Scenario-Based Site Suitability Analysis and Framework for Biodiversity Conservation: Agricultural Zone, Galapagos Archipelago, Ecuador

by

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List of Abbreviations

BV	Bella Vista
CGIAR	Consultative Group on International Agricultural Research
CMt	Camote Volcano
CrM	Crocker Mountain
CSI	Consortium for Spatial Information
GIS	Geographic Information Systems
GNP	Galapagos National Park
FAO	Food and Agricultural Organization
ISRIC	International Soil Reference and Information Centre
ITCZ	Inter-Tropical Convergence Zone
LULC	Land Use Land Cover
MDGs	Millennium Development Goals
NGOs	Non-Governmental Organization
OC	El Occidente
PAy	Puerto Ayora
PET	Potential Evapotranspiration
Sr	Santa Rosa
SSA	Site Suitability Analysis
USC	University of Southern California
USDA	United States Department of Agriculture
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization

Abstract

Galapagos Island's current agricultural system of monocropping, massive food imports, and a booming tourism sector has provided an increase in income for most galapaguenos that reside in the island but has been deemed unsustainable by the UNESCO World Heritage Organization. The tourism-driven urban development and monoculture system of food production have contributed to declines in water, wildlife habitat, soil quality, and an overall loss in biodiversity. This tourism sector growth along with a reduction in agroforestry production has reduced the income diversification potential for galapaguenos that reside in the islands and continues to threaten biodiversity. The most notable and critical of these global initiatives around biodiversity is goal seven of the global Millennium Development Goals (MDGs) of the United Nations (UN) which has since been translated into goal fifteen of the revised Sustainable Development Goals (SDGs). The goal seven of MDGs was targeted at ensuring environmental sustainability and parts of this goal were eventually folded into goal fifteen of the SDGs targeted at restoration and promotion of sustainable use of terrestrial ecosystems or life on land. These targets for goal fifteen have yet to be achieved. The scenario-based fuzzy modeling study was designed to support organizations focused on land use planning and management for agroforestry production and tourism development within the Galapagos Islands agricultural zone of San Cristobal, Santa Cruz, and Isabela utilizing a site suitability analysis framework. The framework was developed based on (1) contextual ecosystem requirements, (2) proximity to built environment infrastructure, and (3) availability of data. The framework implementation identified scenario 1:agroforestry production as being suitable across 20 percent of the study area or 12,386.40 acres and scenario 2: tourism development being 58 percent suitable within the study area or 35,920.56 acres.

CHAPTER 1: Introduction

1.1 The Need to Reduce Biodiversity Loss

The major global issues of inequitable education, poverty, and lack of basic health services have been long-lasting across the globe. In the year 2000, the United Nations (UN) created the Millennium Development Goals (MDGs) which was eventually folded into the revised Sustainable Development Goals (SDGs) in the year 2015. These development goals were developed to set targets and take action towards solving these specific humanitarian issues of poverty, education, children's health, sustainable environment, economic development, and disease prevention. These MDGs and SDGs serve as a global framework for development. The global community has realized progress towards many of the MDGs targets since 2000, and some of the SDGs since 2015 but many targeted areas still require much attention.

Two of the targets (7A,7B) of the MDGs are to substantially reduce biodiversity loss, achieved, by 2010 (UN MDG Report 2015) and to reverse the loss of environmental resources which was translated into the SDGs (15) in the year 2015 targeting the restoration and promotion of life on land. This MDGs declaration and the UN's efforts do appear to have been successful in reducing the loss of rich biodiverse forests. Net loss in forest area declined from 8.3 million hectares annually in the 1990s to an estimated 5.2 million hectares (an area about the size of Costa Rica) each year from 2000 to 2010 (UN MDG Report 2015, 1). This successful reduction in biodiversity and environmental resource loss has been in large part due to the expanded coverage of protected areas since the 1990s. However, this success in environmental sustainability has not been universal especially in regions of Africa and South America where much of the deforestation occurs. Many aspects of the protection and conservation of these biodiverse hotspots need improvement. These include effective and equitable management and connectivity, and protection of areas important for biodiversity and ecosystem services, especially ecologically representative protected area networks (UN MDG Report 2015).

A large portion of these ecologically important species that help maintain the functioning ecosystem required for environmental resources is endemic to South America with some located in the Galapagos Islands known as a hotspot of species endemism. Until 2001 a total of 2,289 terrestrial invertebrate species were registered, of which more than half are supposed to be endemic to the Galapagos Islands (Zachos, 2014).

These conservation and protection efforts in the Galapagos Archipelago and across the globe are under a race against time to save the critical plant and animal species from extinction. Many cantons or provinces within the Archipelago are not on track to meet the previous MDGs or many of the SDGs at the current rate of progress. It is widely recognized that there is a strong need for more effective planning and better decision-making if the MDGs of the UN is going to be met (JC Hyneman, 2014). The study focuses on the Galapagos Archipelago given that it is a globally important region of biodiversity, a hotspot of species endemism, and a source of environmental resources for its residence.

1.1.1 Social Context of Biodiversity Loss

The effectiveness of the MDGs has been long contested which has led to the formation of SDGs. Many perspectives exist on this effectiveness of MDGs and whether SDGs are equitable in its benefits to the private and public organizations of society. This study discusses MDGs and SDGs as an established international framework and reference point for the scope, need, and overall benefit of biodiversity loss reduction and environmental resource conservation. The conversation surrounding MDGs and SDGs is publicly available. A general overview of the discussions around MDGs can be found on the UN official website and by independent researchers like Shobha Raghuram, Manasi Kumar, and Erica Burman. The articles provide both an appreciation and critique of the MDGs (Editorial Critical/Subaltern Perspective on UN MDGs 2009). While articles on SDGs suggest that this revised suit of goals has the potential for holistic sustainable development but also carries some major limits to change. The article by Regina Scheyvens and others provides an overview of this discussion on sustainability potential, limits to change and this movement towards inequitable benefits among the public and private sector when it comes to driving SDGs (Scheyvens et al., 2016).

This discussion of whether to conserve biodiversity-environmental resources or continue urban development for economic benefit and at what rate has been one of great contention. The contentious discussion is taking place globally, regionally, locally, and the Galapagos Archipelago is no exception. Managers, policy-makers, and conservationists must serve multiple masters, many of whom have different points of view, expectations, demands, influence, and power (Epler, 2007). Some of these masters include the global and local scientific community, the local population, tourist industry, the tourist, nation of Ecuador, and developers. These challenges that cause contention specifically around biodiversity conservation and environmental resources will be discussed in the next section. However, most of these challenges especially around social factors are beyond the scope of this study.

1.1.2 Biodiversity Loss Situation in the Galapagos Archipelago

The Galapagos Archipelago is an autonomous region of Ecuador approximately 1000 km (600 miles) off the coast of mainland Ecuador, and is considered one of the natural wonders of the world with renowned natural sites and natural resources. Unlike other oceanic archipelagos, the ecological and evolutionary processes characteristic of the Galapagos have been minimally affected by human activities, and the archipelago still retains most of its original, unique biodiversity. However, several recent reports suggest that the development model has turned unsustainable and that the unique values of the archipelago might be seriously at risk (González et al., 2008). The Galapagos was added to the list of UNESCO World Heritage in Danger in 2007 (González et al., 2008). The community of research provides clear evidence of the linkage between changes in ecology and economics across the Galapagos Islands. An increase in tourism and a decline in the agricultural and fishing sectors are influencing invasive species and urban development growth. A tourism sector providing greater income at the cost of resilient livelihoods and biodiversity loss is unsustainable. This model of tourism reduces the Galapagos system's resilience through its effects on population growth, economy, invasive species arrival, resource consumption, and globalization effects on island residents (González et al., 2008).

The concept of agroforestry is an alternative land management/diversified production method that can provide economic and ecological benefits as studies in Costa Rica (Ricketts et al., 2004) and Indonesia (Steffan-Dewenter, I. et al., 2007) suggest. Agroforestry refers to the land-use systems where woody perennials such as trees, shrubs, palms, bamboo, etc. are cultivated on the related land units as agricultural crops and/or animal rearing. It has been practiced in many countries to offer a wide range of economic, social, and ecological benefits by increasing per capita income of the farms by planting high-value tree species (Ahmad et al., 2017).

The declining agroforestry sector within the Galapagos Islands is shifting further into a predominantly mono-cropped food production system with cattle grazing on pasture or fallowing being the major land use. This monoculture along with tourism development within the Galapagos agriculture zone has greatly contributed to this biodiversity loss with the spread and proliferation of invasive species like guava and blackberry. Information now exists that shows the direct relationship between the abandonment of agricultural land and the subsequent increase of area affected by invasive plant species (Guzman JC et al., 2013). This agricultural system and the food production value chain that is associated with its economic efficiency are threatening the complex diversified and resilient passive agroforestry systems of the Galapagos.

The community of research analyzes several land management scenarios factoring in the major Galapagos sectors of agriculture, fisheries, and tourism using system dynamics models and frameworks. Much of the research suggests locally resilient and diversified food systems as being a viable option to transition to a sustainable Galapagos economy while maintaining and restoring its biodiversity. Diversification of production systems provides a variety of food products for personal consumption, local market access and agritourism, which ultimately builds socioecological resilience (Altieri, 2013).

