial photographs with two or more measured GCPs. First an automatic tie point search run was performed and the results checked. The quantity was set to 50. The search size (50 pixels) had to be increased on steep slopes (up to 100 pixels). The initial accuracy of the exterior orientation parameters was defined between 10-20% according to image quality. Most of the other strategy parameters were accepted with their defaults. Incorrect tie points were deleted in all images where they occurred. The target number of 50 tie points was completed manually if there were enough identifiable features. Then the next aerial photograph was activated and first automatic and then manual tie point collection performed until all of the 295 aerial photographs were processed. For aerial triangulation the bundle block adjustment was applied, setting active initially three to four aerial photographs with well distributed GCPs. The x- and y-image standard deviation was set to 0.5 pixels. The manual tie points were assumed to have residuals smaller than 2 m in x and y-coordinates and 5 m in z-coordinates. GPS elevation measurements without DGPS correction are not exact unless a barometric altimeter is used. The interior parameters and the GCPs were set fixed. For the X0 and Y0-coordinates 10 m were assumed as standard deviations for all images, for the Z0-

coordinates 20 m and for omega, phi and kappa 0.2 degrees. The *Blunder checking model* with *robust checking* to detect wrong tie points and GCPs was activated to omit them from calculations.

Triangulation was run and the triangulation report considered. The position and coordinate numbers of GCPs with large residuals were checked, corrected or set inactive. Successively one image after the other was added and aerial triangulation was run iteratively. The convergence criterion was set to 0.001 m. At first all of the aerial photographs in each flight line were processed separately and then the lines were added one after the other. When the convergence criterion was met, the exterior orientation parameters (X0,Y0, Z0, omega, phi and kappa per aerial photograph) and the ground coordinates for the tie points were updated and accepted with the final parameters found by aerial triangulation. The quality of the model was checked with the Total Image Unit-Weight RMSE that defines the distance between the original coordinates and the position after triangulation.

Orthorectification

Orthorectification uses the interior and exterior orientation results from aerial triangulation and the terrain height from digital elevation models (DEMs) to correct the displacements of each pixel in the aerial photographs of a block (ABER et al. 2010). First an empty, plane x, y-orthomatrix is created. Then for each cell in the orthomatrix the z-value is interpolated from the DEM and the corresponding image x and y-coordinates are calculated by using interior and exterior orientation parameters found through aerial triangulation. The corresponding gray value of the aerial photograph is dedicated to the position in the orthomatrix (KRAUS 2004). The DEM can either be generated during the orthorectification process out of the aerial photographs or an existing DEM can be applied (HÖHLE 1996; NUSKE & NIESCHULZE 2005).

The only existing DEM for the Cordillera Central was the 90 m spatial resolution NASA-SRTM, but it contained many no data values on the steep slopes of the center of the national park situated in the shade during SRTM data recording. A 50 m resolution digital surface model (DSM, elevations represent object heights) was produced out of the triangulated digital aerial photographs applying image matching techniques (see Results). Several attempts with different strategy parameters were made, but the data showed numerous elevation errors. Thus, a 10 m resolution digital terrain model (DTM, elevations represent ground height) was calculated from the 100 m spacing contour lines of the Dominican topographic maps at a scale of 1:50,000 by generating a Triangulated Irregular Network (TIN) with ArcGIS 9.1. A

TIN is a vector based digital data model containing elevation information obtained by triangulating sampled points with known x, y and z-coordinates. For generation of the DTM the Delaunay triangulation method was applied to avoid long and thin triangles (LI et al. 2005). Hard and soft breaklines were specified to define changes in the relief (ABER et al. 2010). Mountain peaks were introduced. The TIN was converted to a grid with a spatial resolution of 10 m and projected to UTM coordinates with the WGS 84 datum to match the projection of the aerial photographs. The altitudes of 100 randomly selected points on the DTM were compared to the elevations in the topographic maps (analysis in ArcGIS 9.1) as there were no other z-data. Artefacts in the flat areas along the border of the national park were corrected manually (GLEITSMANN 2005). The histogram did not show sharp peaks at the digitized contour lines (ROBINSON 1994 in GLEITSMANN 2005). The 295 aerial photographs were resampled one by one to a spatial resolution of 0.4 m per pixel based on the DTM applying the bilinear interpolation algorithm.

For determination of the spatial accuracy 100 clearly to identify features in the orthophotos were selected and compared to the position in the topographic maps. A comparison to GCPs was not possible as all accurate GCPs had been used in triangulation. The distances were calculated in ArcGIS 9.1.

Mosaicking

Mosaics are composites assembled out of multiple images of an area (SABINS 1996). Here a mosaic was produced out of the orthophotographs (controlled mosaic, WOLF & DEWITT 2000). The generation of the seam polygons that represent the spatial coverage of each orthophoto to be used in the mosaic was done automatically. Many of the so created seam polygons had to be edited and optimized. If color of one aerial photograph differed considerably from the others in a line, just a minimum part of this aerial photograph was cropped out. During mosaicking the color and brightness differences between aerial photographs were reduced by radiometric techniques to enhance the overall impression of the assemblage (ABER et al. 2010). Histogram-based modifications of the brightness tones were applied and color enhancements were performed. Each orthophoto was divided in 100 blocks. Color and brightness correction parameters were calculated successively for all adjacent blocks (image dodging) (LEICA GEOSYSTEMS GEOSPATIAL IMAGING 2008). Image dodging applies a filter and global statistics to each selected orthophoto to minimize the light imbalances. Very dark areas were excluded from the procedure as they hampered the process. To make handling of the final mosaic easier it was divided in 21 image files of 10x10 km each. Their sizes ranged between 460 MB and 1.9 GB, depending on the portion of black background in the square. The area size of 10x10 km was chosen as the ESRI Runlength Compression just supported files smaller than 2 GB.

III.2.4 Interpretation of land cover/land use and accuracy assessment

A pre-interpretation of the aerial photograph mosaic was made to get to know the image content and stratify the area in zones to be visited (ALBERTZ 2009). 157 sites were selected for field investigation. They were visited between 2005 and 2006 (Figure III.4). The selection of the sites was based on the following criteria:

- Unknown surface patterns in the aerial photographs;
- Coverage of all zones and of majority of land cover/use types observed in the photos and
- Accessibility of the sites/terrain.

During field work the sites were characterized by their main land cover/land use type, floristic composition, percentage canopy cover, elevation, slope, aspect and former natural or human disturbances.

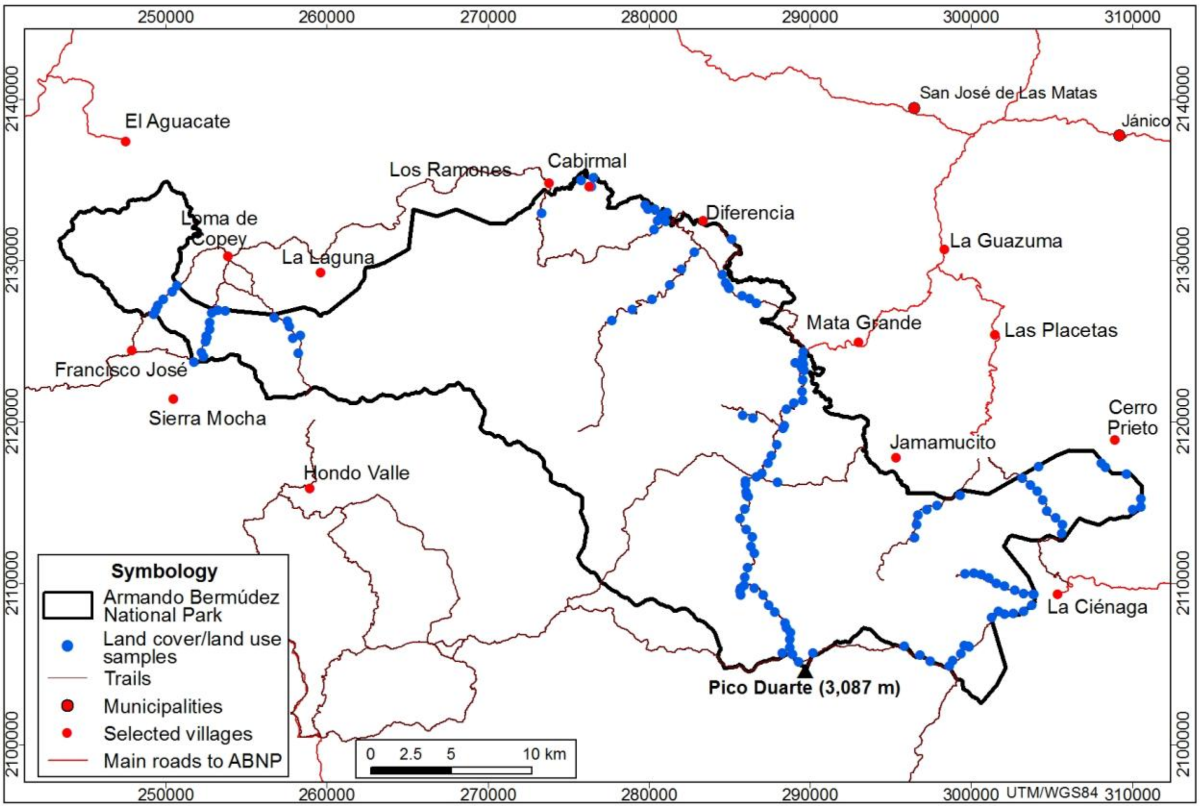


FIGURE III.4. Sampled sites for visual aerial photograph interpretation (Source: GPS field work; Boundaries of ABNP from Law 64-00; Villages, roads from topographic maps 1:50,000, ICM 1983/1984 and field work; trails digitized on aerial photograph mosaic)

UTM WGS84 coordinates of each location were saved to a handheld Trimble GeoXM GPS, running TerraSync Standard Edition 2.50 with an accuracy of ± 5 m (Trimble Navigation Limited, Westminster/USA). Photos were taken of the sites. 82 of the collected GPS points were superimposed over the aerial photograph mosaic in ArcGIS 9.1. The patterns of the aerial photos were correlated to the ground observation to elaborate the classification sceme. Altogether 75 points were set aside for accuracy assessment.

The determination of discrete land cover/land use units is an important step of aerial photograph interpretation (CINGOLANI et al. 2004). Three criteria had to be fulfilled by the classification scheme: The classes of the system had to be in concordance with the objectives of the study and had to be identifiable in the aerial photographs (CINGOLANI et al. 2004). The classes of the system had to allow a division in more detailed subclasses so that these can be integrated for monitoring purposes on future aerial photograph series or large-scale satellite images. The management direction of the national park had to participate and to agree on the classification system of Armando Bermúdez National Park. They were interested to differentiate between the following classes: Dense pine forests, open pine forests, humid broadleaf forests, cloud forests, mixed forests, *Prestoea montana* forests (manaclares), shrubland (*matorral*), land with ferns (*Calimetal*), coffee with shade, coffee without shade, cultivated land (*conucos*), grassland and sparse vegetation.

Analysis of the aerial photographs brought two results: a.) It was not possible to differentiate between all the classes due to the quality of the aerial photographs. b.) Some classes could have been delineated, but it would have been too time consuming (see Discussion).

The process of land cover/land use mapping was based on the characteristic elements of aerial photograph interpretation (RABBEN 1960; HILDEBRANDT 1996; HARALICK 1979; JENSEN 2007; LILLESAND et al. 2008; ALBERTZ 2009). These elements are: Location, shape, size, pattern, tone/color, texture, shadows, height/depth and site/situation/association. The *location* of an object is defined by its coordinates. *Shape* is related to the general form or outline of an object. Its *size* is scale dependent and can be measured accurately on an orthophotograph (length, width, perimeter, area, volume). *Pattern* stands for the spatial arrangement of objects in an aerial photograph and is characteristic for many features (JENSEN 2007) (here e.g. coffee plants on a plantation). *Color* depends on the proportions of energy reflected from the surface materials in the different electromagnetic spectra. Shades of color are better distinguished by the human eye than *tones* of gray (SABINS 1996).

The characteristic spatial interrelationships between tones in an image are referred to as *texture* (HARALICK 1979). Texture is created by tonal repetitions of groups of objects that individually would be too small to be discerned. Texture is extremely scale dependent (HARALICK 1979) and is a long recognized value in aerial photograph interpretation (ANDRESEN et al. 2002; LANGANKE et al. 2004). Pattern and texture are not affected by bidirectional reflectance, other than tone and shadow (HARALICK et al. 1973). *Shadow* helps to estimate the heights of objects, but can also impede the identification of others. Objects in a stereopair can be visualized in three dimensions and their heights measured (LILLESAND et al. 2008; ALBERTZ 2009). *Site*, *situation* and *association* are related to each other and used synergistically together to conclude about the aerial photograph content (JENSEN 2007).

Taking into account these elements, the objectives of the study, the physiognomy and canopy structure of the vegetation in Armando Bermúdez National Park, 13 cover-classes could be differentiated: three related to the main class “Forest”, three to the main class “Rangeland”, two to the main class “Agricultural Land” and five to the main class “Additional Categories”. The digitizing scale of 1:2,500 resulted appropriate to detect small fields, resulting in a minimum mapping unit of 4,500 m^2 (0.45 ha) for the main classes “Rangeland”, “Agricultural Land” and “Additional Categories”. The natural and semi-natural vegetation units in “Forest” were digitized at a scale of 1:4,000. This working scale was a compromise between overall information extraction and man hours to conclude the work. Each class in the classification scheme was characterized by pattern, color and texture (see Results). Pine and broadleaf forests were additionally described according to their crown physiognomy and forest structure (HUDSON 1991).

Surface patterns on the mosaic were reviewed in 3D on the analogue stereopairs with a lens stereoscope (one of the four stereoscopic viewing techniques described by JENSEN 2007). Then homogeneous patches were digitized on the mosaic and labeled according to the properties of the vegetation in the polygon. On-screen digitization is a straightforward method for obtaining spatial units of land cover/land use and accurate area measurements (JENSEN 2007). Additionally the DTM, a hydrology shapefile and an aspect rasterfile derived from the DTM, were opened as collateral data.

Accuracy assessment of the interpretation was undertaken with the 75 field points set aside for accuracy assessment in a contingency table with rows representing the classified data and the columns the reference data (FOODY 2002). Statistical measures as the producer’s accuracy, user’s accuracy and the overall classification accuracy (percentage correctly classified) were calculated (CONGALTON 1991). The producer’s accuracy describes the percentage of reference points of a certain class assigned to the same class in the image (error of omission). The user’s accuracy indicates the percentage of pixels of a class in the classification in concordance with the reference data (error of commission). Landscape metrics such as the percent area occupied by a land cover/land use type (P) and number of patches (NP) (just for the classes in “Agricultural Land”) were extracted per water basin and for the entire protected area in ArcGIS 9.1 (Gardner et al. 1987).

Zonal statistics were calculated to relate the land cover/land use types to altitude and slope. Nearest distances between the centerpoints of the polygons in “Agricultural Land” to the border of the protected area and to the villages were calculated. The workflow of aerial photograph interpretation and analysis of land cover and land use classes is shown in Figure III.5.

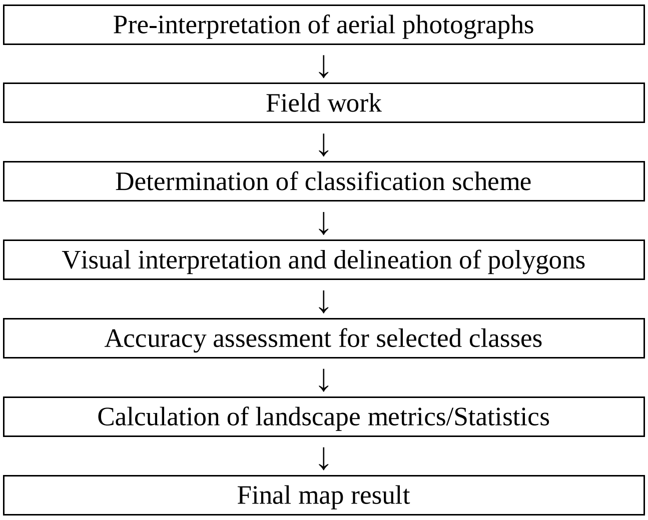


Figure III.5. Workflow of visual interpretation of aerial photographs of Armando Bermúdez National Park (Albertz 2009, modified)

III.3 RESULTS

III.3.1 Generation of orthophotos and mosaic

Interior orientation

Table III.1 displays the RMS errors for all 295 aerial photographs after fiducial setting. On 98% (289) of the aerial photographs a RMS error smaller than 1 pixel was obtained. The six aerial photographs scanned with the desktop scanner had RMS errors between 4-5 pixels. Although this was an unsatisfactory result, the errors had to be accepted as fiducial measurement could not be improved on these images due to the bad geometric accuracy on the desktop scanner.

TABLE III.1. Root mean square (RMS) errors after fiducial setting on each aerial photograph

RMS error classes (in pixels)	**Absolute number of aerial photographs within each RMS error class**	**Percentage of aerial photographs within each RMS error class**
0.00 - 0.20	28	9.50
0.21 - 0.40	204	69.15
0.41 - 0.60	55	18.64
0.61 - 1.00	2	0.68
4.10 - 5.00	6	2.03
Total	**295**	**100.00**

Exterior orientation – GCPs, tie points and aerial triangulation

The 557 measured GCPs were found on two to eight aerial photographs (Table III.2). 121 GCPs were just present on two aerial photographs as they had been collected at the edge of the block. 97 GCPs were placed on six aerial photographs. This is the standard inside a block with a stereoscopic overlap of 60%, a sidelap of 20% and accurate flight performance. 12 GCPs were positioned in more than six aerial photographs.

TABLE III.2. GCPs positioned on number of aerial photographs (in parenthesis number of GCPs used for aerial triangulation)

GCPs	**GCPs positioned on number of aerial photographs**
121 (106)	2
150 (134)	3
84 (69)	4
93 (70)	5
97 (60)	6
8 (4)	7
4 (2)	8
557 (445)	

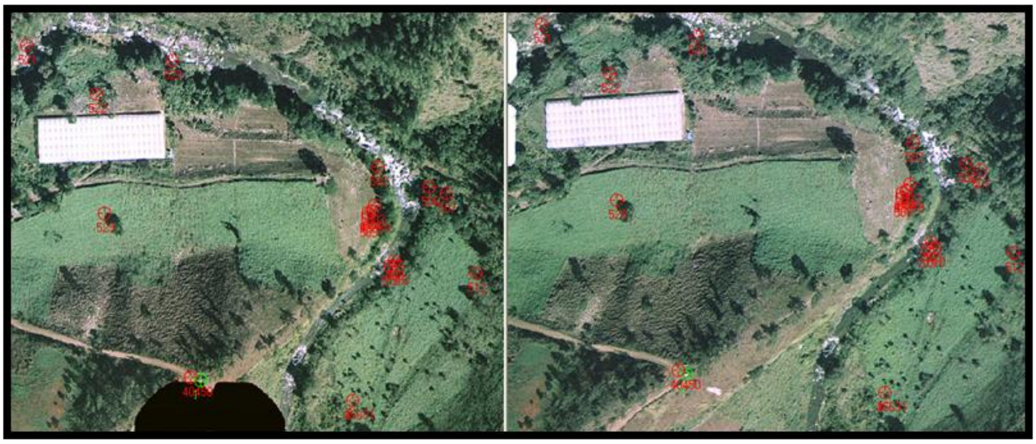
Table III.3 presents the quantities of GCPs on each of the 295 aerial photographs. 42.7% (126) of the 295 aerial photographs were not covered by any GCP as the respective terrain could not be sampled. 57.3% (169) of the aerial photographs counted between one and 37 GCPs. The aerial photographs with the majority of GCPs were the ones along the northern border outside the national park with clearly to identify cultural objects.

TABLE III.3. Number of GCPs in aerial photographs

	Number of GCPs				
GCPs	**in aerial photographs**		**GCPs**	**in aerial photographs**	
	absolute	**%**		**absolute**	**%**
0	126	42.71	**14**	12	4.07
1	3	1.02	**15**	7	2.37
2	14	4.75	**16**	4	1.36
3	15	5.08	**17**	5	1.69
4	7	2.37	**18**	7	2.37
5	6	2.03	**19**	4	1.36
6	9	3.05	**20**	1	0.34
7	7	2.37	**21**	4	1.36
8	13	4.41	**23**	2	0.68
9	8	2.71	**24**	1	0.34
10	8	2.71	**25**	1	0.34
11	7	2.37	**26**	1	0.34
12	9	3.05	**29**	1	0.34
13	12	4.07	**37**	1	0.34

Tie points

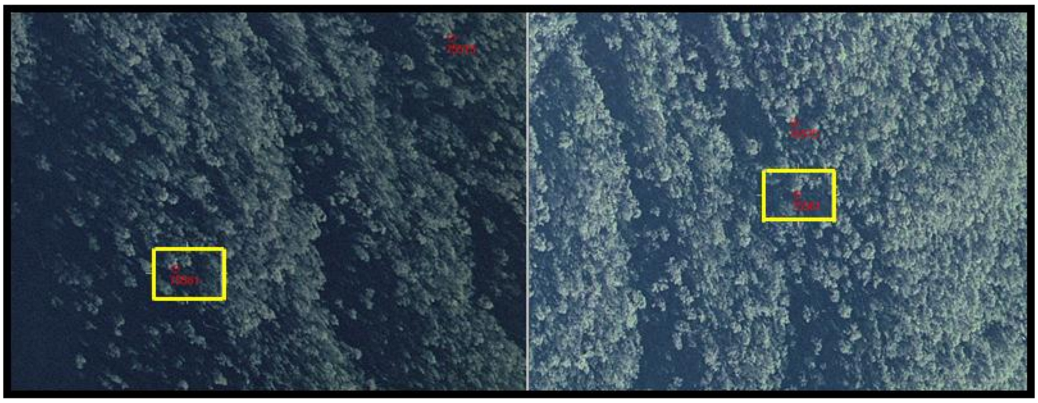
The more GCPs existed in the stereoscopic overlaps, the more successful was the automatic tie point search algorithm of Imagine LPS 9.2. Heterogeneity of the image content also influenced automatic tie point collection positively. In areas with a high amount of cultural objects as in flight lines 29-31 outside the national park 40-50 tie points were correctly positioned in overlap areas with three or more GCPs. Figure III.6 presents 19 correctly placed automatic tie points (all red circles) in two adjacent aerial photographs taken near La Ciénaga.



Line 32, Photo 61 **Line 32, Photo 62**

FIGURE III.6. Correct placement of automatically set tie points (all red circles) in two adjacent aerial photographs with GCPs and with heterogeneous image content outside of ABNP

However, aerial photographs with little differentiation in the image content as given in the flight lines 32-37 inside the national park and without measured GCPs, the automatic tie point algorithm produced numerous errors and delivered 10 tie points at most, mainly incorrect. Up to 10 tie points had to be set manually in the stereoscopic overlaps to produce 10-25 automatic tie points that had to be checked again. Figure III.7 displays the correct (red circle, no frame) and incorrect (red circle, yellow frame) automatic placement of two tie points in the overlap area of the photos 40-41 in flight line 34 without any GCPs. The image contents consisted of close dense pine forests with significant brightness differences.



Line 34, Photo 40 **Line 34, Photo 41**

FIGURE III.7. Correct (red circle, no frame) and incorrect (red circles in yellow frames) placement of automatically set tie points in two adjacent aerial photographs without GCPs and dense pine cover

Unsatisfactory results were produced by the automatic transfer of tie points in the sidelaps of the flight lines (Figure III.8). Here most of the time tie points had to be transferred manually despite existing GCPs. The positions of the automatically transferred tie points from photo 46, line 29 to photo 46, line 30 were completely incorrect (example: red circle, yellow frame). Due to the different flight directions in adjacent lines the features appear “upside down” and feature identification can turn out to be complicated.

Line 29, Photo 46 **Line 30, Photo 46**

FIGURE III.8. Incorrect transfer of tie points (red circle, yellow frames) in the sidelap between two flight lines with heterogeneity in image content and with GCPs

Tie point search in three adjacent images at the same time rarely delivered good results. Difficult was also the automatic tie point search in adjacent aerial photographs taken on different dates. Figure III.9 displays the results for photos 38 and 39 of line 31, taken on January 16th, 2003 and January 28th, 2004 along the northern border of the national park. Of the four tie points two were positioned correctly and two incorrectly (red circles, yellow frames 1 and 2).

Line 31, Photo 38 **Line 31, Photo 39**

FIGURE III.9. Correct and incorrect placement of automatically set tie points in two adjacent aerial photographs of different dates

The tie points for the six images scanned on the desktop scanner had to be set manually as the image correlation techniques applied for automatic tie point search were sensitive to the geometric and scan/image quality. Altogether 17,051 tie points were set homogeneously over the block, one third manually and two thirds automatically.

Aerial triangulation

Only 445 out of the 557 measured GCPs fulfilled the accuracy criteria and entered in aerial triangulation. The final convergence criterion of 0.001 m was met during the fourth iteration of aerial triangulation with a Total Image Unit-Weight RMSE of 0.508 m after having corrected, set inactive and deleted spatially incorrect GCPs and tie points. The final solution exceeded the spatial ground resolution of a pixel by 10 cm. The mean GCP RMSE was 2.63 m for the x-coordinates, 2.86 m for the y-coordinates and 9.21 m for the z-values. The x and y-coordinates of the tie points had an RMSE of 0.595 m and 0.662 m respectively.

Orthophotos

The elevation values of the DSM differed up to 1,000 m compared to the elevation values of the contour lines of the topographic maps. Figure III.10 shows a cutout of the DSM for the overlap area of the photos 40-41 of line 34 at elevations between 1,200-2,500 m a.s.l.. The dark pixels denote areas of low elevation, the bright pixels areas of high elevation. The model did not have clear height structures and looked blurred. Vertical differences of 800 m were measured along a horizontal distance of 300 m which is not real in the Cordillera Central. Thus, the model could not be used for orthorectification.

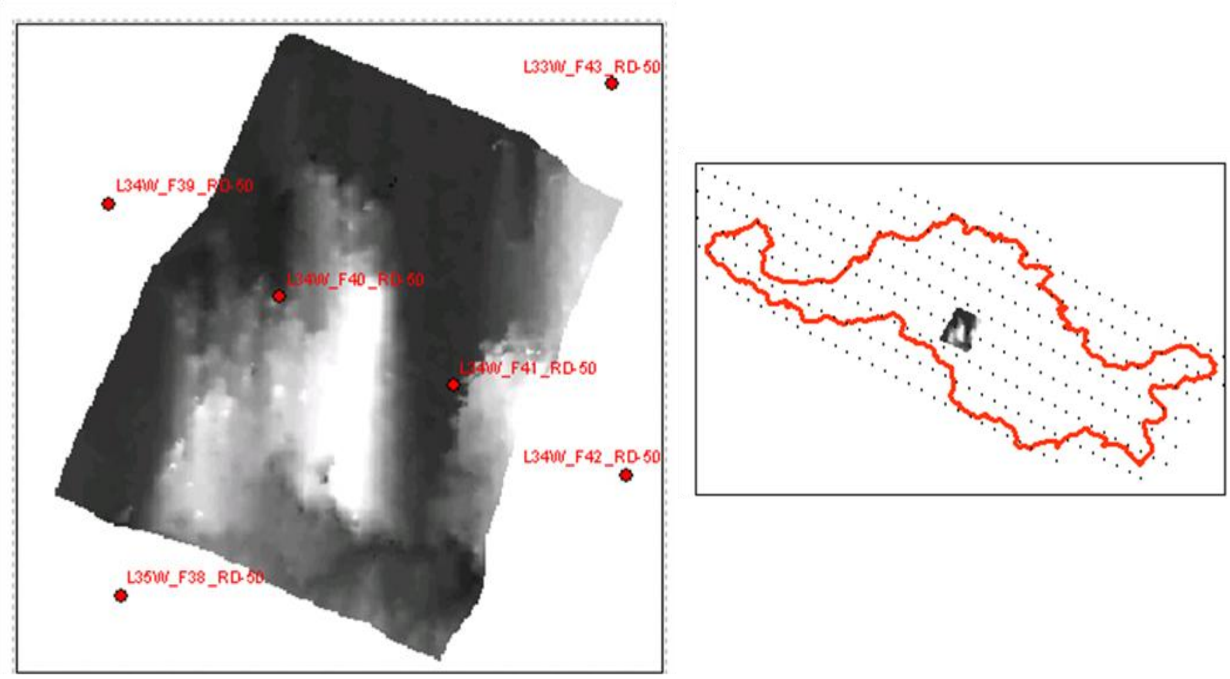


FIGURE III.10. DSM of the stereopair of the photos 40-41, line 34 derived from aerial photographs (left) and position of the presented result in the block (right)

The DTM derived from the contour lines at a spacing of 100 m of the topographic maps were highly accurate on steep slopes of the high mountains as the contour lines were close here. Less accurate were the results of the DTM in the lower and flat areas along the border of the national park. The DTM result for the photos 40-41 of line 34 is presented in Figure III.11. In comparison to the DSM derived from the aerial photograph, the DTM had a clear elevation structure and did not contain large elevation differences between adjacent pixels. Of the 100 random points more than 55% coincided with the topographic contour lines between 0-10 m (Table III.4). Three of the random points had deviations of 30-40 m. The final corrected DTM used for orthorectification is displayed in Figure III.12.

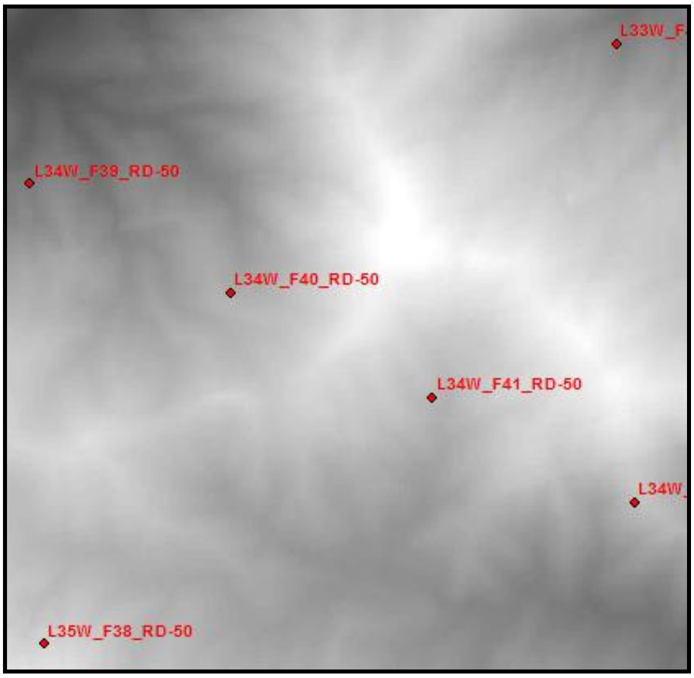


FIGURE III.11. DTM of the stereopair of the photos 40-41, line 34 derived from the 100 m spacing contour lines of the topographic maps at 1:50,000 (Source: ICM 1983/1984)

TABLE III.4. Comparison of elevation of 100 random points on DTM and topographic maps

Range of elevation differences (m)	Number of random points
0–5	31
6–10	24
11–20	24
21–30	18
31-40	3
Sum	**100**

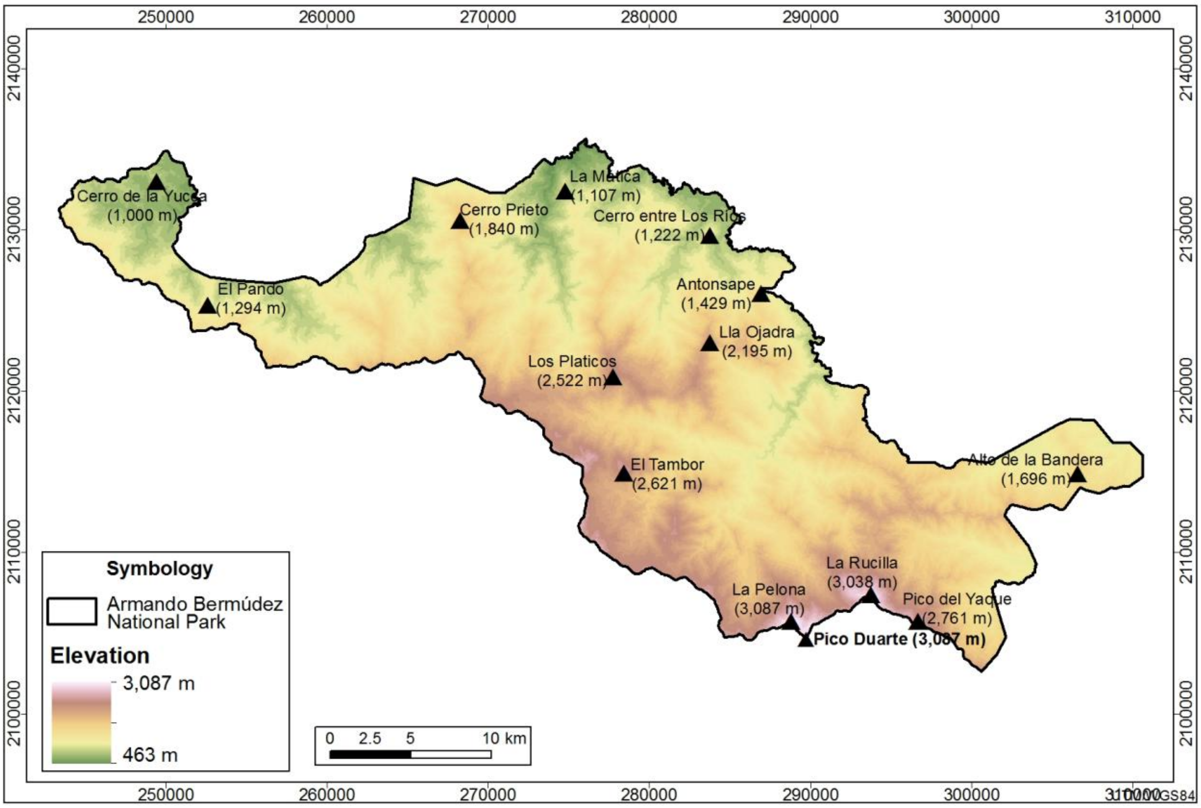


FIGURE III.12. Final DTM derived from 100 m contour lines of Armando Bermúdez National Park used for orthorectification (Source: DTM derived in this study; Boundaries of ABNP from Law 64-00; Peaks, contour lines ICM 1983/1984)

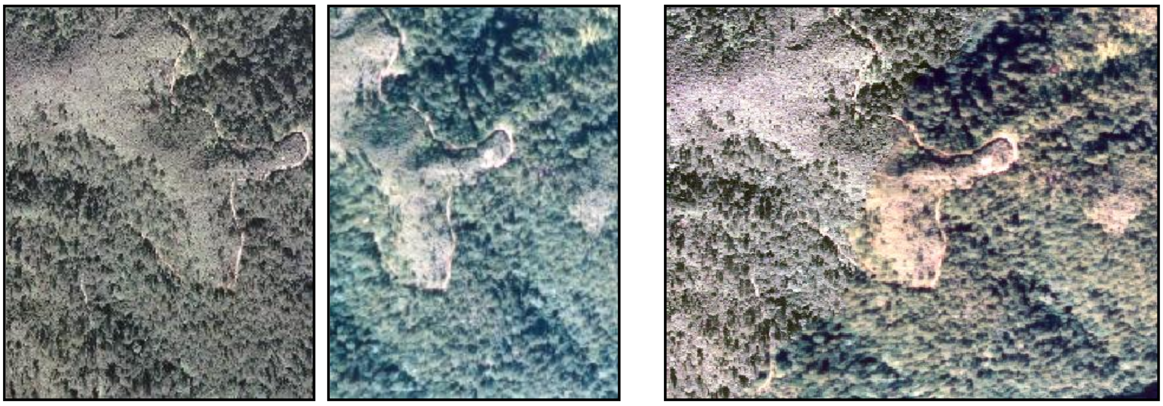
The results of spatial matching between the orthophotographs and the topographic maps are shown in Table III.5. 59% of the evaluation points had a spatial matching of 0-20 m and 41% of 21-50 m. On trail or road intersections where GCPs had been collected, the orthophoto coordinates matched best with the topographic maps. The spatial mismatch between the two data sources is considered as acceptable for the aims of this study – the interpretation of land cover and land use of a national park.

TABLE III.5. Spatial matching between orthophotographs and topographic maps evaluated at 100 points

Range of spatial matching (m)	**Number of random points**
0–10	32
11–20	27
21–30	17
31-40	16
41-50	8
Sum	**100**

Mosaicking

Figure III.13 demonstrates the results of image dodging techniques for two orthophotos of different dates, one scanned on a photogrammetric scanner and the other one on a desktop scanner. The left images present the two adjacent orthophotos before mosaicking and the right image after mosaicking. Color balancing and brightness histogram matching techniques were applied, but the seam could not be concealed.

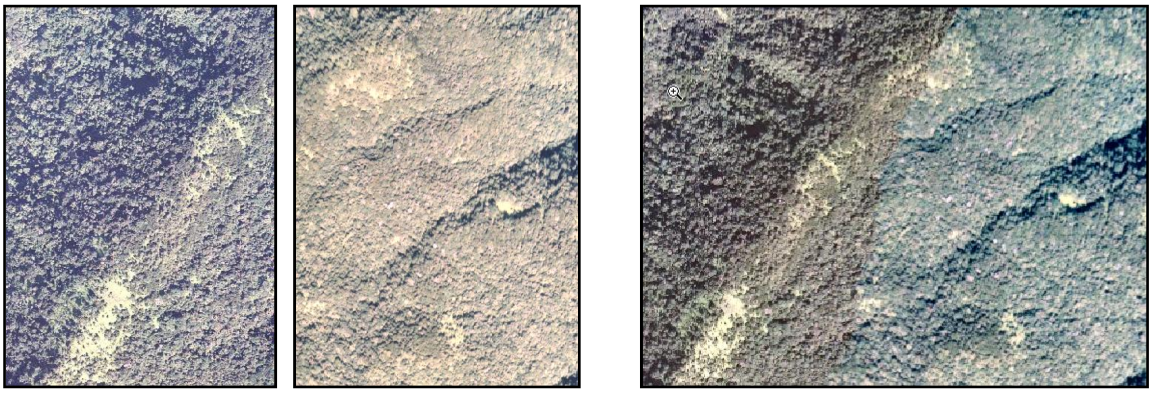


Orthophotos *Line 31, Photo 51* *Line 31, Photo 52*

Mosaick *Line 31, Photo 51* *Line 31, Photo 52*

FIGURE III.13. Result of color balancing and histogram matching of orthophotos of different dates, scanned on a photogrammetric scanner (Photo 51, January 28th, 2004) and on a desktop scanner (Photo 52, December 24th, 2002)

In Figure III.14 the color and brightness differences of two orthophotos taken on the same date, scanned on a photogrammetric scanner and on a desktop scanner are shown. The original images had considerable variations in color and brightness. After applying image dodging techniques the colors and tones were slightly adjusted, but the seam was still notable.