1.2 Goal of this Study

The goal of the research study was to support organizations focused on land use planning for agroforestry conservation and tourism development within the Galapagos Islands agricultural zone of San Cristobal, Santa Cruz, and Isabela (fig.1) by creating a site suitability framework and demonstrating the method of implementation. The implementation of this framework produced recommendations of regions that are optimal for agroforestry production in scenario 1 and tourism development in scenario 2 that minimize risk to biodiversity and maximize the benefit for the Galapagenous community.

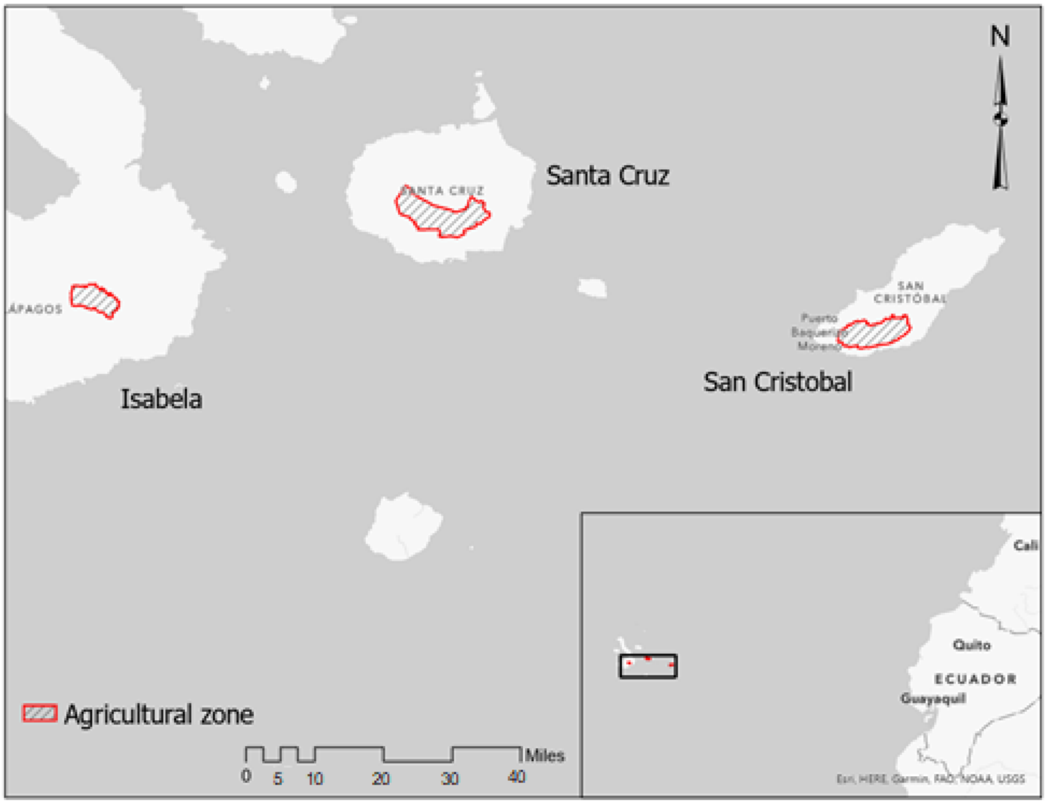

Figure 1. The research study area (agricultural zone) on Isla San Cristobal, Santa Cruz and Isabela, Ecuador.

The framework was applied to a specific study area and context as a model. In framework implementation, the model was refined for optimal performance and to meet the needs of a user's context. The project has two components per model scenario: (1) the development of the framework (study), and (2) the implementation of the framework (model fitting).

The model was created in a standard geographic information system (GIS) format utilizing site suitability analysis mapping techniques that can be applied in environments that lack large sources of data. This limited availability of data is often the case in developing regions. The purpose of this framework and modeling was to produce information that can be used to improve landscape planning and land allocation that contributes to ecologically and economically balanced sustainable development which in turn conserves biodiversity.

The suitability mapping products and framework can be used by NGOs, local organizations, and government as a precursor to on-the-ground engineering, soils, or ecological surveys, thus limiting the area that needs to be assessed in detail while saving resources of time and money.

1.3 Scope of Framework

It is preferred to acquire access to an agroforestry plant database for species-specific habitat requirements and to factor in the Galapagos Islands autonomous regional census data on tourist activity when assessing site suitability. However, quality data on agroforestry plant species endemic to the Galapagos Islands and the Galapagos Islands census data were rare to find or inaccessible as a complete record-dataset. So instead of developing a site suitability analysis (SSA) model for a region that is data-rich like Europe with the plan to apply it in a data deficient region, a limit was placed on the design to exclusively use data readily available to the Galapagos Archipelago and Ecuadorian public. This was designed to ensure the methods used are suitable for the region. To meet the goals of regional model versatility it was necessary to not use agroforestry species-specific data, Ecuadorian census data, or high-resolution commercial satellite data. Just publicly available datasets with global coverage were selected to ensure the framework could be replicated. Given these data limitations, the model and framework focused on locating sites for agroforestry production and tourism development as different scenarios based on the specific cultural and physical geography instead of using plant species or demographic-related metrics. Therefore, in order to locate these scenario-based sites that meet adequate physical and cultural geography requirements, criteria were developed based on (1) contextual ecosystem requirements, (2) proximity to built environment infrastructure, and (3) availability of data. The criteria selection details are covered in chapter three.

The framework was designed to be applied throughout the Galapagos Islands and the greater humid highlands of mainland Ecuador. A study region within the Galapagos Islands was selected due to its biodiversity significance outlined in previous sections, to assess the effectiveness of the framework and its general application.

Given the data deficient context of the study region, the effectiveness of the general framework was accessed by comparing sites identified as suitable (meeting ecosystem or infrastructure requirements) with the locations of existing remotely sensed land use land cover (LULC) data for agriculture and urban classes. This assumes that the existing urban and agricultural land use land cover locations are ideal which is unlikely to be universally correct but does provide a way of refining the model and measuring output.

1.4 The Study Workflow

A SSA study within a GIS often has similar workflows and this study follows a similar basic approach, starting with a detailed literature and methods review followed by the appropriate selection of criteria to be analyzed (fig.2).

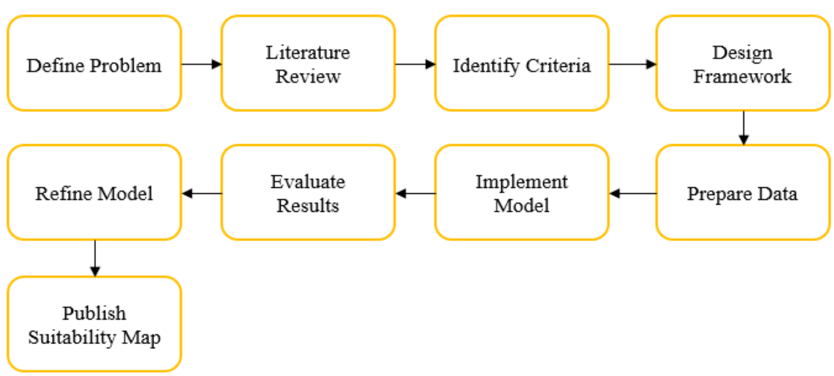

Figure 2. The study workflow diagram.

The study continues in chapter two with a review of relevant published literature on the current biodiversity loss situation in the Galapagos Archipelago, scenario-based land evaluation modeling, and methods of site suitability analysis. The third chapter covers the study area, data attributes, methodology selected, the general framework developed, ground-truthing results, and the details of suitability criteria. The fourth chapter walks through the results of model implementation in detail by describing the evaluation of results for each modeling factor and the scenario results. This study concludes with a final chapter discussing the research findings and areas for future work.

CHAPTER 2: Relevant Background Research

This chapter discusses the literature relevant to the study. The site selection for scenario-based land evaluation is then outlined. Finally, the method of site suitability analysis utilized in this study is reviewed.

2.1 Review of Relevant Studies

The study is situated firmly in the community of research domain around agroforestry, agriculture, and geodesign. This scenario-based methodology was intended to provide a holistic approach to ensure the full range of support information is provided for sustainable development. A large part of this geodesign process and perspective has been pioneered by Richard Neutra and Ian Mcharg. The scenario-based study is similar to the geodesign approach. Design and planning that takes into consideration both environmental and social issues help ensure that our resources are used appropriately and responsibly, to help us move toward a better future for all (Dangermond, 2010). However, the study is dissimilar with its analysis of two scenarios. The criteria within each scenario was determined through empirical means rather than the classic geodesign community-participatory process and iteration.

Most of the research conducted/available around site suitability analysis of agroforestry and agriculture does not include a geodesign or scenario-based approach. These studies are focused on site suitability analysis and the use of remote sensing. The studies within this research domain predominately use biophysical factors or criteria given their lack of variability. Biophysical factors tend to remain stable, unlike socioeconomic factors that are affected by social, economic, and political settings (Vlek et al., 2004). This community of research around the agroforestry or agriculture domain rarely accounts for anthropogenic phenomena outside of land use land cover datasets.