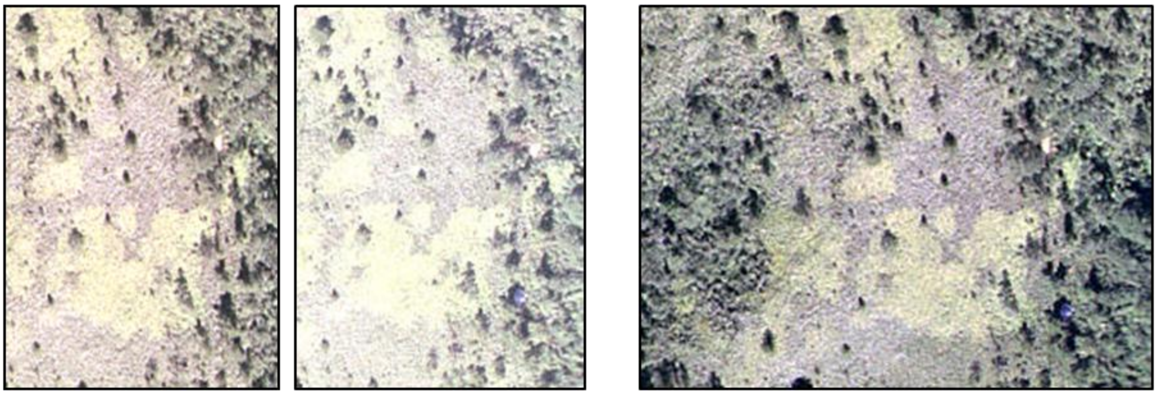


Orthophotos *Line 33, Photo 37* *Line 33, Photo 38*

Mosaick *Line 33, Photo 37* *Line 33, Photo 38*

FIGURE III.14. Result of color balancing and histogram matching of orthophotos of the same date, scanned on a photogrammetric scanner (Photo 37) and desktop scanner (Photo 38)

Figure III.15 shows a satisfactory image matching result of two aerial photographs of the same date and both scanned on a photogrammetric scanner. The brightness differences before matching are still notable while the mosaicked composition is homogeneous in color and has better contrasts than the original orthophotos.



Orthophotos
Line 33, Photo 51 *Line 33, Photo 52*

Mosaick
Line 33, Photo 35 *Line 33, Photo 52*

FIGURE III.15. Result of color balancing and histogram matching of orthophotos of the same date, both scanned on a photogrammetric scanner

The final controlled and enhanced mosaic of all 295 aerial photographs had a spatial resolution of 0.4 m and an overall dimension of 40 km (maximum north-south) by 80 km (maximum east-west), requiring 35.1 GB of storage in the Leica image format (Figure III.16). Color and brightness matching techniques adjusted the differences between the 295 aerial photographs to a certain degree. The visual interpretability was given.

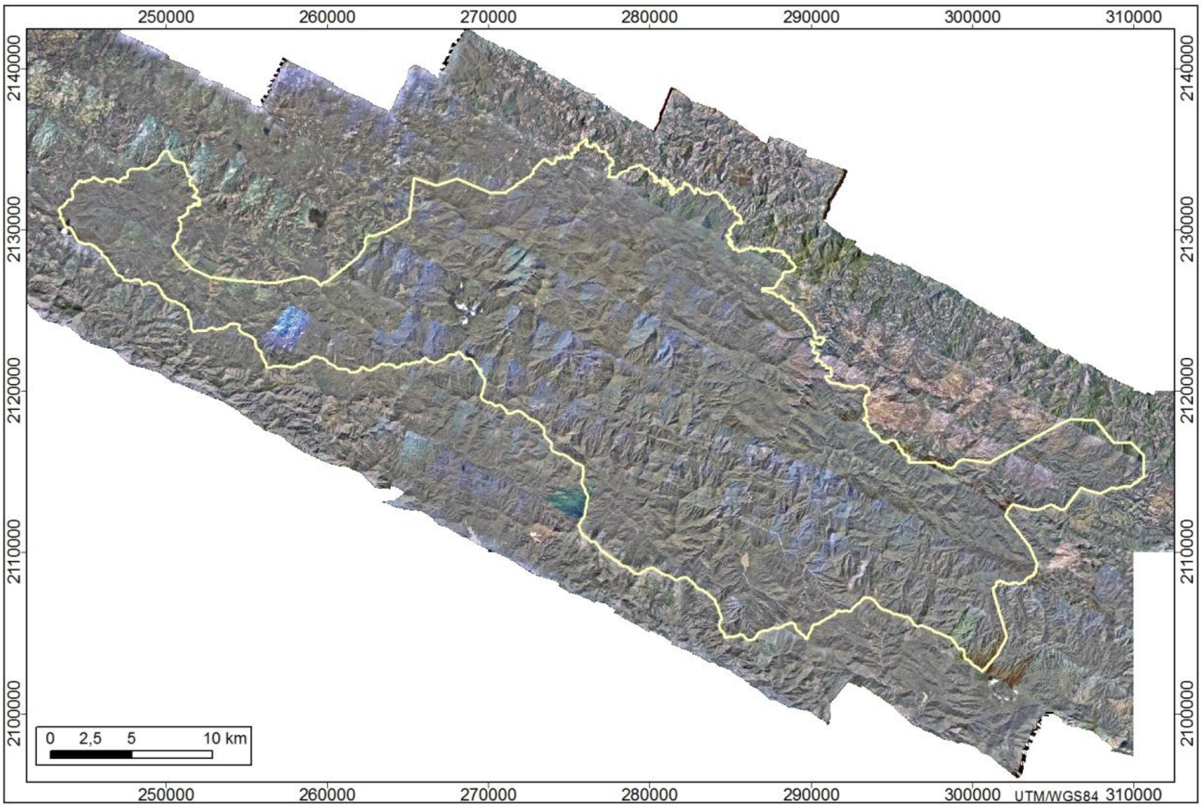


FIGURE III.16. Final color corrected mosaic of 295 orthophotos of Armando Bermúdez National Park (Source: Mosaic derived in this study; Boundaries of ABNP from Law 64-00)

III.3.2 Land cover/land use and accuracy assessment

Development of the classification scheme was an evolutionary process. Some classes were grouped together with others such as *Prestoea montana* (*manaclar*) because of their scattered and difficult to delineate distribution. According to the information content of the aerial photographs and the objective of the study 13 land cover and land use classes were mapped in two hierarchical levels (Table III.6):

Forest: Dense Pine Forest/Pine Dominated Forest; Open Pine Forest; Broadleaf Forest.

Rangeland: Shrub and Herb Dominated Land; *Calimetal* (*Dicranopteris pectinata, Gleichenia bifida*); Natural Grassland (*Danthonia domingensis*).

Agricultural Land: Coffee without Shade Trees; Other Crops.

Additional Categories: Sparse Vegetation; Land slides; Rocks/Stone fields; Built-up area; Water.

Areas were classified as "Forest" if the tree crown density was 10% or more (AVERY 1992; LILLESAND et al. 2008). For delineating the dense pine forest/pine dominated forest crown cover was defined to 60% or more and for the open pine forest 10-60% (Table III.6) (TOLENTINO & PEÑA 1998). *Pinus occidentalis* was the dominant tree species in both pine forest types. Humid broadleaf and cloud forest could not be distinguished on the aerial photographs. Thus, they were labeled both as broadleaf forests.

Mixed forests with a high percentage of broadleaf species were not separable from the broadleaf forest in the aerial photographs, so they formed part of the broadleaf forest class. Mixed forests with a high percentage of *Pinus occidentalis* (over 50%) were classified as pine dominated forest and build one class with the dense pine forests.

Areas with a cover of a minimum of 20% of shrubs combined with grasses and ferns were classified as shrub and herb dominated land (Table III.6). Shrub and herb dominated land differed in species composition. Frequently observed species in these areas were: *Eupatorium* spp., *Baccharis myrsinites* and *Piper aduncum* in combination with *Poacea.* Trees were hardly present.

Land covered by the ferns *Dicranopteris pectinata* and/or *Gleichenia bifida*, recognizable by a light green color in the mosaic and absence of trees, were determined as *Calimetal*.

Clearly to recognize were the coffee plantations without shade trees due to the regular planting pattern and also the small fields, usually planted with beans, manioc and sweet potatoes in the area. A differentiation between the crop types could not be made.

In the following paragraph the principal eight land cover and land use types of the main classes "Forest", "Rangeland" and "Agricultural Land" (Table III.6) are characterized by their appearance in the aerial photographs (screenshots of types taken at a scale of 1:3,000) and their spatial extension. The different appearances of the same land cover/land use class in the mosaic stress the heterogeneity of the processed aerial photographs. The main class "Additional Categories" is not explained in detail as it made just 0.19% of the surface of the entire national park. Area statistics for all land cover/land use types are displayed in Table III.8. Photos of selected land cover/land use classes are shown in Appendix III.B.

TABLE III.6. Final classification scheme and selected photo signatures for Armando Bermúdez National Park land cover/land use classes

Code	Land cover/land use	Definition	Pattern	Color	Texture
1	**FOREST**				
11	Dense Pine Forest/ Pine Dominated Forest	Pine forest with more than 60% crown cover and more than 50% *Pinus occidentalis*, mainly natural	Regular	Dark green	Coarse
12	Open Pine Forest	Pine forest with 10-60% crown cover, grasses in understory, mainly natural	Irregular	Dark green, understory light green/brown	Rough
13	Broadleaf Forest	Areas covered with broadleaf species and scattered pine trees, mainly natural	Regular/ irregular	Light to dark green, brown or grey	Uniform/ Smooth to heterogeneous
2	**RANGELAND**				
21	Shrub and herb dominated land	Areas with more than 20% shrub cover, grasses or ferns, rarely trees, mainly former *conucos* or pasture	Irregular	Light to dark green	Rough
22	*Calimetal* (*Dicranopteris pectinata, Gleichenia bifida*)	Areas covered with both fern species, former *conucos* or natural disturbance	Regular	Light green	Smooth
23	Natural Grassland (*Danthonia domingensis*)	Intramontane valleys covered by the bunch grass *Danthonia domingensis*, no (or little) trees, natural	Regular	Sand color	Smooth
3	**AGRICULTURAL LAND**				
31	Coffee without shade	Coffee plantations without shade trees, man-made	Systematically	Green, brown	Fine
32	Crops	Crops (Beans, manioc,...), no shade trees, man-made	Regular	Green, brown	Fine
4	**ADDITIONAL CATEGORIES**				
41	Sparse vegetation	Bare soil, spare vegetation cover, natural or semi-natural	Regular	Brown	Homogeneous
42	Land slides	Mudslides, result from erosive processes	Irregular	Brown	Rough
43	Rocks/Stone fields	Stonefields around La Pelona/Pico Duarte, natural	Irregular/regular	Brown	“Salt/Pepper”
44	Built-up area*	Small farm houses and yards for drying coffee	Rectangular	Brown	Smooth
41	Water	River Bao	Random	Dark grey	Smooth

* Built-up areas not displayed in map of Figure III.24 due to small area size

Dense pine forest/pine dominated forest and open pine forest (Code 1 and Code 12)

The dense pine forest/pine dominated forest was characterized on the aerial photographs by a coarse texture and a regular pattern (Table III.6, Figure III.17 left). Crown shape of *Pinus occidentalis* was irregular and the crown margins had a fringed outline (Table III.7).

Dense pine/pine dominated forests (Photos III.1a, 1b) were mapped in the center and along the southern border with José del Carmen Ramírez National Park, extending north to Mata Grande along both sides of the Bao River. The final classification result is displayed in the map of Figure III.24 for all classes. Altogether 27,549 ha (275.5 km^2, 34%) of the national park were covered by dense pine forests/pine dominated forests (Table III.8). The dense pine forests/pine dominate forests presented the second largest extension of all cover types. To the west and east these forests were limited approximately by the 1,800 m a.s.l. contour line (analysis ArcGIS 9.1). Along the Bao River they were mapped down to 915 m a.s.l. near Mata Grande. Smaller spots at even lower altitudes were delineated along the northern border near Los Ramones and La Ciénaga in the east. The average slope of these forest types was 26%.

The watershed of the Bao River was covered by 64% of dense pine forests/pine dominated forests. With an extension of 21,822 ha (218 km^2), 80% of the pine forests of Armando Bermúdez National Park were located in this watershed. In contrast to this, the Mao River watershed in the western part of the national park only comprised 1,651 ha (16.5 km^2) of dense pine/pine dominated forests at its highest elevations around 1,800 m a.s.l., resulting in a coverage of 6% in this watershed.

38% of the open pine forests (Photo III.2) occurred in altitudes above 2,000 m a.s.l. at the highest elevations around Pico del Yaque, Loma La Rucilla and Loma La Pelona. The remaining 62% were mapped along De los Negros River and Arroyo Las Lagunas near Rancho en Medio. Open forest had an irregular, noisy pattern in the aerial photographs and were characterized by a rough texture (Table III.6, Figure III.17 right). Soils were always visible in the open pine forests between the individual trees.

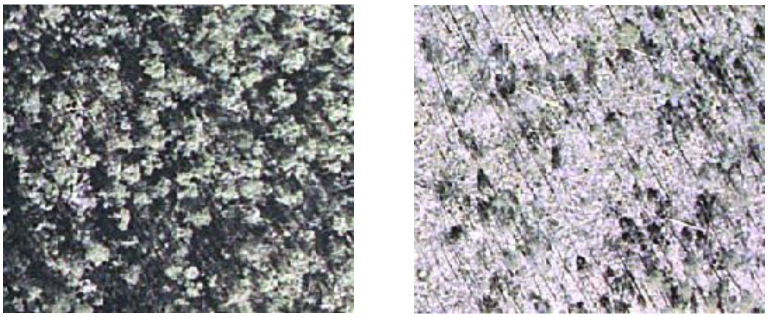


FIGURE III.17. Dense pine forest/forest dominated by pines (left) and open pine forest (right)

TABLE III.7. Crown physiognomy and forest structure in dense pine/pine dominated and broadleaf forests

Feature	**Forest types**	
	Pine forest/Pine dominated forest	**Broadleaf forest**
Crown shape	Irregular shape	Round
Crown margin	Irregular outline	Smooth
Forest Structure	Closed or open/disperse	Closed, never open

Broadleaf forest (Code 13)

In the broadleaf forest (Photo III.3) crowns were rounded (Table III.7) and appeared either as a smooth (Figure III.18, left) or a heterogeneous texture (Figure III.18, right) in the aerial photographs (Table III.6), depending on sun angle, slope of the site and tree heights. Crowns of *Prestoea montana* were recognized as light green scattered stands inside the broadleaf forest and contributed to heterogeneity.

Altogether broadleaf forest summed up to 46,143 ha (461 km^2), representing with 58% the highest proportion of all land cover types in the protected area. The broadleaf forest was mapped to the west and to the east of the pine forest until reaching the border (Figure III.24). The average altitude of broadleaf forests was 1,327 m a.s.l.. Nevertheless broadleaf forests could be mapped on north east facing slopes north of Loma del Pico at altitudes of 2,300 m a.s.l. (analysis ArcGIS 9.1). The lowest occurrences coincided with the northern border of the national park at around 500 m a.s.l.. Broadleaf forests were mapped on a mean slope of 24%.

The watershed of the Mao River contained the largest broadleaf forests extension of all watersheds with 24,300 ha (243 km^2, 88%). In the watershed of the Bao River broadleaf forest were just represented on 26% of the surface of the watershed. A high importance had broadleaf forests also in the watershed of the Yaque del Norte River, covering 60% of the area.

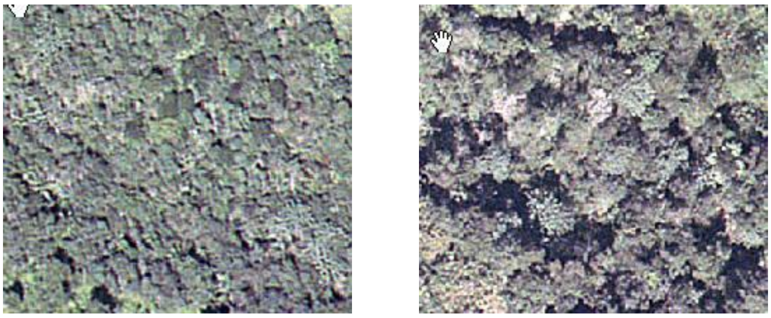


FIGURE III.18. Broadleaf forests of smooth (left) and heterogeneous texture (right)

Shrub and herb dominated land (Code 21)

Shrub and herb dominated land (Photo III.4) had an irregular pattern and rough texture and were clearly recognized in the mosaic as patches in broadleaf forests and pine forests (Table III.6, Figure III.19, Figure III.24). Shrub and herb dominated lands occupied 3,082 ha (30 km^2, 3.8%) of the entire national park (Table III.8) in altitudes between 500-2,432 m a.s.l. and with an average altitude of 1,282 m a.s.l. (analysis ArcGIS 9.1). The highest percentage of this class per watershed was calculated for the Amina River with 5%, the lowest in the watershed of Yaque del Norte River with 0.8%.

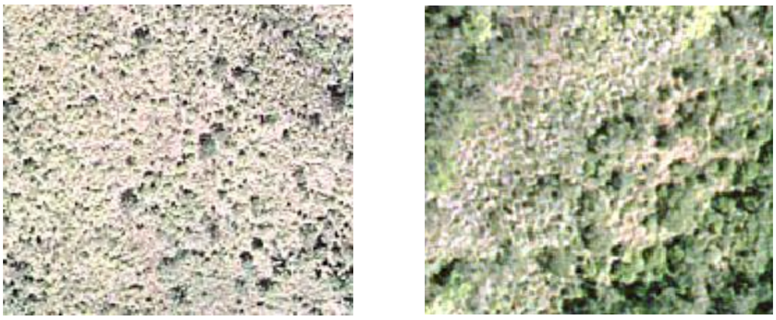


FIGURE III.19. Shrub and herb dominated land (left) and with broadleaf forest at lower right edge (right)

Calimetal (Dicranopteris pectinata, Gleichenia bifida) (Code 22)

In the aerial photographs *Calimetales* (Photo III.5) had smooth textures and regular patterns with a light green color. Shrubs and trees surrounded the patches (Figure III.20).

The fern covered *Calimetales* were mainly detected in the western part of Armando Bermúdez National Park in the watershed of the Mao River (87 ha, 0.32%) (Figure III.24). Altogether 97 ha were delineated in altitudes between 683-2,014 m a.s.l. in the entire park. Mean elevation was 1,113 m a.s.l. (analysis ArcGIS 9.1). Each patch size was smaller than 3 ha. *Calimetales* occurred on average slopes of 21.5%.

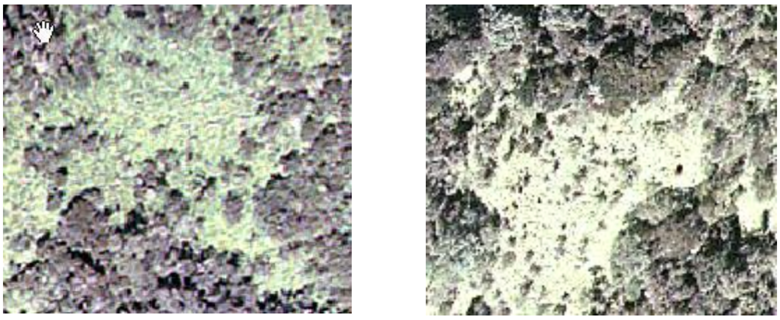


FIGURE III.20. *Calimetal* (*Dicranopteris pectinata*, *Gleichenia bifida*) inside of broadleaf forest

Natural Grassland *(Danthonia domingensis)* (Code 23)

Texture and pattern of the natural grassland (Photo III.6) patches were smooth and regular with a light brown-green color (Figure III.21). The natural grassland of *Danthonia domingensis* without trees and shrubs was just found on three sites in Armando Bermúdez National Park, namely at Laguna Verde, Valle de Bao and Valle de Lilis with an overall extension of 73 ha (0.22%) (Table III.8, Figure III.24). All sites were situated in the watershed of the Bao River in altitudes between 1,749-2,988 m a.s.l. at an average slope of 12% (analysis ArcGIS 9.1). The sizes of the three sites ranged from 15-32 ha.

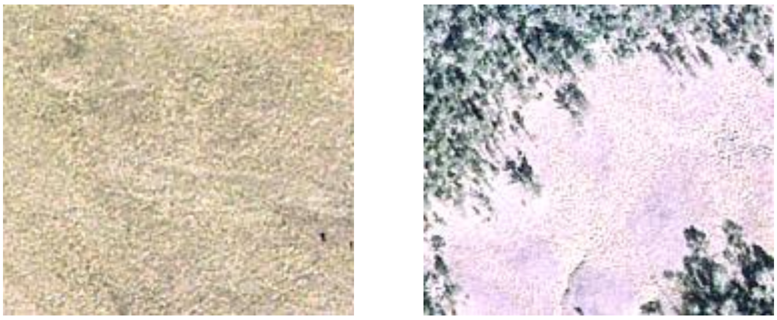


FIGURE III.21. Natural grassland of *Danthonia domingensis* (left) and with pine forest outside (right)

Coffee plantations without shade trees (Code 32)

Coffee plantations without shade trees were mapped along the northern border near Arroyo Bonito in the northeastern part, in the northern part near Manacla and in the northwestern part near Cerrito Redondo (Figure III.24). The average shortest distance between the centerpoint of each plantation to the border of the national park was 260 m and to the nearest village 1.7 km (analysis in ArcGIS 9.1). Due to their regular growing pattern, coffee plantations without shade trees were recognized easily (Table III.6, Figure III.22).

Altogether 111 ha (0.1% of entire protected area) of coffee plantations without shade trees were mapped inside the limits of the national park, half of them in the watershed of the Amina River and the other half in the watersheds of the Bao and Mao Rivers (Table III.8). Plantation sizes ranged from 1.5-20.5 ha with an average size of 5.3 ha. Elevations were between 694-1,725 m a.s.l. with an average of 1,059 m a.s.l.. The average slope was extracted with 20%.

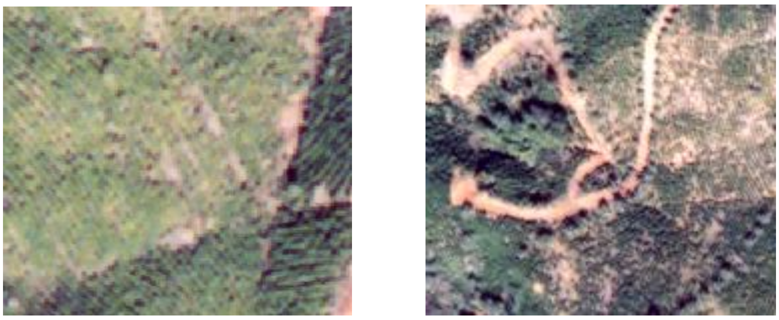


FIGURE III.22. Regularly planted coffee plantations without shade trees (left) and with access ways (right)

Other crops (Code 32)

In between the broadleaf forests of Armando Bermúdez National Park along the northern border small fields were mapped with subsistence products (Figure III.23) (Photo III.7). This land use type was characterized by a regular pattern and a smooth texture. Altogether 65 ha (0.08% of entire protected area) of crops were delineated in the watersheds of the Mao, Amina and Bao Rivers (Table III.8) (Figure III.24). Altitudes ranged between 495-1,471 m a.s.l. with an average height of 816 m a.s.l. (analysis in ArcGIS 9.1). The average slope of the cropland class was 21%. Measurements of the average distance to the nearest village resulted in 1.2 km and to the border of the national park in 488 m. Patch size varied between 0.45-9.0 ha with a mean of 1.7 ha. During field work it turned out that the village of Cabirmal (8 families in 2011) was situated 500 m from the northern border inside the national park between Manacla and Los Ramones. 64 plots were delineated altogether. 29 of them were situated close to the communal area of Cabirmal. The other 35 fields were situated south of the villages of Mayonal, Manacla and Rancho de Caja along the northern border (from west to east) (Figure III.24).

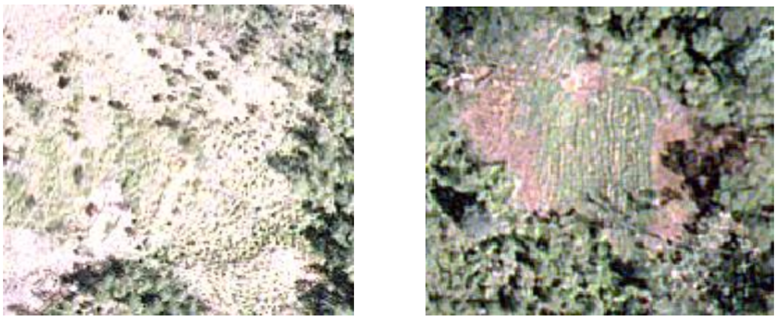


FIGURE III.23. Crops on small fields (left) surrounded by broadleaf forest (right)

TABLE III.8. Size of land cover/land use class per watershed (in ha and percent)

Land cover	Amina	%	Bao	%	Mao	%	Y. Norte	%	Sum
Dense pine/Pine dom. forest	1,628.20	14.47	21,822.20	64.46	1,651.30	6.03	2,447.30	37.69	27,549.00
Open pine forest	14.30	0.13	1,616.50	4.78	24.90	0.09	59.70	0.92	1,720.39
Broadleaf forest	8,961.00	79.65	8,957.30	26.46	24,300.10	88.75	3,925.30	60.45	46,143.70
Shrub/herb dom.	568.00	5.05	1,210.70	3.58	1,236.90	4.52	53.30	0.82	3,082.04
Calimetal	2.30	0.02	6.30	0.02	87.60	0.32	0.45	0.01	97.01
Natural Grassland	0.00	0.00	73.40	0.22	0.00	0.00	0.00	0.00	73.62
Coffee, no shade	58.10	0.52	34.80	0.10	17.50	0.06	0.00	0.00	111.08
Other crops	15.10	0.13	2.50	0.01	47.10	0.17	0.00	0.00	65.01
Sparse vegetation	1.74	0.02	14.90	0.04	6.00	0.02	0.00	0.00	22.72
Land slide	1.44	0.01	10.90	0.03	7.44	0.03	1.57	0.02	21.42
Rocks/Stone fields	0.00	0.00	22.70	0.07	0.00	0.00	6.10	0.09	28.87
Built-up	0.45	0.00	0.00	0.00	0.48	0.00	0.00	0.00	0.94
Water	0.00	0.00	79.20	0.23	0.00	0.00	0.12	0.00	79.55
Sum	11,250.60	100.00	33,851.40	100.00	27,379.32	100.00	6,493.84	100.00	78,995.37

Accuracy assessment

60 of the 68 test areas used for accuracy assessment were grouped correctly (Table III.9). Thus, the overall accuracy for the assessed classes was 88.2%. The classes with the best producer's accuracies were dense pine forest/pine dominated forests (Code 11), broadleaf forests (Code 13), *Calimetal* (Code 22), coffee without shade (Code 31) and crops (Code 32). The best user's accuracies were obtained in pine forest/pine dominated forests (Code 11), open pine forest (Code 12), broadleaf forests (Code 13), *Calimetal* (Code 22) and coffee without shade (Code 31). Open pine forest (Code 12) was misclassified as Shrub and herb dominated land (Code 21) and Shrub and herb dominated land (Code 21) was assigned to the crops (Code 32). These misclassifications can be explained by the different qualities of aerial photographs in the mosaic and the similar appearance of the classes Crops (Code 32) and Shrub and herb dominated land (Code 21) in some aerial photographs. The main forests classes, however, could be differentiated at a high accuracy.

TABLE III.9. Contingency table of land cover/land use classes (selected classes)

Reference Data	**Classified Data**							**Sum**	**PA (in %)**
	11	12	13	21	22	31	32		
11	**12**							12	100.0
12		**4**		2				6	66.7
13			**25**					25	100.0
21				**6**			2	8	75.0
22					**5**			5	100.0
31						**3**		3	100.0
32				2			**5**	7	100.0
Sum	12	4	25	10	5	3	7	**68**	
UA (in %)	100.0	100.0	100.0	60.0	100.0	100.0	71.4		**OA: 88.2**

UA: User's Accuracy; PA: Producer's Accuracy; OA: Overall Accuracy

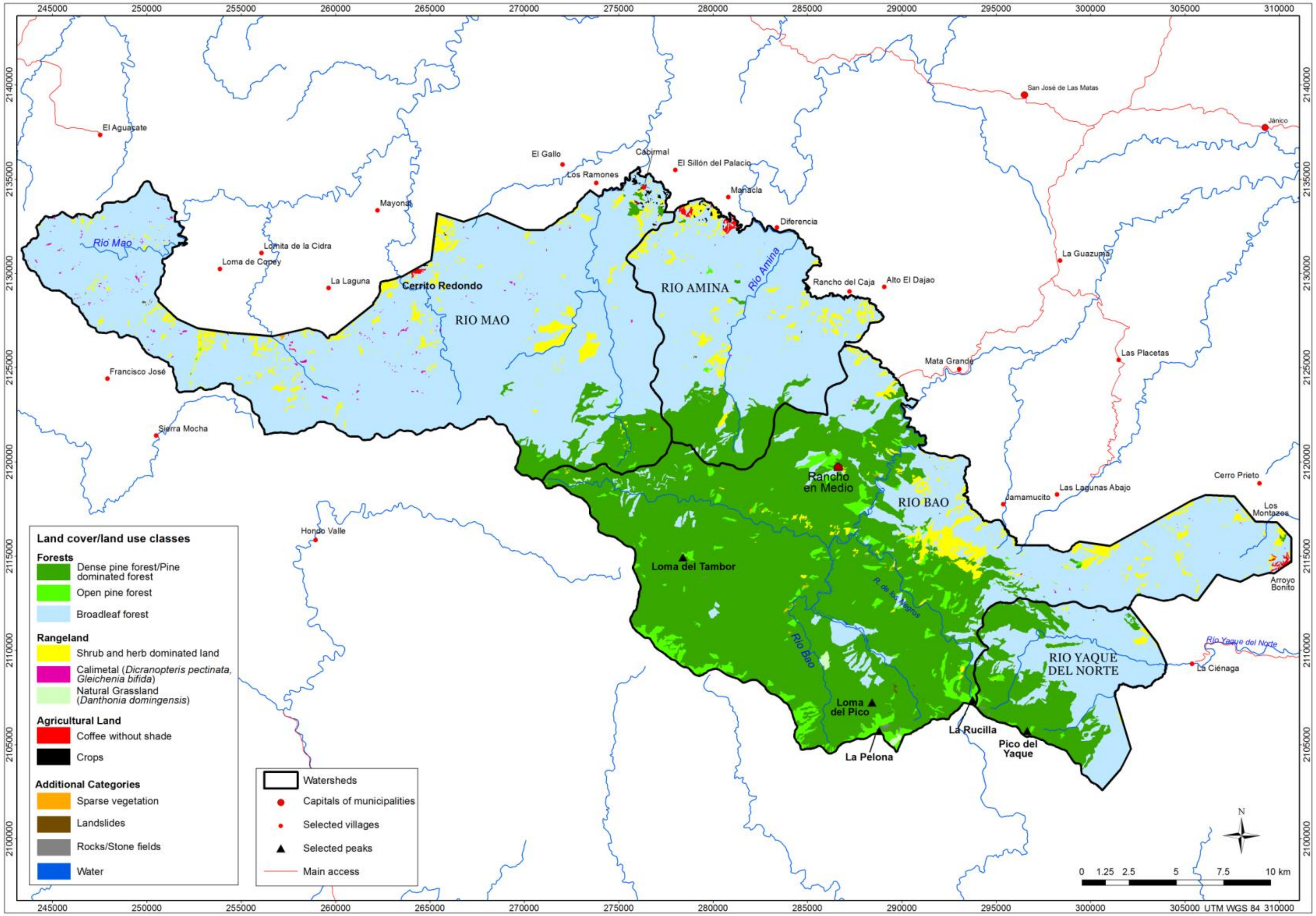


Figure III.24: Result of land cover/land use interpretation on aerial photograph mosaic of Armando Bermúdez National Park (see also digital attachment)

III.4 DISCUSSION OF RESULTS

III.4.1 Digital photogrammetry - orthophotos and mosaic

The digital controlled aerial photograph mosaic was generated out of 295 orthophotos with a Total Image Unit-Weight RMSE of 0.508 m under a convergence criterion of 0.001 m. This final spatial accuracy was regarded as sufficient for the objective of the study. The process of orthorectification and mosaicking was complex due to the following reasons:

First of all the number of aerial photographs of the study area and its surroundings was quite large with 295 color aerial photographs at a scale of 1:20,000. The terrain of Armando Bermúdez National Park is very mountainous and of little access, making well distributed GCP collection difficult. Additionally, clearly to identify objects inside the national park for the determination of GCPs hardly existed. The same problem was described by WELCH et al. (2002) when orthorectifying and mosaicking 1000 color infrared aerial photos of Great Smoky Mountains National Park. As tree cover canopy was nearly continuous over large parts of the area the image matching techniques of LPS Imagine 9.2 mostly failed. Consequently, a large amount of tie points had to be measured manually (WELCH et al 2002). The costly and time consuming process of GCP collection and manual tie point measurement can be substituted in future studies by image-to-image rectification techniques, using the here created mosaic as the reference image (ABER et al. 2010). Image-to-image rectification can even be undertaken automatically (e.g. by Imagine AutoSync).

The varying exposure dates of the aerial photographs in the block and the integration of singular aerial photographs in a flight line led to spatial mismatch, geometric errors and considerable color and brightness differences between adjacent aerial photographs (e.g. Line 34, Photos 30-32 and Line 37, Photos 34-36, see Appendix III.A) (KUHN 1999). Automatic tie point collection and color correction were also affected by this. The color correction tools of LPS Imagine 9.2 could not eliminate these differences thoroughly due to strongly varying brightness distributions (ABER et al. 2010). Underexposure and overexposure of various images in then block exacerbated the problem. Furthermore two camera systems, Wild RC-30 and RMK, had been used resulting in image quality differences within the block. Additionally, the scanning of six aerial photographs on a desktop scanner produced images of low geometric accuracy and quality, interfering with the automatic tie point collection algorithm, DSM extraction and mosaicking. Limitations of using aerial photographs as standard digital data for the assessment of vegetation change were also described by FENSHAM & FAIRFAX (2002) due to the high rectification effort.

Nevertheless, the production of a controlled mosaic by digital photogrammetrical techniques was indispensable for the creation of an exactly referenced GIS database containing land cover and land use information (WOLFF & DEWITT 2000). Uncontrolled and semi-controlled mosaics are less time consuming, but spatially incorrect.

Orthorectification was based on a photogrammetric solution and a DTM, a methodology also found appropriate by JORDAN (2004) for the creation of vegetation overlays of various protected areas of high relief in the USA. Similar to the algorithm for automatic tie point collection, the area and feature based image matching techniques for DSM generation were hampered by the smooth texture and contrast differences in extensive areas of the national park (ABER et al. 2010). In overlap areas of little texture, with spatial mismatch or poor scan quality, the image matching techniques failed to identify conjugate features. Thus, a DTM had to be derived from the 100 m spacing contour lines of the topographic maps.

In mountainous regions integrated GPS/inertial systems for direct georeferencing of airborne sensors or standard frame cameras can avoid extensive GCP collection (CRAMER 2001). GPS/inertial systems facilitate the direct measurement of the exterior orientation parameters during data recording by measuring the position and the angles of the sensor or camera at the time of exposure. Ideally the process of aerial triangulation can be replaced by *direct georeferencing* with the known exterior orientation parameters and make aerial photographs easier to use as georeferenced base maps.

III.4.2 Photointerpretation

13 different land cover/land use classes were distinguished and their extension digitized on the aerial photograph mosaic at scales between 1:2,500 and 1:4,000. Visual aerial photograph interpretation for vegetation mapping is directly related to the skills, experience and a-priori knowledge of the interpreter. This is both strength and weakness of the approach (ALBERTZ 2009). The three natural forest classes distinguished here represented aggregated classes of natural vegetation. Thus, misclassifications could be largely avoided and a high accuracy obtained (Chapter III.3.2). By reducing complexity in aerial photograph interpretation, equal results between two interpreters become more likely which is especially important for monitoring purposes (KUHN 1999). In monitoring programs interpretation has to be carried out based on the same criteria and concepts to make detection of land cover/land use change possible.

Each classification scheme is an appropriate (or inappropriate) segmentation of reality related to image resolution, working scale and objectives of the study (LILLESAND et al. 2008). Sharp natural vegetation boundaries occur in the field at sites of abrupt breaks in environmental conditions, where dominant species reach their environmental limits or human impact altered the landscape abruptly (KIRCKPATRICK & DICKINSON 1986). Here delineation of the units is less problematic.

However, mostly natural vegetation passes gradually into another vegetation type or a site is temporally at a certain stage of succession (AUSTIN 1985; BRONDIZIO et al. 1996; SCHMIDTLEIN et al. 2007). Here the placement and definition of boundaries was performed by applying the quantitative criteria and elements of aerial photograph interpretation described in Chapter III.3.2 to minimize the effects of subjectivity. Solutions to mapping the floristic continuum are offered by object-oriented approaches which produce fuzzy classifications based on the fuzzy set theory (ZADEH 1965; GLEITSMANN 2005). These approaches are not limited to force one pixel to a certain class. Uncertainty is rather accounted for by permitting partial memberships and adding possibilities to a pixel in a class. In this study the object-oriented methodology could not be applied as the aerial photographs of the block were very heterogeneous in color and brightness. The differences could not be adjusted entirely by image matching techniques during mosaicking. Furthermore the amount of aerial photographs was large. An advantage of visual interpretation over automated classification procedures is the ability of the human brain to filter valuable information from non valuable one so that the effects of bidirectional reflectance are leveled out. Bidirectional reflectance provokes that similar objects have different spectral characteristics in the image caused by sun position and viewing angle (TUOMINEN & PEKKARINEN 2005; ABER et al. 2010). Here especially the three forest classes were affected by bidirectional reflectance (data not shown).

For monitoring reasons the error of measurements in each class had to be quantified to use the interpretation results for decision taking in protected area management (GROSS & ADLER 1996; KUHN 1999). The overall accuracy of the revised classes was 88.2%, under the premise that 68 check points was a low number. Not all of the classes could be assessed due to insufficient field data in the main class “Additional Categories”.

Identification of individual tree species in aerial photographs depend on quality, scale, tone of crown trees, stand age, topographic site and the interpreter’s background (AVERY 1968). KUHN (1999) stated that a scale of 1:5,000 was required for tree species mapping, but detection is also possible at lower scales (AVERY 1968). Here the palm *Prestoea montana* (Manaclares) and *Syzigium jambos* could be identified visually. *Prestoea montana* was recognizable in the mosaic by its light green to yellow color. It occurs on humid, stony soils along small creeks and also scattered on slopes in the broadleaf forest (MAY 1997a). It would have been too time consuming to digitize the extensions of the Manaclares so that this edaphic vegetation type was subsumed to the broadleaf forests. A screenshot of the appearance of *Prestoea montana* in the aerial photographs is presented in Figure III.25 (left).

Syzigium jambos dominated the lowland forests near the village La Diferencia. As the species was not the focus of this study it was also assigned to the broadleaf forest. Theoretically its extension could still be delineated in future studies on the mosaic (Figure III.25 right).

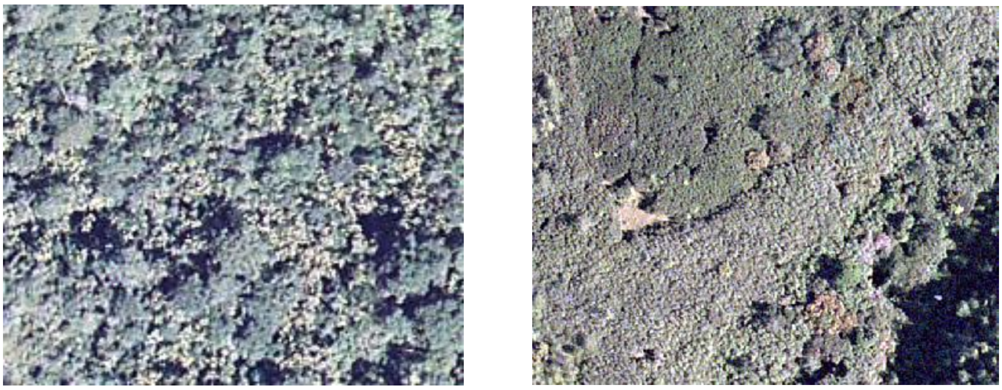


Figure III.25. *Prestoea montana* (light green to yellow) and *Syzigium jambos* along a river at the border near the village of La Diferencia

Actual human impact in Armando Bermúdez National Park is concentrated along the northern border west of the village Arroyo Bonito, south of Manacla, around Cabirmal and around Cerro Redondo (Figure III.24). Thus, Armando Bermúdez National Park belongs to the protected areas that have experienced net clearance since establishment (BRUNER et al. 2001). Still the extensions of human impact are moderate compared to the size of the entire national park, but they could increase in the coming years, aggravating the negative consequences of deforestation and land conversion and putting in danger the ecosystem services provided by the national park (FOLEY et al. 2005). Above this *caturra* production is related to a high input of fertilizers and agro-chemicals, contaminating the nearby rivers and soils.

Many of the shrub and herb dominated land showed traces from former agriculture and pasture practiced in the national park until 2000 (PEGUERO et al. 2007). These areas were at different stages of succession, covered with shrubs, herbs and some trees. The *Calimetales* occupied clearings caused by hurricanes or human infractions, inhibiting the succession of tree species at all (May 2000b).

PAULSCH et al. (2001) found in Ecuador that tropical montane forests converted to pasture land made succession of tree species sometimes impossible. Similar findings were made by

CINGOLANI et al. (2007) in mountainous regions in Argentina. We consider that agricultural activities are not compatible with the objectives of the national park.

Can vegetation types be delimited sharper in the future by other data and methodologies?

Information about land cover/land use in protected areas can either be extracted from aerial photographs, airborne hyperspectral sensors or high and very high resolution satellite images (ROGAN & CHEN 2004).

Color infrared aerial photographs offer more possibility for software based analysis of vegetation characteristics due to the contained infrared band compared to three band color aerial photographs. Early detection of vegetation stress caused by lack of water, disease or parasite infestation is possible on infrared color aerial photographs (SABINS 1996; GIBSON 2000). While stressed leaves might still appear green in color aerial photographs, the infrared reflection in an IR-color aerial photograph is already reduced and indicates that the cells of the spongy parenchyma of the mesophyll layer are collapsing which is called the *previsual symptom* of plant stress (SABINS 1996). Consequently for assessing the health of vegetation the infrared channel is needed. Besides this color infrared aerial photographs permit the derivation of meaningful indicators for the quantification of plant vigor or biomass production (e.g. Normalized Difference Vegetation Index, NDVI).

Advantages of satellite based images over aerial photographs for land cover/land use extraction consist in the reduced ground sampling (SCHARDT et al. 2005). Solutions for accurate land cover/land use generation offer the high resolution satellites IKONOS (3.2 m multispectral resolution at nadir), Quickbird (2.6 m multispectral resolution at nadir), GeoEye-1 (1.6 m multispectral resolution at nadir) and WorldView-2 (1.8 m multispectral at nadir!). The main disadvantages of these high resolution satellites are the high costs for protected area management institutions in developing countries.

GLEITSMANN & KAPPAS (2005) used IKONOS satellite data for land cover/land use mapping of the watershed of Yaque del Norte River east to this study area and improved classification results by including texture parameters and filtering. In high spatial resolution imagery textural features have advantages for forestry applications compared to spectral features (TUOMINEN & PEKKARINEN 2005).

The WorldView-2 satellite with a spatial resolution of 50 cm (panchromatic) and 1.8 m (multispectral) provides eight spectral bands in the visible and near-infrared range (http://worldview2.digitalglobe.com/about/). Additional to the *blue*, *green* (plant vigor), *red* (vegetation discrimination) and *NIR1* (moisture content, plant biomass and soil types), WorldView-2 also introduces a *coastal blue* band (vegetation analysis and bathymetric studies), a *yellow* band (vegetation applications), a *red edge* band (plant health and classification of vegetation) and a *NIR2* band (biomass and vegetation studies). The satellite has an average revisit of 1.1 days and measured accuracy is of 4.1 m. WorldView-2 is expected to deliver a 10-30% higher classification accuracy than traditional visible and near infrared high resolution images (DIGITALGLOBE 2009). A comparison between the *red* and *red-edge* bands (705-750 nm, transition between minimum and maximum reflectance) of WorldView-2 permits the determination of plant health (DIGITALGLOBE 2009). Vegetation stress caused by lack of water or diseases can be quantified by the Red-Edge Vegetation Stress-Index (RSVI) so that also the effects of climate change on the natural vegetation of the national park could be assessed early. On WorldView-2 images the differentiation between mixed, pine and broadleaf forests and between trees and mature young plants would also be feasible (DIGITALGLOBE 2009).

Time line

The field work for GCP collection and gathering of land cover/land use information of the 157 selected sites were realized in ten field trips between October 2005 and March 2006, each one lasting between three and seven days. It took nine man-month of office work to go through the photogrammetrical processes. Very time consuming was the manual search of the tie points, the analysis of the automatically set tie points and the definition of the search parameters. The definition of the interpretation key and digitalization of the land cover/land use classes took four man-months.

III.4.3 Implications for management and further use of the results

It is recommended to design a participative management concept with all stakeholders of the national park to develop strategies for reducing the human impact along the northern border (BORRINI-FEYERABEND 1996, 1997; BORRINI-FEYERABEND et al. 2000; THOMAS & MIDDLETON 2003). The main focus of this concept should lie on the investigation about alternative income strategies, commonly agreed on, and payment of ecosystem services (JACK et al. 2008; TOGNETTI et al. 2010; CALVO-ALVARADO et al. 2010; MORSE-JONES et al. 2011).

The here created and analyzed land cover/land use data represent the baseline for a monitoring program that should be initiated using remote sensing images. Field plots must be an integral part of this program to observe the succession of plant species on impacted sites and the changes in floristic composition and vegetation structure on natural ones.

The aerial photograph mosaic can be used for image-to-image rectification of historic or future images. Thus, high costs and time consuming GCP collection can be avoided and spatial matching between different data sources improved.

III.5 Conclusion

The central objective of this study was to derive and analyze actual land cover and land use information of Armando Bermúdez National Park. This was done on an aerial photograph mosaic. Photogrammetric processing of the aerial photographs was time consuming and had to be adapted to the special data structure and environmental situation. The controlled mosaic could be finished with high spatial accuracy. The results of land cover/land use information extraction showed human impact in form of agriculture inside the protected area along the northern border.

We conclude that the first land cover/land use database of Armando Bermúdez National Park was generated from a color aerial photograph mosaic at a scale of 1:20,000, encompassing an improved understanding about the extension and location of anthropogenic disturbed areas and natural forests. It is considered that the methodology applied here could also be used for other mountain protected areas to gain information about land cover and land use. High spatial resolution satellite images can be a valuable option for future monitoring programs.

Appendix III.

Appendix III.A Flight lines and dates of aerial photographs used in this study

	Flight Line Number								
Aerial Photographs Number	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**
15							27.01.03	27.01.03	
16							27.01.03	27.01.03	
17							27.01.03	27.01.03	16.01.03
18						27.01.03	27.01.03	**27.01.03**	28.01.04
19						27.01.03	28.01.04	28.01.04	28.01.04
20					27.01.03	27.01.03	28.01.04	28.01.04	28.01.04
2					27.01.03	27.01.03	28.01.04	28.01.04	28.01.04
22					27.01.03	16.01.03	28.01.04	28.01.04	28.01.04
23					27.01.03	27.01.03	28.01.04	28.01.04	28.01.04
24					27.01.03	27.01.03	28.01.04	28.01.04	28.01.04
25					27.01.03	27.01.03	28.01.04	28.01.04	28.01.04
26					27.01.03	27.01.03	28.01.04	28.01.04	28.01.04
27					27.01.03	27.01.03	28.01.04	28.01.04	28.01.04
28					27.01.03	27.01.03	28.01.04	**28.01.04**	28.01.04
29					27.01.03	27.01.03	28.01.04	28.01.04	28.01.04
30					27.01.03	28.01.04	28.01.04	28.01.04	28.01.04
31				16.01.03	28.01.04	01.01.03	28.01.04	28.01.04	28.01.04
32				16.01.03	28.01.04	17.01.03	17.01.03	28.01.04	28.01.04
33				16.01.03	28.01.04	17.01.03	17.01.03	28.01.04	28.01.04
34				16.01.03	28.01.04	17.01.03	17.01.03	28.01.04	28.01.04
35				16.01.03	28.01.04	17.01.03	17.01.03	28.01.04	19.01.04
36				28.01.04	28.01.04	17.01.03	17.01.03	28.01.04	17.01.03
37			16.01.03	28.01.04	28.01.04	17.01.03	17.01.03	28.01.04	17.01.03
38			16.01.03	28.01.04	**28.01.04**	17.01.03	17.01.03	28.01.04	17.01.03
39		14.03.01	28.01.04	28.01.04	28.01.04	17.01.03	17.01.03	13.01.03	17.01.03
40		14.03.01	28.01.04	28.01.04	28.01.04	17.01.03	17.01.03	13.01.03	**17.01.03**
41		14.03.01	28.01.04	28.01.04	28.01.04	17.01.03	17.01.03	13.01.03	17.01.03
42		14.03.01	28.01.04	28.01.04	28.01.04	17.01.03	17.01.03	13.01.03	17.01.03
43		14.03.01	28.01.04	28.01.04	17.01.03	17.01.03	17.01.03	13.01.03	17.01.03
44		14.03.01	28.01.04	28.01.04	17.01.03	17.01.03	17.01.03	13.01.03	17.01.03
45		14.03.01	28.01.04	28.01.04	17.01.03	17.01.03	17.01.03	13.01.03	17.01.03
46	21.12.00	14.03.01	28.01.04	28.01.04	17.01.03	17.01.03	17.01.03	13.01.03	17.01.03
47	21.12.00	14.03.01	28.01.04	28.01.04	24.12.02	17.01.03	17.01.03	13.01.03	17.01.03
48	21.12.00	14.03.01	28.01.04	28.01.04	24.12.02	17.01.03	17.01.03	13.01.03	17.01.03
49	14.03.01	14.03.01	28.01.04	24.12.02	24.12.02	17.01.03	17.01.03	13.01.03	17.01.03
50	14.03.01	14.03.01	28.01.04	24.12.02	24.12.02	17.01.03	17.01.03	13.01.03	17.01.03
51		14.03.01	28.01.04	24.12.02	24.12.02	17.01.03	17.01.03	13.01.03	
52		14.03.01	**24.12.02**	24.12.02	24.12.02	17.01.03	17.01.03	13.01.03	
53		14.03.01	24.12.02	24.12.02	24.12.02	17.01.03	22.01.03	13.01.03	
54		14.03.01	24.12.02	24.12.02	24.12.02	17.01.03	22.01.03	13.01.03	
55		14.03.01	24.12.02	24.12.02	24.12.02	17.01.03	22.01.03	13.01.03	
56		14.03.01	24.12.02	24.12.02	24.12.02	17.01.03	22.01.03		
57		14.03.01	24.12.02	24.12.02	24.12.02	17.01.03			
58		14.03.01	24.12.02	24.12.02	24.12.02	17.01.03			
59		14.03.01	24.12.02	24.12.02	24.12.02				
60		14.03.01	24.12.02	22.01.03	24.12.02				
61		14.03.01	24.12.02	22.01.03					
62		14.03.01	24.12.02	22.01.03					
63		14.03.01	24.12.02						
64		14.03.01	**24.12.02**						
65		14.03.01	24.12.02						
66		14.03.01	24.12.02						
67		14.03.01							
	Date of capture								

Bold dates: Hardcopy scan with a desktop scanner

░ Aerial photographs taken with Camera Wild RC 30
□ Aerial photographs taken with Camera RMK
▓ Aerial photographs with seven or eight GCPs

APPENDIX III.B Photos of selected land cover/land use classes

PHOTO III.1A. Dense pine forest (*P. occidentalis*) (Filo de la Navaja, 1,100-1,400 m a.s.l.)

PHOTO III.1B. Pine dominated forest (*Pinus occidentalis* (Photo: T. Montilla)
(Loma de Oro, 1,292 m a.s.l.)

PHOTO III.2. Open pine forest with *Tillandsia usneoides* (Filo de la Navaja, 1,400 m a.s.l.)

PHOTO III.3. Broadleaf forest
(in detail: cloud forest El Descansadero, 1,402 m a.s.l.)

PHOTO III.4. Shrub and herb dominated land with *Pinus occidentalis* in the background
(near La Ciénaga, 1,300 m a.s.l.)

PHOTO III.5. *Calimetal* with *Dicranopteris pectinata* (Loma de La Barranca, 1,250 m a.s.l.)

PHOTO III.6. Natural grassland with *Danthonia domingensis* (Valle de Bao, 1,800 m a.s.l.)

PHOTO III.7. *Conuco* with crops
(Photo: T. Montilla) (near Cabirmal,
815 m a.s.l.)

IV. Explaining and predicting the distribution of the mountain forest types

IV. 1 INTRODUCTION

Generally tropical montane forests are found along mountain chains in the tropics, but they vary considerably in structure, composition and diversity according to latitudinal position, continental/maritime location, atmospheric circulation regime, site exposure and elevation (BRUIJNZEEL 2001; SHERMAN et al. 2005; RICHTER 2008). Although understanding of these ecosystems has increased during the last years (HAMILTON et al. 1995; BRUIJNZEEL 2001; BECK et al. 2008; GRADSTEIN et al. 2008; BRUIJNZEEL et al. 2010) there are still gaps of knowledge about the gradients that influence species composition and community patterns as global variety of mountain forests is high (SHERMAN et al. 2005). The spatial distribution of montane forests has only been mapped rudimentarily (SCATENA et al. 2010).

The most comprising environmental gradients influencing composition and distribution of tropical (and extra tropical) mountain forests are altitude and directly related to altitude temperature and precipitation (WHITTAKER 1967; GENTRY 1988; BECK et al. 2008). Along the altitudinal gradient between *tierra templada* and *tierra fría* the major compositional differences are observed in tropical mountain forests (RICHTER 2008). Generally the lower perhumid zones are dominated by evergreen broadleaf forests that gradually pass with increasing altitude into montane broadleaf forests and then into different types of cloud forests (OHSAWA 1995). Species-poor monotypic forests or woodlands adapted to cold and semiarid conditions follow at the higher elevations (RICHTER 2008). Other important gradients for the occurrence of different mountain forest compositions and distributions are topography (e.g. aspect and slope), soil characteristics, geological substrates and natural or anthropogenic disturbances (WEAVER 1991; PAULSCH et al. 2001; GEROLD 2008).

Conservation of tropical montane forest is a very important, but challenging task as these ecosystems are being exposed to land conversion, logging and climatic drying - with all the ecological consequences (MULLIGAN 2010; NAIR et al. 2010; SCATENA et al. 2010). Only with site-specific information local variability of tropical montane forests regarding composition, vegetation-environment relationships and spatial distribution can be assessed and integrated in monitoring programs, management decisions and vegetation-specific conservation plans.

Only 10-15% of the former mountain forests still persist in the Dominican Republic. The remaining forests present high levels of phytodiversity and endemism (KAPPAS 1999). Armando Bermúdez National Park in the Cordillera Central conserves a unique vegetation pattern that has evolved between 495-3,087 m a.s.l. and that consists of humid broadleaf, gallery, mixed, cloud and monotypic pine forests. The treeline is not even reached at the highest peak (Loma La Pelona, 3,087 m a.s.l.). The elevations of the Cordillera Central are unique in the Caribbean.

Most of the studies realized up to now in Dominican mountain forests had a floristic focus (MAY & PEGUERO 2000; MAY 2001; PEGUERO et al. 2007) while studies analyzing the gradients of the mountain forest are scarce (SHERMAN et al. 2005). The spatial patterns of the natural mountain forests have never been analyzed or predicted. This study aims to close the information gap and provides essential data which can be used to improve management of the site.

The specific objectives of this study are:

(i) to identify the main environmental factors explaining the spatial distribution of the different natural mountain forest types in Armando Bermúdez National Park;

(ii) to characterize the main natural mountain forest types according to their indicator species (woody species) and

(iii) to develop a model to map the spatial distribution of the different natural mountain forest types based on the environmental factors determined in (i), transferring the punctual floristic plot-based information into spatially explicit forest cover prediction.

IV. 2 MATERIALS AND METHODS

IV.2.1 Vegetation sampling

The floristic field data for characterization of the vegetation of Armando Bermúdez National Park was collected in February 2011 on 137 plots (Figure IV.1). Prior to field work the plots had been selected along the trails according to a stratified random design based on altitude and precipitation raster data to guarantee a representative sampling of the different habitat types (low, medium and high elevation; humid, medium and very humid conditions). Each identified plot coordinate was sited off the trail by 20 m. The positions of the so derived plots were stored as waypoints for navigation in a Garmin 62 GPS. Due to the poor - and insufficiently maintained - network of hiking trails inside the national park an even distribution of plots over the entire protected area was not possible.

Vegetation sampling was performed on plots of 20 m x 10 m (200 m^2). This plot size had been evaluated as suitable for the characterization of the mountain forest types of Armando Bermúdez National Park (PEGUERO et al. 2007). All woody species were sampled per plot in three layers between 0.5-5 m, 5-20 m and above 20 m – if existed. Shrub species were just recorded if they grew like trees (single stems). Percentage canopy cover was estimated visually for each woody species according to BRAUN-BLANQUET (1932) (Appendix IV.A, as digital attachment). Forest types were differentiated using the following physiognomic parameters and observations: Pine forest (minimum of 40% percentage canopy cover of *Pinus occidentalis* or less if *P. occidentalis* only tree species with heights > 5 m), mixed forest (20-40% percentage canopy cover of *Pinus occidentalis*), gallery forest (in small creeks and shady, humid valleys, presence of *Prestoea montana*), humid broadleaf forests (not in creeks, below cloud level) and cloud forests (at sites where fog, clouds and a high density of epiphytes were observed, presence of some characteristic cloud forest species).

Two botanists of the National Botanical Garden of Santo Domingo accompanied me during field work and helped to identify the plants to species level. Those plants only identified to genus level were collected and identified at the herbarium in Santo Domingo. Voucher specimens of the samples reside there. The nomenclature used in this study follows LIOGIER (1989, 1994, 1995, 1996a-e, 2009).

IV.2.2 Environmental factors

The environmental factors were selected based on their possible potential to explain the composition and patterns of the mountain forest types in the study area. Furthermore availability of data and spatial coverage had to be taken into account.

Some of the environmental factors just represented measured or observed conditions at plot level while others were raster datasets of the entire protected area compiled from thematic maps, remote sensing data and meteorological data models by applying GIS-tools.

Plot-specific environmental factors

Along the diagonal line of each plot three soil samples of the mineral soil were taken in a depth of 15-20 cm. These samples were mixed thoroughly and mineral soil pH was analyzed with a calibrated handheld PCE-PH 20S in a 1:2.5 soil-water ratio suspension. Evidence of past disturbances caused by agriculture, hurricanes or fires was recorded per plot. The distances from each plot to the closest river digitized on the topographic maps (1:50,000) were calculated. Field estimates on total vegetation cover, herb cover and no vegetation cover were also introduced.

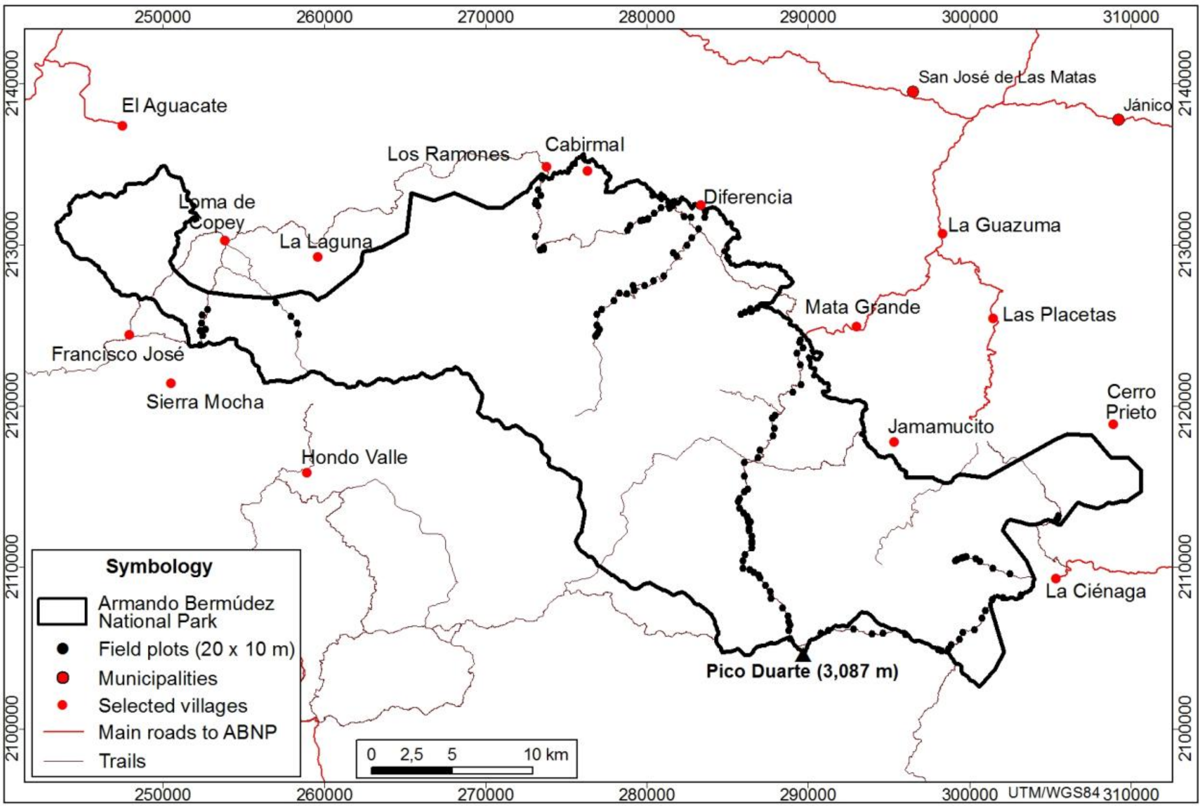


FIGURE IV.1. Study area and location of the 137 sampled plots (Source: Plots and trails from GPS field work; Boundaries of ABNP from Law 64-00; Villages, municipalities, roads from topographic maps 1:50,000, ICM 1983/1984 and field work; trails digitized on aerial photograph mosaic)

Protected area-wide environmental factors

Of the area-wide environmental factors one was a spectral index derived from remote sensing data, seven were related to topography, six to climate, one to insolation and one to soil humidity.

Spectral vegetation indices like the Normalized Difference Vegetation Index (NDVI) (ROUSE et al. 1974) have been used in numerous ecological studies, many of them reviewed by KERR & OSTROVSKY (2003), PETTORELLI et al. (2005) and GLENN et al. (2008). Most vegetation indices make use of the fact that plant pigments absorb solar radiation in the visible electromagnetic spectrum used as a source of energy in the process of photosynthesis. In the near-infrared spectral region incoming energy is scattered by the leaf structure (JENSEN 2007). The NDVI is based on the ratio of the reflection of solar radiation in the visible red (RED) and near-infrared (NIR) sections of the spectrum. The equation is: NDVI=(NIR-RED)/NIR+RED). Possible values of the dimensionless index are between –1 und +1. Values between 0.3-0.8 stand for a considerable photosynthetic activity in dense vegetation with a high biomass production. Soils with little vegetation cover tend to have small values. Here NDVI was used to represent biomass production in the different forest types along the altitudinal gradient (WHITTAKER & NIERING 1975). FEELY et al. (2005), HE et al. (2009) and OLDELAND et al. (2010) employed the NDVI for analyzing the floristic composition and structure of forests.

Here NDVI was calculated on the May 3, 2003 Landsat 7 ETM+ scene downloaded from the ftp-server of the University of Maryland (ftp://ftp.glcf.umd.edu/glcf/Landsat/; Path: 008, Row: 047). On May 31, 2003 the Scan Line Corrector (SLC) of the Landsat 7 ETM+ failed so that all images taken after this date contain gapped data that increase towards the edge of a scene (SLC-off) (http://landsat.usgs.gov/Landsat_7_ETM_SLC_off_data_products.php). A functioning SLC would compensate for the forward motion of the satellite. As field work took place in February of 2011 a second SLC-off image with missing scan lines was downloaded from March 6, 2011. NDVI-values of the 2003 and the 2011 scene were compared for each plot. Six plots presented no data values in the 2011 scene as they coincided with missing data lines. The NDVI values of the plots on the two scenes were highly correlated (Pearson, $r=0.727$, $p<0.001$, $N=137$) and as tree composition was not considered to change rapidly the 2003 scene was used for further analysis. After downloading the image was registered to UTM coordinates (Zone 19N, WGS84) and referenced to a digital mosaic of the topographic maps of Armando Bermúdez National Park with a first order polynomial equation and nearest neighbor resampling technique. RMS error was smaller than 1 pixel.

Elevation is the primary source for deriving secondary environmental variables such as slope, aspect, hillshade and solar radiation, most widely used to determine differences in vegetation composition and prediction in mountainous areas, amongst other variables (WHITTAKER 1967; CAYUELA et al. 2006; SHERMAN et al. 2005). Elevation data were digitized as 100 m contour lines from topographic maps (1:50,000) at the Institute of Cartography, GIS and Remote Sensing at the University of Göttingen. The contour lines were interpolated to a 30 m spatial resolution digital elevation model (DEM) by the ArcInfo topogrid command integrating mountain peaks and the hydrological network, digitized on topographic maps (HUTCHINSON 1988). Aspect, slope (in degrees) and hillshade were derived from the DEM. Slope is related to the hydrologic conditions, potential soil moisture and soil development (MOORE et al. 1991).

The hillshade was only used for reference of the relief, but not for analysis. All of the datasets were projected to UTM coordinates (Zone 19N, WGS84). To account for the different precipitation regime along the north-west and south-east facing slopes of the Cordillera Central one binary variable was calculated from aspect (north-east: 315-135° and south-west 135-315°). Furthermore aspect was transferred to two non-correlated linear variables representing north-/southness (cos (radian)) and east-/westness (sin (radian)). Aspect is related to the radiation balance and potential evapotranspiration of an area (MOORE et al. 1991).

As soil moisture is one of the most important determinants of vegetation composition (KOPECKÝ & ČÍŽKOVÁ 2010; DIEKMANN 2003), the SAGA wetness index (SWI) was selected as a proxy. SWI is similar to the topographic wetness index (TWI), but works with a modified catchment area so that the grid cells in valley floors are assigned a more realistic, higher potential wetness (BÖHNER et al. 2002).

Another important factor for biological processes is incoming solar radiation. It was calculated here from the DEM as the mean for the 12 months of 2003 (FU & RICH 2002).

The climatic regime was assessed by Worldclim data (HIJMANS et al. 2005) as high resolution meteorological data in continuous grids were not available in the Dominican Republic. The following climatic variables were downloaded from the Worldclim internet page (http://www.worldclim.org): annual mean temperature, mean diurnal temperature range (mean of monthly (max temp – min temp), temperature seasonality (standard deviation *100), annual precipitation, precipitation of wettest and driest month. As the three temperature variables were highly correlated (Pearson, all $r > 0.8$, $p<0.001$) and the three precipitation parameters also (Pearson, all $r > 0.9$, $p<0.001$), just annual mean temperature and annual precipitation were selected for further processing. To understand the effect of the trade wind inversion in the Worldclim precipitation model, it was plotted against the DEM (see Discussion of results).

All datasets were masked with the DEM to the extent of the study area. Analyses were conducted at two spatial resolutions of 60 m x 60 m and 30 m x 30 m. As the results were similar the results for the 30 m x 30 m spatial resolution is presented here.

Processing was done with ERDAS Imagine 9.2 (ERDAS Inc., Atlanta, USA), SAGA-GIS 2.0 (SAGA User Group Association, Hamburg, Germany) and ArcGIS 9.3 (ESRI Inc., Redlands, USA).

IV.2.3 Analysis of the data

The strategy “first classification, then modeling” was applied for data analysis (FERRIER et al. 2002). First the botanical data were classified with the help of ordination techniques, then the identified vegetation types were predicted to the national park (FERRIER et al. 2002). Predictive vegetation modeling – other than the more frequently applied predictive species modeling - seeks to explain the geographic distribution of an entire vegetation or community type in response to meaningful environmental variables (FRANKLIN 1995). The methodology has been accomplished for a variety of ecosystems in and outside the tropics (DAVIS & GOETZ 1990; FERRIER & GUISAN 2006) and for past, present and future climates (HILBERT & OSTENDORF 2001).

IV.2.3.1 Statistical analysis of floristic and ecological data

The floristic composition of the plots was analyzed by ordination techniques. Ordination reduces the dimensionality of species plot data by arranging them along a few ordination axes (MCCUNE & GRACE 2002). Floristic similar sites are positioned close to each other in the ordination space and can be interpreted as the same vegetation type. Here Detrended Correspondence Analysis (DCA), an ordination technique based on reciprocal averaging, was applied to analyze the principal tree community assemblages (HILL & GAUCH 1980). This multivariate data analysis technique was chosen as the calculated length of gradient of the analyzed data (here 5.055) required a unimodal model (MCCUNE & GRACE 2002). With four DCA-units, a total species turnover is inherent in the dataset. Down-weighting to rare species was applied as rare species can have disproportionate influences on the analysis results.

Prior to DCA, percentage canopy cover values of the third level (tree height > 20 m) was summed to the percentage canopy cover values of the second level (tree height 5-20 m) to carry out the analysis just on two height levels. Percentage canopy cover values of all species were arcsine square root transformed and the metric environmental factor values were standardized (MCCUNE & MEFFORD 2006). Ordination was carried out a.) with all plots and b.) without the secondary vegetation plots as the aim of the study was to explain and predict the natural mountain forest types of Armando Bermúdez National Park. For the ordination with all plots (a.)) woody species richness of the secondary and the natural broadleaf forest plots were compared by a two-sided t-test to analyze the effects of human impact on species richness. For the ordination without the secondary plots (b.)) Pearson’s product moment correlation coefficients were calculated between the scores of the first DCA axis and the metric environmental factors to identify their explanatory potential for the different floristic compositions in the ordination space. Spearmans-Rho coefficient was computed to quantify correlation between the scores of the first DCA axis and the categorical environmental factors. Relationships between the environmental factors altitude and temperature, precipitation and pH were determined following Pearson. Ordination helped to reconfirm the field impression about the forest types and they could be visualized in the DCA.

For each mountain forest type indicator species values (IV) were extracted by subsequent k-means clustering (DUFRÊNE & LEGENDRE 1997). Indicator species add an ecological meaning to the plots grouped by ordination. Following LEGENDRE & LEGENDRE (1998) just the species that are mainly found in a single vegetation type and that are present in most of the plots belonging to that vegetation type are considered. The indicator value was calculated on basis of the occurrence and percentage canopy coverage of each species in the different vegetation types. The selection of the most characteristic species was made by setting thresholds for the indicator values (> 30) and the p-values (< 0.05).

Differences in vegetation structure (here as: total area covered by vegetation, area covered by herbs and vegetation-free area) between the forest types were assessed by t-test.

Ordination and statistical analysis were performed with PC-ORD 5.10 (MJM Software, Gleneden Beach, USA), R 2.11.0 (R Foundation of Statistical Computing, Vienna, Austria) and IBM SPSS Statistics 19.0 (IBM Corp., Armonk, USA).

IV.2.3.2 Ecological niche modeling for predictive forest type mapping

The results obtained by ordination and gradient analysis were used as input data to predict the spatial distribution of the mountain forest types in Armando Bermúdez National Park. Predictive vegetation modeling aims to predict "…the distribution of vegetation across a landscape based on the relationship between the spatial distribution of vegetation and certain environmental variables" (MILLER & FRANKLIN 2002). Remotely derived environmental predictors and the applications and tools of GIS have gained considerable importance in vegetation modeling during the last decades (DAVIS & GOETZ 1990; FERRIER & GUISAN 2006). Predictive vegetation modeling has been conducted for a variety of ecosystems (for a review see FRANKLIN 1995; MILLER & FRANKLIN 2002). In mountainous areas BROWN (1994) and CAIRNS (2001) predicted vegetation types in Glacier National Park using a combination of different statistical models. As far as we know predictive vegetation modeling has only rarely been applied to tropical mountain forests at local scale. Predictions for the distribution of cloud forests have been based on altitude (CAMPANELLA 1995), forest cover data (ALDRICH et al. 1997; UNITED NATIONS ENVIRONMENT PROGRAMME-WORLD CONSERVATION MONITORING CENTRE 2004) and variables such as land cover/land use and hydro-climate (MULLIGAN 2010; LAWTON et al. 2010) at regional and pan-tropical scale.

The predictive models of the spatial distribution of the mountain forest types were built on the principal environmental gradients determined by correlation analysis between the scores of the first ordination axis and the environmental factors (Chapter IV.3.1). Different combinations and numbers of environmental parameters as predictors were tested. The plots of each mountain forest type entered as occurrence data. The ecological niche modeling (ENM) program Maxent, version 3.3.3, was used for prediction (PHILLIPS & DUDIK 2008, AT&T Labs-Research, Princeton University).

Maxent

Maxent is a general-purpose machine learning method for modeling species distributions (SDs) from presence-only-species records. Species distribution models (SDMs) explore the relationship between known occurrence species records (or records of assemblages of species) at sites and the environmental conditions of those sites. This relationship is used to establish a model of the species' environmental requirements and to predict its distribution across the geographical and environmental space (PHILLIPS & DUDIK 2008). SDMs are being applied worldwide in biogeography, conservation and reserve planning, ecology, invasive-species management, evolution, epidemiology and others (ELITH et al. 2011; PHILLIPS et al. 2006). The results of SDMs or ecological niche models (ENM) represent an approximation of Hutchinson's realized-niche of the species (HUTCHINSON 1957; GUISAN & THUILLER 2005).

Maxent requires georeferenced occurrence points as the pair of latitude and longitude where the species was observed (Figure IV.2). All of the environmental data (called here: covariates) of the study area have to be provided as georeferenced grid data (Figure IV.2). The basic functions and transformations of the data are termed features. Currently six feature classes are implemented in Maxent.

Maxent seeks to estimate a target probability distribution (Figure IV.2) by finding the probability distribution of maximum entropy. This is the one which is closest to uniform and less constrained. The target probability distribution of maximum entropy is subject to the constraint that each feature must have the same expected value under the estimated probability distribution as its empirical average. Such a target probability distribution matches with everything that is known and avoids assumptions about what is not known (PHILLIPS et al. 2006.)

The numerical results of the Maxent outputs are to be interpreted as the environmental suitability of a grid cell for a species derived as a function of the given environmental variables (PHILLIPS et al. 2006). Values range between 0 and 1. High values represent a high suitability of adequate environmental conditions for the species at the grid cell, low values represent a low suitability of adequate environmental conditions at the grid cell (Figure IV.2) (PHILLIPS et al. 2006; PHILLIPS & DUDIK 2008).

Maxent has been proven to be robust towards low occurrence record numbers in comparative studies (ELITH et al. 2006; PHILLIPS et al. 2006; HERNÁNDEZ et al. 2006; WISZ et al. 2008).