2.2 Site Selection for Scenario-Based Land Evaluation

The partnership between local organizations and Galapaguenos agroforestry managers within the agricultural zone has helped create successful local biodiversity-based businesses that have conserved natural resources and introduced alternative crops into the global and regional consumer food markets. Some of these alternative crops include the Wild Galapagos Tomato, Galapagos coffee, and exotic fruits. The economic value of crops grown in the Galapagos has the potential to grow along with the appreciation of agroforestry as a science, management system, and biodiversity conservation measure. The Galapagos National Park and many local organizations who partner with Galapagos agrarian communities have come to realize that scaling up conservation of agroforestry with the development of tourism in a sustainable manner is viable, challenging, and will require mapping along with integrative land-use planning. This makes the non-protected zones (urban coastal zone and agricultural zone) of the Galapagos a critical area for land evaluation-site suitability analysis to support balanced land allocation decisions.

The capabilities of GIS are well suited to provide these mapping and land use planning needs. Most business development organizations based in Ecuador are familiar with GIS and use it for inventory mapping purposes but lack studies within a community of research to pull from to conduct more in-depth geoprocessing and modeling. This gap in deep spatial analysis and modeling research is precisely the reason why an agroforestry and tourism scenario-based site suitability assessment study is critical and worthwhile.

2.3 Methods for Site Suitability Analysis

This SSA method is distinctive as it ascertains measurable potential for the expansion or reorganization of land use for agroforestry and/or tourism within the agricultural zone of the Galapagos Islands.

To investigate and find suitable locations, a user can overlay several layers in a GIS. This overlaying method for suitability evaluation was first devised and used by Ian McHarg. He is well known for his seminal work, *Design With Nature* where he showed how a user could superimpose a set of transparent layers, one for each criterion, to create an overall suitability map (McHarg, 1994). This technique is regarded as a precursor of modern GIS overlay (Qiu et al., 2014).

There are many methods available today for modeling suitability. A common method for modeling suitability divides locations being measured into two sets: those that are suitable and those that are not. This method is known as the Boolean overlay and it evaluates whether a location meets each criterion, on a yes/no basis (Mitchell, 2012). This method works well when the attributes or spatial boundaries of a criterion are crisp. However, if attributes and boundaries of criterion are not crisp, which is the case for this study, two common methods that can be used to rate a location on a scale from more suitable to less suitable. The two methods are fuzzy overlay and weighted overlay.

A weighted overlay allows users to assign importance to a specific criterion. When a user assigns importance, a weight is assigned to the layer (Mitchell, 2012). This assignment of importance can also be understood as a process of setting percentages of influence for each layer. In the context of a raster cell within GIS, cell values of each layer inputted are multiplied by their percentage influence and the results are summarized together to create the final output raster. This non-crisp method was not used in the study because the information that can be used to assign the weights is not known for each specific context in which it might be applied. The framework developed in this study also does not function optimally when setting weights in a way that can be applied universally.

However, the fuzzy overlay suitability analysis method was found to be well suited and was utilized for this study. The fuzzy overlay method ranks and combines hard to quantify data using mathematical or logical functions to produce a scale of suitability (Mitchell, 2012). It is a method that is particularly good for creating a suitability model that attempts to capture the knowledge of experts in a particular field. Fuzzy logic is built on the concept of fuzzy sets which allow partial membership within a range of 0 to 1 when representing the extent to which an entity belongs to a certain class. This method assigns importance to raster cells assessed within the GIS based on a measurement of belonging or scale of membership which is reclassified as an appropriate scale of suitability.

This suitability method and scale illustrate the potential for targeted land allocation of agroforestry and tourism land use across the agricultural zones of the Galapagos Archipelago (Isla San Cristobal, Santa Cruz, and Isabela). The scale used with suitability analysis is well established and developed by the United Nations, Food and Agricultural Organization (FAO) for land evaluation purposes. Land evaluation is a process for matching the characteristics of land resources for certain uses using a scientifically standardized technique (Ritung et al., 2007). The land suitability classification, using the guidelines of FAO (1976) is divided into Order, Class, Sub Class, and Unit. Order is the global land suitability group. Land suitability Order is divided into S (Suitable) and N (Not Suitable). Class is the land suitability group within the Order level.

Based on the level of detail of the data available, land suitability classification is divided into different orders and in this case its divided with the S order common to semi detailed maps (scale 1:25.000-1:50.000) which is comprised of Highly Suitable (S1), Moderately Suitable (S2), Marginally Suitable (S3) and Not Suitable (N) (Ritung et al. 2007). The number of classes is determined based on the number of characteristics/variables being evaluated and the level of database detail.

This study utilizes semi-detailed maps and an extensive database of variables for both scenario 1 and 2. The SSA is measured and qualitatively standardized using four classes of the S order as listed (table.1). The four classes of S order are converted from a fuzzy overlay model output measurement ranging from a scale of 0 to 1 which is discussed further in chapter three and into four distinct categories or suitability classes.

Table 1. The site suitability classification system used for land evaluation (FAO guidelines (1976)) (Ritung et al., 2007).

Suitability Class	Description
S1	Highly Suitable: Land having no significant limitation or only have minor limitations to sustain a given land utilization type without significant reduction in productivity or benefits and will not require major inputs above acceptable level.
S2	Moderately Suitable: Land having limitations which in aggregate are moderately severe for sustained application of the given land utilization type; the limitations will reduce productivity or benefits and increase required inputs to the extent that the overall advantage to be gained from the use, although still attractive, will be appreciable compared to that expected from Class S1 land.

S3	Marginally Suitable: Land having limitations which in aggregate are severe for sustained application of the given land utilization type and will so reduce productivity or benefits, or increase required inputs, that any expenditure will only be marginally justified.
N	Not Suitable as the range of inputs required is unjustifiable.

CHAPTER 3: A Scenario-Based Land Evaluation Framework for Biodiversity Conservation in the Galapagos Archipelago

The chapter describes the study area and its geographic properties. Then it discusses the attributes of data collected, prepared, and utilized. It continues with a discussion of fuzzy overlay processes, the definition of the land evaluation scenarios, ground-truthing as validation, the suitability criteria, and the geoprocessing workflow used. Finally, the major and minor model criteria within the framework are reviewed.

3.1 Study Area

The total geographic extent of the Galapagos Islands is over 799,313 ha, of which only 25,059 ha (61,922 acres) are designated for agriculture and referred to as the agricultural zone (fig. 1). All four inhabited islands of the Galapagos, Santa Cruz, San Cristobal, Isabela, and Floreana, have a zone in the humid highlands that has been designated for agricultural use (Colloredo-Mansfeld et al., 2020). These agricultural zones face the south or windward side of the islands, which receive high levels of precipitation during the warm season (January–May) and remain enveloped in clouds during the cool season (June–December) (Colloredo-Mansfeld et al., 2020).

The Galapagos National Park (GNP) charged with managing and protecting the Islands ecology, is in control of 97 percent of the terrestrial area. While the local community lives in the non-protected 3 percent referred to as the agricultural zone which is fully surrounded by the protected region. Inhabitants of the agricultural areas of the Galapagos devote their land to three general activities: cattle ranching (bovine, poultry, pork), crop production (permanent and annual crops), and tourism activities (Colloredo-Mansfeld et al., 2020).

The Galapagos Islands was selected as the area of interest for three main reasons: the autonomous region is experiencing rapid tourism development that is affecting the quantity and quality of essential natural resources, the local community is interested in agroforestry methods of biodiversity conservation, and open-source geospatial data is available. An area of interest with open-source geographic data will help ensure that the study can be replicated in a variety of other locations of similar contexts.

3.2 Data

The suitability data collected, prepared, and analyzed in this study was categorized as either critical or background data. These critical datasets consist of digital elevation, soils, aridity, potential evapotranspiration, agricultural zone polygon delineation, average annual temperature, average annual precipitation, and land use land cover data. While the essential background datasets consist of open street map roads, open street map derived market center points, open street map derived coastal port route points, and satellite imagery (table. 2). All datasets were standardized to a raster cell resolution of 30 arc seconds. This standardization of spatial dataset resolution was executed through the resampling operation within the ArcGIS Pro platform. The standardization of these critical and background datasets ensured the highest possible accuracy of criteria or environmental phenomena representation while allowing all datasets to be compatible for combined analysis.

Table 2. Summary of Data

Data	Author	Temporality	Data Type	Resolution	Extent of Coverage	Content
Agricultural Zone Polygon Data	Petros Maskal (created in ArcGIS Pro)	2020	Vector	N/A	Regional	This is a boundary feature layer that delineates the agricultural zone.
Digital Elevation Data	CGIAR-CSI GeoPortal developers	2004-2020	Raster	90 m	Global	This is a digital elevation model (DEM) shapefile originally obtained in TIFF format with aspatial elevation measurements. A total of three SRTM DEM frames were collected to capture the full Galapagos Island surface area. The majority of slope and elevation datasets are developed from this DEM data source.
Open Street Map Data	Open Street Map community	2020	Vector (raster transformation)	30 arc sec	Global	This is a road polyline shapefile for the Galapagos region.
ISRIC-FAO Soils Data	International Soil Reference and Information Centre group	2017	Vector (raster transformation)	30 arc sec	South American Continent	This is a vector shapefile of South America and the surrounding Islands that contains soil texture, symbology and descriptive aspatial data.