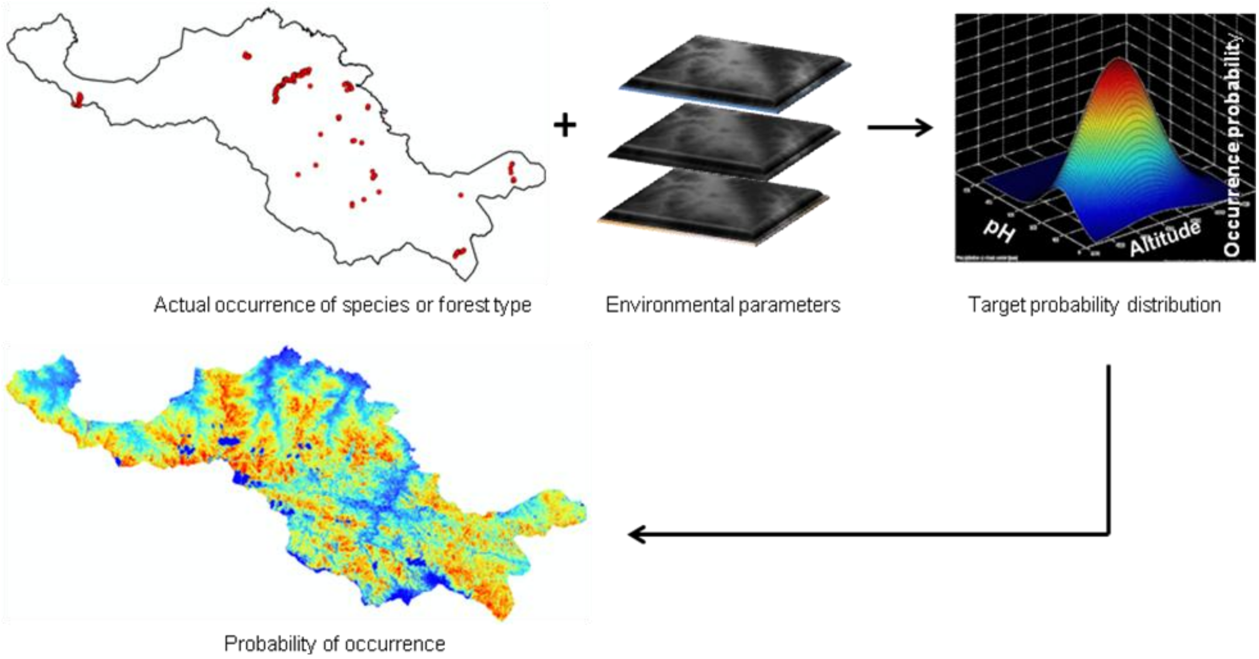


Figure IV.2. Workflow of Maxent

Four runs were performed with bootstrapping for each modeled forest type to assess uncertainty (Young et al. 2009). The simulations of Maxent were evaluated by analyzing the area (AUC) under the receiver operating characteristics (ROC). The ROC curve is a graph with the true positive fraction (as sensitivity on the y-axis) and false positive fraction (as 1-specificity on the x-axis) for all possible thresholds on the x-axis (Fielding & Bell 1997). If the ROC curve maximizes sensitivity for low values of the false positive fraction, the model is considered suitable and is quantified by the AUC-value (Hernández et al. 2006). The AUC is a threshold independent quantitative measure of the overall accuracy of the model (DeLeo 1993) and ranges usually between 0.5 and 1.0. A value of 0.5 implies that the scores for the two groups (true positives and false positives) do not differ (=random). A score of 1.0 indicates no overlap in the distribution of the group scores (=perfect differentiation). Values smaller than 0.5 represent a performance worse than random. The testing if the model fits to the data is also called qualitative assessment (Segurado & Aráujo 2004). Contributions of the environmental factors to each modeled output were discussed. Binary maps of predicted presence and absence were generated by applying the logistic equal test sensitivity and specificity threshold to the average dataset of each forest type (Liu et al. 2005). The spatial overlap between the modeled predictions for the forest types was determined. Furthermore the results of the interpretation of the aerial photograph mosaic (Chapter III) were compared to the Maxent prediction. This represented a quantitative assessment method (Segurado & Aráujo 2004).

IV.3 RESULTS

IV.3.1 Mountain forest types and environmental gradients

Ordination results of DCA with all 137 sampled plots are displayed in Figure IV.3. The first axis of the ordination explained 36.7% of the total variance while the second axis accounted for 15.6%. The second axis separated secondary broadleaf forests from natural forests. Spearman-Rho correlation coefficient between the axis scores of the second axis and the variable 'Impact' (by agriculture or hurricanes) was 0.525 (N=137, p<0.01, two-sided test).

12 of the sampled secondary broadleaf forest plots are located along the rivers Los Guanos and Los Tablones close to the village of La Ciénaga in the eastern part of the national park (Figure IV.1). Here the natural vegetation had been cleared prior to the establishment of the protected area in 1956. Coffee was planted then and animals grazed along the river shores.

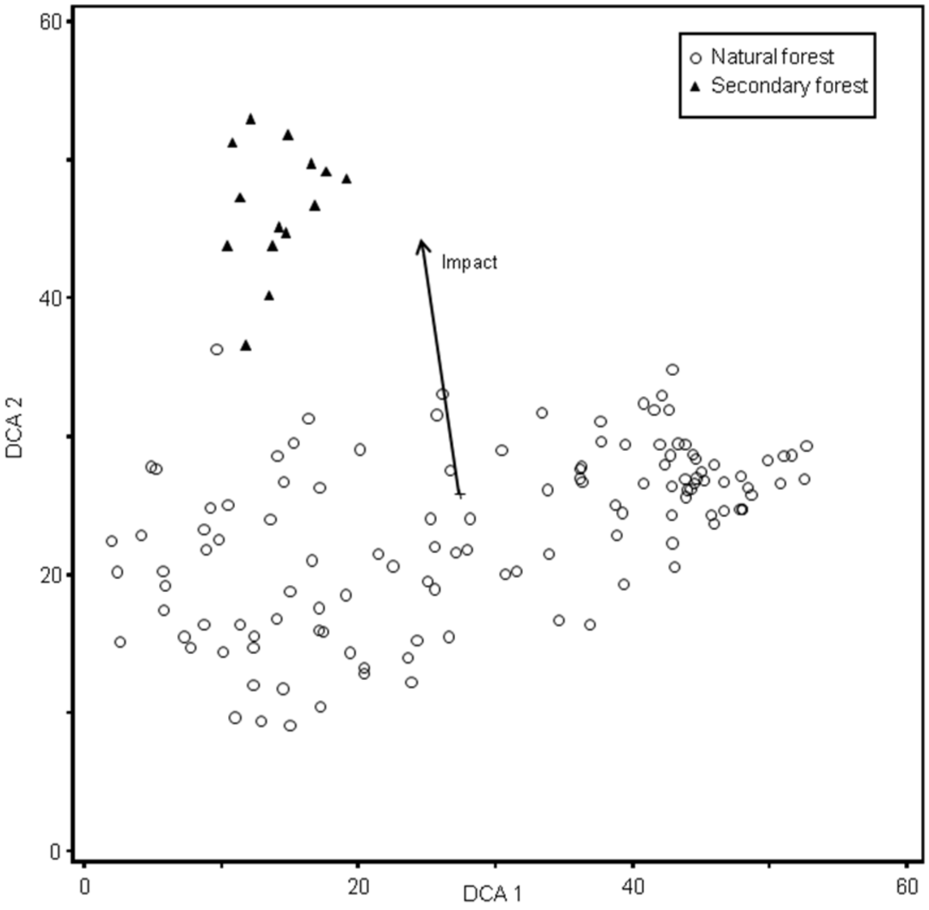


FIGURE IV.3. Ordination-diagram of the natural forests and secondary broadleaf forests of Armando Bermúdez National Park
The ordination was based on 124 woody species in 137 plots. Length of first axis: 4.989, explained variance of first axis: 36.7%, explained variance of second axis: 15.6%, explained variance of third axis: 8.9%.

Furthermore two broadleaf forest plots with high DCA 2 scores had been affected by hurricane George in 1998. Treefall gaps were still visible at these sites. Mean woody species richness of the 14 secondary broadleaf forest plots was significantly lower (11.38 species,± 0.657) compared to the mean woody species richness of the natural broadleaf forests (20.35 species, ± 0.895) (t=6.48, p<0.001, df=48, two-sided test).

The ordination results of the Detrended Correspondence Analysis performed on 121 natural vegetation plots are represented in Figure IV.4. Altogether 123 woody species of 85 genera and 53 families had been recorded. The species-richest genera recorded during field work on the plots in Armando Bermúdez National Park were *Ocotea*, *Miconia*, *Ilex* and *Tabebuia*.

Four mountain forest types were distinguished with the help of ordination: Humid broadleaf/gallery forest (35 plots), cloud forest (24 plots), mixed forest (14 plots) and pine forest (48 plots).

The first ordination axis explained 44.4% of the total variance in the data and was interpreted as an altitudinal gradient. The second and third ordination axis did not have much explanatory potential. Altitude explained 48.3% of the variance inherent in the data along the first axis. Directly related to altitude are annual mean temperature and annual mean precipitation. Altitude correlated highly negative with annual mean temperature (Pearson, r=-0.983, p<0.001) and highly positive with annual mean precipitation (Pearson, r=0.913, p<0.001). The correlations between altitude, annual mean temperature and annual mean precipitation and the first axis were all greater than 0.5 (Figure IV.4).

The NDVI, the measure of photosynthetic activity and biomass production, correlated highly negative with the first axis (Pearson, r=-0.819, p<0.001) and so did soil pH (Figure IV.4). The correlation between soil pH and altitude was significant (Pearson, r=-0.462, p<0.001). The mean pH-values were 5.34 in pine forests, 6.3 in humid broadleaf/gallery forests and 6.07 in cloud forests. *Pinus occidentalis* tolerated the widest pH-range (4.51 to 7.16).

Moderate positive correlations with the first axis showed the factors Distance to rivers, Herb cover, No vegetation cover (Figure IV.4) and the binary variable Fire (Spearman-Rho, r=0.496, p<0.001). On 2/3 of the pine forest plots fires scars were recorded at the trunks or branches of *Pinus occidentalis*.

Moderate negative correlations were the result between the first axis of ordination and Total vegetation cover and the SWI (Figure IV.4). Total vegetation cover per plot was higher in humid broadleaf/gallery forests and cloud forests than in mixed and pine forest. There were neither significant correlations between one of the environmental factors and the scores of the second nor the scores of the third axis of ordination.

Typical for the pine forests were high elevation values, low annual mean temperature, low NDVI-values and high annual mean precipitation (Table IV.1).

Humid broadleaf/gallery forest had low to medium elevation values, the highest annual mean temperature of all four forest types, high NDVI-values and high annual mean precipitation (Table IV.1). Humid broadleaf/gallery forests gradually passed at medium elevations into cloud forests.

The cloud forest were characterized by medium to high elevation values, average annual mean temperature, high NDVI-values and high annual mean precipitation (Table IV.1). Cloud forest plots had a high variability in the floristic composition and extended along the second axis.

The mixed forests were heterogeneous and contained floristic elements of all the other forest types, depending on the site where they occurred (Figure IV.4). They occurred in low to medium elevations with high values of annual mean temperature and precipitation and medium NDVI-values. Soil-pH was lower in pine and mixed forests than in cloud and humid broadleaf forests.

Pine forests had the widest altitudinal range from the border of the national park to the highest peaks (Table IV.1). Above 2,000 m a.s.l. pine forests were the only forest association in Armando Bermúdez National Park according to the sampled data. Below 2,000 m a.s.l. mainly cloud forests, humid broadleaf/gallery forests and mixed forests determined the vegetation pattern according to our data (Table IV.1).

IV.3.2 Characteristic species and vegetation cover

The first three characteristic woody species with the highest indicator values and lowest p-values for the 5-20 m tree height level are listed in Appendix IV.C (for all significant species): *Alchornea latifolia, Beilschmiedia pendula* and *Guarea guidonea* were the most characteristic tree species in the humid broadleaf/gallery forests (Photo IV.1). In 33% of all humid broadleaf/gallery forest plots these three species accounted for over 20% percentage canopy cover.

In the cloud forest (Photo IV.2) *Cyrilla racemiflora*, *Clusia clusioides* and *Brunellia comocladifolia* were determined the most characteristic species. *Cyrilla racemiflora* and *Brunellia comocladifolia* accounted for over 40% percentage canopy cover in 33% of all plots labeled cloud forest. Together with *Clusia clusioides* percentage canopy cover exceeded 50% in 35% of the cloud forest plots.

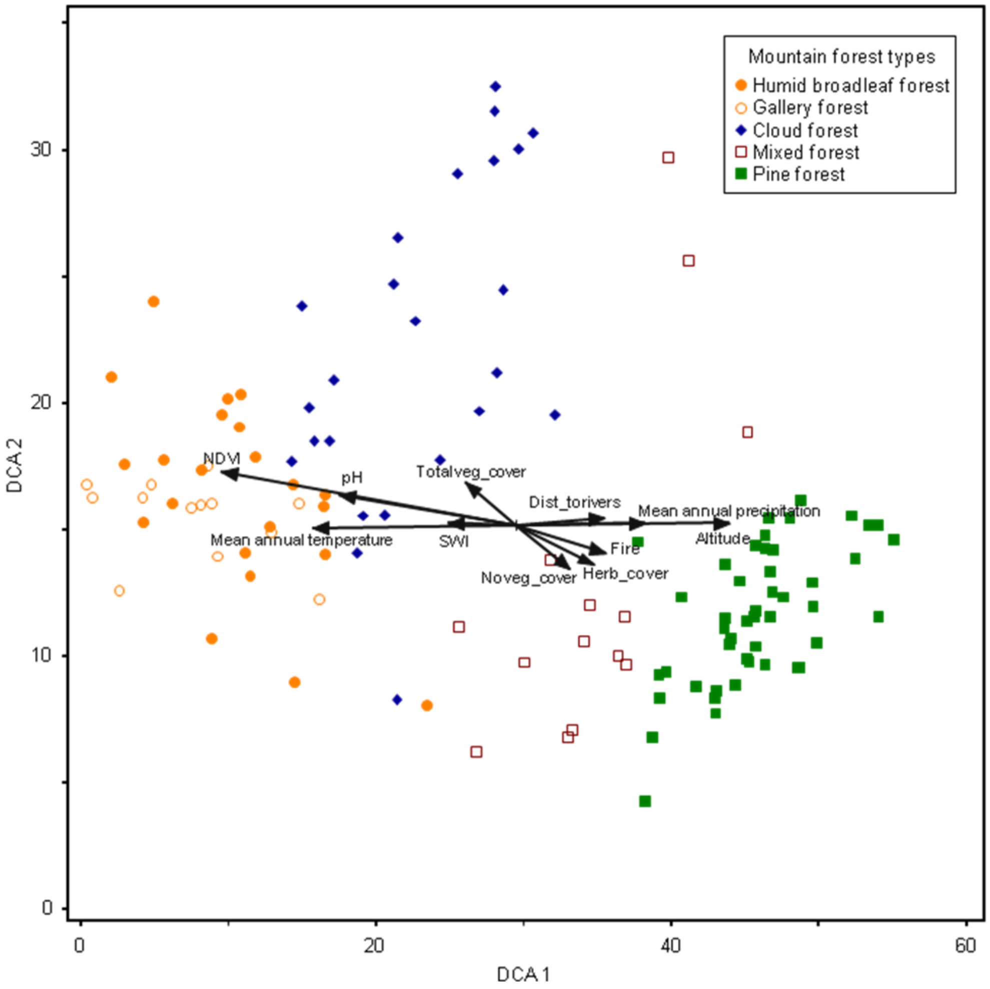


FIGURE IV.4. Ordination-diagram of the natural mountain forest types of Armando Bermúdez National Park

The ordination was based on 121 woody species in 121 plots, length of first axis: 5.055, explained variance of first axis: 44.4%, explained variance of second axis: 7.9%, explained variance of third axis: 4.2%. Correlation of environmental variables with the axes are shown for those with r>0.34 or r<-0.34; 1. Axis: NDVI, r=-0.819; Altitude, r=0.676; Annual mean temperature, r=-0.659; pH, r=-0.636; Annual mean precipitation, r=0.521; Distance to river, r=0.430; Herb coverage, r=0.428; Fire, r=0.496; SWI, r=-0.393; No vegetation cover, r=0.355 and Total vegetation cover, r=-0.353 (for all correlation analysis: N=121 and p<0.001). The values of these environmental parameters are listed in Appendix IV.B.

TABLE IV.1. Minimum, mean (bold letters) and maximum values of significant environmental factors determined by ordination for mountain forest differentiation (r>0.50 and r<-0.50)

	Altitude	**Annual mean Temperature**	**Annual mean precipitation**	**NDVI**	**pH**
Mean					
Humid broadleaf/ Gallery forest	688-**979**-1,502	16.4-**20.2**-23.0	1,246-**1,318**-1,412	0.30-**0.38**-0.46	4.93-**6.30**-7.26
Cloud forest	1,157-**1,527**-1,908	14.2-**16.5**-19.3	1,335-**1,436**-1,563	0.23-**0.32**-0.39	5.02-**6.07**-7.46
Mixed forest	748-**1,272**-2,052	12.3-**18.0**-22.6	1,248-**1,371**-1,678	0.15-**0.28**-0.37	5.20-**5.93**-6.70
Pine forest	782-**1,835**-3,062	7.2-**14.5**-22.6	1,230-**1,556**-2,164	0.04-**0.19**-0.27	4.51-**5.34**-7.16

Pinus occcidentalis was the only characteristic tree species listed for pine forest (Photo IV.3). The percentage canopy cover of *Pinus occidentalis* exceeded 45% in all plots labeled pine forest (analysis of primary table). No characteristic species were identified for the mixed forests (Photo IV.4) for the respective height level. The percentage canopy cover of *Pinus occidentalis* in all mixed forests was between 20% and 40% (analysis of primary table). Where percentage canopy cover of *Pinus occidentalis* was less than 20%, the plots were either classified humid broadleaf/gallery or cloud forests (analysis of primary table). In both forest types scattered mature individuals of *Pinus occidentalis* were recorded, but no saplings or treelets of *Pinus occidentalis* were observed.

The vegetation structure regarding the total area covered by vegetation, the herb cover and vegetation-free area (all in percent) differed significantly between pine forests and the other three forest types (Table IV.2). In the pine forests the highest mean percentage of vegetation-free area was recorded and consequently the lowest mean percentage of the total area covered by vegetation. The mean herb cover was significantly higher in pine forest than in the other three forest types. The most abundant grass in pine forests was the endemic bunch grass *Danthonia domingensis*.

TABLE IV.2. Mean total area covered by vegetation, area covered by herbs and vegetation-free area for pine forest and the other three forest types

Coverage	**Mean area covered (%) of** **Pine forest**	 **Other forests**	**t-value**	**df**	**p-value**
Totalcov	83.04±1.65	90.38±0.932	-4.160	119	0.000
Herbbcov	32.91±3.33	17.27±2.15	4.134	119	0.000
Noveg	16.97±1.65	9.58±0.93	4.180	119	0.000

PHOTO IV.1. *Beilschmiedia pendula*
(Humid broadleaf forest, near La Diferencia, 1,236 m a.s.l.)

PHOTO IV.2. *Cyrilla racemiflora*, *Clusia clusioides* and Bromeliaceae
(Cloud forest, Los Platicos, 1,928 m a.s.l.)

PHOTO IV.3. *Pinus occidentalis*
(Pine forest, Loma La Pelona, 2,450 m a.s.l.)

PHOTO IV.4. *Pinus occidentalis* and *Clusia rosea*
(Mixed forest, El Piquito, 883 m a.s.l.)

IV.3.3 Forest type prediction

The three environmental factors altitude, annual mean temperature and NDVI built the final ecological niche models for 37 samples of humid broadleaf/gallery forest, 34 samples of pine forest, 19 samples of cloud forest and 17 samples of mixed forest. Models with just one or two environmental parameters were also tested, but showed lower AUC-values and therefore are not presented. The AUC-values and ranges of the average datasets of each forest type based on the testing data are displayed in Table IV.3. AUC-values were highest for the two forest types with the highest sample sizes, humid broadleaf/gallery forest and pine forest. The best AUC-value was achieved for the pine forest prediction (0.879). The lowest AUC-value was calculated for the prediction of cloud forests (0.744).

TABLE IV.3. Mean and ranges for test AUC (averages of four replicate run types) and area predicted present and absent (km^2) for all forest types

	Average test AUC	**Range test AUC**	**Area predicted present* (km^2)**	**Area predicted absent* (km^2)**
Humid broadleaf/ Gallery forest	0.839	0.794-0.911	162	628
Cloud forest	0.744	0.707-0.798	221	569
Mixed forest	0.741	0.705-0.783	100	690
Pine forest	0.879	0.804-0.913	133	657

*Equal test sensitivity and specificity threshold applied

Figure IV.5 (a-d) reflects the response of each forest type to the environmental predictors used in the model. In humid broadleaf/gallery forests predicted suitability was small at low annual mean temperatures, but increased steadily from 16˚C on (Figure IV.5a). Regarding altitude predicted suitability decreased substantially between 600 and 1,500 m a.s.l.. Annual mean temperature and altitude contributed most to the model (Table IV.4). The geographic distribution of humid broadleaf/gallery forest is shown in Figure IV.6a. It extended over an area of 162 km^2 from the lower to medium altitudes of Armando Bermúdez National Park in relatively warm areas along the river valleys at the northern border south of the villages Loma El Copey, Los Ramones, La Diferencia and Mata Grande. The average annual mean temperature of 20.2˚C found for this forest type with the help of ordination of the plots is displayed as an isotherm in Figure IV.6a. The modeled average annual mean isotherm was 20.5˚C and the modeled mean elevation was 958 m a.s.l. (analysis in ArcGIS 9.3, Table IV.5). Small spots of high suitability for occurrence were modeled in the eastern part close to the border of the national park near La Ciénaga and Loma de los Ríos.

For cloud forest the response to annual mean temperature consisted in a decreasing suitability with increasing temperatures (Figure IV.5b). In contrast to this increasing altitudes produced higher predicted suitabilities for this forest type. For NDVI predictive suitability increased steadily with increasing NDVI values from zero on. The predicted geographic distribution of the cloud forest after thresholding is displayed in Figure IV.6b. Altogether 221 km^2 were modeled present on mountain chains and slopes between 1,100 and 2,300 m a.s.l.. The mean annual isotherm of 16.5˚C calculated from the plots in ordination is displayed in Figure IV.6b. The modeled distribution resulted in an average annual isotherm of 15.8˚C and a mean elevation of 1,608 m a.s.l. (analysis in ArcGIS 9.3, Table IV.5).

The model for mixed forest was built on altitude and NDVI (Table IV.4). With increasing altitude predicted suitability decreased. The response to NDVI resulted in an optimum response curve. High suitabilities were predicted for low NDVI values. Towards higher NDVI values the curve falls and ends up in low suitabilities (Figure IV.5c). Higher annual mean temperatures led to an increase in predicted suitability. The predicted geographic distribution (100 km^2) of the mixed forests along the northern border of the national park covered areas of low to mean elevation, largely consistent with the modeled pattern for humid broadleaf/gallery forests (Figure IV.6c). Along the valleys of the Bao River, La Guácara River and de los Negros River the areas predicted “present” coincided with the areas predicted “present” for pine forests.

Overall main contributor to the pine forest model was NDVI with 96.9% (Table IV.4). NDVI had also played an important role in the ordination diagram for explaining the position of the pine forest plots (Figure IV.4). The maximum response curve given as the result for pine forest to NDVI had its peak for NDVI values around zero, decreasing then towards very low and medium NDVI values (Figure IV.5d). For high NDVI values the suitability was predicted as zero. Along the altitudinal gradient predicted suitability increased and decreased with warmer annual mean temperatures.

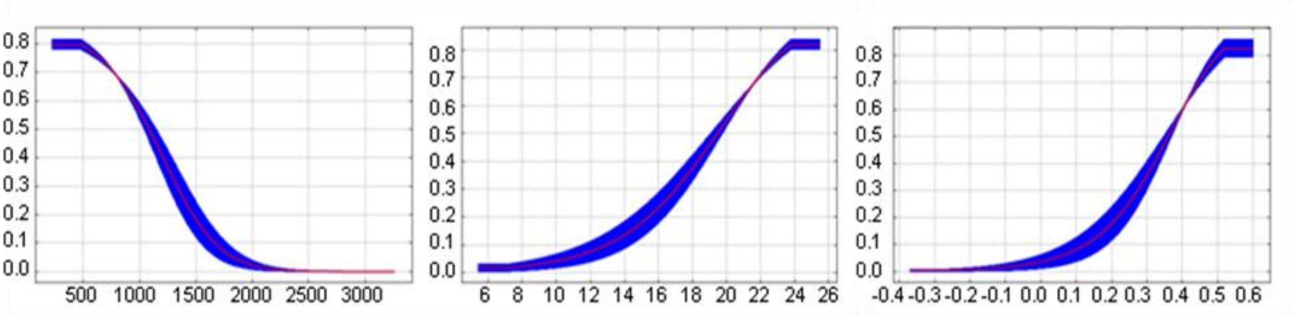
The annual mean isotherm of 14.5˚C of the ordinated pine plots is displayed in Figure IV.6d. Maxent returned an average annual mean temperature of 13.9˚C and a mean elevation of 1,906 m a.s.l. (analysis in ArcGIS 9.3, Table IV.5).

TABLE IV.4. Relative contributions of the environmental variables to the Maxent model

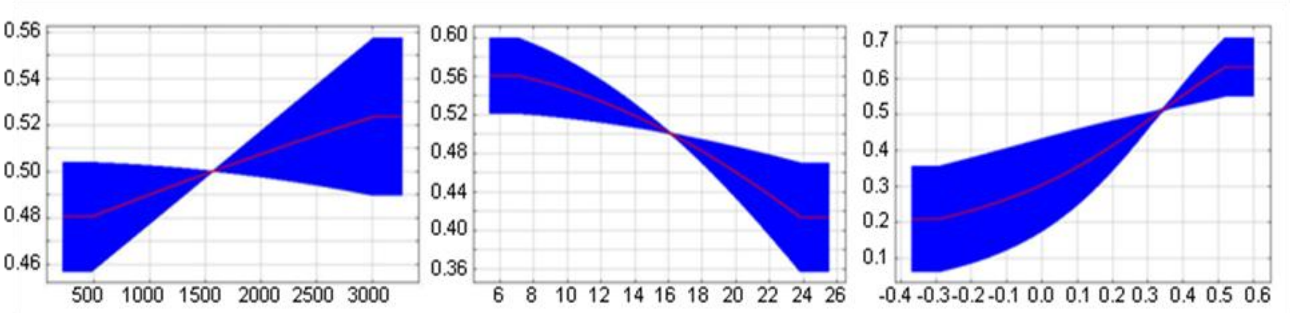
	Altitude	**Annual mean temperature**	**NDVI**
Humid broadleaf/Gallery forest	69.0	26.2	4.8
Cloud forest	49.4	5.5	45.0
Mixed forest	60.0	0.4	39.7
Pine forest	0.3	2.8	96.9

PS

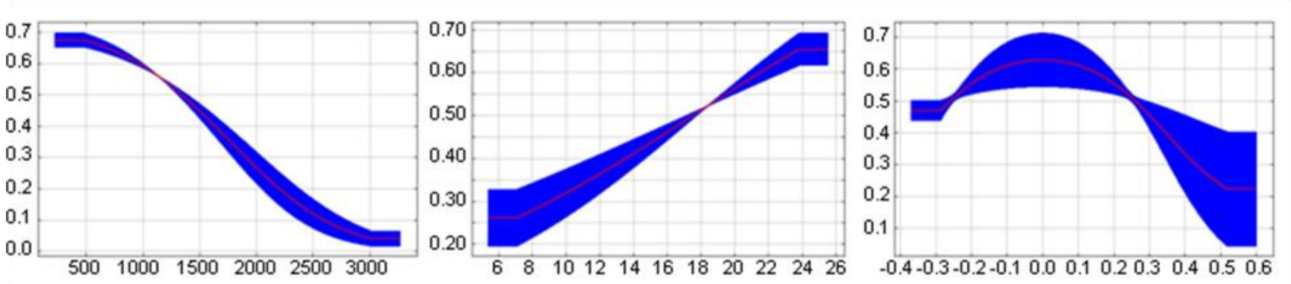
a.) Humid broadleaf/gallery forest



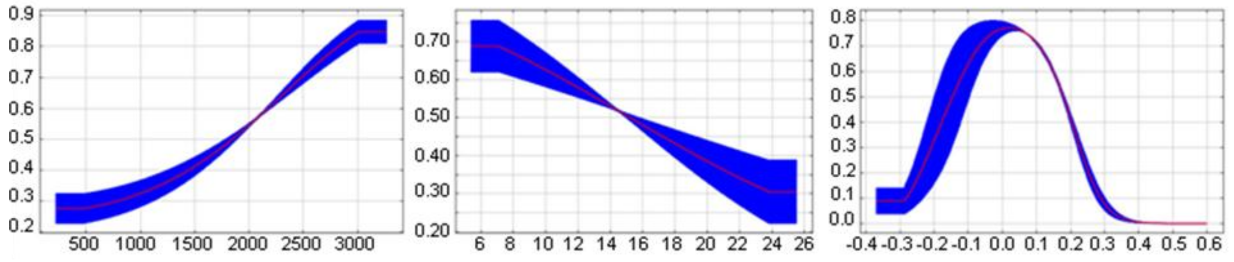
b.) Cloud forest



c.) Mixed forest



d.) Pine forest



Altitude **Annual Mean Temperature** **NDVI**

FIGURE IV.5. Response curves for forest types (a-d) to each single environmental variable used in the prediction
The curves reflect the dependence of the predicted suitability on the selected variable per forest type (Maxent html file). The red curve represents the mean response of the 4 replicate runs and the blue curve the mean +/- one standard deviation. The first curve in each row shows the response of the forest type to altitude, the second to annual mean temperature and the third to NDVI.
PS: Probability of Suitability of conditions (plottet on the y-axis of each diagram)

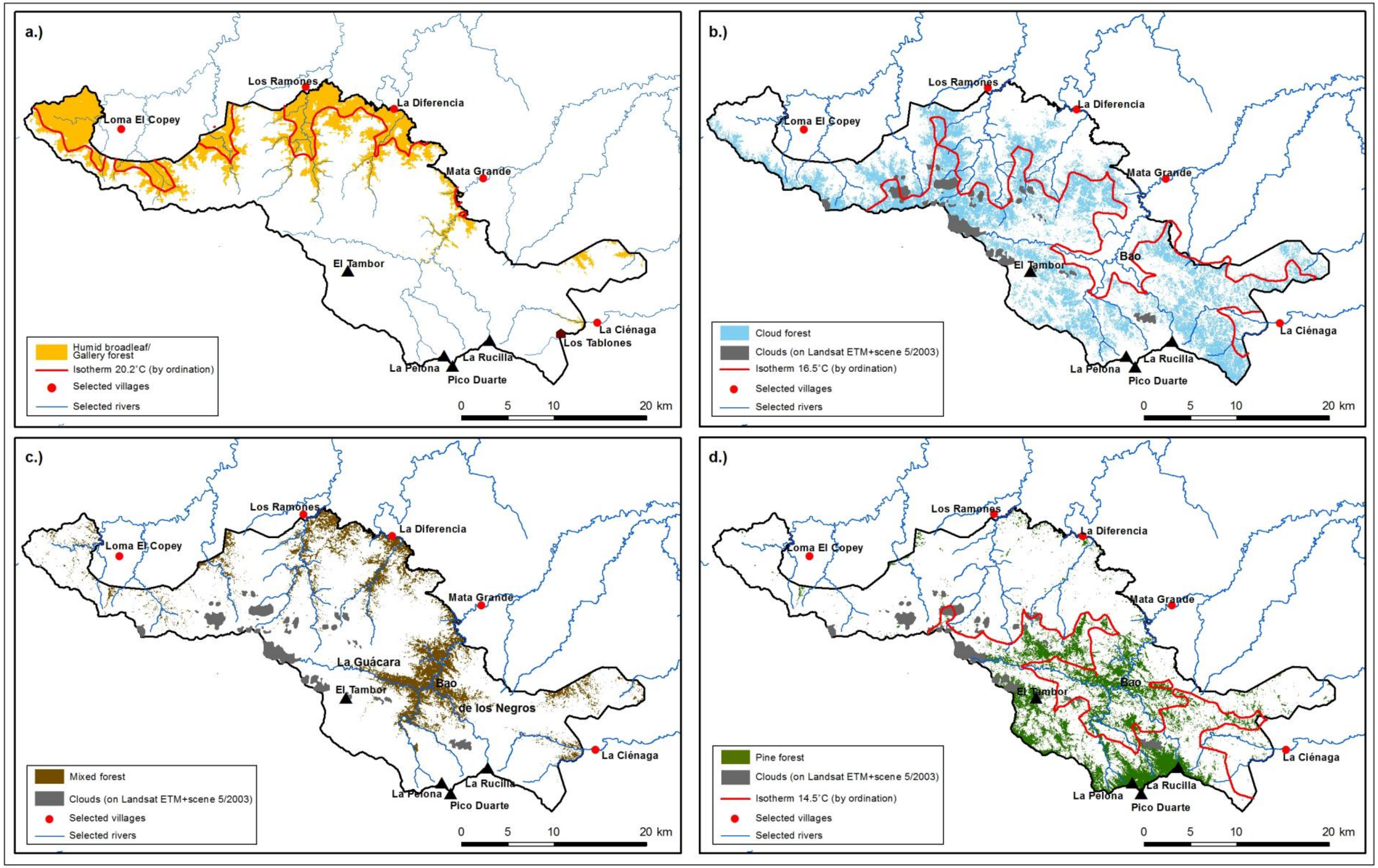


FIGURE IV.6. Modeled potential distribution of humid broadleaf/gallery, cloud, mixed and pine forests (Source: Maxent models; Annual mean temperature value as isotherms from Table IV.1; Boundaries of ABNP from Law 64-00; Villages, rivers, peaks from topographic maps 1:50,000, ICM 1983/1984 and field work)

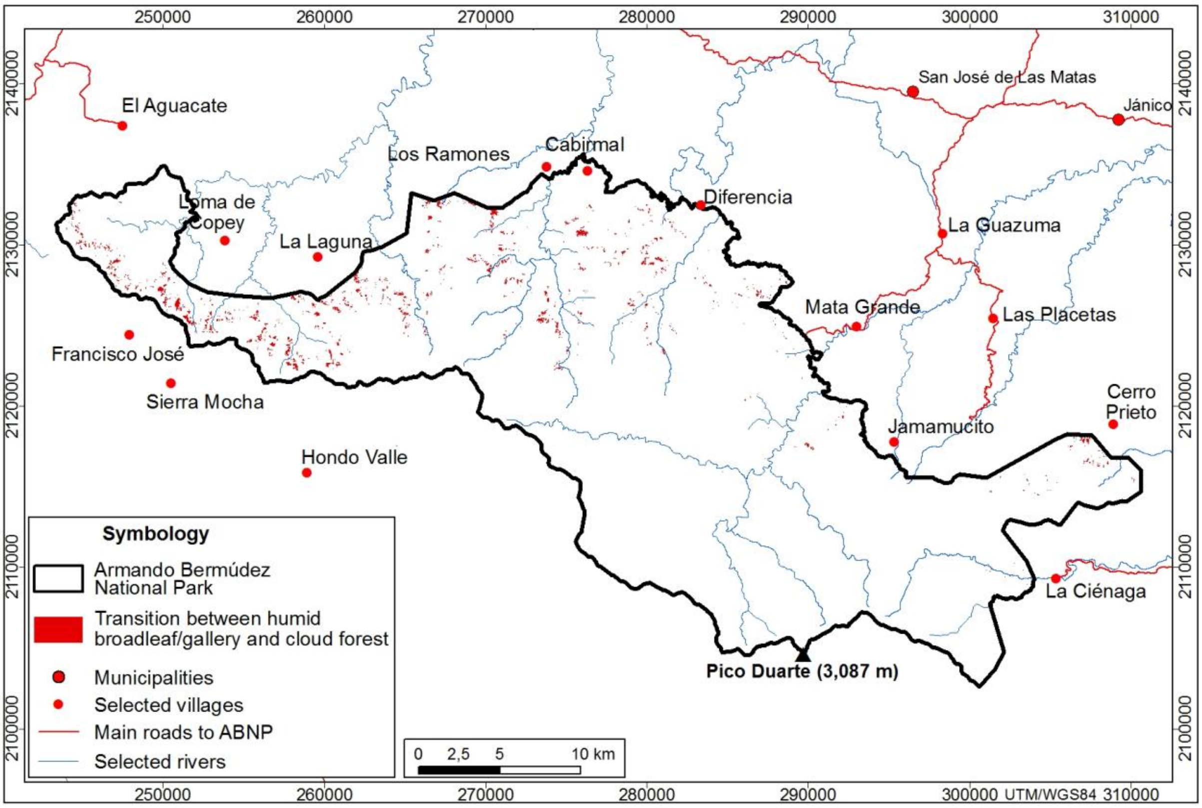


FIGURE IV.7. Transition zone between modeled potential distribution of humid broadleaf/gallery and cloud forests (Source: Transition zone from GIS-analysis; Boundaries of ABNP from Law 64-00; Villages, roads, rivers from topographic maps 1:50,000, ICM 1983/1984 and field work)

The geographical pattern included areas in the center and southern parts of Armando Bermúdez National Park with low NDVI values between 800 and 3,087 m a.s.l.. The total predicted area for pine forest was of 133 km^2. Absence was predicted for a triangle between Bao River, Loma El Tambor and Loma La Pelona (Figure IV.6d).

The transition between humid broadleaf/gallery forest and cloud forests is presented in Figure IV.7. The areas of high suitability for forest types were predicted at an elevation of 1,100 and 1,200 m a.s.l.. Between cloud and pine forests no area was predicted in common.

IV.4 DISCUSSION OF RESULTS

DCA ordination techniques were used in this study to analyze vegetation samples of the mountainous forests of Armando Bermúdez National Park. The objective was to determine the natural forest types and identify the main environmental factors responsible for their spatial distribution. Characteristic species were extracted for each forest type. Furthermore a predictive model was developed to map the spatial distribution of the different natural mountain forest types to the entire area of the national park.