CGIAR-CSI Potential Aridity Data	CGIAR CSI Consortium for Spatial Information	1982-2012	Raster	30 arc sec	Global	This is an aridity (combined factors of annual rainfall and temperature) shapefile originally in TIFF format with aspatial aridity metrics. The global Landsat based frame was collected to capture the full Galapagos Island surface area.
CGIAR-CSI Potential Evapotranspiration (PET) Data	CGIAR CSI Consortium for Spatial Information	1982-2012	Raster	30 arc sec	Global	This is a PET (combined factors of annual evaporation, transpiration and temperature) shapefile originally obtained in TIFF format with aspatial evapotranspiration metrics. The global Landsat based frame was collected to capture the full Galapagos Island surface area.
Coastal Port Routes	Petros Maskal (created in OSM)	2020	Vector (raster transformation)	30 arc sec	Global	This is a point feature layer that marks all the major coastal ports and docks of the Galapagos Archipelago.
Road Network Data	Petros Maskal (created in OSM)	2020	Vector (raster transformation)	30 arc sec	Global	This is a polyline feature layer that marks all the primary and secondary roads of the Galapagos Archipelago.
Land Use Land Cover (LULC) Data	European Space Agency Group	2018	Raster	30 arc sec	South America, West Africa	This is a LULC shapefile classified using the USGS standard system. The dataset contains aspatial LULC measurements.

Average Annual Temperature Data	WorldClim Group	2018	Raster	30 arc sec	Global	This is an average annual temperature shapefile originally obtained in TIFF format with aspatial temperature metrics. The global WorldClim based frame was collected to capture the full Galapagos Island surface area.
Average Annual Precipitation Data	WorldClim Group	2018	Raster	30 arc sec	Global	This is an average annual precipitation shapefile originally obtained in TIFF format with aspatial precipitation metrics. A global WorldClim based frame collected to capture the full Galapagos Island surface area.

3.3 Methodology

Many methods of site suitability analysis exist and several of these methods have been considered and described in chapter two. This section describes the fuzzy overlay method in more detail which is most appropriate for this study, the geoprocessing workflow of the model framework, details of modeling criteria, and a summary of data attributes.

3.3.1 Fuzzy Overlay Process

This GIS platform and the fuzzy membership functions or fuzzy logic methodology enabled multicriteria analyses which includes physical and cultural geography factors within the study area like slope, aspect, elevation, and land cover among other properties.

This study also factored in the established local and community-based research around economic growth trends and land use parameters within the agricultural zones of Isla San Cristobal, Santa Cruz, and Isabela. This GIS fuzzy suitability overlay modeling was executed using a fuzzification framework that assigns importance to layers/model factors through fuzzy membership sets using sub-model criteria. These major categories or factors of landscape and geographical characteristics critical to Galapagos tourism development or scenario 2 and agroforestry production or scenario 1 are in the form of curated datasets organized within the framework (fig. 3). These spatial datasets/layers within each category were assigned scores and ranked through the reclassification process. The fuzzy logic procedure of assigning membership was then executed on these reclassified values using criteria parameters validated by research and relevant to the study area. The model computed scores and membership values for each raster cell in the study area resulting in a spatial output range of S1, S2, S3, and N for agroforestry production or scenario 1 and tourism development or scenario 2.

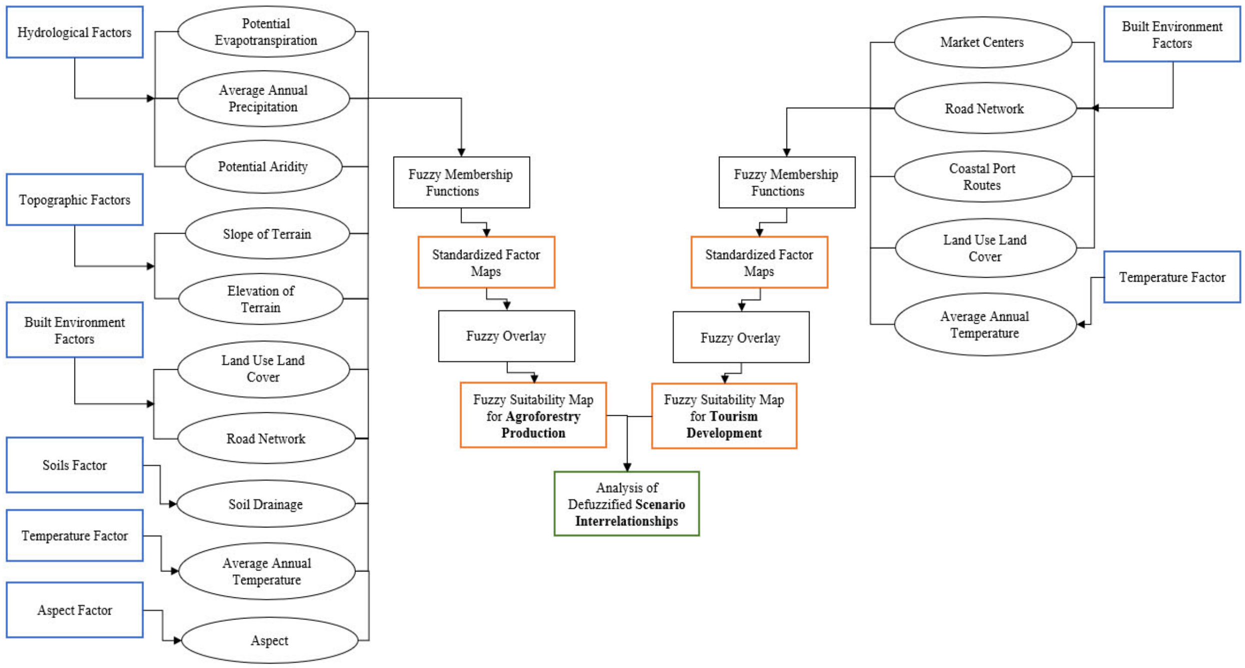

Figure. 3 The site suitability analysis workflow for both scenario 1 and scenario 2.

This site suitability method of fuzzification was more appropriate for the study when compared to Boolean overlay or graduated screening methods. The fuzzification method allows for land evaluation where hard boundaries may not exist, and predictive accuracy is required. These fuzzy logic functions also provide a clear advantage over Boolean overlays and graduated screening in their ability to allow for customizable sub modeling of nuanced or continuous variables like seasonal rainfall fluctuations.

The fuzzy models achieve better predictive accuracies than their classic counterparts. By incorporating fuzzy suitability membership of environmental factors in the modeling process, these fuzzy models also produce more informative fuzzy suitability maps. (Qui et al., 2014). The result of more informative suitability maps increases the effectiveness of land evaluation, land use decision making, and land allocation for scenario 1 and 2.

3.3.2 Land Evaluation Scenarios

Both the agroforestry and tourism land use were evaluated for their suitability within the Galapagos agricultural zone. The models for scenario 1 and scenario 2 used a select set of elevation, aspect, slope, aridity, drainage, evapotranspiration, temperature, land use land cover, and built environment layers.

Scenario 1: Agroforestry Production

The scenario consists of annual and perennial crop and timber production with the most common tree stands of *Scalesia pedunculata*, *Scalesia cordata* also referred to as the Scalesia forest, and Galapaguenos in this region commonly produce cocoa, coffee, or livestock. Most Galapaguenos under this land use generate a portion of their income by selling harvested crops and timber at the local market or by providing forms of agritourism to visitors. This land use has been known to suppress invasive weed growth and as a result, can conserve the surrounding natural resource capital.

Scenario 2: Tourism Development

The scenario consists of impermeable surfaces of bare soil, concrete structures, village centers, vertical buildings that house, and entertain tourists. The Galapaguenos in this scenario of land use rely on public utilities and generate a portion of their income from dining, accommodations, or recreational hospitality.

3.3.3 Ground Truthing

A collection of location points with general land ownership boundaries, site photos, and observations were collected within the agricultural zone across all three Islands of Santa Cruz, San Cristobal, and Isabela to verify tourism and agroforestry land use patterns in combination with the data acquired.

The occurrence of agroforestry production was successfully verified across four locations and tourism development at one location within the agricultural zone of Santa Cruz Island (fig. 4). These observation site photos in figure 4 of agroforestry production starting from the top are depicting a silvopasture agroforestry system for cattle grazing, second was a mixed vegetable polyculture agroforestry system, third was a shaded coffee agroforestry system, and fourth the intercropping agroforestry system of both perennials like banana plantings, and annuals like pineapple plantings. The observation site photo on the right of figure 4 is depicting the front entrance of a Galapagos eco-lodge for tourists.

Figure 4. The site map of four agroforestry locations and one tourism location recorded within the agricultural zone of Santa Cruz Island, near and within Bella Vista (sites observed in the month of November 2020).

The occurrence of agroforestry production was successfully verified across three locations and tourism development at one location within the agricultural zone of Isabela Island (fig. 5). These observation site photos in figure 5 of agroforestry production from the top are depicting an orchard agroforestry system, second was an intercropping agroforestry system of papaya with annual vegetables, and third was an agroforestry system of shaded coffee with banana plantings. The site observation photo for tourism development in figure 5 is depicting the front entrance of an eco-lodge.