IV.4.1 Environmental gradients, mountain forest types and characteristic species

Gradients

Elevation together with annual mean temperature, annual mean precipitation and soil pH were determined as the principal environmental factors explaining the occurrence of the different mountain forest types in Armando Bermúdez National Park. All factors correlated significantly with the scores of the first axis of ordination: Altitude and annual mean precipitation showed high positive correlations and annual mean temperature high negative ones. The first axis was called the altitudinal gradient. Considering the high correlations between altitude and annual mean temperature and altitude and annual mean precipitation, the floristic changes along the altitudinal gradient can be explained by a varying temperature and precipitation regime. Altitude increased by a factor of 4.45 over the sampled plots, annual precipitation by a factor of 1.7 and annual mean temperature decreased by a factor of 3.2. The identification of the altitudinal gradient together with temperature and precipitation as proxies to explain differences in woody species composition in tropical mountain forests was consistent with the results of previous studies realized in tropical mountain forests (GENTRY 1988; HAGER & ZANONI 1993; LIEBERMAN et al. 1996; SCHRUMPF et al. 2001; SHERMAN et al. 2005; HOMEIER 2008; HÄGER 2010). Altitudinal variation of tree species composition and vegetation structure is generally explained by nutrient limitations (TANNER et al. 1998; HOMEIER 2008; WILCKE et al. 2008), heterogeneous topographical effects (HOMEIER 2008), decreasing temperatures, reduced incoming radiation due to elevated cloud and fog cover (GRUBB 1977; HAGER & ZANONI 1993; GEROLD 2008) and an increase of humidity (BRUIJNZEEL 2001). Here neither the topographical factors slope and aspect, nor incoming solar radiation or soil moisture had explanatory potential for the determination of the floristic compositions of the sampled plots in the ordination diagram. It is assumed that these data were not differentiated enough to deliver explanatory results. Additional data on air humidity and soil nutrients and higher resolution data on air temperature, precipitation and soil humidity could contribute to improve the explanation of the vegetation patterns along the altitudinal gradient and the spatial predictions (KAPPAS 1999; WANGDA & OHSAWA 2010). Collection or generation of these data at the (high) spatial resolution needed is not trivial.

The vertical precipitation profile in the Cordillera Central is influenced by the north eastern trade winds and the trade wind inversion (TWI). Precipitation maxima occur below the base of the TWI which is considered to be at approximately 2,150 m a.s.l. (map for the Caribbean in SCHUBERT et al. 1995 according to tabular data of GUTNICK 1958). Above the TWI rainfall and humidity decrease (SCHUBERT et al. 1995). However, the Worldclim annual precipitation data model steadily increased with altitude (data not shown). Thus, the base of the TWI was not adequately represented in this model. Although there are no climate stations inside of Armando Bermúdez National Park, MAY (1997a) assumed that the annual mean precipitation must be between 1,500-1,800 mm around 3,087 m a.s.l. and between 2,100-2,400 m a.s.l at the base of the TWI. The Worldclim data model contained precipitation values of 2,150 mm at 3,000 m a.s.l. and 1,700 mm at the base of the TWI.

Soil pH-values correlated negatively with the first axis of ordination and with elevation (Pearson, $r=-0.460$, $p<0.001$). Up to 2,000 m a.s.l. pH-values decreased significantly (Pearson, $r=-0.533$, $p<0.001$). Our findings were consistent with the results of MAY (2007) in Armando Bermúdez National Park. In upper montane forests in the tropics soils are typically wet and close to saturation so that decomposition of organic matter is impaired and acidity increases (BRUIJNZEEL & PROCTOR 1995). WILCKE et al. (2008) found correlations between altitude, duration of water logging and acidity in montane forests in southern Ecuador.

Above 2,000 m a.s.l. the pH-values measured on the plots did not fallow a clear spatial pattern (Pearson, $r=0.376$, $p<0.001$) and ranged between 4.50 and 6.10. The changing precipitation pattern above the base of the TWI with drier conditions would suggest less acid soils and increasing pH-values. MAY hypothesized that fire could also be a reason for increased soil pH-values of the upper soil horizons at high elevations (pers. communication MAY 2011). The causes why partially also low pH-values were measured on the plots above the base of the TWI could not be assessed.

High correlations with the first ordination axis and with altitude were calculated for the NDVI. The index reflected the variation of photosynthetic activity and biomass production in the different forest types. The highest vegetation belt in the Cordillera Central is composed of subalpine pine forests. Here the lowest NDVI values were obtained. NDVI decreased with altitude by a factor of 3.28.

Mountain forest types and characteristic species

The four mountain forest types discriminated with the help of the ordination diagram are humid broadleaf/gallery forest, cloud forest, mixed forest and pine forest. SHERMAN et al. (2005) identified in the eastern part of the Cordillera Central secondary riparian, broadleaf, mixed, cloud and four different subtypes of pine forests using ordination techniques. Their main explanatory gradients (elevation, steepness, terrain shape index and pH-mineral) resulted from plot based observations and measurements.

Here gallery forests could not be distinguished floristically from the humid broadleaf forests. Consequently they were treated as one forest type. PEGUERO et al. (2007) stated that the floristic composition of gallery forests either resembles the floristic composition of humid broadleaf or cloud forests, depending on the altitudinal position in the water basin.

Two principal transitions in floristic composition were observed in this study along the altitudinal gradient: a.) the transitions between humid broadleaf/gallery forests and cloud forests, b.) the transition between cloud forests and pine forests.

The transition between humid broadleaf/gallery forest and cloud forests occurred between 1,150-1,500 m a.s.l. or 16-19˚C annual mean temperature (Table IV.1). Patches of cloud forests that occurred under suitable microclimatic conditions (e.g. in creeks and on wind exposed slopes) were observed within areas of general humid broadleaf cover. GRUBB & WHITMORE (1966) stated that the transition between lower to upper montane forests in Ecuador took place where cloud condensation became more persistent. We could not confirm this with hard data as there was no information on cloud formation frequency or on heights of cloud bases.

Species-rich families observed in the humid broadleaf/gallery forests were Myrtaceae and Lauraceae. Lauraceae was also listed by RICHTER (2008) as an important family in lower montane forests. *Ocotea*, *Miconia* and *Ilex* were the most species-rich genera in the here studied plot data of the mountain forests and also in the mountain forests of Costa Rica, Nicaragua and Mexico (GENTRY 1995).

Characteristic humid broadleaf/gallery forest species such as *Alchornea latifolia* have hygromorphic leaves appropriate to adapt to humid and shady environments with a high supply of water. Hygromorphic leaves are soft, have thin cuticles and epidermis (ELLENBERG & LEUSCHNER 2010). Stomata are inverted out of the epidermis to facilitate the transpiration and absorption of new minerals (ELLENBERG & LEUSCHNER 2010).

The second transition zone was the one between cloud and pine forests, located around 1,800-1,900 m a.s.l. (Table IV.1). This zone is not a gradual one like the first one described above, it is abrupt. Low annual mean temperature is one explanatory factor for the change of vegetation types at these altitudes (Figure IV.4) (BRUIJNZEEL 2001; JARVIS & MULLIGAN 2010). The annual mean temperature isotherm was 14.2˚C at 1,900 m a.s.l. in our data (Table IV.1). HAGER & ZANONI (1993) estimated that the annual mean temperature above 2,000 m a.s.l had to be lower than 12˚C. According to their opinion precipitation and humidity did not have a large effect on the occurrence of *Pinus occidentalis* (HAGER & ZANONI 1993). *Pinus occidentalis* occurred in the study area over a wide precipitation range on sites that received between 1,230-2,160 mm of annual mean precipitation.

However, for the occurrence of the cloud forests, annual mean precipitation, soil and air humidity and air temperature are crucial (STADTMÜLLER 1987; HAGER & ZANONI 1993; SHERMAN et al. 2005; SCATENA et al. 2010). Decreasing precipitation above the TWI and a higher variability in humidity (SHERMAN et al. 2005; PEGUERO et al. 2007; HAGER & ZANONI 1993) are supposed to affect the distribution of the cloud forests besides the decreasing annual mean temperatures. Due to the low resolution Worldclim precipitation data the complex relationship between cloud forest distribution and change of precipitation patterns above the TWI could not be assessed. Therefore a high resolution precipitation climatic model based on local station data would have been needed. Another important factor for determining the distribution of cloud forests is the frequency of cloud and fog formation and the height of the cloud base (BRUIJNZEEL & PROCTOR 1995; LAWTON et al. 2010). None of these data were available and it would have been very difficult to gather these data by field work or from remote sensing data.

Cloud forests were richer in ferns and epiphytes of the families Orchidaceae and Bromeliaceae than the humid broadleaf/gallery forests. Together with trees, epiphytes are the most frequent life form in tropical montane forests (RICHTER 2008). In the cloud forests of Armando Bermúdez the principal plant families recorded were Cyrillaceae, Clusiaceae, Melastomataceae, Araliaceae, Aquifoliaceae, Euphorbiaceae and Myrsinaceae. Tree species with small leaves in the cloud forest were *Cyrilla racemiflora*, *Weinmannia pinnata, Ilex microwrightioides*, *Podocarpus aristulatus* and *Ditta maestrensi*s. Leaf area and leaf sizes decrease with increasing altitude to minimize extreme transpiration rates and radiation maxima (RICHTER 2008).

Pinus occidentalis was the only tree species recorded above 2,300 m a.s.l. during field work. No other woody species follows *Pinus occidentalis* in the natural succession above 2,200-2,300 m a.s.l. (ZANONI 1993). Saplings of *Pinus occidentalis* were commonly observed at these elevations during field work. Their heights depended on the years that had passed since the last fire event (pers. communication RADHAMES 2011).

Mature pine trees are protected from fire by the hard and resistant bark (DARROW & ZANONI 1993). Around 2,200 m a.s.l. *Brunellia comocladifolia* was the first tree species observed during field work associated with *Pinus occidentalis* on sites with a long fire absence (pers. communication RADHAMES 2011). Fires are caused naturally by lightning or have their origin in uncontrollable man-made fires in the valleys (HORN et al. 2001). *Brunellia comocladifolia* is a short lived post-fire successor in cloud and pine forests that declines after 30-40 years (MAY 1997b).

Above 2,500 m a.s.l just small growing (1-2 m) woody species were observed and Ericaceae and Asteraceae gained importance. These families were also described by RICHTER (2008) for high elevation tropical mountain forests. The main woody species observed besides *Pinus occidentalis* above 2,300 m a.s.l. were: *Myrsine coriacea*, *Baccharis myrsinites*, *Eupatorium illitum*, *Lyonia truncata* var. *montecristina*, *Lyionia stahlii* var. *costata*, *Gaultheria domingensis*, *Rondeletia ochracea*, *Ilex microwrightioides*, *Ilex tuerckheimii*, *Garrya fadyenii*, *Weinmannia pinnata*, *Myrica picardae*, the bunch grass *Danthonia domingensis* and the fern *Gleichenia bifida*. *Danthonia domingensis* and *Gleichenia bifida* are fire resistant by sprouting ability (pers. communication MAY 2011). *Myrsine coriacea, Myrica picardae, Garrya fadyenii* and *Baccharis myrsinites* are considered to be common postfire colonists in these altitudes (MAY 1997b; MAY 2000a; HORN et al. 2001). According to HORN et al. (2001) the pine and shrub dominated vegetation of the higher elevations of the Cordillera Central are well adapted to fire and the limit between the cloud forests and the monotypic pine forest is a result of fire pattern (MARTIN et al. 2007).

IV.4.2 Predictive forest type mapping

The average values of the annual mean temperature and elevation derived by ordination and in ecological niche modeling were similar per forest type (Table IV.5).

The modeled prediction for humid broadleaf/gallery forest had a high AUC-value, was consistent with our field impression and with the observations made by PEGUERO et al. (2007). Additionally to our modeled areas of high suitability, PEGUERO et al. (2007) reported larger humid broadleaf/gallery forest along the river section between La Ciénaga and Los Tablones (Figure IV.6a). As our samples of this secondary forest (MARTIN et al. 2004) were neither used in ordination nor in the ecological niche model, spatial prediction for this forest type was low in this part of the national park. Annual mean temperature and altitude played the most important roles for humid broadleaf/gallery forests in the Maxent model.

The model with the highest accuracy of prediction was the pine forest model. Relationships between quality of the model (here as AUC) and sample sizes seemed to exist (PETERSON 2001), but could not be statistically secured due to the low case numbers.

TABLE IV.5. Comparison between average annual mean temperature (in ˚C) and average elevation (in m) per forest type determined by ordination and in ecological niche modeling

Forest type	**Average altitude (in m)**		**Average annual mean temperature (in ˚C)**	
	Ordination	**Maxent**	**Ordination**	**Maxent**
Humid broadleaf/Gallery forest	979	958	20.2	20.5
Cloud forest	1,527	1,608	16.5	15.8
Mixed forest	1,272	1,202	18.0	18.6
Pine forest	1,835	1,906	14.5	13.9

NDVI was the overall determining environmental parameter of the ecological niche model of pine forests. Pine forest had comparatively low NDVI values (Table IV.1). Due to the large altitudinal range of pine forest occurrence, a model based only on the parameters annual mean temperature and altitude predicted nearly 3/5 of the national park as suitable for pine forest. Including NDVI, the predicted area was reduced significantly and coincided with the field impression and descriptions given by DARROW & ZANONI (1993). However, the predicted area was underestimated. Actually the entire center of Armando Bermúdez National Park in the triangle between Loma El Tambor, Bao River and Loma La Rucilla (Figure IV.6d) should have been predicted as pine forests.

The reasons for the underestimation had their origin in the sampling scheme of the pine forest plots. The samples were taken along the main trail from Mata Grande to Pico Duarte and La Ciénaga, primarily in open forests. However, pine forests also occur in dense forests on inaccessible slopes of the high mountains that could not be reached during field work. NDVI values in these dense forests varied between 0.25-0.33 (analysis in ArcGIS 9.3). These areas were not predicted as suitable for pine forests in the Maxent model as sampled plots were missing here.

A comparison between the prediction of Maxent (red) and the delineation of the pine forest extension on the aerial photograph mosaic (dark green) (see also Chapter III) is displayed in Figure IV.8. Pixels that coincided as pine forests in both methodologies are displayed in yellow (104 km^2). These coincidently predicted and delineated areas represented altitudes above 2,000 m a.s.l. and embarked in the lower parts the catchment system of the Bao River (analysis in ArcGIS 9.3). The outer limit of the pine forest area was similar in wide parts of both datasets. The non-present white patches inside the large pine forest block coincided also between the two methodologies. These areas were predicted as suitable for cloud forest (Figure IV.9).

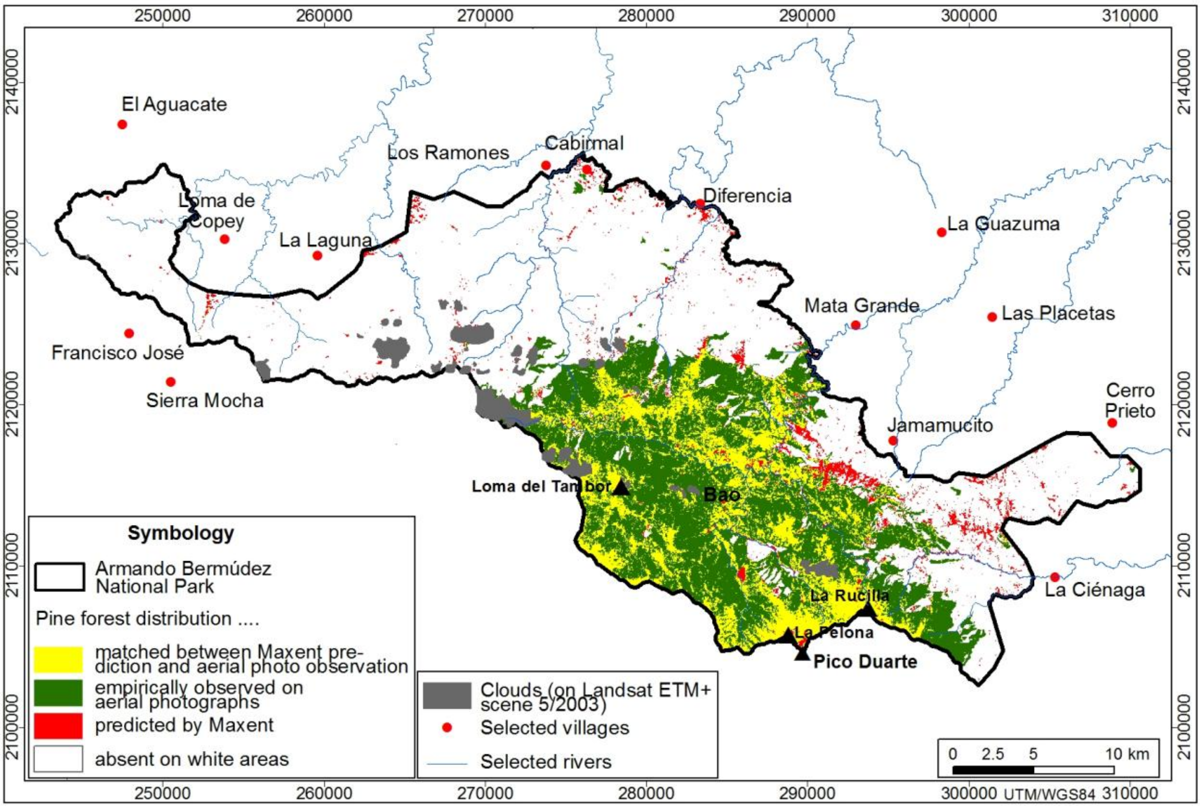


FIGURE IV.8. Pine forest geographic distribution: Modeled (red), empirically observed on aerial photographs (dark green) and matched pixels of both approaches (yellow) (Source: Distributions from Maxent, aerial photographs/GIS analysis for matched areas; Boundaries of ABNP from Law 64-00; Villages, rivers, peaks from topographic maps 1:50,000, ICM 1983/1984)

Gaps in the Maxent prediction for pine forests occurred in areas of high NDVI values in the triangle mentioned above in this chapter. To close the gaps, the sampling scheme had to be extended to the dense pine forest areas on the high mountains.

The modeled prediction of mixed forests included areas south of the villages of Los Ramones, La Diferencia and Mata Grande which was in concordance with our field impression and also the description given by PEGUERO et al. (2007). However, mixed forests neither cover the western nor the eastern part of Armando Bermúdez National Park as modeled with our data (Figure IV.6c). Mixed forests occurrence is always related to some kind of disturbance (land slide, fire event, wind throw or human impact) (PEGUERO et al. 2007). Integration of a disturbance dataset in the model could improve the predicted results.

Between 1,100-1,900 m a.s.l. the ecological niche model for the cloud forest distribution was consistent with our field observation, with the ordination results (Table IV.1) and observations made by PEGUERO et al. (2007) (Figure IV.9). However, Maxent also predicted areas between 1,900-2,300 m a.s.l. as suitable for cloud forests (Figure IV.9). SHERMAN et al. (2005) reported the occurrence of cloud forests on northeastern slopes of the eastern part of the Cordillera Central up to 2,200 m a.s.l.. All of the predictions in question occurred on northeastern facing slopes (analysis in ArcGIS 9.3). Nevertheless it is known from field work, that some areas were predicted incorrectly. The catchment area around Bao River with its tributaries and the elevations around Loma El Tambor were correctly predicted “not present” as low NDVI values (< 0.2) were recorded here, not compatible with the high photosynthetic activity and fractional coverage of cloud forests. To improve the prediction of the geographic distribution of the cloud forests, especially at its upper limit between 1,800-2,000-2,200 m a.s.l. a higher resolution precipitation model would be needed that represents as accurate as possible the spatio-temporal changes of the precipitation pattern at the TWI. As not only vertical precipitation, but also horizontal plays a crucial role for the distribution of cloud forests, the spatio-temporal patterns of cloud cover and cloud cover immersion of the study site should be known. Raising elevations of the cloud base provoked by global warming or land conversion threaten cloud forests (KAPPAS 1999; NAIR et al. 2010). KAPPAS (1999) showed that between July and December horizontal precipitation was three times the amount of vertical precipitation in cloud forests in the Scientific Reserve Ebano Verde in the eastern part of the Cordillera Central.

Cloud cover can be extracted from satellite images such as MODIS-Terra and MODIS Aqua, providing data twice a day with a spatial resolution of 250 m (red and infrared), 500 m (blue and green) and 1000 m (infrared) in altogether 36 channels. The 250 m data could be used to map the cloud locations and frequencies of formation as done by LAWTON et al. (2010). For cloud base determination observations by ceilometers, radiosondes, photographs and local observers (SHERMAN et al. 2005) are possible solutions. Cloud base height calculation from Landsat images were undertaken over flat terrain by matching cloud and shadow edges trigonometrically (BERENDES et al. 1992).

A soil map at the scale 1:50,000 is currently being produced for the entire Dominican Republic by the Dirección General de Minería in Santo Domingo. If the information were detailed in the area of the national park the data should also be introduced as an environmental factor in ordination and ecological niche modeling.

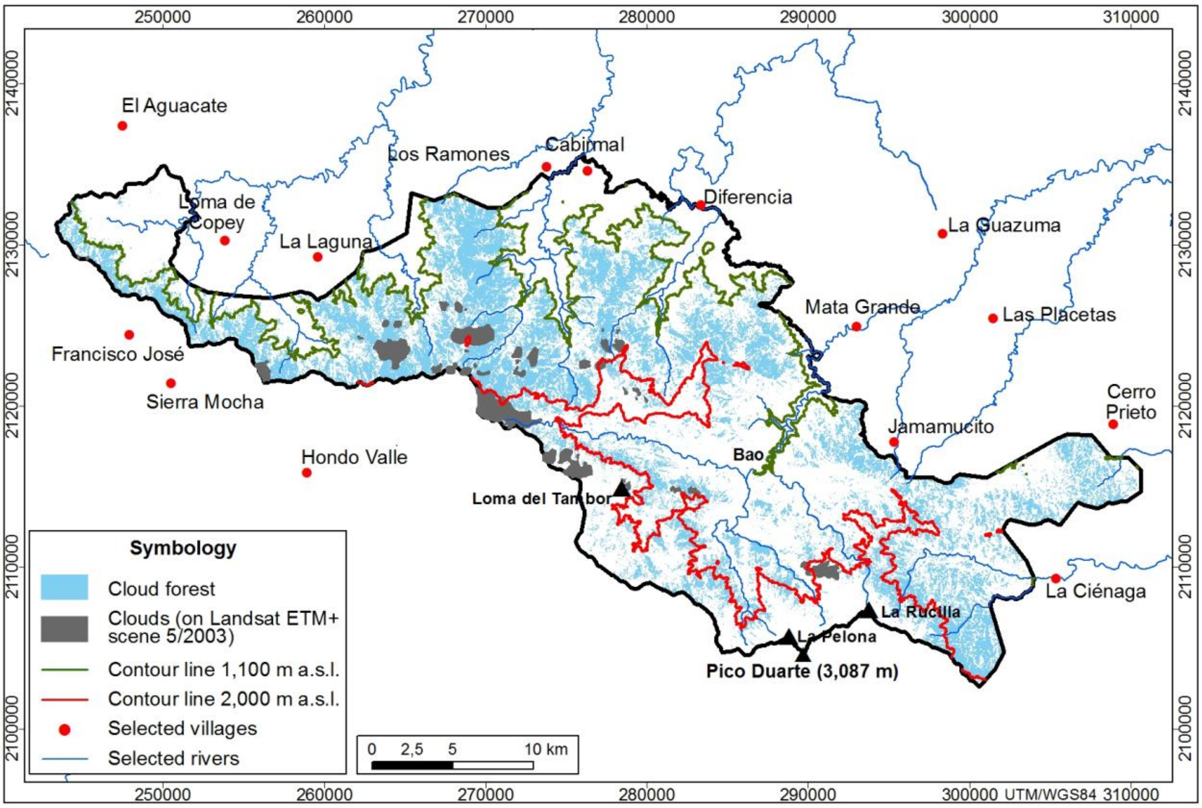


FIGURE IV.9. Modeled potential distribution of cloud forests and altitudinal range of cloud forest plots in the ordination diagram (Source: Distribution results from Maxent; Contour lines from DEM; Boundaries of ABNP from Law 64-00; Villages, rivers, peaks from topographic maps 1:50,000, ICM 1983/1984)

IV.4.3 Implications for management and conservation needs

For the first time spatial distribution maps of the main forest types of Armando Bermúdez National Park were elaborated that can be used by the park directive as a baseline for monitoring and assessment of management effectiveness (AREENDRAN et al. 2010).

As the occurrences of the cloud and the pine forests are restricted to the Cordillera Central, the Sierra de Bahoruco and the Sierra de Neyba (HAGER & ZANONI 1993), conservation of these forests types is extremely necessary. *Pinus occidentalis* dominated pine forests are unique to Hispaniola due to the endemism of the Creolan pine (DARROW & ZANONI 1993). The endemic, endangered bird *Loxia megaplaga* (common name: Pico cruzado) lives in the high mountains of the Cordillera Central, the Sierra de Bahoruco and the Massifs de la Selle and de la Hotte (both Haiti) and feeds exclusively on pine cones (BIRDLIFE INTERNATIONAL 2011). A reduction of the pine forest is equivalent with a reduction of the habitat of this and other endangered bird species.

The sensitivity of the mountain forest types to climate change and land conversion can be determined by submitting the here predicted forest distributions to future climate and land use scenarios. Based on the sensitivity results forest type-specific management strategies can be developed. Especially for the cloud forest distribution climatic drying and land conversion will have negative consequences as cloud formation and humidity will be affected, amongst others (NAIR et al. 2010). With increasing cloud base heights due to global warming, cloud forests will disappear from the lower elevations.

RYMER et al. (2008) predicted for the Dominican Republic a reduction of available surface freshwater by 85% between 1970-2100. Thus, conservation of all of the existing mountain forests is of vital importance. Frequent and longer droughts and more extreme events are predicted for the Caribbean (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE 2007).

The forests of the Cordillera Central are also substantial for climate regulation and carbon sequestration. Permanent long term observations could be installed on the 137 georeferenced 20x10 m plots used in this study to monitor the changes in the floristic compositions of the respective forest types, determine the impact of disturbances and monitor the effectiveness of management.

IV.5 CONCLUSION

Ordination and ecological niche modeling played two complementary roles in this study. Ordination helped to identify the main mountain forest types and to determine the significant environmental factors responsible for their occurrence. The ecological niche modeling technique predicted the spatial potential distribution of each forest type to the entire national park based on the significant environmental factors found by ordination. An important achievement of the study consisted in the transformation of punctual vegetation data to spatially explicit information which did not exist before.

We conclude, the study contributed to an improved understanding of the vegetation-environment relationships and distribution patterns of the main forest types along the altitudinal gradient of a mountain protected area in the tropics with a high conservation value.

APPENDIX IV.

APPENDIX IV.A. Botanical data of 137 plots (see digital attachment)

APPENDIX IV.B. Environmental parameter values of 137 plots

Plot ID	Habitat type*	Impact **	Fire ***	Total veget. cover (in %)	Herb cover (in %)	No veget. cover (in %)	Altitude (in m)	Soil Wetness Index	Annual mean temperature (in °C)	Annual mean precipitation (in mm)	NDVI	Distance to river (in m)	Soil pH
s1	4	0	0	85.0	0.0	15.0	1546.83	8.41	16.4	1408	0.29	567.84	6.05
s2	4	0	0	85.0	0.0	15.0	1538.91	8.0	16.4	1408	0.23	541.97	6.22
s3	1	0	0	100.0	30.0	0.0	1501.46	9.82	16.4	1408	0.36	600.65	6.61
s4	4	0	0	95.0	10.0	5.0	1360.51	11.08	17.8	1336	0.30	233.95	6.12
s5	4	0	0	85.0	75.0	15.0	1251.18	9.6	17.8	1336	0.37	2.16	6.22
s6	4	0	0	95.0	10.0	5.0	1482.28	8.96	17.7	1343	0.34	384.06	6.63
s7	5	0	0	90.0	85.0	10.0	1011.60	9.37	19.4	1257	0.34	366.40	6.70
s8	1	0	0	95.0	95.0	5.0	1056.33	8.92	19.4	1257	0.30	473.17	6.87
s9	5	0	1	97.0	20.0	3.0	756.70	8.83	22.6	1286	0.15	174.31	5.54
s10	7	0	1	76.0	60.0	25.0	821.46	10.32	22.6	1286	-0.08	177.25	5.50
s11	4	0	0	95.0	15.0	5.0	1907.92	10.3	14.2	1563	0.23	676.70	5.45
s12	4	0	0	98.0	10.0	2.0	1900.33	8.89	14.7	1533	0.25	538.76	5.80
s13	4	0	0	85.0	18.0	15.0	1825.98	8.02	14.7	1533	0.29	457.26	5.65
s14	4	0	0	95.0	5.0	5.0	1770.37	8.37	14.7	1533	0.28	226.40	5.59
s15	4	0	0	95.0	10.0	5.0	1676.18	7.79	14.8	1528	0.34	483.41	5.77
s16	4	0	0	90.0	5.0	10.0	1662.47	8.78	14.8	1528	0.28	383.67	6.07
s17	4	0	0	95.0	25.0	5.0	1468.30	9.59	15.4	1490	0.37	451.27	5.70
s18	4	0	0	95.0	5.0	5.0	1488.59	9.74	15.4	1490	0.39	116.12	5.30
s19	4	0	0	95.0	60.0	5.0	1451.72	9.24	17.5	1373	0.35	366.39	6.31
s20	5	0	0	70.0	30.0	30.0	1333.67	8.75	16.8	1412	0.38	331.16	5.95
s21	3	0	0	95.0	25.0	5.0	1294.20	14.3	16.8	1412	0.32	2.50	5.74
s22	3	0	0	90.0	28.0	10.0	1230.88	9.35	17.8	1360	0.33	86.38	5.86
s23	3	0	0	96.0	5.0	4.0	1188.55	9.65	19.3	1307	0.42	560.48	5.83
s24	1	0	0	75.0	5.0	25.0	1072.67	8.91	20.2	1294	0.31	554.76	6.03
s25	1	0	0	75.0	5.0	25.0	933.53	9.08	20.4	1294	0.39	91.33	6.02
s26	3	0	0	80.0	15.0	20.0	892.46	15.5	20.4	1294	0.36	4.01	6.08
s27	1	0	0	97.0	10.0	3.0	965.81	8.82	19.7	1311	0.32	395.60	5.90
s28	1	0	0	90.0	10.0	10.0	953.92	8.75	21.0	1291	0.41	350.46	6.13
s29	1	0	0	90.0	10.0	10.0	874.57	9.23	21.6	1293	0.30	313.66	6.30
s30	5	0	0	90.0	45.0	10.0	857.22	9.17	22.0	1297	0.30	324.46	6.35
s31	1	0	0	85.0	20.0	15.0	822.10	12.97	22.0	1297	0.40	3.05	6.21
s32	7	0	0	75.0	15.0	25.0	781.96	8.98	22.6	1294	0.26	199.18	5.50
s33	5	0	1	70.0	50.0	30.0	940.66	9.38	20.8	1311	0.24	391.72	6.36
s34	3	0	0	97.0	5.0	3.0	1041.90	10.33	20.8	1311	0.42	1.50	6.21
s35	1	0	0	97.0	15.0	3.0	1164.51	8.49	18.7	1346	0.38	730.44	5.86
s36	3	0	0	90.0	5.0	10.0	1131.94	9.42	18.7	1346	0.36	477.84	5.80
s37	4	0	0	95.0	5.0	5.0	1157.16	8.68	19.3	1335	0.37	225.25	5.87
s38	1	0	0	80.0	20.0	20.0	1227.85	7.35	19.3	1335	0.33	334.64	6.03
s39	1	0	0	90.0	5.0	10.0	1084.03	11.53	18.7	1346	0.35	300.78	5.80
s40	1	0	0	95.0	3.0	5.0	1175.51	9.34	18.7	1346	0.39	690.79	6.01
s41	5	0	0	75.0	5.0	25.0	748.45	9.7	22.6	1294	0.25	173.21	6.07
s42	1	0	0	95.0	4.0	5.0	766.33	11.25	23.0	1312	0.42	514.47	6.50
s43	1	0	0	90.0	4.0	10.0	688.40	14.22	20.8	1341	0.38	71.34	7.02
s44	1	0	0	80.0	5.0	20.0	738.30	9.09	21.8	1325	0.35	101.93	6.83
s45	3	0	0	90.0	3.0	10.0	759.40	11.41	22.0	1301	0.39	3.05	6.76
s46	1	0	0	95.0	2.0	5.0	754.95	13.59	22.0	1301	0.44	87.08	6.41
s47	1	0	0	80.0	5.0	20.0	769.92	9.63	22.0	1301	0.41	156.06	6.78
s48	1	0	0	95.0	2.0	3.0	763.16	12.68	19.9	1335	0.41	202.32	6.72
s49	1	0	0	85.0	4.0	15.0	729.55	8.66	22.6	1311	0.44	261.54	6.25
s50	5	0	1	70.0	10.0	30.0	801.25	8.4	23.0	1312	0.28	285.37	6.09
s51	1	0	0	95.0	5.0	5.0	730.93	9.25	22.7	1323	0.46	438.50	6.93

Plot ID	Habitat type*	Impact **	Fire ***	Total veget. cover (in %)	Herb cover (in %)	No veget. cover (in %)	Altitude (in m)	Soil Wetness Index	Annual mean temperature (in °C)	Annual mean precipitation (in mm)	NDVI	Distance to river (in m)	Soil pH
s52	7	0	1	75.0	25.0	25.0	1243.39	9.2	18.7	1421	0.13	531.85	7.16
s53	4	0	0	95.0	15.0	5.0	1211.95	9.54	19.0	1410	0.39	474.15	7.35
s54	4	0	0	100.0	20.0	0.0	1338.03	9.70	17.6	1447	0.38	445.20	7.46
s55	4	0	0	95.0	20.0	5.0	1437.52	12.93	17.6	1447	0.31	507.60	7.23
s56	7	0	1	100.0	90.0	0.0	1316.44	8.98	19.0	1410	0.20	249.79	5.30
s57	4	0	0	90.0	20.0	10.0	1192.15	10.95	19.0	1410	0.40	496.03	6.90
s58	4	0	0	90.0	25.0	10.0	1174.60	10.30	18.7	1421	0.38	568.46	6.98
s59	3	0	0	95.0	3.0	5.0	790.64	11.07	21.3	1353	0.43	5.05	7
s60	3	0	0	75.0	5.0	25.0	870.02	10.13	21.3	1347	0.45	6.01	7.26
s61	3	0	0	85.0	15.0	15.0	864.96	12.47	20.9	1344	0.40	3.05	7.24
s62	3	0	0	98.0	10.0	2.0	904.30	14.99	21.0	1337	0.46	2.01	7.05
s63	5	0	0	75.0	20.0	25.0	1046.23	8.05	19.4	1257	0.23	197.17	6.1
s64	3	0	0	90.0	25.0	10.0	1018.70	10.35	19.4	1257	0.37	2.07	5.7
s65	1	0	0	90.0	15.0	10.0	1133.05	10.66	18.6	1274	0.32	368.11	4.9
s66	5	0	0	70.0	15.0	30.0	1276.96	8.78	17.3	1329	0.25	296.72	5.8
s67	7	0	0	90.0	30.0	10.0	1410.34	9.05	17.3	1329	0.22	354.93	5.3
s68	7	0	0	80.0	20.0	20.0	1165.00	9.37	19.2	1238	0.14	267.61	5.6
s69	3	0	0	100.0	5.0	0.0	1065.26	10.97	19.0	1246	0.36	3.61	5.80
s70	7	0	0	80.0	25.0	20.0	1198.05	10.49	19.3	1230	0.16	391.63	5.43
s71	7	0	0	80.0	5.0	20.0	1206.00	9.04	18.1	1278	0.14	150.27	5.65
s72	5	0	0	90.0	10.0	10.0	1204.01	10.11	18.7	1248	0.33	165.90	5.51
s73	7	0	0	60.0	20.0	40.0	1325.98	8.1	17.7	1296	0.13	331.04	5.32
s74	7	0	0	70.0	10.0	30.0	1399.60	8.55	18.7	1250	0.22	571.77	5.21
s75	4	0	0	80.0	20.0	20.0	1151.67	10.28	17.9	1285	0.11	2.06	6
s76	7	0	0	75.0	30.0	25.0	1233.51	8.75	18.0	1270	0.26	78.01	5.7
s77	7	0	0	95.0	20.0	5.0	1303.20	8.24	17.8	1289	0.22	238.30	**5.2**
s78	7	0	0	75.0	20.0	25.0	1319.76	9.33	17.8	1289	0.24	150.06	5.3
s79	5	0	0	95.0	15.0	5.0	1383.14	8.84	17.8	1289	0.24	331.51	5.2
s80	7	0	0	95.0	60.0	5.0	1379.46	9.33	17.2	1321	0.20	236.38	5.2
s81	7	0	0	85.0	5.0	15.0	1345.98	8.08	17.2	1321	0.22	225.17	5.1
s82	7	0	0	80.0	15.0	20.0	1267.41	13.43	17.1	1322	0.12	46.08	5.6
s83	7	0	0	70.0	25.0	30.0	1336.04	11.59	16.7	1345	0.26	78.94	6.3
s84	7	0	0	95.0	25.0	5.0	1427.70	8.47	16.7	1345	0.23	246.45	4.7
s85	7	0	0	90.0	15.0	10.0	1470.66	8.06	16.7	1345	0.23	139.80	5.1
s86	7	0	0	95.0	20.0	5.0	1528.04	9.77	16.7	1345	0.23	474.08	5.3
s87	7	0	0	95.0	30.0	5.0	1540.97	10.11	16.7	1345	0.17	505.67	5.4
s88	7	0	0	90.0	5.0	10.0	1465.31	7.98	16.2	1379	0.24	293.43	4.8
s89	5	0	0	100.0	30.0	0.0	1435.02	13.45	16.2	1379	0.30	25.99	5.9
s90	4	1	0	100.0	30.0	0.0	1480.67	10.07	16.2	1379	0.33	132.57	5.7
s91	4	1	0	100.0	10.0	0.0	1550.32	9.05	15.4	1434	0.39	253.38	5.7
s92	7	0	0	75.0	20.0	25.0	1706.76	8.41	15.4	1434	0.27	163.24	4.6
s93	7	0	0	90.0	20.0	10.0	1788.50	8.46	14.2	1527	0.25	274.62	4.8
s94	7	0	0	100.0	100.0	0.0	1790.57	9.19	14.2	1527	0.22	395.69	4.6
s95	7	0	0	85.0	30.0	15.0	1849.96	8.98	13.8	1556	0.20	636.03	4.51
s96	7	0	0	70.0	25.0	30.0	1902.11	8.36	13.8	1556	0.21	694.14	4.6
s97	7	0	0	60.0	25.0	40.0	2032.44	8.59	14.0	1545	0.20	497.42	5
s98	7	0	0	90.0	60.0	10.0	2098.29	8.68	13.1	1616	0.18	556.87	5
s99	7	0	0	95.0	40.0	5.0	2225.34	8.14	13.1	1616	0.19	958.19	4.6
s100	7	0	0	80.0	10.0	20.0	2319.94	8.31	12.0	1706	0.16	1145.37	5
s101	7	0	0	90.0	60.0	10.0	2299.67	9.02	12.0	1706	0.16	783.84	6.1
s102	7	0	1	90.0	15.0	10.0	2525.71	7.77	10.5	1831	0.08	783.08	4.54
s103	7	0	1	70.0	40.0	30.0	2603.06	8.1	10.2	1858	0.09	677.94	5.7
s104	7	0	1	75.0	60.0	25.0	2722.98	8.27	8.2	2051	0.03	692.13	6
s105	7	0	1	90.0	60.0	10.0	2795.97	8.3	8.2	2051	-0.06	709.45	5.9
s106	7	0	1	100.0	75.0	0.0	2891.80	8.98	8.2	2051	-0.09	779.83	5.9
s107	7	0	1	70.0	60.0	30.0	3062	8.33	7.2	2164	-0.14	579.27	5.5
s108	7	0	1	95.0	15.0	5.0	2718.98	9.56	9.7	1910	0.11	494.61	5.9
s109	7	0	1	75.0	50.0	25.0	2569.07	8.5	9.7	1910	0.12	518.17	5.3
s110	7	0	1	70.0	20.0	30.0	2424.9	12.88	10.0	1890	0.22	565.32	5.2