Figure 5. The site map of three agroforestry locations and one tourism location recorded within the agricultural zone of Isabela Island, near and within the rural homesteads (sites observed in the month of November 2020)

The occurrence of agroforestry production was successfully verified across three locations and tourism development at three locations within the agricultural zone of San Cristobal Island (fig. 6). These site observation photos in figure 6 for agroforestry production from the top are depicting a silvopasture agroforestry system of dense tree plantings, second was a polyculture of annual vegetables with trees, and third was an intercropping agroforestry system of annual corn and perennial fruit trees. The site observation photos in figure 6 of tourism development from the top depicts a seafood restaurant catering to tourists, second was a local ice cream business catering to tourists, and third was an open-air pizza restaurant.

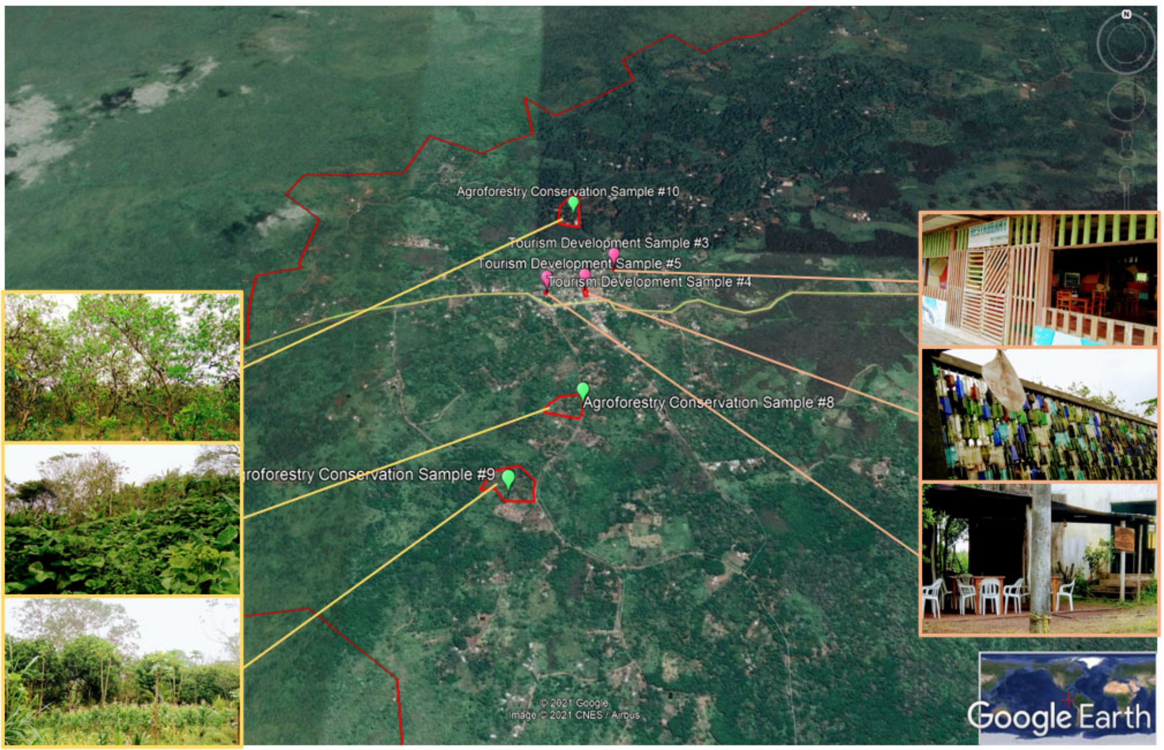

Figure 6. The site map of three agroforestry locations and three tourism locations recorded within the agricultural zone of San Cristobal Island, near and within the rural homesteads (sites observed in the month of November 2020).

3.3.4 Suitability Criteria for the General Framework

This section covers the suitability criteria and data summary (table. 5) identified for use in the framework. The categories of criteria were ranked as either being major or minor model parameters based on supporting research described in the following chapter sections for both scenarios 1 and 2. A total of ten criteria were analyzed in scenario 1 contained within six categories of hydrology, topography, built environment, temperature, soils, and solar energy in relation to the aspect (table. 3). While scenario 2 includes an analysis of five criteria contained within two categories of temperature and built environment (table. 4).

Table 3. Scenario 1 Site Suitability Analysis Criteria

Category	Criteria ID	Criteria	Summary Statement for Selection of Criteria
1. Avoid major hydrological constraints on agroforestry production	1a	Should not be established within low potential evapotranspiration zones	The potential evapotranspiration provides a clear indication of healthy active plant communities through the measurement of gas exchange.
	1b	Should not be established on terrain that receives a low quantity of precipitation	Annual precipitation is a major factor that directly affects plant survival and overall health
	1c	Should not be established in areas of high aridity	The combination of chronic high temperatures with low rainfall produces an arid climate which is a climate not conducive for large plant community growth.
2. Select regions where the topography is adequate for agroforestry production	2a	Should be established within the optimum altitude where the humid and transition zone exists	The elevation and altitude of terrain are a major factor in plant community assemblage (ecozones) in addition to the quantity of ecological interaction.
	2b	Should not be established on steep slopes that are difficult to access, plant or harvest	Terrain with a certain percent slope or greater can be difficult to access and operate for crop production without causing soil degradation and a resulting loss of yield.

3. Avoid regions with a built environment where development exists	3a	Should not be established within the urban land use	The establishment of plant communities in the urban environment is avoided due to growth limitations from impermeable surfaces and the shadow effect of buildings.
	3b	Should not be established within primary and secondary roads	The establishment of plant communities within the road network is avoided due to growth limitations from impermeable surfaces.
4. Avoid regions with higher or lower than average temperature	4a	Should not be established in regions with high or low annual temperature	High or low long-lasting temperature (more than a week) is known to damage and weaken most plants.
5. Select a region where soils provide optimal drainage	5a	Should be established in soils with an optimal drainage class range	A well-drained soil with moderate porosity and permeability allows for adequate plant community rootzone growth.
6. Avoid terrain with low solar energy related to the aspect	6a	Should not be established on aspects with low annual sunlight	The specific direction of terrain in relation to the sun has an effect on photosynthetic energy potential for most plant communities.

Table 4. Scenario 2 Site Suitability Analysis Criteria

Category	Criteria ID	Criteria	Summary Statement for Selection of Criteria
1. Select regions near the existing built environment and Infrastructure	3c	Should be developed near primary and secondary roads	The placement of tourism facilities and structures near major roads ensures public visibility and provides ease of mobility for tourists exploring the Island.
	3d	Should be developed in proximity to a market center	The quick access to restaurants, cafes, bars and the potential site seeing benefits in market centers can increase tourism traffic.
	3e	Should be developed near or within the existing urban land use	The development of tourism facilities and structures near existing urban development increases the probability of having access to existing public utilities like water or gas lines and can make other building requirements more affordable. This also has the potential to decrease the amount of urban land use expansion.
	3f	Should be developed in proximity to a coastal port	A tourism development in close proximity to coastal ports or docks can cut down on travel time for tourists traveling by boat which is one of the main modes of tourist access to the Islands.
2. Avoid regions that contain higher or lower than average temperatures that may be uncomfortable for recreation	4b	Avoid regions that contain higher or lower than average temperature for the majority of the year	A tourism development location that holds higher or lower than average outside temperature year-round can be undesirable to explore, physically uncomfortable, and cut down on tourist traffic.

Table 5. Data Summary and Attributes of Analysis Criteria

Criteria ID	Map Layer	How Data were Created	Source	Resolution	Extent of Coverage	Accessibility
1a	Potential Evapotranspiration	Data developed by NASA using remote sensing classification tools computed from primary data collected by orbiting satellites.	Government/NGO (CGIAR-CSI)	30 arc sec	Global	Public
1b	Average Annual Precipitation	Data developed by NASA using remote sensing classification tools computed from primary data collected by orbiting satellites.	Government/NGO (NASA, WorldCim)	30 arc sec	Global	Public
1c	Potential Aridity	Data developed by NASA using remote sensing classification tools computed from primary data collected by orbiting satellites.	Government/NGO (CGIAR-CSI)	30 arc sec	Global	Public
2a	Terrain Elevation	Data developed using geo-processing tools computed from original dataset.	SRTM-CGIAR	90 m	Global	Public

2b	Slope of Terrain	Data developed using geo-processing tools computed from original dataset.	SRTM-CGIAR	90 m	Global	Public
3a, 3e	Land Use Land Cover	Data developed by the European space agency using remote sensing classification tools computed from primary data collected by orbiting satellites.	European Space Agency	30 arc sec	South America, West Africa, Western Siberia	Organization
3b, 3c	Road Network	Data digitized from secondary data source.	OSM	Vector (raster transformation to 30 arc sec)	Global	Public
3d	Market Center	Data digitized from secondary data source.	OSM	Vector (raster transformation to 30 arc sec)	Global	Public
3f	Coastal Port Routes	Data digitized from secondary data source.	OSM	Vector (raster transformation to 30 arc sec)	Global	Public
4a, 4b	Average Annual Temperature	Data developed by NASA using remote sensing classification tools computed from primary data collected by orbiting satellites.	Government/NGO (NASA, WorldCim)	30 arc sec	Global	Public
5a	Soil Drainage	Data digitized from original dataset.	ISRIC	Vector (raster transformation to 30 arc sec)	South American Continent	Public

6a	Aspect	Data developed using geo-processing tools computed from the original dataset.	SRTM-CGIAR	90 m	Global	Public

3.4 Major Model Criteria and the Implied Constraints

The next two sections describe the major and minor suitability criteria identified for use in the framework outlined in the previous section. These major criteria for scenario 1 are average annual precipitation, potential evapotranspiration, potential aridity, terrain elevation, and slope of the terrain. While the major criteria for scenario 2 are market centers, road networks, land use land cover, and coastal port routes. These major and minor criteria were differentiated from a modeling perspective through the GIS fuzzy membership geoprocessing tool of *Hedges* also known as the concentration or dilation component of fuzzy membership functions. All the major criteria were assigned a hedge termed *Somewhat* or known as dilation which is the square root of the fuzzification membership function. While all minor criteria were assigned a hedge termed *Very* or known as concentration which is the fuzzy membership function squared.