Plot ID	Habitat type*	Impact **	Fire ***	Total veget. cover (in %)	Herb cover (in %)	No veget. cover (in %)	Altitude (in m)	Soil Wetness Index	Annual mean temperature (in °C)	Annual mean precipitation (in mm)	NDVI	Distance to river (in m)	Soil pH
s111	7	0	1	70.0	20.0	30.0	2503.2	8.52	8.4	2039	0.08	543.97	4.9
s112	7	0	1	60.0	5.0	40.0	2622.9	9.67	8.4	2039	0.10	1057.27	5.5
s113	7	0	1	95.0	75.0	5.0	2682.8	9.1	8.8	2009	-0.03	1457.86	6
s114	7	0	0	80.0	20.0	20.0	2277.5	9.36	11.0	1796	0.20	856.42	5.4
s115	7	0	0	95.0	30.0	5.0	2197.7	8.84	12.3	1678	0.22	933.82	5.6
s116	5	0	0	100.0	25.0	0.0	2051.75	8.88	12.3	1678	0.28	876.21	5.9
s117	5	0	0	98.0	25.0	2.0	1948.70	8.86	12.3	1678	0.30	679.08	5.3
s118	5	0	0	90.0	30.0	10.0	1806.65	8.98	14.5	1484	0.31	456.40	6.5
s119	4	0	0	95.0	30.0	5.0	1713.14	8.06	15.2	1420	0.30	287.14	5.2
s120	7	0	0	95.0	50.0	5.0	1539.93	8.49	16.3	1330	0.25	766.81	5.1
s121	2	1	0	95.0	10.0	5.0	1450.54	8.05	16.8	1296	0.39	120.01	6.7
s122	1	0	0	100.0	10.0	0.0	1319.41	10.63	17.1	1264	0.41	8.67	6
s123	2	1	0	95.0	15.0	5.0	1267.23	12.57	17.5	1232	0.37	6.79	6.24
s124	2	1	0	100.0	20.0	0.0	1217.44	13.33	18.0	1194	0.26	3.47	5.5
s125	2	1	0	95.0	15.0	5.0	1156.46	13.97	18.5	1158	0.31	5.45	6.4
s126	7	0	0	95.0	25.0	5.0	1435.69	8.92	16.6	1326	0.23	127.44	5.7
s127	2	1	0	90.0	5.0	10.0	1412.34	8.43	17.1	1282	0.31	50.01	5.91
s128	2	1	0	95.0	5.0	5.0	1335.08	9.75	17.1	1282	0.31	20.67	6.00
s129	2	1	0	90.0	5.0	10.0	1298.14	13.13	17.1	1282	0.30	6.01	5.88
s130	2	1	0	90.0	8.0	10.0	1286.22	12.16	17.1	1282	0.31	7.98	6
s131	2	1	0	90.0	5.0	10.0	1286.93	10.78	17.7	1234	0.20	15.01	6
s132	2	1	0	90.0	5.0	10.0	1288.26	9.85	17.7	1234	0.27	10.98	5.3
s133	2	1	0	90.0	5.0	10.0	1217.35	11.05	17.8	1219	0.34	8.96	6.2
s134	2	1	0	90.0	10.0	10.0	1184.28	10.81	17.9	1212	0.33	7.98	6.5
s135	4	0	0	100.0	5.0	0.0	1718.59	8.53547	15.8	1391	0.32	523.51	5.3
s136	4	0	0	95.0	15.0	5.0	1659.04	8.5945	15.8	1391	0.32	508.77	5.5
s137	4	0	0	90.0	20.0	10.0	1716.01	8.30482	15.8	1391	0.26	529.55	5

*Habitat type:
1 Humid broadleaf forest
2 Secondary broadleaf forest
3 Gallery forest
4 Cloud forest
5 Mixed forest
7 Pine forest

** Impact (Agriculture or hurricane): no (0), yes (1)

*** Fire: no (0), yes (1)

APPENDIX IV.C. Indicator species analysis for 121 forest plots, indicator species listed if indicator value > 30 and p < 0.05

Indicator species	Family	Tree height	Indicator value (IV)	p-value	Mean cover (%)
		HUMID BROADLEAF FOREST/GALLERY FOREST			
Alchornea latifolia	Euphorbiaceae	5-20 m	60.1	0.0002	4.6
Beilschmiedia pendula	Lauraceae	5-20 m	46.4	0.0002	5.1
Guarea guidonia	Meliaceae	5-20 m	45.7	0.0002	8.1
Turpinia occidentalis	Staphyleaceae	5-20 m	45.3	0.0002	3.7
Cecropia schreberiana	Urticaceae	5-20 m	35.4	0.0004	2.4
Ocotea globosa	Lauraceae	5-20 m	31.5	0.0004	3.6
Dendropanax arboreus	Araliaceae	5-20 m	30.3	0.0006	1.5
Gomidesia lindeniana	Myrtaceae	5-20 m	30.1	0.0016	2.9
Beilschmiedia pendula	Lauraceae	0.5-5 m	53.4	0.0002	3.6
Chionanthus domingensis	Oleaceae	0.5-5 m	48.6	0.0002	2.4
Myrcia deflexa	Myrtaceae	0.5-5 m	47.5	0.0002	2.6
Guarea guidonea	Meliaceae	0.5-5 m	43.6	0.0002	3.2
Turpinia occidentalis	Staphyleaceae	0.5-5 m	40.9	0.0002	2.8
Gomidesia lindeniana	Myrtaceae	0.5-5 m	39.3	0.0004	3.8
Sloanea ilicifolia	Elaeocarpaceae	0.5-5 m	36.3	0.0002	2.2
Chrysophyllum argenteum	Sapotaceae	0.5-5 m	31.4	0.0008	1.2
		CLOUD FOREST			
Cyrilla racemiflora	Cyrillaceae	5-20 m	55.6	0.0002	23.0
Clusia clusioides	Clusiaceae	5-20 m	54.3	0.0002	5.0
Brunellia comocladifolia	Brunelliaceae	5-20 m	43.9	0.0002	10.4
Myrsine coriacea	Primulaceae	5-20 m	35.3	0.0004	3.2
Schefflera tremula	Araliaceae	5-20 m	33.8	0.0002	3.7
Haenianthus salicifolius	Oleaceae	5-20 m	33.3	0.0002	1.5
Torralbasia cuneifolia	Celastraceae	5-20 m	33.3	0.0002	2.0
Ditta maestrensis	Euphorbiacea	0.5-5 m	51.2	0.0002	2.3
Haenianthus salicifolius	Oleaceae	0.5-5 m	37.5	0.0002	1.3
		MIXED FOREST			
Myrsine coriacea	Primulaceae	0.5-5 m	30.8	0.012	5.4
		PINE FOREST			
Pinus occidentalis	Pinaceae	5-20 m	50.6	0.0002	54.5
Pinus occidentalis	Pinaceae	0.5-5 m	71.8	0.0002	17.0

V. Analysis of woody species richness and endemism

V. 1 INTRODUCTION

Tropical mountain (or montane) forests are very rich in species and are considered as hotspots of plant biodiversity (BARTHLOTT et al. 2007; GRADSTEIN et al. 2008). They provide essential ecosystem services for human well-being, e.g. water basin protection, freshwater production, generation of hydro-power, soil stabilization, carbon sequestration, biodiversity conservation and environment for recreation (STADTMÜLLER 1987; DOUMENGE et al. 1995; MILLENIUM ECOSYSTEM ASSESSMENT 2005). In many parts of the world tropical montane forests are severely threatened as they occur under climates and soils also suitable for agriculture and pasture (KAPPELLE & BROWN 2001 in MULLIGAN 2010). Most of the 20 global centers of vascular plant species richness are found in tropical mountain areas (BARTHLOTT et al. 2007).

The effectiveness of sustainable management and conservation of natural resources, especially of fragile mountain forest ecosystems, strongly depends on the knowledge about species, biodiversity and endemism of an area (BARTHLOTT et al. 2007). GENTRY (1992) and HERNÁNDEZ-STAFANONI et al. (2011) described mapping of distributional patterns of individual species and of species richness and endemism as indispensable methods to improve conservation of plant biodiversity.

Species richness und endemism are the main measurements for characterization of biodiversity (WHITTAKER 1972; ESCALANTE et al. 2009; GOTELLI & COLWELL 2001). Species richness represents the number of species in a certain geographic area. Endemism refers to the uniqueness of species in a geographic area. Endemism very likely evolves in biologically isolated areas, such as islands or high mountain systems (CARLQUIST 1974 in KESSLER & KLUGE 2008). Species richness and endemism show different patterns along altitudinal gradients.

Some authors found a linear decrease of woody species richness with altitude in tropical areas of moderate to high precipitation (HAMILTON & PERROTT 1981; GENTRY 1988, 1995; KITAYAMA 1992; VÁZQUEZ & GIVNISH 1998). Others reported a hump-shape curve with maximum species numbers at low to intermediate elevations between 500-2000 m a.s.l. (LIEBERMAN et al. 1996; KESSLER & KLUGE 2008; HEMP 2010). Among the explanation for these patterns several causes are being discussed. The main important ones are: the “area-effect”, edaphic and climatic factors (temperature, precipitation and humidity), energy availability, productivity, historical and evolutionary processes and dispersal limitation (WRIGHT 1983; GENTRY 1995; VAZQUEZ & GIVNISH 1998; BARTHLOTT et al. 2005; KESSLER & KLUGE 2008; RICHTER 2008; HEMP 2010).

Patterns of endemic woody species in tropical mountain forests differ considerably from patterns of woody species richness. Endemism increases with altitude in tropical mountains and often peaks above 2000 m a.s.l. (KESSLER & KLUGE 2008). The maximum number of endemic species in mountain forests is reached at elevations much higher than the areas where species richness is at its maximum. Consequently, the factors influencing the patterns of woody species endemism are different. The “area-effect” influences tree species endemism inversely. While species richness of trees increases in larger areas, the fraction of endemic trees increases in smaller areas. The “area-effect” is directly related to the topography of an area. Small populations of tree species on islands habitats such as for example well separated individual mountain ranges are extremely able to diverge genetically and ecologically and form rapidly new, endemic taxa. This is the most cited cause for explaining endemism patterns along altitudinal gradients (KESSLER & KLUGE 2008). Furthermore ecoclimatic stability (FJELDSÅ et al. 1999), taxon-specific traits (KESSLER 2002) and disturbance (KESSLER et al. 2001) have been investigated as factors determining the patterns of endemism rates along altitudinal gradients.

On Hispaniola 36% of the 5600 known vascular plant species are known to be endemic (GENTRY 1992; PEGUERO et al. 2007). Hispaniola holds the second place regarding endemism rates in the Caribbean after Cuba (BORHIDI 1996). 25% (186) of the 750 vascular plants of Armando Bermúdez National Park are endemic, some of them with limited distribution to the high mountains (PEGUERO et al. 2007).

Up to now predictions and analysis about the spatial patterns of woody species richness or endemism in the national park do not exist. Such information is urgently needed to improve management effectiveness and to predict future patterns of species richness and endemism in the light of environmental change. Endemic species are considered “…a prime target of conservation activities…” (KESSLER & KLUGE 2008) due to their limited distribution range and scarce occurrence within it.

In this study spatial prediction of woody species richness and endemism of Armando Bermúdez National Park were based on the maximum entropy modeling (ENM) technique, Maxent (PHILLIPS et al. 2004, 2006; PHILLIPS & DUDIK 2008) in combination with GIS-tools. Ecological niche models (ENM) predict the geographic distributions of species based on occurrences and environmental variables. They are often used in biogeography, conservation and ecology (PETERSON 2006; ELITH & LEATHWICK 2009) and to assess overall biodiversity and endemism patterns (GIOIA & PIGOTT 2000; GRAHAM et al. 2006; ESCALANTE et al. 2009). For a more detailed description consider Chapter IV.2.3.2.

The specific objectives of this study are:

(i) to develop predictive models to map the spatial potential distribution of selected sampled woody species of Armando Bermúdez National Park;

(ii) to map and analyze woody species richness based on the predictions obtained under (i);

(iii) to map and analyze endemism of woody species based on the predictions obtained under (i).

V. 2 MATERIALS AND METHODS

V.2.1 Woody species sampling

Sampling of the woody species took place in February of 2011 in Armando Bermúdez National Park. Altogether 161 different woody species ≥ 5 cm dbh of 55 families (5,640 occurrence points) were recorded along eleven trails inside the national park. Reliable spatial predictions require that the occurrence data represent the environmental variability of the study area where the species occur (ELITH & LEATHWICK 2009). Thus, the entire altitudinal range of the national park between 495-3,087 m a.s.l. was sampled, each 50 m in altitude. Observations were made at a 20 m lateral distance from the trails in a randomly chosen direction in a plot of 20 x 10 m. Rare species were also recorded in between. The sampled sites were georeferenced with a Garmin 62 GPS and the coordinates saved in the Universal Transverse Mercator projection (UTM) with a WGS84 datum. Each species was characterized by its life form and status (Appendix V.A). From the herbarium and field records of the Botanical Garden of Santo Domingo 154 additional occurrence points of 80 woody species were entered in the database. Furthermore 262 occurrence points of 57 woody species were digitized from botanical field sheets used in the project "Madre de las Aguas" (GUERRERO 2004). The Global Biodiversity Information Facility (GBIF) contained 22 occurrence points of 16 woody species inside the limits of Armando Bermúdez National Park which were downloaded from http://www.gbif.de/ in March 2011. Altogether 6,161 occurrence points of 169 woody species built the final database. In Figure V.1 the occurrence points which entered in the modeling process are displayed (Chapter V.2.3).

Two botanists of the National Botanical Garden of Santo Domingo helped to identify the plants to species level. Voucher specimens of the sampled species reside in the Botanical Garden of Santo Domingo. The nomenclature used in this study followed LIOGIER (1989, 1994, 1995, 1996a-e, 2009).

V.2.2 Environmental factors

To predict the distribution of species either direct or indirect measures of gradients such as climatic parameters, elevation, vegetation and/or soil type data are introduced in ecological niche models. Often these proxies have to be processed by Geographic Information Systems (GIS) or compiled by analysis of remote sensing data. Here the environmental variables used to predict the potential distribution of woody species in Armando Bermúdez National Park were the ones determined as significant by ordination (Chapter IV.3.1): elevation and NDVI. Elevation was used as a proxy for climatic (temperature and precipitation) changes along the altitudinal gradient and NDVI as a proxy for productivity of the ecosystem (PETTORELLI et al. 2005). The 30 m resolution elevation model had been derived from the 100 m spacing contour lines of the topographic maps (Chapter IV.2.2). NDVI had been extracted from a Landsat 7 ETM+ image from May 3, 2003 (Chapter IV.2.2).

The resolution of the Worldclim temperature and precipitation data was too low for modeling the ecological niche of single species and could not be used. As Maxent requires geographic coordinates, the occurrence points and all environmental variables were transformed to geographic coordinates with a WGS84 datum using ArcGIS 9.3 (ESRI Inc., Redlands, USA).

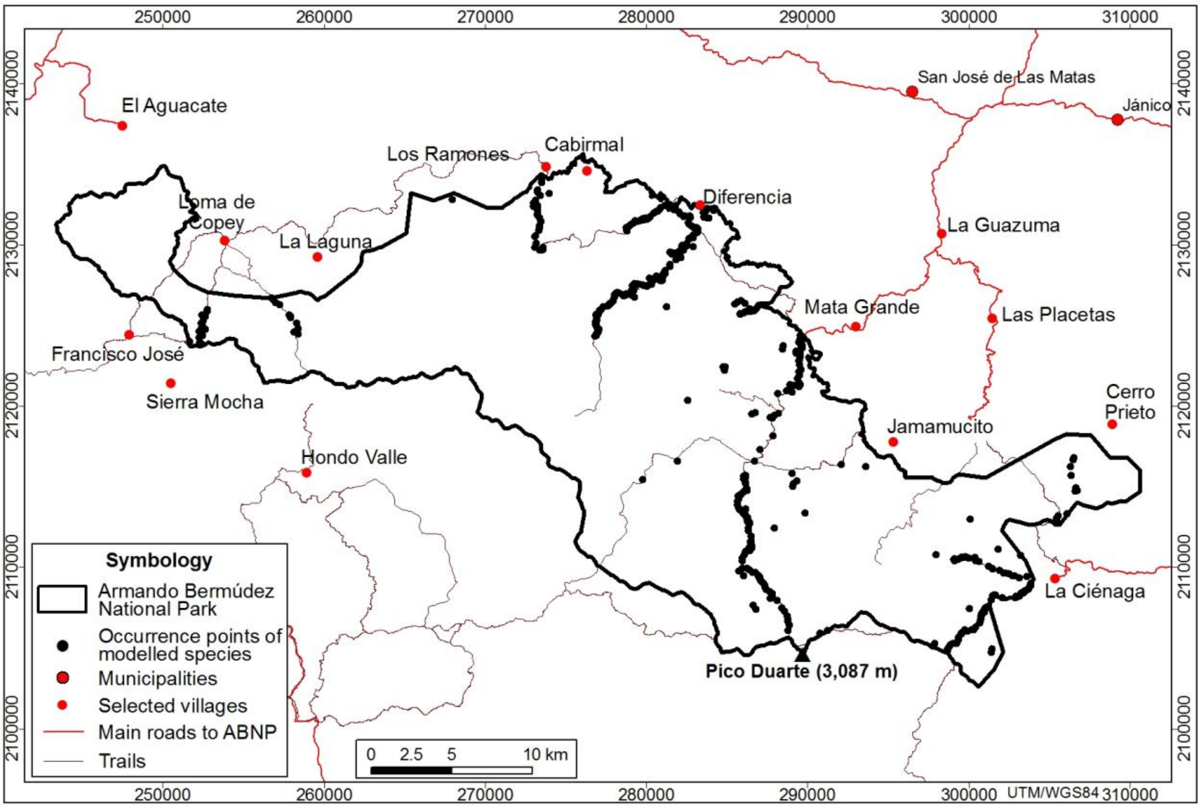


FIGURE V.1. Occurrence points of the 66 woody species used for ecological niche modeling (Source: Occurrence points from GPS field work; Boundaries of ABNP from Law 64-00; Villages, roads, trails from topographic maps 1:50,000, ICM 1983/1984 and field work)

V.2.3 Analysis of the data

Prediction of the potential distribution of the sampled woody species was based on the maximum entropy modeling technique with the program Maxent 3.3.3 (PHILLIPS et al. 2004, 2006; PHILLIPS & DUDIK 2008, AT&T Labs-Research, Princeton University). The centers of woody species richness and endemism were identified by GIS-analysis applied to the predicted potential distribution files for the woody species.

Ecological niche modeling for species distribution prediction

Maxent was developed for modeling species distributions from presence-only data (ELITH et al. 2011) and is a general-purpose machine learning method that seeks to describe the geographic distribution of a species by finding the distribution of maximum entropy (PHILLIPS et al. 2006). The geographic distribution space is defined by two or three-dimensional map coordinates while the multidimensional environmental space is characterized by the environmental predictors (ELITH & LEATHWICK 2009, for more information see Chapter IV.2.3.2).

The numerical results of the Maxent ASCII files are to be interpreted as the environmental suitability of a cell for a species derived as a function of the given environmental variables (PHILLIPS et al. 2006). Values range between 0 and 1. High values represent a high suitability of environmental conditions for the species at the cell, low values represent a low suitability (PHILLIPS et al. 2006; PHILLIPS & DUDIK 2008). Thresholds can be set to obtain binary presence and absence maps. Here the logistic equal test sensitivity and specificity threshold was used to generate binary maps for all woody species (LIU et al. 2005). Modeling of the ecological niche with Maxent has been conducted for vascular plant species and birds in the Neotropics (CARNAVAL & MORITZ 2008; MURRAY-SMITH et al. 2009; YOUNG et al. 2009; SORIA-AUZA et al. 2010) and for threatened, rare and endangered tree species in other ecozones (WILLIAMS et al. 2009; KUMAR & STOHLGREN 2009).

Only 66 species (37 families) of the 169 sampled species presented 30 or more occurrence points. These species were used for modeling. The threshold of 30 occurrences was set as the algorithms of species distribution models often perform poorly with small sample sizes of less than 30 occurrences, although Maxent was found to be less sensitive to small sample sizes than other distribution models (HERNÁNDEZ et al. 2006; WISZ et al. 2008). 25% of the occurrence points of each sampled species were set aside for testing. Maximum iterations (500) and convergence threshold (1.0E-5) were accepted with the default setting. The “extrapolation” option was turned off to force prediction to the environmental space within the limits encountered during training.

The 66 binary Maxent ASCII files based on the logistic equal test sensitivity and specificity threshold were imported to the Erdas Imagine image file format. The area under the curve (AUC) of the receiver operating characteristics (ROC) was consulted to evaluate the model results (FIELDING & BELL 1997) (for detailed description of meaning of AUC see Chapter IV.2.3.2). Interpretation of AUC-values was carried out by applying the scale proposed by SWETS (1988): AUC > 0.90: good; 0.9>AUC>0.7: useful and AUC < 0.7: poor (SWETS 1988; GUISAN et al. 2007). Only 63 predictions with an AUC value > 0.6 were taken into account for further analysis. The relationship between test AUC-value and altitudinal distribution range of species was analyzed with IBM SPSS Statistics 19.0 (IBM Corp., Armonk, USA) following Pearson.

Four prediction results were presented as binary presence-absence maps based on the logistic equal test sensitivity and specificity threshold. Each here presented species, the endemic *Meliosma impressa* and *Ilex tuerckheimii* and the native *Tetragastris balsamifera* and *Beilschmiedia pendula* stood for one of the four main modeling results. Each species could be related to one of the forest types or transition zones modeled in Chapter IV. To do this the mean altitude of the woody species modeled potential distribution was compared to the mean altitudes of the humid broadleaf/gallery forests, cloud forests and pine forests determined by ordination (Chapter IV.3.1). Furthermore the environmental factors elevation and NDVI utilized to build the niche models were discussed.

GIS-Analysis for determination of species richness and endemism

The woody species richness dataset was produced by stacking the 63 binary presence-absence image files with a test-AUC value > 0.6. Thus, each cell (30 x 30 m) obtained a value of the total number of woody species predicted at the cell. Species-rich areas were characterized by high numbers at a cell, species poor areas by low numbers. Stacked species distribution modeling (S-SDM, GUISAN & RAHBEK 2011) has been used recently for predicting hotspots of threatened plants (PARVIAINEN et al. 2009), plant species richness (DUBUIS et al. 2011), species richness of insects (ESCALANTE et al. 2009), birds (STOCKWELL & PETERSON 2003) and of amphibians (PINEDA & LOBO 2009). This approach first predicts the potential distribution of individual species to a study area. Then the single model results are stacked and the community properties are reconstructed with the help of the environmental variables (GUISAN & RAHBEK 2011).

The so created species richness dataset was overlaid separately with the modeled spatial distributions of the humid broadleaf/gallery forest, of the cloud forest and of the pine forest, all modeled in Chapter IV.3.3. Mean woody species richness of each forest type was calculated by applying zonal statistics in ArcGIS 9.3 (ESRI Inc., Redlands, USA). Furthermore seven woody species richness classes were built (1-5 species, 6-10 species, 11-20 species, 21-30 species, 31-40 species, 41-50 species and 51-53 species) and zonal statistics were calculated on altitude. The relationship between woody species richness and altitude was analyzed with IBM SPSS Statistics 19.0 (IBM Corp., Armonk, USA) following Pearson. The main plant families contributing to each of the seven woody species richness classes were identified. Coverages of each woody species per class were sorted from the largest to the smallest and summed up until reaching 50% of the total area of the respective class (Tabulate area, ArcGIS 9.3). Family names of the main species accounting for 50% of coverage were counted per woody species richness class.

To improve the visual presentation of woody species richness between the humid broadleaf/gallery forest and the cloud forest the modeled distribution of the humid broadleaf/gallery forest (Chapter IV.3.3) was vectorized. Then the line of the upper distribution limit was added to the woody species richness map (Figure V.3).

The endemism dataset of woody species was created by selecting all endemic species from the 63 niche models (AUC > 0.6) and by stacking the respective binary image files. Altogether 13 of the woody species were identified as endemic. Furthermore the altitudinal parameters of the nine endemism classes were determined and area statistics derived (ArcGIS 9.3). An endemism map was produced and discussed.

V.3 RESULTS

V.3.1 Modeled distributions for sampled woody species

Test AUC-values ranged from 0.631 for *Ilex microwrightioides* with 79 occurrence points to 0.965 for *Trichilia pallida* with 39 occurrence points. 57.1% of all models had a model performance classified as “useful” (test AUC > 0.9), 14.3% as “good” (0.9 > test AUC < 0.7) and 28.6% as “poor” (test AUC < 0.7) according to SWETS (1988) (Table V.1). For the endemic woody species test AUC-values ranged from 0.647 (*Brunellia comocladifolia* subs. *domingensis*) with 260 occurrence points to 0.862 for *Tabebuia bullata* A. H. Gentry with 68 occurrence points. Individual test AUC-values for all modeled woody species are displayed in Appendix V.A. Correlation analysis revealed that the test AUC-values correlated highly negative with the altitudinal distribution range of the species (Pearson, r= - 0.60, p<0.01, N=63) (see Discussion of results).

TABLE V.1. Test AUC-values of all 63 ecological niche models classified according to SWETS (1988)

Test AUC-value	Model performance	Absolute number of species	Percentage of species
> 0.9	Good	9	14.3
0.9 > test AUC < 0.7	Useful	36	57.1
< 0.7	Poor	18	28.6

18 modeled species showed a potential distribution in the lowest parts of the humid broadleaf/gallery forest areas with mean altitudes of 951 m a.s.l. (Appendix V.A). The mean altitude of the humid broadleaf/gallery forests derived by ordination of the floristic data of 121 plots was 979 m a.s.l. (Chapter IV.3.1). An example for a species restricted to the lowest parts of the humid broadleaf/gallery forest was *Tetragastris balsamifera* (Figure V.1a). Figure V.1a also contains the annual mean isotherm of 20.2˚C of humid broadleaf/gallery forests derived by ordination (Chapter IV.3.1). *Tetragastris balsamifera* was modeled as present on 73.3 km^2 along the northern and north-western border of the national park south of the villages La Diferencia, Los Ramones and Loma El Copey. Altitude contributed with 100% to the model (Table V.2). Other species with similar patterns were: *Clusia rosea*, *Inga vera*, *Guarea guidonia*, *Dendropanax arboreus*, *Trichilia pallida*, *Eugenia domingensis*, *Eugenia odorata* and *Casearia sylvestris*, amongst others (Appendix V.A). Lauraceae and Meliaceae were the species-richest families at these altitudes, each with two species in one genus (*Ocotea* (2), Lauraceae) and in two genera (*Guarea*, *Trichilia*, Meliaceae).

25 models presented potential distributions in the entire area of the humid broadleaf/gallery forests extending slightly into the transition zone between humid broadleaf and cloud forests with mean elevations of 1,098 m a.s.l. (Appendix V.A). The example for this group was *Beilschmiedia pendula*. Its distribution extended around the annual mean isotherm of 20.2˚C of the humid broadleaf/gallery forests derived by ordination (Chapter IV.3.1) (Figure V.1b). The area modeled as present was of 246.2 km^2 following the main rivers and adjacent slopes along the northern border.

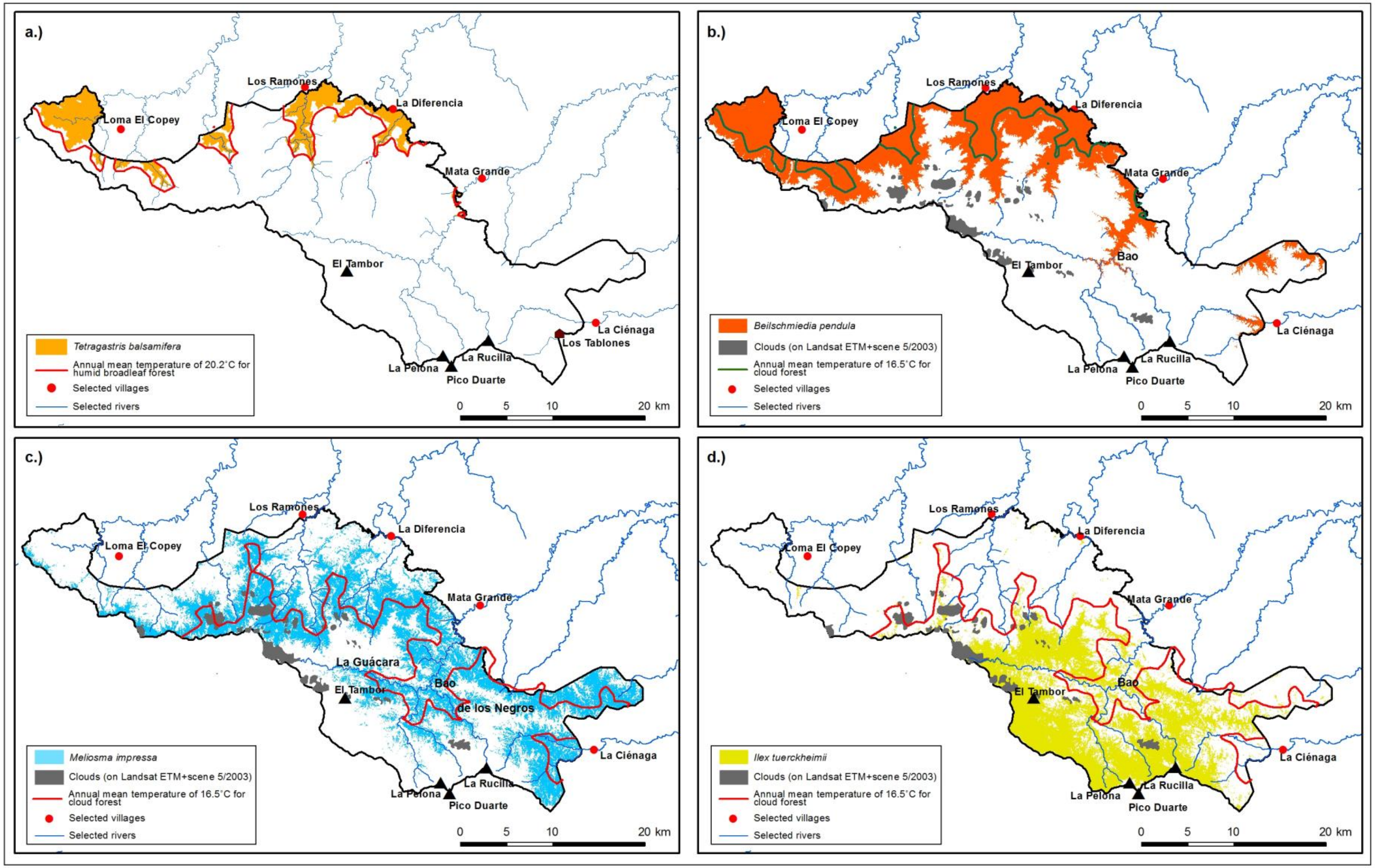


FIGURE V.2. Modeled distribution of *Tetragastris balsamifera*, *Beilschmiedia pendula*, *Meliosma impressa* and *Ilex tuerckheimii* (Source: Maxent models; Annual mean temperature (Worldclim) for forest types determined by ordination (Chapter IV.3.1); Boundaries Law 64-00; Villages, rivers, peaks from topographic maps 1:50,000, ICM 1983/1984 and field work)

Main contributor to the model was altitude (Table V.2). *Alchornea latifolia*, *Cecropia schreberiana*, *Chionanthus domingensis*, *Gomidesia lindeniana*, *Ilex microwrightioides*, *Turpinia occidentalis* and *Ocotea globosa* had similar patterns like *Beilschmiedia pendula* (Appendix V.A). The families with the highest number of species in this group were Lauraceae and Melastomataceae. Lauraceae were represented with four species in three genera (*Beilschmiedia*, *Cinnamonum*, *Ocotea* (2)), Melastomataceae with two species in one genus (*Miconia* (2)).

15 species were modeled in the area of the cloud forests with a mean altitude of 1,507 m a.s.l. (Appendix V.A). Mean altitude of the cloud forest derived by ordination was 1,527 m a.s.l. (Chapter IV.3.1). The distribution of the endemic species *Meliosma impressa* represented the group of cloud forest species (Figure V.1c). The prediction for *Meliosma impressa* was made mainly in the center of the national park along the annual mean isotherm of 16.5˚C which had been found as annual mean temperature for the cloud forest by ordination (Chapter IV.3.1). The model was built with 58.5% on the altitudinal and 41.5% on the NDVI information (Table V.2). Other species modeled in the cloud forest were for example: *Cyrilla racemiflora*, *Clusia clusioides*, *Brunellia comocladifolia* subsp. *domingensis*, *Schefflera tremula*, *Haenianthus salicifolius* subsp. *obovatus*, *Torralbasia cuneifolia* and *Ditta maestrensis*.

Each of the families Bignoniaceae (*Tabebuia* (2)), Melastomataceae (*Miconia* (2)) and Lauraceae (*Ocotea*, *Persea*) were represented with two species in the cloud forest while all other families were only represented with one (Appendix V.A).

The modeled distribution of the endemic species *Ilex tuerckheimii* (Aquifoliaceae) represented one of three species predicted with mean altitudes of 1,853 m a.s.l. to the upper cloud and pine forest areas (Appendix V.A). 235.1 km^2 were predicted as present for *Ilex tuerckheimii* mainly above the cloud forest annual mean temperature isotherm of 16.5˚C (Chapter IV.3.1) and in the Bao valley also below it (Figure V.1d). NDVI was the main contributor to the model (85.8%). The other two woody species predicted in this group were *Weinmannia pinnata* (Cunoniaceae) and *Garrya fadyenii* (Garryaceae).

Two species showed a wide distribution over the entire altitudinal range: *Pinus occidentalis* (Pinaceae) and *Myrsine coriacea* (Primulaceae).

The predictions of the example species for the four modeling results (*Beilschmiedia pendula*, *Tetragastris balsamifera*, *Meliosma impressa*, *Ilex tuerckheimii*) were significant on a confidence level of 95% (Table V.2).

TABLE V.2. Test AUC-values, areas predicted present and absent, p-values and relative contributions of environmental factors to the four presented Maxent models

Species	**Test AUC**	**Area predicted present* (km^2)**	**Area Predicted absent* (km^2)**	**P-value* (one-sided)**	**Mean predicted altitude (m)**	**Contribution to model**	
						DEM (%)	**NDVI (%)**
Beilschmiedia pendula	0.730	246.2	543.8	1.0 E-4	1,045	96	4
Tetragastris balsamifera	0.964	73.3	716.7	1.2 E-7	832	100	0
Meliosma impressa	0.765	278.4	511.6	2.2 E-3	1,485	58.5	41.5
Ilex tuerckheimii	0.780	235.1	554.9	4.7 E-2	1,984	14.2	85.8

* Logistic equal test sensitivity and specificity threshold

V.3.2 Patterns and characteristics of woody species richness

The species-richest families of the entire gradient were Lauraceae with eight species in four genera (*Beilschmiedia*, *Cinnamonum*, *Ocotea* (5), *Persea*) and Myrtaceae with six species in four genera (*Eugenia* (2), *Gomidesia*, *Myrcia* (2), *Syzigium*). Woody species richness correlated highly negative with altitude (Pearson, r=-0.83, p<0.001, N=878628, all 30 x 30 m pixels in study area). Figures V.3 and V.4 explain the decline of woody species richness with increasing elevation. The curve in Figure V.4 started with a plateau with the highest mean woody species richness values at lower elevations of 500 and 1,100 m a.s.l.. Above 1,100 m a.s.l. a strong decline followed until reaching 1,500 m a.s.l.. From 1,500 m a.s.l. on the curve fell gradually. Lowest mean woody species numbers were recorded between 2,900-3,087 m a.s.l.. For the area of predicted distribution of the humid broadleaf/gallery forests of Chapter IV.3.3 a mean of 38.8 woody species was calculated while the predicted cloud and pine forests had averages of 10.5 and 9.6 woody species respectively.

The highest absolute woody species richness (51-53 woody species) was predicted between 550-1,084 m a.s.l. around a mean altitude of 948 m a.s.l. within the humid broadleaf/gallery forests on only 7.9 km^2 (Table V.3). 180.3 km^2 of the surface of the national park showed a woody species richness of over 30 woody species, coinciding spatially with the lower parts of the protected area (479-1,272 m a.s.l.) (Figure V.3, Table V.3).

The lowest woody species richness (1-5 woody species) was modeled between 1,294-3,041 m a.s.l. at a mean altitude of 2,167 m a.s.l. in the highest cloud and pine forests on 109.3 km^2 (Table V.3). 6-10 species per cell were predicted between 1,208-2,567 m a.s.l. with a mean of 1,806 m a.s.l. and 11-20 woody species at elevations between 1,079-2,142 m a.s.l. with a mean of 1,528 m a.s.l. (Table V.3).