Average Annual Precipitation

The Galapagos Islands agricultural zone is characterized as a humid highland zone with two seasonal climates which is atypical for the equatorial zone but makes it suitable for year-round agroforestry. This two-season cycle brings with it a limiting factor of irregular rainfall. The driver of regional and global rainfall-precipitation across the archipelago is a mix of oceanic currents, trade winds from the southeast, and the Inter-Tropical Convergence Zone (ITCZ) movement. This intra-annual ITCZ migration gives rise to the two seasons which characterize the Galapagos climate: a hot season and a cool season (Trueman et al., 2010). It is in this warm (hot) season that the agricultural zone receives most of its annual precipitation across all three Islands of Isabela, Santa Cruz, and San Cristóbal. Average annual rainfall ranges from 500 mm (20 inches) on the coast to 1500-2000 mm (59-79 inches) in the highlands (above 500 m a.s.l) on the southern windward side (Taboada et al., 2016). This annual precipitation was visible through local observation, aerial imagery, and measurements of geologic weathering, soil formation, and bioclimatic belts of distinct vegetation. This agroforestry suitability of average annual precipitation within the study area based on this geologic weathering, soils formation, and bioclimatic indicators was highest within the 22 to 28 inch zone (fig. 7). The agroforestry suitability within the average annual precipitation criteria decreases with decreasing precipitation geographically.

Figure 7. A visualization of average annual precipitation criteria for the year 2018 within the Galapagos Island study area.

This study classified the variation in average annual precipitation into four categories starting with the highly suitable region utilizing the land evaluation suitability system covered in chapter two. The average annual precipitation criteria were measured in inches of rainfall-precipitation in the following order of 22-28 inches, 15-21 inches, 8-14 inches, and 7 inches or less.

Terrain Elevation

This two-season cycle of high and low precipitation or bioclimatic phenomena has had a major bio-physical effect on the landscape in the form of clear vegetation zones across the islands. However, the bioclimatic phenomena would not be possible without the orographic effect of elevation in terrain which pushes this moisture in the form of clouds higher up into the atmosphere that eventually allows for cooling in the form of rain. These four general vegetation zones catalyzed by elevation in terrain or increasing altitude are the semi-arid coast, low shrub-fern, and grass transition belt the humid south-facing slopes, and lastly, the top caldera locally referred to as the brown zone section of volcanoes. This altitudinal zonation and rising moisture followed by rain have also contributed to intensive volcanic rock weathering followed by soil formation. At the same time, the degree of weathering is related to the bioclimatic zones described by Stoops (2013 a and b): soils with the lowest degree of weathering, PAy, are located in the arid coastal zone; in the transition zone (ST), BV y OC soils located at 140-240 m a.s.l.(459-787 feet) show slightly higher values; soils from CMt, Sr, and CrM develop in the Scalesia zone (SZ) at altitudes between 240-400 m a.s.l (787-1312 feet).; while soils from CMt, Sr, and CrM with the largest degree of weathering appear in the brown zone, at elevations higher than 400 m a.s.l (1312 feet) (Taboada et al., 2016). It is this climatic cycle of annual moisture movement and geologic weathering catalyzed by elevation change that makes agroforestry production possible within the Galapagos. The agroforestry suitability based on elevation is also visibly highest from ariel imagery of vegetation density and on the ground observation within the 440 to 339 m (1444 to 1115 feet) range across the three Galapagos Islands and decreases as you move lower in elevation or above 499 m (1640 feet) (fig. 8).

Figure 8. A visualization of the terrain elevation criteria within the Galapagos Island study area.

This study classified the variation in elevation into four categories starting with the highly suitable region utilizing the land evaluation suitability system covered in chapter two. The elevation criteria were measured in feet (meters) of altitude above sea level in the following order of 1444-1116 feet, 1115-788 feet, 1445-1772 feet, and 787 feet or less in altitude.

Potential Evapotranspiration

The criteria and geographic phenomenon of evapotranspiration are dependent on many other geographic phenomena like temperature, elevation, and precipitation but also influences several geographic phenomena like vegetation composition or soil moisture as it relates to soil development which is of particular importance in the biodiversity hotspot of the Galapagos Islands. The vegetation distribution shows direct dependence on altitude, slope, exposition to trade winds, and level of air moisture (Adelinet et al., 2007). This air moisture is generally a result of evapotranspiration which is defined as the process of atmospheric removal of water through evaporation (water moving from the liquid to gaseous state from the earth's surface) and transpiration (gaseous water being released from plant leaves or stomata as a function of metabolism). The assessment and analysis of this atmospheric moisture as a result of evapotranspiration was vital in understanding the potential of plant productivity or agroforestry productivity-scenario 1 within the study area. This factor of atmospheric moisture specifically condensation within the Galapagos Islands directly influences plant growth by providing a continuous source of water for nutrient and energy exchange. This condensation usually occurs above 250 m altitude and creates extensive stratus clouds, often down to ground-level, locally called garua (Hamann 1979, Colinvaux 1984, Nieuwolt 1991). These clouds result in two forms of precipitation; vertical (rainfall) and occult, the latter consisting of fog that condenses on vegetation and drips or runs down to the grounds (Trueman et al., 2010). In Galapagos, occult precipitation can significantly increase the total precipitation amount under dense vegetation (Trueman et al., 2010).

The study accounted for this atmospheric moisture phenomena through the measurement of PET defined by the FAO as a measure of the ability of the atmosphere to remove water through Evapo-Transpiration processes. The PET is classified across a range of 10 classes from 9.8 inches or less of potential atmospheric removal of water per year to 98.4 inches or greater. This FAO PET classification standard was utilized across the study area to visualize the phenomena (fig. 9) and determine the site suitability of scenario 1.

Figure 9. A visualization of the potential evapotranspiration criteria measuring potential atmospheric removal of water per year within the Galapagos Island study area.

The study classified PET into 4 categories with 0.0 inches to 44.3 inches as highly suitable, 44.4 inches to 49.2 inches as moderately suitable, 49.3 inches to 59.0 inches as marginally suitable, and 59.0 inches or greater as not suitable. However, regions within the 59.0 inches or greater range do not exist within the study area for this criterion.

Potential Aridity

The criterion of potential aridity is a phenomenon that exists in many regions of the world. This potential aridity is defined as the ratio of long-term trends in precipitation over long-term trends of potential evapotranspiration. It is vital to understand and assess the potentiality of this aridity especially when plant communities or plant production is being considered, given that plant growth and survival requires conducive atmospheric temperature with adequate water regimes. The potential effect of aridity on agroforestry production or scenario 1 as it relates to site suitability was particularly important especially because this scenario was comprised of long-term perennial plant production along with annual species as discussed in previous sections.

The UN classifies this aridity phenomenon using an index of 5 values with the following climate classes of hyper-arid at less than 0.03, arid at 0.03 to 0.2, semi-arid at 0.2 to 0.5, dry sub-humid at 0.5 to 0.65, and humid at greater than 0.65. This study however was largely focused on the visualization and analysis of arid and semi-arid climate classes within the study area (fig. 10).

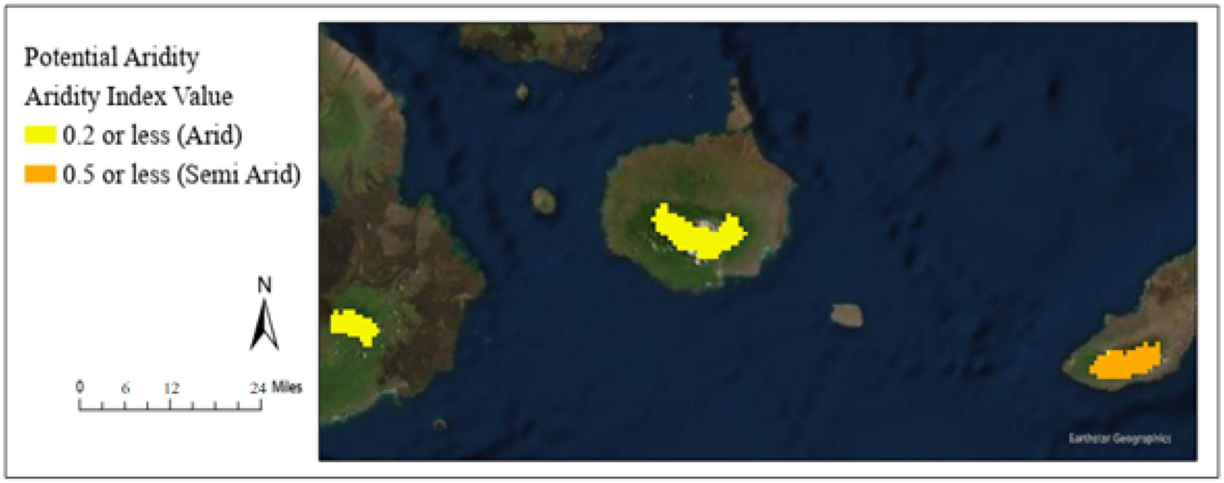

Figure 10. A visualization of the potential aridity criteria measuring mean annual precipitation over mean annual evapotranspiration deriving an index or classes of aridity within the Galapagos Island study area.

The defining characteristics of the arid and semi-arid climate have been standardized by Monique Mainguet in the classic droughts and human developments text published in 1999 titled Aridity. The characteristics of the arid zone as the text defines is its ratio of precipitation over potential evapotranspiration which equates to an index value of 0.03 to 0.2 and this landscape is generally comprised of barren areas or those covered by sparse vegetation of perennial and annual plants. While the semi-arid zone is characterized by a ratio of precipitation over potential evapotranspiration which equates to an index value of 0.2 to 0.5 and this landscape is generally covered by steppe open vegetation cover and tropical bush with perennial plants being most frequent.

The study measured the aridity criteria using this UN-established system of aridity index values into 4 classes. All humid values at 0.65 or greater were highly suitable, dry sub-humid values at 0.5 to 0.65 were moderately suitable, semi-arid values at 0.2 to 0.5 were marginally suitable, and arid values at 0.2 or less were not suitable. However, regions within the 0.65 or greater and 0.5 to 0.65 range do not exist within the study area for this criterion.

Slope of Terrain

The criteria of slope or ratio of vertical change and also referred to as relief in the landscape was critical to understanding the site suitability of agroforestry production or scenario 1 within the study area. This relief is an important factor when it comes to land evaluation overall but particularly for land use that requires plant growth and management. The relief is related to land management and erosion hazard and elevation is related to temperature and solar radiation and thus closely linked to plant requirements (Ritung et al., 2007). This relief-slope factor is linked to many other geographic phenomena in addition to cultures of management and thus influences the where of agroforestry production which is a management system of food production.

According to the United States Department of Agriculture (USDA), its most optimal to produce food and manage production on slopes ranging from 0 percent or flat as ideal, to 30 percent or hilly as the limit. The study utilized a standard FAO land evaluation system of topography to visualize slope which classified 7 types of relief or percent slope ranging from flat at less than 3 percent to very steep at greater than 60 percent.

This study however only considered 4 classes given the food production requirements of scenario 1 (fig. 11).

Figure 11. The criteria and visualization of percent slope of terrain within the Galapagos Island study area.

The percent slope of 8 or less is classified as highly suitable, 15 or less as moderately suitable, 30 or less as marginally suitable, and 100 percent or less as not suitable.

Market Centers

The market centers of the Galapagos Islands and the accessibility to them was a critical component in determining the suitability of tourism development or scenario 2 from an economic perspective. These market centers or hubs of economic activity within the study area also provide employment and were located in the towns of Bella Vista and Santa Rosa on Santa Cruz Island or El Progreso on San Cristobal Island. The National Institute of Statistics and Censuses of Ecuador estimated that 8,772 people were economically active in the archipelago as of the year 2002 and employed in 18 sectors. These towns or market centers are considered central hubs for much of these employment sectors. According to their data, the most important sectors and their percent of island employment were: transport, storage, and communications (15.3%); vehicle and motorcycle servicing (11.2%); agriculture and ranching (10.3%); public administration (10.3%), and construction (7.6%) (Epler, 2007). This tourism industry was not listed as a separate sector but is known to be one of the largest employers in the Galapagos. Wilen and Stewart (2000) reported that in 1999, 40% of the Galapagos population was employed within the tourism sector or connected business (Epler, 2007). These market centers function as centers for employment but also hubs for tourists to exchange essential goods and services (food, water, toiletries, Wi-Fi, and communication equipment).

This study equated the degree of suitability based on the concept of accessibility to these market centers which were measured by a range of distance from these market center points or centroids (fig. 12). The tourism modeling study within the Galapagos authored by Francesco Pizzitutti and others provided precedence for a hotel, cruise ship, and road network-based measurement of accessibility at ranges of 0 to 5 miles, between 5 and 6 miles, and 6 miles or greater. This sort of modeling parameter is effective for measuring accessibility to market centers given that the market centers or the central plaza phenomena have similar structural properties to hotels or cruise ship-ports like economic or social centralization.

Figure 12. A visualization of the market center criteria along with its associated euclidean distance measurements within the Galapagos Island study area.

This study measured and classified the degree of accessibility into three ranges with locations at the market center point or centroid equating to 0. The zones that are less than 5 miles out from the point were highly suitable, those within the zone of 5 to 6 miles were moderately suitable and any zone 6 miles or greater from the point were marginally suitable.

Road Network

The location and arrangement of road networks is a critical factor in determining whether visitors to the Galapagos Islands continue to have access to pristine sites of world heritage and convenient accommodations for their stay. Any future Galapagos Island tourism development plans will require the utilization and visualization of existing road networks-infrastructure (fig. 13).

This study equated the degree of suitability based on the concept of accessibility to roads which were measured by a range of distance from these roads. The tourism modeling study within the Galapagos authored by Francesco Pizzitutti and others provided precedence for a hotel, cruise ship, and road network-based measurement of accessibility at ranges of 0 to 5 miles, within the zone of 5 to 6 miles, and 6 miles or greater.

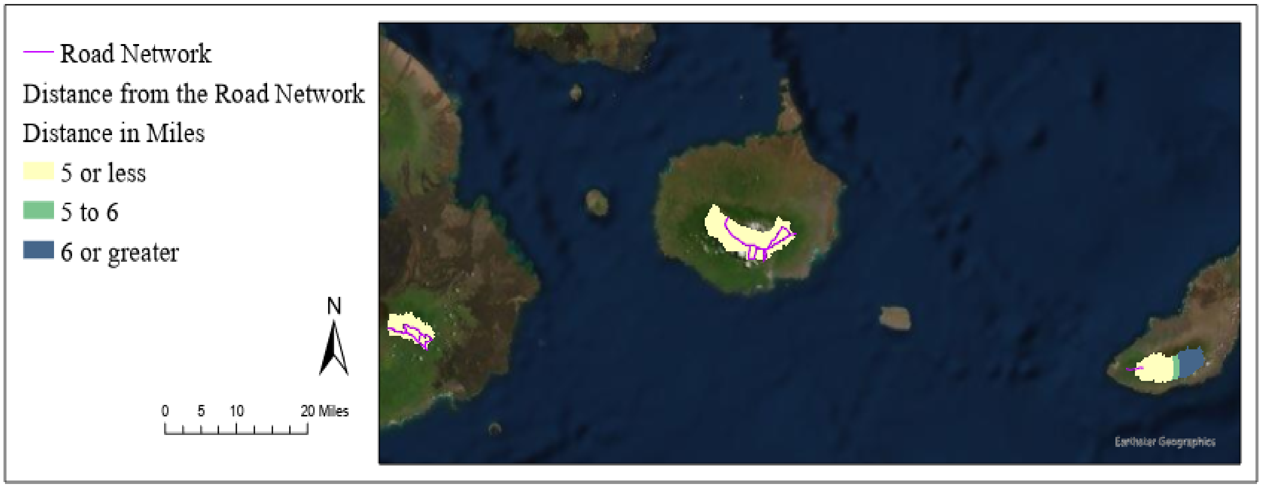

Figure 13. A visualization of the primary and secondary road network criteria along with its associated euclidean distance measurements within the Galapagos Island study area.

This study measured and classified the degree of accessibility into three ranges with locations on or adjacent (roads were assigned as the centroid) to the road at zero. The zones that are 5 miles or less out from the roads were highly suitable, those within the zone of 5 to 6 miles were moderately suitable and any zone 6 miles or greater from the roads were marginally suitable.

Coastal Port Routes

This coastal port route factor is important to consider, to ensure accessibility to and for fleet or cruise-based Galapagos Island tourists. The distance and resulting travel time from hotels or accommodations within the study area to Galapagos Island ports was a criterion critical to understanding optimal tourism development or scenario 2. A large portion of Galapagos Island tourists arrive and depart by charter vessels and cruise ships. Most owners cater to the higher income, predominately foreign tourists. At the other end of the spectrum are vessels oriented towards budget-minded backpackers and Ecuadorians (Epler, 2007). If less time is spent to and from locations in this case from the Galapagos Island agricultural zone to coastal ports more time can be spent touring or exploring locations. Any future Galapagos Island tourism development plan will require a firm understanding of this distance and time factor in relation to coastal ports.