TABLE V.3. Woody species richness, altitudinal parameters and predicted area size (in km^2)

Woody species richness	Altitude (m a.s.l.) minimum-mean-maximum	Altitudinal Range (m)	Area (km^2)
1-5 species	1,294-2,167-3,041	1,747	109.3
6-10 species	1,208-1,806-2,567	1,359	172.2
11-20 species	1,079-1,528-2,142	1,063	247.2
21-30 species	496-1,228-1,394	898	72.6
31-40 species	479-1,017-1,272	793	80.7
41-50 species	479-968-1,202	723	91.7
51-53 species	550-948-1,084	534	7.9
Sum			781.6*

* 8.4 km^2 were predicted without any species

21-30 woody species per cell were counted in the humid broadleaf/gallery forest and the transition zone to the cloud forests (496-1,394 m a.s.l.) (Table V.3, Figure V.3).

The plant family Lauraceae contributed with two to six species in each of the seven woody species richness classes over all altitudes (479-3,041 m a.s.l.) (Tables V.3 and V.4.). Lauraceae, Ericaceae and Aquifoliaceae were the woody species-richest families in classes with few woody species (< 11 species) at altitudes of 1,208-3,041 m a.s.l.. Species-rich areas in the lower parts of the national park (> 30 species) were characterized by the presence of species of the families Lauraceae, Myrtaceae, Melastomataceae and Euphorbiaceae. The family Lauraceae counted five and six woody species in areas with more than 40 species at an altitude between 479 and 1,084 m a.s.l. (Tables V.3 and V.4). Tables V.3 and V.4 resume the decrease of species within the main families and of family diversity with increasing altitude.

V.3.3 Patterns and characteristics of woody species endemism

The majority of endemic woody species per family of the field database were counted in the families Ericaceae and Bignoneaceae. Both families had three endemic species in one genus each: *Lyonia* for the Ericaceae family and *Tabebuia* for the Bignoneaceae family (Appendix V.A). The families Aquifoliaceae, Araliaceae, Brunelliaceae, Euphorbiaceae, Pinaceae, Podocarpaceae, Sabiaceae and Symplocaceae were present with one endemic woody species. Nine of the 13 endemic woody species layers showed mean altitudinal predictions between 1,368 m a.s.l. (*Pinus occidentalis*) and 1,984 m a.s.l. (*Ilex tuerckheimii*) and four between 968 m a.s.l. (*Tabebuia bullata*) and 1,246 m a.s.l. (*Tabebuia berteroi*) (Appendix V.A).

TABLE V.4. Woody species richness classes and main families

Woody species richness classes	Families represented by				
	five to six species	**four species**	**three species**	**two species**	**one species**
1-5 species					Aquifoliaceae, Cunoniaceae, Garryaceae, Ericaceae
6-10 species				Lauraceae	Ericaceae, Bignoniaceae, Cunoniaceae, Celastraceae, Podocarpaceae, Oleaceae, Euphorbiaceae
11-20 species				Ericaceae, Lauraceae	Clusiaceae, Araliaceae, Sabiaceae, Brunelliaceae, Podocarpaceae, Primulaceae, Cyrillaceae, Oleaceae, Polygonaceae
21-30 species		Lauraceae		Aquifoliaceae	Cannabeaceae, Staphyleaceae, Arecaceae, Rubiaceae, Myrtacaea, Rosaceae, Cyrillaceae, Sapindaceae, Araliaceae, Malpighiceae, Polygonaceae, Bignoniaceae, Melastomataceae
31-40 species		Lauraceae	Euphorbiaceae	Melastomataceae	Rosaceae, Cannabeaceae, Staphyleaceae, Elaeocarpaceae, Urticaceae, Myrtaceae, Sapindaceae, Annonaceae, Symplocaceae, Araliaceae, Rubiaceae, Malpighiaceae
41-50 species	Lauraceae		Myrtaceae	Melastomataceae, Euphorbiaceae	Rosaceae, Urticaceae, Elaeocarpaceae, Annonaceae, Symplocaceae, Cannabeaceae, Staphyleaceae, Araliaceae, Bignoniaceae, Sapindaceae
51-53 species	Lauraceae	Myrtaceae		Euphorbiaceae, Melastomataceae	Urticaceae, Clusiaceae, Araliaceae, Annonaceae, Fabaceae, Sapindaceae, Rosaceae, Elaecarpaceae, Symplocaceae, Bignoniaceae, Cannabeaceae, Staphyleaceae

The curve of mean species richness in relation to elevation classes showed a hump-shaped pattern with a maximum mean number of endemic woody species in the cloud forest zone between 1,500-1,700 m a.s.l. (Figure V.5). Values decreased to both sides, but much more pronounced towards the highest elevations. At around 1,300 and 1,200 m a.s.l. the decrease in the mean number of endemic woody species stopped and remained nearly constant in all following elevation classes.

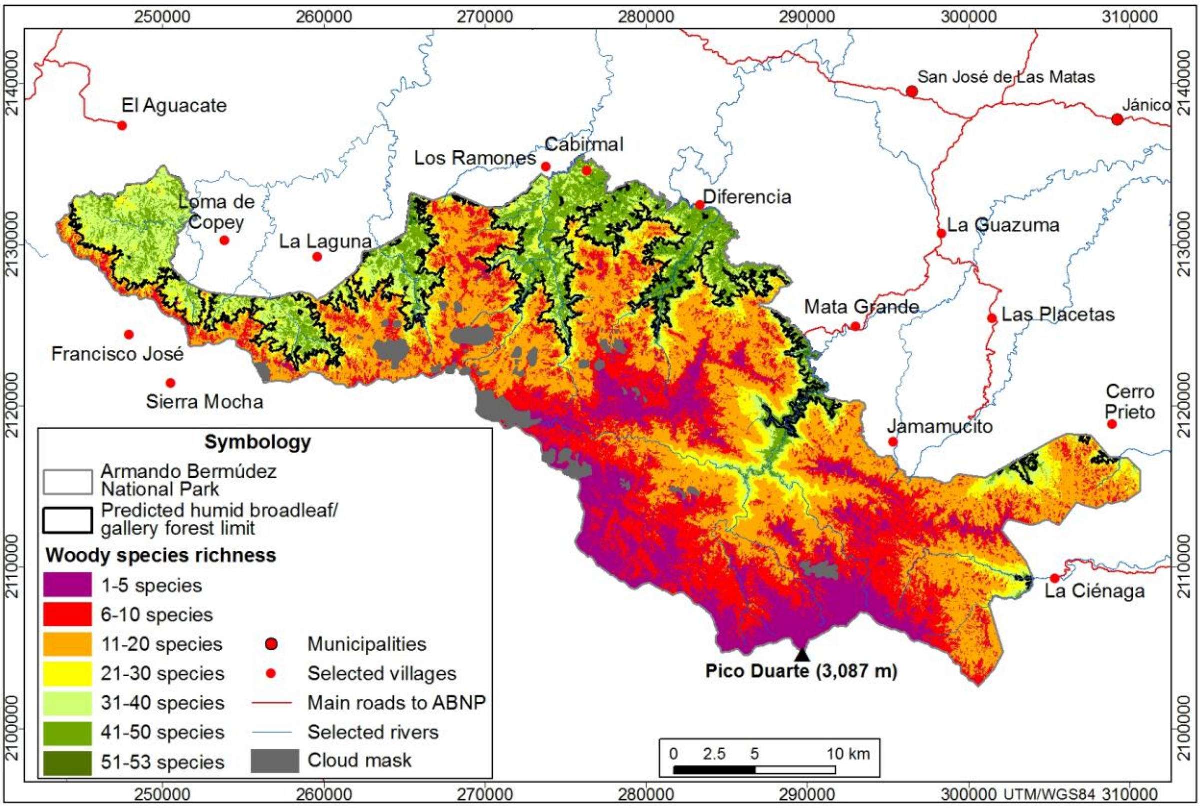


FIGURE V.3. Woody species richness pattern in Armando Bermúdez National Park (Source: Stacked Maxent predictions; Humid broadleaf/gallery forest limit vectorized from Maxent prediction of forest types (Chapter IV.3.3); Boundaries of ABNP from Law 64-00; Villages, roads, trails, peak from topographic maps 1:50,000, ICM 1983/1984 and field work)

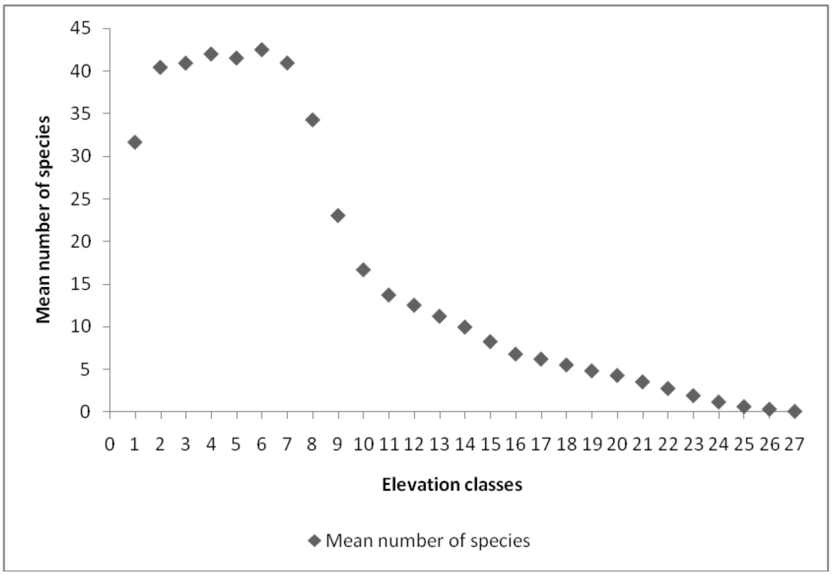


FIGURE V.4. Mean number of woody species in relation to elevation

Elevation classes (in m a.s.l.): 1 (400-500), 2 (500-600), 3 (600-700), 4 (700-800), 5 (800-900), 6 (900-1,000), 7 (1,000-1,100), 8 (1,100-1,200), 9 (1,200-1,300), 10 (1,300-1,400), 11 (1,400-1,500), 12 (1,500-1,600), 13 (1,600-1,700), 14 (1,700-1,800), 15 (1,800-1,900), 16 (1,900-2,000), 17 (2,000-2,100), 18 (2,100-2,200), 19 (2,200-2,300), 20 (2,300-2,400), 21 (2,400-2,500), 22 (2,500-2,600), 23 (2,600-2,700), 24 (2,700-2,800), 25 (2,800-2,900), 26 (2,900-3,000) and 27 (3,000-3,087)

Figure V.6 shows the spatial endemism patterns in Armando Bermúdez after summing up the 13 endemic woody species distribution predictions.

Low endemic woody species numbers (1-3) were predicted to high elevations above 2,000 m a.s.l. and also inside the limits of the humid broadleaf/gallery forest in the western part of the protected area and in the Magua River valley south of Los Ramones. Comparable high endemic species values inside the humid broadleaf/gallery forests were obtained south of the villages Cabirmal and La Diferencia along the northern border (Figure V.6).

The areas with one to four endemic woody species covered 55.5% of the entire area predicted with endemic species. The peak of endemism was reached with modeled nine species per cell at a mean altitude of 1,426 m a.s.l. (Table V.5). Nine endemic woody species occurred on 5.8 km^2. Seven to eight endemic woody species were predicted mainly along the Bao River around 1,359 m a.s.l. on 137.9 km^2 (Table V.5). The altitudinal range of the areas with seven to nine endemic woody species was considerably narrower than the ones of less than seven endemic species. Above 2,931 m a.s.l. either one of the two endemic woody species *Pinus occidentalis* or *Ilex tuerckheimii* were predicted present on 83.6 km^2.

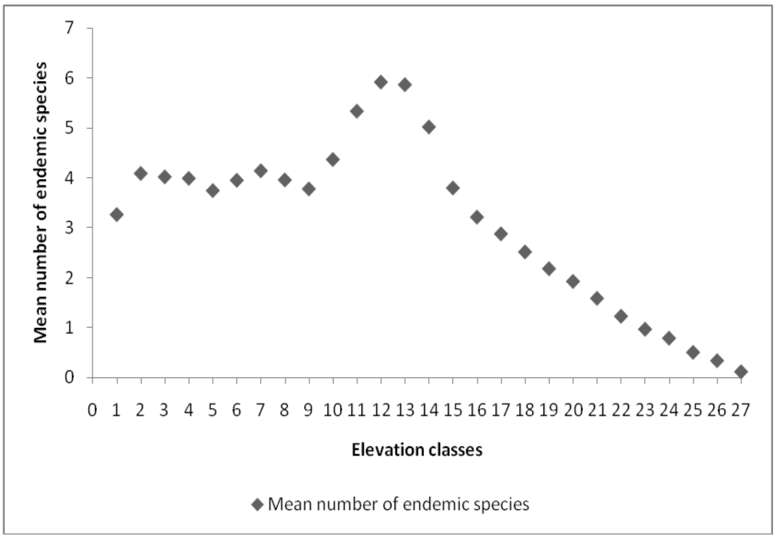


FIGURE V.5. Mean number of endemic woody species in relation to elevation (elevation class values see Figure V.4)

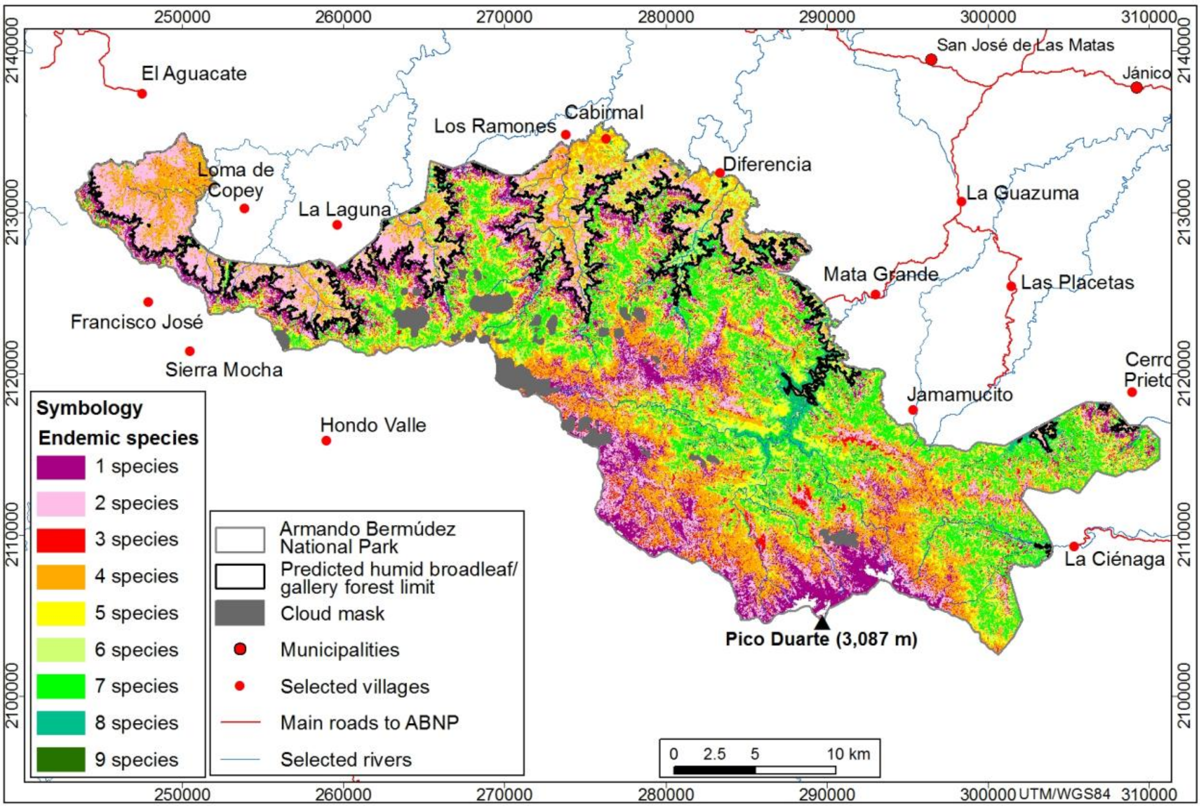


FIGURE V.6. Endemic woody species pattern in Armando Bermúdez National Park (Source: Stacked Maxent predictions for endemic species; Humid broadleaf/gallery forest limit vectorized from Maxent prediction of forest types (Chapter IV.3.3); Boundaries of ABNP from Law 64-00; Villages, roads, trails, peak from topographic maps 1:50,000, ICM 1983/1984 and field work); White areas: predicted without any endemic woody species

TABLE V.5. Endemic species, altitudinal parameters and predicted area size (in km^2)

Endemic woody species	**Altitude (m a.s.l.) minimum-mean-maximum**	**Altitudinal range (m)**	**Area (km^2)**
1 species	1,079-1,838-3,041	1,962	83.6
2 species	496-1,511-2,931	2,434	147.1
3 species	496-1,697-2,573	2,076	48.9
4 species	479-1,555-2,527	2,048	147.9
5 species	479-1,464-2,224	1,745	101.8
6 species	513-1,380-2,094	1,581	99.9
7 species	558-1,483-1,981	1,423	113.6
8 species	550-1,235-1,577	1,026	24.3
9 species	634-1,426-1,528	893	5.8
Sum			772.9*

* 17.1 km^2 were predicted without any endemic species

V.4 DISCUSSION OF RESULTS

V.4.1 Niche modeling results of sampled woody species

Of the 63 ecological niche models 71.4% (45) had a test AUC-value larger than 0.7. Relationships between quality of the model (here: test AUC-value) and sample sizes as found by PETERSON (2001) could not be proved. However, the highly negative correlation between test-AUC-values and species distribution range suggested the missing of meaningful environmental parameters for species with large distribution ranges besides our used parameters altitude and NDVI (Pearson, r=-0.60, p<0.01, N=63). GUISAN et al. (2007) found that species with narrow distributions tend to be better modeled. Model performance is also influenced by species' traits such light requirements, frost and drought tolerance and also competitive strength (GUISAN et al. 2007). It is assumed that high resolution spatially explicit data (30 x 30 m as DEM) on air temperature (annual mean temperature, average temperature of the coldest month, amount of frost events), precipitation, air humidity (relative humidity) and soil moisture could improve the modeling results (WANGDA & OSHAWA 2010). Convex-shaped or concave shaped terrain variables were explaining factors for species occurrences in the eastern part of the Cordillera Central (SHERMAN et al. 2005). In our study eight of the nine models with "good" AUC-values were obtained for species of the humid broadleaf/gallery forest. More than half of the "poor" AUC-values could be identified for species of the cloud forests, the rest for species of the humid broadleaf/gallery forests and transition to cloud forests.

The environmental parameter altitude was used as a proxy for temperature and precipitation and was the main contributor to the Maxent models of the 18 niche models of the lower parts of the humid broadleaf/gallery forests. Here altitude contributed with over 90% (mean: 98.8%) to all models and NDVI had a mean contribution of 1.1%. In the 25 models of the humid broadleaf/gallery forests and lower transition zone to the cloud forest altitude accounted for more than 68% to all models. Mean contribution of NDVI was 8.9%.

In the models of the species predicted to the cloud and pine forest, NDVI gained importance as altitude alone was not sufficient to explain the distribution patterns. Mean contribution of altitude here was 35.9% and of the NDVI 64.1%. NDVI values were lower in the cloud and especially pine forests compared to the values obtained in the humid broadleaf forests, indicating a lower biomass production at these altitudes (Chapter IV.3.1). The models of the high elevation species of *Garrya fadyenii* and *Ilex tuerckheimii* were composed to 90.6% and 85.7% by NDVI information. The geographic predictions of the models were classified in four groups: species of low altitudes in humid broadleaf/gallery forests (mean altitude:

951 m a.s.l.) close to the northern border of the national park, species of the humid broadleaf/gallery forest and lower transition zone to cloud forests (mean altitude; 1,098 m a.s.l.), species predicted to the cloud forests (mean altitude: 1,507 m a.s.l.) and species predicted to the cloud and pine forests (1,853 m a.s.l.). P-values of the applied logistic equal test sensitivity and specificity threshold ranged from 2.3E-9 to 6.0E-2.

As species distribution maps had not been elaborated in the Dominican Republic before, the modeled predictions were evaluated by comparing the mean modeled altitude to the written altitudinal information or respective forest type found in literature (Table V.6). Altogether 23 of the 63 modeled species distributions could be related to studies realized in the Cordillera Central by the following authors: HAGER & ZANONI (1993), ZANONI (1993), MAY (1997a), SHERMAN et al. (2005), MARTIN et al. (2007) and PEGUERO et al. (2007). All of the 23 listed species coincided with the forest types given by PEGUERO et al. (2007) regarding their mean altitudinal distribution value. When comparing the altitudinal means to the elevation values, they also matched in general. However, comparison was hampered by the different elevation parameters given in literature, appearing as a mixture of core distribution ranges, absolute distribution ranges, means and lower and upper distribution limits.

Additionally mean altitudinal distribution of ten of the woody species of Table V.6 were compared with the indicator species extracted for the 121 plots and four modeled forest types in Chapter IV.3.2. The indicators species of Chapter IV.3.2 are listed with their respective forest type in Appendix IV.1.

All ten woody species showed mean altitudinal distribution prediction values consistent with the species determined as indicator species analysis in the four modeled forest types (Chapter IV.3.2 and Appendix IV.A).

It is assumed that the general patterns of the modeled woody species are realistic as they match with the field impressions and with the documented information. Local variations are possible and the introduction of more meaningful high resolution environmental factors could deliver improved results.

Table V.6. Comparison of the modeled altitudinal means and the documented altitudinal values and forest types of selected species (different authors)

Species	**Modeled Mean altitude**	**Forest types of indicator species analysis***	**Hager & Zanoni (1993) and Zanoni (1993)**	**May (1997a)**	**Sherman et al. (2005)**	**Martin et al. 2007**	**Peguero et al. (2007)****
Beilschmiedia pendula	1,045	HBF/GF					HBF/GF
Brunellia comocladifolia	1,411	CF	around 1,500		core range 1,120-2,200	1,100-2,250	CF
Clusia clusioides	1,490	CF			core range 1,120-2,200	1,100-2,00	CF
Cupania Americana	962						HBF
Cyrilla racemiflora	1,283	CF		> 900			CF
Dendropanax arboreus	999	HBF/GF	650-1,500				HBF/GF
Ditta maestrensis	1,779	CF				1,300-2,200	CF
Garrya fadyenii	1,766		up to 3,100		core range 1,700-2,100	1,250-2,600	CF/PF
Gomidesia lindeniana	1,167	HBF/GF	650-1,500				
Guarea guidonia	942	HBF/GF					HBF/GF
Haenianthus salicifolius	1,749	CF		> 900			CF
Ilex tuerckheimii	1,984						CF/PF
Inga vera	962				< 1,300		HBF/GF
Meliosma impressa	1,485					1,000-2,250	
Persea krugii	1,696						CF
Podocarpus aristulatus	1,764		1,800-2,200	> 1,500	core range 1,900-2,200	1,650-2,300	CF
Prestoea montana	1,160		600-1,250 (max 1,775)	800-1,500	core range 1,300-1,500	1,150-1,700	HBF/GF/CF
Schefflera tremula	1,546	CF	> 900	> 800		1,400-2,100	CF
Sloanea ilicifolia	1,021		650-1,500	< 1,500/1,600			CF
Syzigium jambos	960				< 1,300		HBF/GF
Tabebuia berteroi	1,246		around 1,200			1,100-1,900	HBF/GF
Tabebuia vinosa	1,818		> 1,500			1,550-2,250	CF
Weinmannia pinnata	2,024		up to 2,500			1,500-2,500	CF/PF

*Indicator species analysis results of forest types taken from Chapter IV.3.2 and Appendix IV.A (blank fields in this column represent species not determined as indicator species in Chapter IV.3.2)

**HBF: Humid broadleaf forest, GF: Gallery forest, CF: Cloud forest, PF: Pine forest, MF: Mixed Forest

V.4.2 Woody species richness and endemism

Woody species richness

To evaluate the influence of model quality expressed by AUC-value on the identified species richness-elevation relationship, the woody species richness file based on the 63 stacked woody species (with AUC-values > 0.6) and a second file based on the 45 woody species (with AUC-values > 0.7) were compared. Both woody species richness datasets correlated significantly with the mean elevation of the 27 elevation classes (Pearson, r=-0.91, p<0.01, N=27 for models with AUC > 0.6 and Pearson, r=-0.85, p<0.01, N=27 for models with AUC > 0.7). The courses of the two graphs also coincided, although parting from different maximum species numbers (42.4 mean maximum woody species for the dataset with AUC-value > 0.6 and 36.2 mean maximum woody species for dataset with AUC-value > 0.7). As the general trend regarding the decrease of species richness with elevation was similar in both datasets, the species richness file based on the 63 predictions was accepted for further analysis.

The elevation range of the modeled predictions reached from 495-3,087 m a.s.l.. Maximum woody species richness was modeled in the study area between 500 and 1,100 m a.s.l. with 51-53 species per pixel (size: 30 x 30 m) and minimum woody species richness between 2,900-3,087 m a.s.l. with 1-5 woody species. The decreasing trend of woody species richness along the altitudinal gradient found here (Figure V.4) was consistent with the findings made in neotropical mountain forests by other authors like GENTRY (1995) in South America, Central America and Mexico, VÁZQUEZ & GIVNISH (1998) in Mexico and HOMEIER (2008) in Ecuador. Here the pattern of the curve did not indicate a linear decline, but rather implied a plateau at the beginning of the curve between 500 and 1,100 m a.s.l.. As samples below 400 m a.s.l. (outside of the national park) were not taken, the continuation of the curve at low elevations could not be given.

HEMP (2010) observed two peaks (humps) of tree species diversity at 1,000 m a.s.l. and 1,800 m a.s.l. on Mount Kilimanjaro and hypothesized that the gap in species richness was related to human influence in the area. RAHBEK (1995) hypothesized that the hump-shape curve of species richness along elevation gradients might have its cause in a stable water supply due to increasing precipitation patterns in many tropical mountains until certain elevations.

In Armando Bermúdez National Park the water supply is not yet at its peak between 500-1,100 m a.s.l. (Worldclim precipitation model, Chapter IV.3.1) so that we assume that the combination of the area-effect, the still high annual mean temperatures (19˚C at 1,100 m a.s.l., Worldclim data), less acid soil conditions (Chapter IV.3.1) and a sufficient water supply might be an explanation for the high woody species richness values between 500-1,100 m a.s.l.. Undoubtedly plant species richness is related to environmental conditions (VÁZQUEZ & GIVNISH 1998), being climate a strong predictor (CAYUELA et al. 2006; KREFT & JETZ 2007). High annual energy input with constant water supply and high spatial heterogeneity accurately predicted global centers of plant richness (KREFT & JETZ 2007). In the study area further research with high resolution climate, soil and disturbance data is necessary to identify the mechanisms and processes that determine species richness along the altitudinal gradient.

The observation of decrease in family richness and taxonomic richness at the genus and family level with increasing altitude was consistent with results made by SHERMAN et al. (2005) in the eastern part of the Cordillera Central, by GENTRY (1988, 1995) in South and Central America and LIEBERMAN et al. (1996) in Costa Rica. Lauraceae was the species-richest family here, followed by Myrtaceae (low to medium elevations), Euphorbiaceae (low to medium elevations), Melastomataceae (low to medium elevations), Aquifoliacea (medium to high elevations) and Ericaceae (medium to high elevations). Similar findings were made by HOMEIER (2008) in Ecuador and GENTRY (1995) in the Andes, where Lauraceae was the most species-rich family, followed by Melastomataceae and Rubiaceae above 1,500 m a.s.sl.. Below 1,500 m a.s.l. Lauraceae occupied the second or third place in the Andes and the family Euphorbiaceae was genera rich.

Richness of non-woody-taxa, such as of epiphytes for example, would show a different pattern along the altitudinal gradient of mountain forests with increasing species richness up to the humid cloud forests (HEMP 2010). Epiphytic richness is worth being studied in Armando Bermúdez National Park.

CAYUELA et al. (2006) predicted tree species richness in tropical mountain landscapes based on generalized linear models and GIS-processed explanatory spatial data, amongst them NDVI and NDVI-within site heterogeneity (created by a standard deviation filter). GILLESPIE (2005) used landscape metrics and NDVI to predict stand and patch-level species richness in tropical dry forests. BAWA et al. 2002 found a positive relationship between NDVI and species richness of different forest types in India. In our dataset correlation between NDVI and amount of predicted woody species was also significant (Pearson, r=0.41, p<0.001, N=878628, all 30 x 30 m pixels in study area).

It is assumed that the general woody species richness pattern along the altitudinal gradient was modeled well due to consistency of the results with field impression and findings of other authors in neotropical mountain forests.

Endemism

The curve of mean endemic woody species numbers showed a hump-shaped pattern at medium altitude, consistent with findings made by BORHIDI (1996) and KESSLER (2002) in neotropical mountain forests. The maximum mean number of endemic species was predicted between 1,500 and 1,700 m a.s.l. in the cloud forest zone, the minimum number above 2,000 m a.s.l. at the highest elevations of the national park in the pine forests.

High levels of endemic woody species in areas of low human disturbance were modeled close to the villages Cabirmal and La Diferencia and have also been found by KESSLER et al. (2001) in Bolivia. The authors hypothesized that many endemic species must be adapted well to disturbances as montane forests are often exposed to landslides and tree fall (KESSLER et al. 2001).

BORHIDI (1996) described that absolute endemic species numbers increased in Cuba on Pico Turquino until 1,500 m a.s.l. and then declined sharply (BORHIDI 1996). According to GENTRY (1992), BORHIDI (1996), MAY (2001) and KESSLER & KLUGE (2008) the mountainous areas of mean elevation and rugged topography favor the speciation of endemics. However with increasing altitude the climatic and edaphic conditions become extreme with low mean temperatures, high solar radiation, shallow, nutrient poor soils and changes in precipitation patterns. BOLAY (1997) stated that cold air masses during winter can produce temperatures below zero above 2,000 m a.s.l. in the Cordillera Central (Chapter II.3.2).

V.4.3 Implications for management

A conservation plan for the species-rich areas of the lower part of the national park should be set up soon as these areas are also threatened by human impacts. During field work cut trunks of *Pera bumelifolia* and *Popocarpus hispaniolensis* were seen along the trails. Additionally, on the aerial photograph mosaic small fields and coffee plantations were observed in the species-rich lower elevations of the national park along the northern border.

The endemic-rich cloud forests also requires special attention as the occurrence of the cloud forest species is limited to the few high mountains of the Dominican Republic (Cordillera Central, Sierra de Bahoruco and Sierra de Neiba). Destruction of areas with high numbers of endemic or non-endemic species with a restricted distribution areal can lead to extinction of many other species and reduce diversity (MAY 1997c).

The here generated datasets about woody species richness and endemism can serve as an input to modify or revise the existing zoning plan of the national park. The data can also be used for ecological modeling and sensitivity analysis of single species, biodiversity and endemism to environmental change.

Permanent plots have to be established in different altitudinal belts inside the protected area for long-term observation of the floristic compositions to monitor possible changes on species distributions or diversity and endemism patterns and assess the conservation efforts.

V.5 CONCLUSION

Based on field samples 63 distribution models of woody species of Armando Bermúdez National Park were set up with the explanatory factors altitude obtained by a digital elevation model and the Normalized Difference Vegetation Index (NDVI) derived from a Landsat 7 ETM+ image. The Worldclim climatic data raster format could not be used as the resolution was too low for modeling the niches of individual species. Characteristic species for the humid broadleaf/gallery forest, humid broadleaf/gallery forest and transition zone, cloud forest and high elevation cloud and pine forests were identified with their respective families.

Predicted species richness was highest at elevations between 500-1,100 m a.s.l. and then decreased sharply. Endemism patterns in Armando Bermúdez National Park showed a hump-shaped curve with largest endemism numbers in the cloud forests around 1,500 m a.s.l..

It is concluded that this study contributed to an improved understanding about the patterns of woody species, woody species richness and endemism of woody species in a tropical mountain protected area. Our results provide important input for the formulation of adequate management strategies and for further ecological modeling approaches.

APPENDIX V.

APPENDIX V.A. 66 woody species and 37 families used for modeling with Maxent (included the three model results with AUC < 0.6)

Family/Species	Common Name	Lifeform	Status	Occurrence points	Test AUC	Interpretation AUC*	Mean altitude (m a.s.l.)	Forest Type**
Annonaceae								
Guatteria blainii (Griseb.) Urb.	Yaya prieta	T	N	63	0.839	Useful	990	HBF
Aquifoliaceae								
Ilex tuerckheimii Loes.		T	E	48	0.780	Useful	1,984	CF/PF
Ilex macfadyenii (Walp.) Rehder		T	N	104	0.690	Poor	1,201	HBF/THBCF
Ilex microwrightioides Loes.		T	N	79	0.631	Poor	1,117	HBF/THBCF
Araliaceae								
Dendropanax arboreus (L.) Decne. & Planch.	Palo de burro	T	N	54	0.818	Useful	999	HBF
Oreopanax capitatus (Jacq.) Decne & Planch.	Palo de viento	T	N	189	0.673	Poor	1,224	HBF/THBCF
Schefflera tremula (Krug & Urb.) A. H. Liogier	Palo de viento	T	E	93	0.697	Poor	1,546	CF
Arecaceae								
Prestoea montana (Graham) G. Nicholson	Manacla	ST	N	125	0.710	Useful	1,160	HBF/THBCF
Bignoniaceae								
Tabebuia berteroi (DC.) Britton	Aceituno	T	E	108	0.839	Useful	1,246	CF
Tabebuia bullata A. H. Gentry	Yaguasa	T	E	68	0.862	Useful	968	HBF
Tabebuia vinosa A. H. Gentry	Palo de yuca	T	E	34	0.663	Poor	1,818	CF
Brunelliaceae								
Brunellia comocladifolia subsp. *domingensis* Cuatrec.	Sangre de gallo	T	E	260	0.647	Poor	1,411	CF
Burseraceae								
Tetragastris balsamifera (Sw.) Oken	Amacey	T	N	38	0.964	Good	832	HBF
Cannabeaceae								
Trema micrantha (L.) Blume	Memiso de paloma	T	N	75	0.734	Useful	1,147	HBF/THBCF
Celastraceae								
Torralbasia cuneifolia (C. Wright ex Griseb.) Krug. & Urb.	Palo amarillo	T	N	46	0.715	Useful	1,815	CF
Clusiaceae								
Clusia clusioides (Griseb.) D'Arcy	Copeyito	T	N	128	0.633	Poor	1,490	CF
Clusia rosea Jacq.	Copey	T	N	51	0.920	Good	942	HBF

Family/Species	**Common Name**	**Lifeform**	**Status**	**Occurrence points**	**Test AUC**	**Interpretation AUC***	**Mean altitude (m a.s.l.)**	**Forest Type****
Cunoniaceae								
Weinmannia pinnata L.	Tamarindo de loma	S	N	43	0.760	Useful	2,024	CF/PF
Cyrillaceae								
Cyrilla racemiflora L.	Granado	T	N	132	0.689	Poor	1,283	CF
Elaeocarpaceae								
Sloanea ilicifolia Urb.	Chicharrón	T	N	85	0.796	Useful	1,021	HBF/THBCF
Ericaceae								
Lyonia buchii Urb.	Palo de reina	T	E	52	0.685	Poor	1,453	CF
Lyonia stahlii var. *costata* (Urb.) Judd	Palo de reina	T	E	37	0.390	Poor	1,839	CF/PF
Lyonia truncata var. *montecristina* (Urb. & Ekman) Judd	Palo de reina	T	E	84	0.729	Useful	1,190	HBF/THBCF
Euphorbiaceae								
Alchornea latifolia Sw.	Bija macho	T	N	110	0.800	Useful	1,015	HBF/THBCF
Ditta maestrensis Borhidi, Imkhan. & O. Muñiz		T	E	62	0.671	Poor	1,779	CF
Drypetes alba Poit.	Palo blanco	T	N	40	0.811	Useful	1,010	HBF/THBCF
Pera bumeliifolia Griseb.	Hicaco	T	N	77	0.787	Useful	1,043	HBF/THBCF
Fabaceae								
Inga vera Willd.	Guama	T	N	68	0.856	Useful	962	HBF
Garryaceae								
Garrya fadyenii Hook.	Palo amargo	T	N	129	0.650	Poor	1,766	CF/PF
Lauraceae								
Beilschmiedia pendula (Sw.) Hmsl.	Aguacatillo	T	N	138	0.730	Useful	1,045	HBF/THBCF
Cinnamonum grisebachianum Mez	Aguacatillo	T	N	39	0.732	Useful	1,095	HBF/THBCF
Ocotea foeniculacea Mez	Canela	T	N	55	0.583	Poor	1,687	CF
Ocotea floribunda (Sw.) Mez	Cigua laurel	T	N	53	0.840	Useful	987	HBF
Ocotea globosa (Aubl.) Schltr. & Cham.	Aguacatillo	T	N	118	0.762	Useful	1,097	HBF/THBCF
Ocotea leucoxylon (Sw.) Laness.	Aguacatillo	T	N	90	0.750	Useful	1,080	HBF/THBCF
Ocotea patens (Sw.) Nees	Aguacatillo	T	N	33	0.865	Useful	973	HBF
Persea krugii Mez	Cigua canela	T	N	64	0.637	Poor	1,696	CF
Malpighiaceae								
Byrsonima lucida (Miller) DC.	Doncella	T	N	32	0.481	Poor	1,226	HBF/THBCF
Melastomataceae								
Miconia dodecandra Cogn.		T	N	47	0.879	Useful	1,012	HBF/THBCF
Miconia mirabilis (Aubl.) L. O. Williams	Tres filos	T	N	73	0.903	Good	964	HBF

Family/Species	Common Name	Lifeform	Status	Occurrence points	Test AUC	Interpretation AUC*	Mean altitude (m a.s.l.)	Forest Type**
Miconia punctata (Desr.) D. Don ex DC.	Auquey	T	N	59	0.803	Useful	1,040	HBF/THBCF
Meliaceae								
Guarea guidonia (L.) Sleumer	Cabirma	T	N	64	0.879	Useful	942	HBF
Trichilia pallida Sw.	Palo amargo	T	N	39	0.965	Good	903	HBF
Myrtaceae								
Eugenia domingensis O. Berg	Guázara	T	N	36	0.909	Good	963	HBF
Eugenia odorata O. Berg	Escobón	S	N	40	0.846	Useful	965	HBF
Gomidesia lindeniana O. Berg	Aukey	T	N	151	0.703	Useful	1,167	HBF/THBCF
Myrcia deflexa (Poir.) DC.	Auquey chiquito	T	N	83	0.835	Useful	1,002	HBF/THBCF
Myrcia splendens (Sw.) DC.	Escoboncillo	T	N	88	0.692	Poor	1,281	CF
Syzygium jambos (L.) Alston	Pomo	T	Nat	30	0.894	Useful	960	HBF
Oleaceae								
Chionanthus domingensis Lam.	Tarana, Lirio	T	N	79	0.806	Useful	1,032	HBF/THBCF
Haenianthus salicifolius var. *obovatus* (Krug & (Urb.) Knobl.	Cara de hombre	T	N	57	0.759	Useful	1,749	CF
Pinaceae								
Pinus occidentalis Sw.	Pino criollo	T	E	253	0.691	Poor	1,286	MF/PF
Podocarpaceae								
Podocarpus aristulatus Parl.	Caracoli	T	E	46	0.662	Poor	1,764	CF
Polygonaceae								
Coccoloba wrightii Lindau	Chicharroncillo	T	N	57	0.774	Useful	1,331	CF
Primulaceae								
Myrsine coriacea (Sw.) R. Br. ex Roem. & Schult.	Botoncillo cimarrón	T	N	264	0.690	Poor	1,412	HBF/CF/PF
Rosaceae								
Prunus occidentalis Sw.	Almendro	T	N	90	0.694	Poor	1,049	HBF/THBCF
Rubiaceae								
Rondeletia ochracea Urb.		S	N	97	0.669	Poor	1,145	HBF/THBCF
Sabiaceae								
Meliosma impressa Krug & Urb.	Chicharrón bobo	T	E	71	0.765	Useful	1,485	CF
Salicaceae								
Casearia sylvestris Sw.	Cafetillo	T	N	37	0.923	Good	889	HBF
Sapindaceae								
Cupania americana L.	Guarano	T	N	60	0.907	Good	962	HBF
Matayba domingensis (DC.) Radlk.	Nisperillo	T	N	81	0.909	Good	1,074	HBF/THBCF

Family/Species	Common Name	Lifeform	Status	Occurrence points	Test AUC	Interpretation AUC*	Mean altitude (m a.s.l.)	Forest Type**
Sapotaceae								
Chrysophyllum argenteum Jacq.	Caimitillo	T	N	33	0.923	Good	937	HBF
Staphyleaceae								
Turpinia occidentalis (Sw.) G. Don	Violeta cimarrona	T	N	146	0.718	Useful	1,085	HBF/THBCF
Symplocaceae								
Symplocos berteroi Miers	Moradilla	T	E	52	0.749	Useful	988	HBF
Urticaceae								
Cecropia schreberiana Miq.	Yagrumo	T	N	96	0.866	Useful	1,010	HBF/THBCF
Verbenaceae								
Citharexylum discolor Turcz.	Penda	T	N	43	0.802	Useful	1,263	HBF/THBCF

Life form: Tree (T), Shrub (S), Stipe (ST); **Status:** Native (N), Endemic (E), Naturalized (Nat), Introduced (IC)

* According to SWETS (1988); ** According to forest type ranges derived in Chapter IV.3.1, Table IV.1 (HBF: Humid broadleaf forest, THBCF: Transition between humid broadleaf and cloud forest; CF: Cloud forest, MF: Mixed forest, PF: Pine forest)

VI. Final discussion and outlook

The major objective of the study was to create detailed ecological and environmental baseline data about the mountain protected area Armando Bermúdez National Park in the Dominican Republic.

The following topics were assessed in this thesis:

1. Production of a controlled mosaic of 295 digital aerial photographs of the study site and interpretation and analysis of land cover and land use patterns on this base map (Chapter III);
2. Analysis of the floristic composition and vegetation-environment relationships of the main mountain forest types by ordination techniques and spatial prediction of the main forest types applying ecological niche modeling techniques (Chapter IV);
3. Modeling and analysis of the spatial potential distribution of selected woody species, patterns of woody species richness and endemism applying ecological niche modeling techniques (Chapter V).

VI.1 LAND COVER AND LAND USE

Data source

High resolution digital color aerial photographs at a scale of 1:20,000 were used to extract land cover and land use information of Armando Bermúdez National Park. The image data partially contained quality differences, spatial mismatch and brightness variations due to the two different scan methods applied (photogrammetric and non-photogrammetric scanner), due to the two camera systems used in the block and due to the extremely varying exposure dates (Appendix III.A). The photogrammetrical steps had to be refined to overcome the problems caused by the aerial photograph characteristics.

Besides color aerial photographs high resolution digital images like GeoEye-1 or World View-2 are excellent datasets for baseline data generation and monitoring purposes in protected areas regarding their high spectral, spatial and temporal resolutions (DigitalGlobe 2009). However, they cannot be afforded by conservation institutions in developing countries.

An alternative dataset for the extraction of land cover and land use information is represented by digital infrared aerial photographs. Due to the infrared band, differentiation between various land cover types can be improved. Like color aerial photographs, they require extensive photogrammetric processing.

Methodological aspects

Digital photogrammetrical processing of large amounts of digital aerial photographs is very time consuming. Here the automatic tie point extraction routine was hampered by the geometric errors and quality differences of the photos in the block, by the lack of identifiable ground features for GCP sampling and by the homogeneous vegetation cover over large parts of the protected area. Ground control point collection was difficult in the rugged terrain and tie point setting had to be done manually for one third of all tie points. Image dodging techniques were also influenced by the color and brightness differences between the images in the block so that the seam lines could not be eliminated consistently.

The interpretation of the land cover and land use classes was done visually, taking into account field data as reference and the elements of visual image interpretation. The color and brightness differences of the images and the size of the block did not permit the application of an automatic object-oriented approach.

Results

Altogether 13 land cover and land use classes were identified and mapped on the mosaic. The three natural forest classes represented aggregated classes of natural vegetation and can serve as a starting point for a monitoring program. More detailed land cover/land use class differentiation requires image data of homogeneous quality (such as high resolution satellite images).

Human infractions along the northern border make the development of a participative management concept necessary. A long-term monitoring program based on remote sensing is essential for the northern border and for the entire national park to evaluate the effectiveness of the strategies which are to be developed. Field plots must be an integral part of this program to observe the succession of plant species and soil properties on impacted sites and the floristic composition and vegetation structure on natural sites

VI.2 FLORISTIC COMPOSITIONS, VEGETATION-ENVIRONMENT RELATIONSHIPS AND SPATIAL PREDICTION OF THE MAIN FOREST TYPES

Data source

Floristic data used in ordination were sampled on 137 plots along the main trails. The environmental factors were selected according to their potential to explain the differences in composition and patterns of the mountain forests of Armando Bermúdez National Park. Climatic data was available at a resolution of 1 km (Worldclim), all of the other environmental data at a resolution of 30 m.

High resolution data on air temperature and precipitation could improve ordination and modeling results (SORIA-AUZA et al. 2010). Continuous climate surfaces are mostly interpolated from climate station data. Without a dense and homogeneous network of climate stations the spatial interpolation results will be insecure (HIJMANS et al. 2005). In the high elevation of the Cordillera Central climate stations are entirely missing. Interpolation of the existing station data, especially precipitation, would not be reliable for the mountainous areas.

Continuous precipitation data are available from remote sensing satellites, but presently only at low resolutions, for example the images taken by the Geostationary Operational Environmental Satellites (GOES) program (spatial resolution: 4 km) or by the Advanced Very High Resolution Radiometer (AVHRR) (spatial resolution: 1 km) on board the National Oceanographic and Atmospheric Administration (NOAA) polar-orbiting satellites. For our study purpose these resolutions are too low.

Climate data can also be raised by setting up climate stations in the study area. In cloud forests, these climate stations should be equipped additionally with fog gauges to measure the contribution of fog/clouds to humidity and precipitation. Air humidity and soil humidity are significant environmental factors influencing the occurrence of cloud forests (KAPPAS 1999). Air humidity can be assessed by direct measurements in the field or by using cloud cover and cloud base height as proxies (MULLIGAN 2010). Cloud cover can be determined by remote sensing data, for example from the MODIS Terra and Aqua images with a spatial resolution of 250-1,000 m (LAWTON et al. 2010). Cloud base height might either be observed directly from the ground (SHERMAN et al. 2005) or calculated from Landsat images (BERENDES et al. 2007).

By the end of 2011 the National Geological Service of Santo Domingo will have finished a nationwide geological dataset at a scale of 1:50,000 which should be integrated in the analysis of composition and modeling of patterns of mountain forests along the altitudinal gradient.

Methodological aspects

For analysis of the floristic compositions of the mountain forest types a Detrended Correspondence analysis was performed on 137 field plot data and environmental factors. By correlation of the environmental factors with the axis of the DCA the significant environmental factors for the forest types were assessed. Then, an ecological niche model was established using the mountain forest type as occurrence data and the significant environmental data as environmental factors. In predictive vegetation modeling a vegetation or community type unit represents the occurrence data (DAVIS & GOETZ 1990; FERRIER & GUISAN 2006).

Results

Four mountain forest types were established by ordination: Humid broadleaf/gallery forest, cloud forest, mixed forest and a monotypic pine forest, dominated by *Pinus occidentalis*. The identification of the environmental factors altitude with temperature and precipitation and soil pH as proxies to explain differences in woody species composition in tropical mountain forests was consistent with the results of other studies realized in tropical mountain forests (GENTRY 1988; HAGER & ZANONI 1993; LIEBERMAN et al. 1996; SCHRUMPF et al. 2001; SHERMAN et al. 2005; HOMEIER 2008; HÄGER 2010).

By using the Normalized Differenced Vegetation Index (NDVI) as an indicator for biomass production the spatial prediction between the pine forest and the other three forest types was significantly improved. We assume that cloud forest predictions could be improved by the integration of more meaningful environmental parameters (see *Data source* in this chapter).

Besides Armando Bermúdez National Park there are more protected areas in the Cordillera Central: Jimenoa Natural Monument, the Ebano Verde Area of Strict Protection and the national parks Baiguate, Valle Nuevo, José del Carmen Ramírez, Loma Nalga de Maco and Montaña La Humeadora. To get a complete picture of the compositions and spatial distributions of the mountain forests in the Cordillera Central, floristic sampling and analysis of the data should be conducted in the entire region. A large interconnected mountain protected area system could be rational in conservations terms. Naturally interconnected and adequately managed protected areas are considered as strategic and adaptive responses to environmental change (e.g. climate change) (WORBOYS et al. 2010). Connected reserves improve the long-term survival of species as they contribute to maintain natural processes and viable populations.

VI.3 SPATIAL DISTRIBUTION OF SELECTED WOODY SPECIES, PATTERNS OF WOODY SPECIES RICHNESS AND ENDEMISM

Data

The data source for the prediction of the spatial distribution of woody species was built mainly on collected field data. Herbarium data of the Botanical Garden of Santo Domingo and field data from the project “Madre de las Aguas” were also included (GUERRERO 2004). Due to the rugged terrain sampling had to follow the existing trail system. The entire altitudinal range of the national park was sampled at elevation steps of 50 m.

The two environmental parameters altitude and NDVI entered in the ecological niche model as explanatory variables. These two high resolution parameters had been determined as significant by ordination (Chapter IV.3.1). It is assumed that high resolution spatially explicit climate data on air temperature (annual mean temperature, average temperature of the coldest month, amount of frost events), precipitation and air humidity (relative humidity), disturbances and soil types and moisture could improve the modeling results (see also Chapter VI.2) (WANGDA & OSHAWA 2010). Convex-shaped or concave-shaped terrain variables could also be explaining factors for species occurrences in mountainous terrain (SHERMAN et al. 2005).

Methodological aspects

To obtain higher model accuracies 66 woody species with 30 or more occurrences were used as presence only data to fit the ecological niche models. 25% of the occurrence points of each sampled species were set aside for testing. Model evaluation was undertaken by revising the AUC-value of the ROC-plot (FIELDING & BELL 1997) using the scale proposed by SWETS (1988). Correlation analysis was performed to test the relationship between the AUC-values and altitudinal distribution range of the species. Only 63 predictions with an AUC value > 0.6 were taken into account for further analysis. Biodiversity and endemism patterns were calculated by stacked species distribution modeling (S-SDM, GUISAN & RAHBEK 2011).

Macroecological modeling (MEM) approaches predict species richness directly, based on theoretical assumption or on factors hypothesized to control the number of species that can coexist in an area (GUISAN & RAHBEK 2011). DUBUIS et al. (2011) recommended combining MEM with S-SDM to predict species diversity. A proposal for a combination of a macroecological approach and S-SDM was given by GUISAN & RAHBEK (2011). Comparative studies could be made in the national park with the two different methodologies to evaluate their influences on the results.

Results

Four groups of woody species distributions were differentiated: one in the low parts of the humid broadleaf/gallery forest, one in the humid broadleaf/gallery forest and the transition zone to cloud forests, one in the cloud forests and one in the high elevation cloud and pine forests. Correlation analysis revealed that the test AUC-values correlated highly negative with the altitudinal distribution range of the species (Pearson, $r= -0.60$, $p<0.01$, $N=63$). Species with narrow ecological niches as the ones of the humid broadleaf/gallery forests were easier to predict with our environmental factors than the species with broad ranges. This finding was coincident with GUISAN et al. (2007).

Mean woody species richness was highest between (500 and 1,100 m a.s.l.) and decreased then with elevation. Endemism showed a hump- shape with highest mean values at mid-elevations (1,500-1,700 m a.s.l.). Both results are consistent with observations made in other tropical mountain forests around the world. Further studies should be conducted to explain the causes of the patterns of woody species richness and endemism.

Summary

Tropical mountain forests are very rich in species and essential providers of vital ecosystem services for human well-being. During the last years pressure on these ecosystems has increased considerably. Presently, the most important threat is the conversion of natural forests to agriculture and pasture land, resulting in loss of vegetation cover and biodiversity and decrease of air/soil humidity and stability.

Protected areas are an important means to manage and reduce human impact on tropical mountain forests. However, this requires an effective management, which unfortunately is not given in all protected areas.

Sustainable management and effective conservation planning of protected areas are only possible if detailed, site-specific baseline data are available, if they are scientifically analyzed and interpreted and the results are used in the management process.

Especially in developing countries, ecological and environmental baseline data of protected areas, scientifically analyzed so that the results can be used for improved management are often scarce.

The major objective of the study was to generate and analyze ecological and environmental data that can be used to improve management of Armando Bermúdez National Park, situated in the Cordillera Central of the Dominican Republic in the Caribbean.

In particular the following objectives were fulfilled:

- Generation of a controlled aerial photograph mosaic, extraction and analysis of land cover and land use information;
- Analysis of the floristic composition of the main natural mountain forest types and determination of vegetation-environment relationships;
- Development of a predictive model to map the spatial potential distribution of the main natural mountain forest types and analysis of the spatial potential distributions;
- Development of a predictive model to map the spatial potential distribution of selected woody species and analysis of the spatial potential distributions;
- Mapping and analysis of the patterns of woody species richness and endemism;
- Recommendations for management.

Chapter I contains a general introduction about tropical mountain forests and explains the need of scientifically gathered and analyzed baseline data to improve management of protected mountain forests. Here also the main objectives of the study are unrolled and an outline of the structure of the thesis is given.

In Chapter II the study site, Armando Bermúdez National Park in the Cordillera Central of the Dominican Republic, is presented.

In Chapter III the generation of the first land cover and land use map of Armando Bermúdez National Park based on 295 digital color aerial photographs at a scale of 1:20,000 is described. The aerial photographs were orthorectified and mosaicked to establish a spatially accurate base map. Visual interpretation of land cover and land use was conducted on this base map taking into account the characteristic elements of aerial photograph interpretation. These were the main results obtained:

The largest land cover class of Armando Bermúdez National Park was the broadleaf forest, covering 461 km^2 or 58% of the entire national park. The broadleaf forests were mapped at an average altitude of 1,327 m a.s.l. to the north, northwest and east of the watershed of the Bao River. The dense pine/pine dominated forests (*Pinus occidentalis*) were mainly situated in the watersheds of the Bao and Yaque del Norte Rivers, extending to the highest elevation (3,087 m a.s.l.). In the lower parts of the Bao watershed pine forests occurred down to 915 m a.s.l.. In total, 275.5 km^2 or 34% of the surface of the national park belonged to this land cover type. Although the national park is widely known for its large pine forests, the main cover consists in broadleaf forests.

Human impact was observed in form of agriculture along the northern border. Crop cultivation on small fields (*Conucos*) made 0.08% of the surface of the national park. The village of Cabirmal turned out to be within the limits of the national park (500 m from the border). Here the major agglomeration of subsistence fields was delineated on the aerial photograph mosaic. Besides the small fields for subsistence agriculture, coffee plantations without shade trees were recognized on the aerial photograph mosaic near the villages of Arroyo Bonito, Manacla and around Cerrito Redondo. 0.1% of the entire area was composed by this land use class.

We conclude that the first land cover/land use database of Armando Bermúdez National Park was generated from a color aerial photograph mosaic at a scale of 1:20,000, encompassing an improved understanding about the extension and location of anthropogenic disturbed areas and natural forests. It is considered that the methodology applied here could also be used for other mountain protected areas to gain information about land cover and land use. High spatial resolution satellite images can be a valuable option for future monitoring. A participative management program with all stakeholders is recommended to commonly develop solutions to reduce the human impact on the protected area.

In the following study the floristic compositions and vegetation-environment relationships of the principal forest types of Armando Bermúdez National Park were assessed and their potential distributions predicted area-wide. The significant environmental factors which determined the occurrences of the main forest types were identified by Detrended Correspondence Analysis (DCA) (Chapter IV). Applying ecological niche modeling techniques (ENM) the principal forest types were spatially predicted to the entire national park based on the environmental factors determined as significant by DCA. Four different forest types were distinguished with the help of ordination: Humid broadleaf/gallery forest, cloud forest, mixed forest and pine forest. The main environmental parameters for their occurrence were altitude together with annual mean temperature and annual mean precipitation, soil-pH and the Normalized Difference Vegetation Index (NDVI) calculated on a Landsat 7 ETM+ scene.

Humid broadleaf forests were predicted along the northern border following the main rivers on 162 km^2 at a modeled mean elevation of 958 m a.s.l. and average annual mean temperature of 20.5˚C. Representative woody species were *Alchornea latifolia*, *Beilschmiedia pendula* and *Guarea guidonea*. *Pinus occidentalis* (Creolan Pine) dominated the pine forests and was above 2,300 m a.s.l. the only recorded tree species. The Creolan pine had the widest altitudinal range of all woody species in the study area and was predicted at an average annual mean temperature of 13.9˚C on 133 km^2.

In large parts the here modeled potential distribution coincided with the delineated extension of the dense pine forests in the watershed of the Bao River interpreted on the aerial photograph mosaic. Cloud forest extension was predicted around a modeled mean altitude of 1,608 m a.s.l. and an average annual mean temperature of 15.8˚C. Its predicted area was the largest of all forest types (221 km^2). Characteristic species were *Cyrilla racemiflora*, *Clusia clusioides* and *Brunellia comocladifolia*. Mixed forests were predicted on 100 km^2 around an average annual mean temperature of 18.6˚C and a mean elevation of 1,202 m a.s.l., primarily along the northern part of the Bao River.

We conclude that the study contributed to an improved understanding of the vegetation-environmental relationships and distribution patterns of the main forest types along the altitudinal gradient of Armando Bermúdez National Park. The main environmental factors that determine the vegetation pattern in Armando Bermúdez National Park could be assessed and the vegetation distribution predicted to the geographic space of the national park. Conservation of all vegetation types is of great importance as their occurrences are limited to the highest mountains of the country. The here modeled potential distributions can be used to predict vegetation type-specific sensitivity to environmental change so that vegetation-type specific strategies can be developed.

Effective conservation planning requires information about spatial distribution of species and knowledge about patterns of diversity and endemism. Thus, in the next chapter (Chapter V), the potential distribution of 63 sampled woody species was predicted by ecological niche modeling techniques to the entire area of Armando Bermúdez National Park. Environmental parameters were altitude and the Normalized Difference Vegetation Index (NDVI). Climatic data were not available at the high spatial resolution needed. Stacked species distribution modeling was applied to create a woody species richness map and an endemism map of woody species.

The ecological niche models showed that characteristic woody species groups of different altitudes and forest types existed. 18 modeled woody species presented a potential distribution completely within the humid broadleaf/gallery forest limits predicted in Chapter IV. Mean modeled elevation of this species group was 951 m a.s.l. and Lauraceae and Meliaceae were the species-richest families. 25 models predicted potential woody species distributions to the elevations of the humid broadleaf/gallery forests and lower transition zone to the cloud forests. Mean modeled elevation of these species reached 1,098 m a.s.l. and Lauraceae and Melastomataceae represented the species-richest families. For 15 woody species the cloud forest areas were modeled as potential distribution altitudes around 1,507 m a.s.l.. Bignoniaceae, Melastomataceae and Lauraceae were represented with two species in this group, all of the other families with one. The high elevation cloud and pine forests coincided in wide parts with predictions for *Ilex tuerckheimii*, *Weinmannia pinnata* and *Garrya fadyenii* (mean modeled altitude: 1,853 m a.s.l.).

Altitude correlated highly significant with species richness. High numbers of woody species richness were predicted between 500 and 1,100 m a.s.l. in the humid broadleaf/gallery forest. Above 1,100 m a.s.l. woody species richness declined sharply. The lowest absolute values were predicted for the highest elevations around 3,000 m a.s.l. (1-5 woody species), the highest absolute woody species richness values for low elevations between 550-1,084 m a.s.l. (51-53 woody species).

With increasing altitude species numbers within the main families decreased and so did family diversity. Lauraceae, Myrtaceae, Euphorbiaceae and Melastomataceae were the species-richest families in the class of 51-53 woody species at low elevations. Over the entire elevation gradient Lauraceae was the species-richest family. It is hypothesized that the combination of the area-effect, the still high annual mean temperatures (19°C at 1,100 m a.s.l., Worldclim data), less acid soil conditions and a sufficient water supply favor high woody species richness values between 500-1,100 m a.s.l..

Endemism patterns in Armando Bermúdez National Park showed a hump-shaped curve with largest endemic woody species numbers (9 endemic species) in the cloud forests around 1,500 m a.s.l.. Endemism numbers decreased to both altitudinal directions, but much more pronounced towards the highest elevations. Above 2,931 m a.s.l. either one of the two endemic woody species *Pinus occidentalis* or *Ilex tuerckheimii* were predicted. Ericaceae and Bignoneaceae were the families with the majority of endemic species. We assumed that the rugged topography of the mean elevations of Armando Bermúdez National Park favor the speciation of endemics. Furthermore special ecological traits and history of evolution could influence the patterns of endemism along the altitudinal gradient. Scientific analysis on the causes of the patterns of species richness and endemism in Armando Bermúdez National Park should be conducted.

This study contributed to an improved understanding about the patterns of woody species, woody species richness and endemism of woody species in a tropical mountain protected area. Our results provide important input for the formulation of adequate management strategies and for further ecological modeling approaches. The elaboration of conservation plans for the species-rich lower elevations up to 1,100 m a.s.l. and for the endemic-rich cloud forests are recommended.

Zusammenfassung

Tropische Bergwälder sind sehr artenreich und stellen viele für den Menschen lebenswichtige ökosystemare Dienstleistungen bereit. Während der letzten Jahrzehnte hat der Nutzungsdruck auf diese Ökosysteme ständig zugenommen, wobei die größte Bedrohung die Umwandlung natürlicher Wälder in landwirtschaftliche Flächen und Weideland darstellt. Dies führt zum Verlust von natürlichen Habitaten, zur Verminderung der Artenvielfalt und zur Abnahme der Luft- und Bodenfeuchtigkeit sowie -stabilität.

Schutzgebiete verhindern bzw. reduzieren den anthropogenen Einfluss auf tropischen Bergwald. Dies setzt jedoch ein effektives Schutzgebietsmanagement voraus, welches nur in wenigen Schutzgebieten realisiert ist.

Nachhaltiges Management und *effektive Erhaltung* von *Schutzgebieten* sind nur möglich, wenn detaillierte ökologische und umweltrelevante Basisdaten zur Verfügung stehen und diese mit wissenschaftlichen Methoden analysiert werden. Die Ergebnisse solcher Analysen sollten als Entscheidungsbasis im Schutzgebietsmanagement herangezogen werden. Besonders in Entwicklungsländern fehlen solche Daten und Analysen meist vollständig.

Hauptziel dieser Studie war es, ökologische und umweltrelevante Basisdaten im Nationalpark Armando Bermúdez zu generieren und diese zu analysieren. Der Nationalpark liegt in der Zentralkordillere der Dominikanischen Republik in der Karibik.

Im Einzelnen wurden folgende Arbeiten durchgeführt:

- Erstellung eines Luftbildmosaicks aus Orthofotos und Ableitung der Landbedeckungs- und Landnutzungstypen;
- Analyse der floristischen Zusammensetzung der wichtigsten Vegetationstypen des Bergwaldes in Bezug auf Umweltfaktoren;
- Entwicklung eines Vorhersagemodells zur potentiellen räumlichen Verbreitung der wichtigsten Vegetationstypen des Bergwaldes und Analyse der potentiellen räumlichen Verbreitungsmuster;
- Entwicklung eines Vorhersagemodells zur potentiellen räumlichen Verbreitung ausgewählter Gehölzarten und Analyse der potentiellen räumlichen Verbreitungsmuster;
- Darstellung der räumlichen Muster von Biodiversität und Endemismus
- Umsetzung der gewonnenen Kenntnisse für praktisches Management des untersuchten Schutzgebietes.

Kapitel I dieser Arbeit gibt einen allgemeinen Überblich über tropische Bergwälder, beschreibt die Notwendigkeit detaillierter wissenschaftlicher Erkenntnisse zur Verbesserung des Schutzgebietsmanagements tropischer Bergwälder und stellt die Hauptziele der Arbeit vor.

In Kapitel II wird das Untersuchungsgebiet, der Nationalpark Armando Bermúdez in der Zentralkordillere der Dominikanischen Republik, genauer beschrieben.

Kapitel III legt zunächst die notwendigen photogrammetrischen Arbeitsschritte dar, die zur Erstellung eines Luftbildmosaicks basierend auf 295 Farbluftbildern im Maßstab 1:20.000 notwendig waren. Die Luftbilder wurden orthorektifiziert und mosaickiert, um eine räumlich exakte Basiskarte zur Ableitung der Landbedeckungs- und Landnutzungstypen zu erhalten. Unter Berücksichtigung der charakteristischen Elemente der Auswertung von Luftbildern wurden die Landbedeckung und die -nutzung auf dem Luftbildmosaick analysiert.

Die Ergebnisse dieser Studien zeigen, dass die flächenmäßig größte Vegetationsklasse im Armando Bermúdez Nationalpark die Laubwälder sind. Insgesamt waren 461 km^2 bzw. 58% des gesamten Nationalparks von Laubwäldern bedeckt. Die Laubwälder kamen bei einer mittleren Höhe von 1,327 m ü. NN vor und erstreckten sich nördlich, nordwestlich und östlich des Wassereinzugsgebietes des Flusses Bao. Die dichten, von *Pinus occidentalis* dominierten Kiefernwälder befanden sich hauptsächlich im Wassereinzugsgebiet der Flüsse Bao und Yaque del Norte, und erstreckten sich bis auf die höchsten Erhebungen (3,087 m ü. NN). In den unteren Abschnitten des Wassereinzugsgebietes des Flusses Bao reichten die Kiefernwälder bis 915 m ü. NN. Insgesamt wurden 275.5 km^2 bzw. 34% der Oberfläche des Nationalparks diesem Landbedeckungstyp zugewiesen. Obwohl der Nationalpark für seine ausgedehnten Kiefernwälder weithin bekannt ist, ist der vorherrschende Landbedeckungstyp der Laubwald.

Anthropogener Einfluss im Nationalpark konnte in Form von Landwirtschaft entlang der nördlichen Grenze nachgewiesen werden. Der Anbau von verschiedenen Feldfrüchten auf kleinen Feldern (*Conucos*) machte 0.08% der Oberfläche des Nationalparks aus. Es stellte sich heraus, dass die Ortschaft Cabirmal 500 m von der Nordgrenze entfernt innerhalb des Nationalparks liegt. Hier wurde auch die Mehrheit der Felder des kleinbäuerlichen Subsistenzanbaus nachgewiesen. Neben den Feldern des Subsistenzanbaus konnten auf dem Luftbildmosaick Kaffeeplantagen in der Nähe der Ortschaften Arroyo Bonito, Manacla und rund um Cerrito Redondo nachgewiesen werden. Es wurden insgesamt 0.1% des gesamten Schutzgebietes von dieser Landnutzungsklasse bedeckt.

Durch diese Studie wurde die erste Landbedeckungs- und Landnutzungskarte des Nationalparks Armando Bermúdez auf Basis von Farbluftbildern im Maßstab 1:20,000 erstellt. Die Ergebnisse der Luftbildinterpretation und –analyse trugen zu einem verbesserten Verständnis über Ausdehnung und Lage der einzelnen Landbedeckungen bei und es wurden Gebiete identifiziert, die vom Menschen genutzt werden. Die hier angewandten Methoden der Orthorektifizierung digitaler Farbluftbilder, der Mosaickierung und der visuellen Interpretation können auch in anderen Bergwäldern zum Einsatz kommen. Aufgrund der wirtschaftlichen Aktivitäten im Nordteil des Parks, wird empfohlen, ein partizipatives Managementprogramm mit allen Interessenvertretern auszuarbeiten, um Lösungsansätze zur Verbesserung des Schutzes der natürlichen Ressourcen des Nationalparks zu entwickeln.

In der folgenden Studie (Kapitel IV) wurde die floristische Zusammensetzung der relativ natürlichen Vegetationstypen des Nationalparks untersucht und die Beziehung zwischen Vegetationszusammensetzung und Umweltbedingungen analysiert. Außerdem wurden Vorhersagemodelle zur potentiellen räumlichen Verbreitung der Hauptwaldtypen erstellt. Die ausschlaggebenden Umweltfaktoren wurden durch eine Detrended Correspondence Analysis (DCA) identifiziert. Mit Hilfe einer ökologischen Nischenmodellierung wurde die potentielle räumliche Verbreitung aller Hauptwaldtypen im Nationalpark vorhergesagt. Diese Analyse basierte auf den Umweltfaktoren, die durch die DCA als signifikant eingestuft worden waren.

Mit Hilfe der Ordinationstechnik konnten vier verschiedene Waldtypen unterschieden werden: Feuchter Laubwald/Galeriewald, Nebelwald, Mischwald und Kiefernwald. Die wichtigsten Umweltparameter für deren Vorkommen waren die Höhe über NN zusammen mit der mittleren Jahrestemperatur und des mittleren Jahresniederschlags, dem pH-Wert des Bodens und dem NDVI, abgeleitet von einer Landsat 7 ETM+ Szene.

Feuchte Laubwälder wurden an der nördlichen Grenze entlang der größten Flüsse auf einer Fläche von 162 km^2 bei einer mittleren Höhe von 958 m ü. NN und einer durchschnittlichen mittleren Jahrestemperatur von 20.5˚C modelliert. Repräsentative Gehölzarten waren *Alchornea latifolia, Beilschmiedia pendula* und *Guarea guidonea.*

Pinus occidentalis (Kreolische Kiefer) dominierte die Kiefernwälder und war über 2,300 m ü. NN die einzige vorkommende Baumart. Die Kreolische Kiefer hatte die weiteste Höhenspanne aller Gehölzarten in dem Untersuchungsgebiet und wurde auf 133 km^2 bei einer durchschnittlichen mittleren Jahrestemperatur von 13.9˚C vorhergesagt.

Der Großteil der modellierten potentiellen Verbreitungsfläche des Kiefernwaldes stimmte mit der aus dem Luftbildmosaick abgeleiteten Landbedeckungsklasse „Dichter Kiefernwald“ im Wassereinzugsgebiet des Bao Flusses überein. Die modellierte potentielle Verbreitung des Nebelwaldes wurde auf einer mittleren Höhe von 1,608 m ü. NN vorhergesagt, bei einer durchschnittlichen mittleren Jahrestemperatur von 15.8˚C. Das Gebiet war mit 221 km^2 das ausgedehnteste aller modellierten Waldtypen. Unter den charakteristischen Arten waren *Cyrilla racemiflora, Clusia clusioides* und *Brunellia comocladifolia.*

Mischwälder wurden auf 100 km^2 bei einer durchschnittlichen mittleren Jahrestemperatur von 18.6˚C und einer mittleren Höhe von 1,202 m ü. NN modelliert, überwiegend entlang des nördlichen Teils des Flusses Bao.

Die Studie trug dazu bei, die wichtigsten Umweltgradienten, die für die Verbreitung der unterschiedlichen Bergwaldtypen verantwortlich sind, zu identifizieren. Mit Hilfe dieser Umweltgradienten konnte die räumliche Verbreitung der verschiedenen Vegetationstypen des Bergwaldes modelliert und analysiert werden.

Da sich das Vorkommen aller nachgewiesenen Waldtypen größtenteils auf die Bergregionen des Landes beschränkt, ist ihr Erhalt von großer Bedeutung. Die hier modellierten potentiellen Verbreitungsgebiete können als Ausgangsdaten für weiterführende Analysen mit Schwerpunkt auf Umweltveränderungen genutzt werden. Aus den hier gewonnenen Ergebnissen können konkrete Managementstrategien für jeden Vegetationstyp des Bergwaldes formuliert werden.

Für eine *effektive Erhaltung* von *Schutzgebieten* sind Informationen über die räumliche Verbreitung der Arten, der Artenvielfalt und des Endemismus erforderlich. Aus diesem Grund wurde im anschließenden Kapitel (Kapitel V) die potentielle Verbreitung von 63 Gehölzarten ermittelt. Bei der ökologischen Nischenmodellierung waren die Höhe über NN und der NDVI die ausschlaggebenden Umweltfaktoren. Klimadaten standen nicht in der hohen Auflösung zur Verfügung wie sie für die Einzelartenmodellierung benötigt worden wären.

Um Verbreitungskarten der Gehölzartenvielfalt und endemischer Arten zu erstellen, wurden die Modellierungsergebnisse der Einzelarten aufsummiert.

Die ökologischen Nischenmodelle zeigten, dass es charakteristische Gehölzarten für verschiedene Höhenstufen und Waldtypen gibt, die jeweils zu Gruppen zusammengefasst wurden. Insgesamt hatten 18 der modellierten Gehölzarten ihre potentielle Verteilung gänzlich innerhalb des Laubwaldes/Galeriewaldes. Diese Artengruppe kam auf einer durchschnittlichen modellierten Höhe von 951 m ü. NN vor, wobei Lauraceae und Meliaceae die artenreichsten Familien stellten.

Verbreitungsmodelle von 25 Arten stimmten mit den modellierten Gebieten der Laubwälder/Galeriewälder und Übergangszonen zu den Nebelwäldern überein. Die mittlere modellierte Höhe des Verbreitungsgebiets dieser Arten betrug 1,098 m ü. NN. Lauraceae und Melastomataceae stellten die artenreichsten Familien dieser Gruppe. Bei 15 Gehölzarten fiel die potentielle Verbreitung zusammen mit den modellierten Nebelwäldern in einer mittleren Höhe von 1,507 m ü. NN. Bignoniaceae, Melastomataceae und Lauraceae waren mit jeweils zwei Arten in dieser Gruppe vertreten, alle anderen Familien mit einer Art. Die modellierte Verbreitung der Nebel- und Kiefernwälder der hohen Lagen stimmten in großen Teilen mit den Prognosen für *Ilex tuerckheimii*, *Weinmannia pinnata* und *Garrya fadyenii* überein (mittlere modellierte Höhe: 1,853 m ü. NN).

Der Gehölzartenreichtum korrelierte stark negativ mit der Höhe. Die höchste Anzahl von Gehölzarten (51-53) wurde zwischen 500 und 1,100 m ü NN für feuchten Laubwald/Galeriewald vorhergesagt. Oberhalb von 1,100 m ü. NN nahm die Gehölzartenvielfalt deutlich ab. Die niedrigsten absoluten Werte wurden für Geländehöhen um 3,000 m ü. NN (1-5 Gehölzarten) vorhergesagt. Mit zunehmender Höhe nahm auch die Anzahl der Arten innerhalb einer Familie sowie die Diversität der Familien ab. Lauraceae, Myrtaceae, Euphorbiaceae und Melastomataceae waren die Familien des höchsten Gehölzartenreichtums. Über den gesamten Höhengradienten war Lauraceae die artenreichste Familie. Die hohe Gehölzartenvielfalt der tieferen Lagen wird wahrscheinlich durch den „area-effect" begünstigt mit relativ hoher mittlerer Jahrestemperatur (19˚C auf 1,100 m ü. NN, Worldclim data), günstigen pH-Werten des Bodens und ausreichender Wasserversorgung. Weiterführende wissenschaftliche Studien sind notwendig, um diese Verbreitungsmuster besser verstehen zu können. Die höchste Anzahl endemischer Arten entlang des Höhengradienten wurde in den Höhen des Nebelwaldes um 1,500 m ü NN gefunden. Für diese Höhenstufe wurden im Schnitt 9 endemische Arten pro Pixel vorhergesagt. In beide Höhenrichtungen nahm die Anzahl der endemischen Arten ab. Stärker ausgeprägt war die Abnahme jedoch hin zu den höheren Lagen. Oberhalb von 2,931 m ü. NN wurde das Vorkommen der beiden endemischen Arten *Pinus occidentalis* oder *Ilex tuerckheimii* modelliert. Ericaceae und Bignoneaceae waren die Familien mit den meisten endemischen Arten.

Die hier gewonnenen Ergebnisse lassen vermuten, dass die wechselhafte Topographie der mittleren Höhen die Evolution endemischer Arten begünstigt. Des Weiteren spielen ökologische Pflanzenmerkmale und die artspezifischen Evolutionsgeschichten eine große Rolle für das Endemismus-Muster entlang des Höhengradienten. Auch hier besteht weiterer Forschungsbedarf. Die Studie trägt dazu bei, die räumlichen Muster der Diversität und des Endemismus der Gehölzarten in einem tropischen Bergwaldschutzgebiet anhand signifikanter Umweltparameter vorherzusagen und zu einem besseren Verständnis über diese Muster zu kommen. Besonders die artenreichen niedrigeren Lagen entlang der Grenze des Schutzgebietes sowie die Nebelwälder mit dem hohen Anteil endemischer Arten sollten einem besonderem Schutzkonzept unterworfen werden.

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