This study equated the degree of suitability based on the concept of accessibility to the closest points within the road network to coastal routes. The access to these coastal route points were measured by the range in euclidean distance from these points in miles (fig. 14). The tourism modeling study within the Galapagos authored by Francesco Pizzitutti and others provided precedence for a hotel, cruise ship, and road network-based measurement of accessibility at ranges of 0 to 5 miles, within the zone of 5 to 6 miles, and 6 miles or greater.

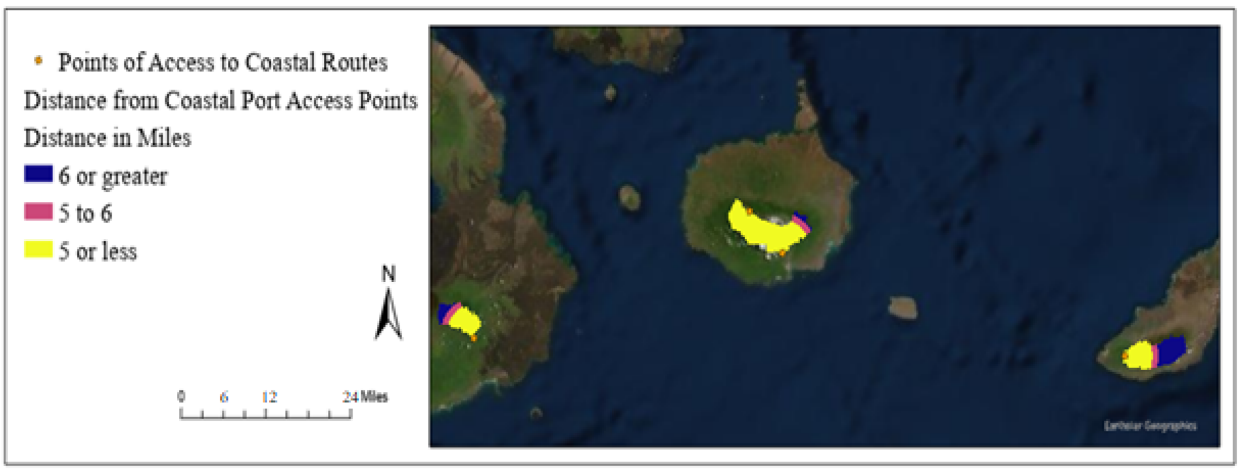

Figure 14. A visualization of points of access to coastal port routes criteria along with its associated euclidean distance measurements within the Galapagos Island study area.

This study measured and classified the degree of accessibility into three ranges with locations at the point or centroid equating to 0. The zones that were 5 miles or less out from the point are highly suitable, those within the zone of 5 to 6 miles were moderately suitable and any zone 6 miles or greater from the point were marginally suitable.

Land Use Land Cover

The identification and consideration of existing land use land cover (LULC) are vital, particularly within the Galapagos Island study area. These ecosystems and the unique plant communities within them are of high importance to maintain biodiversity. The Island's natural composition of land cover is generally made up of clear climatic or vegetation zones as mentioned in previous sections. Whilst these climatic zones have not been mapped, they correspond to naturally occurring semi-arid and humid vegetation zones as described by Hamann (1979) and mapped by Huttel (1986) (Trueman et al., 2010). These regions of land cover are usually referred to as climatic zones rather than vegetation zones partly because it's a factor of climate and partly because these zones have been completely altered by anthropogenic change or land use. To contribute towards arresting this change in natural land cover, future land use like agroforestry production or scenario 1 must be assessed for its suitability in relation to land use land cover types-classes that already exist. The three major land use land cover classes that exist within the study area determined/mapped by the European Space Agency (ESA) are the rainfed cropland mosaic greater than 50 percent, broadleaf tree cover greater than 15 percent, and open shrubland (fig. 15).

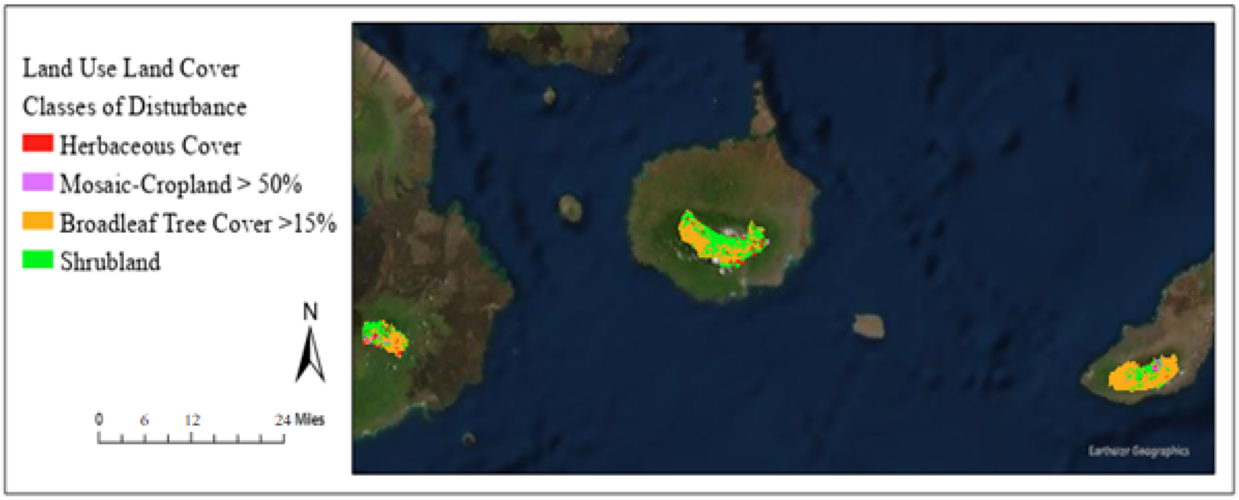

Figure 15. A visualization of the ESA classified LULC criteria within the Galapagos Island study area.

This study utilized the ESA's established LULC system and classified suitability based on the degree of disturbance. The urban-built environment or bodies of water were most disturbed or not suitable (classes 0 and 160 to 220), regions with sparse canopy cover or deciduous plant species were marginally suitable (classes 120 to 153), regions with higher-than-average canopy cover with broadleaf plant species were moderately suitable (classes 11, 12 and 40 to 110) and regions currently under crop production were highly suitable (classes 10, 20 and 30) or the least disturbed for scenario 1 land use.

3.5 Minor Model Criteria

Road Network

The location and arrangement of road networks within the Galapagos Islands determines largely the accessibility and availability of food resources for its population. This food produced on the island must be exported off the island or transported to local markets through the conduits of primary and secondary road infrastructure networks. This road network also plays an essential role in providing a conduit for transporting imported processed food to the island which composes the bulk of food resources consumed by Galapagenous or tourists (fig. 13). Additionally, transport and communications are critical issues, as a failure in either one may cause uncertainty in the timely supply of products (Sampedro et al., 2018). These products include scenario 1 of local agroforestry harvested food supply for the community and visitors alike.

The study provides a system for measuring this degree of accessibility/availability to food resources by applying the distance and time factor utilized by the author Francesco Pizzitutti and others in a Galapagos Island tourism modeling study. This system of measurement classifies the degree of accessibility into three ranges with locations on or adjacent (roads are assigned as the centroid) to the road at zero. The zones that are less than 5 miles out from the roads are highly suitable, those within the zone of 5 to 6 miles are moderately suitable and any zone 6 miles or greater from the roads are marginally suitable.

Soil Drainage

The soil drainage or more specifically the soils hydrodynamic properties is an important factor that determines what plant diversity (plant root access to water and nutrients) and assemblages can exist in a particular site and this diversity is necessary for agroforestry production in the Galapagos Islands as described in previous sections. Some of the key determining characteristics within the soil drainage factor are soil texture- degree of permeability (measured as the rate of hydraulic conductivity or water conveyance in meters per second) along with porosity (measured as the void space within a total volume of soil), dependance on the rate of rainfall and terrain elevation. The physical properties of the soil are in good agreement with the variations of the rainfall according to the elevation, which appears as the main factor controlling the soil development (Adelinet et al., 2007). Understanding that the hydrological cycle is fundamental for water resource management, soil porosity, permeability, mineral composition, and particle size are important elements within this cycle (Adelinet et al., 2007). This variation in soil hydrodynamic properties is heterogeneous across the Galapagos Islands with the greatest contrast between Isla Santa Cruz and Isla San Cristóbal due in part to the difference in elevation and rainfall as mentioned in previous sections. Two groups of soils were identified, with a major difference between them. The first group consists of soils located in the highlands (> 350 m a.s.l.), characterized by low hydraulic conductivity (< 10^{-5} m s^{-1}) and low porosity (< 25%). These soils are thick (several meters) and homogenous without coarse components. Their clay fraction is considerable and dominated by gibbsite. The second group includes soils located in the low parts of the islands (< 300 m a.s.l.). These soils are characterized by high hydraulic conductivity (> 10^{-3} m s^{-1}) and high porosity (> 35%) (Adelinet et al., 2007). The major soil types are referred to as Umbric Leptosols (LPq) across Isla Santa Cruz, Dystric Cambisols (CMd) across Isla Isabela, and Eutric Regosols (RGe) across Isla San Cristóbal following the international soil reference system (fig. 16).

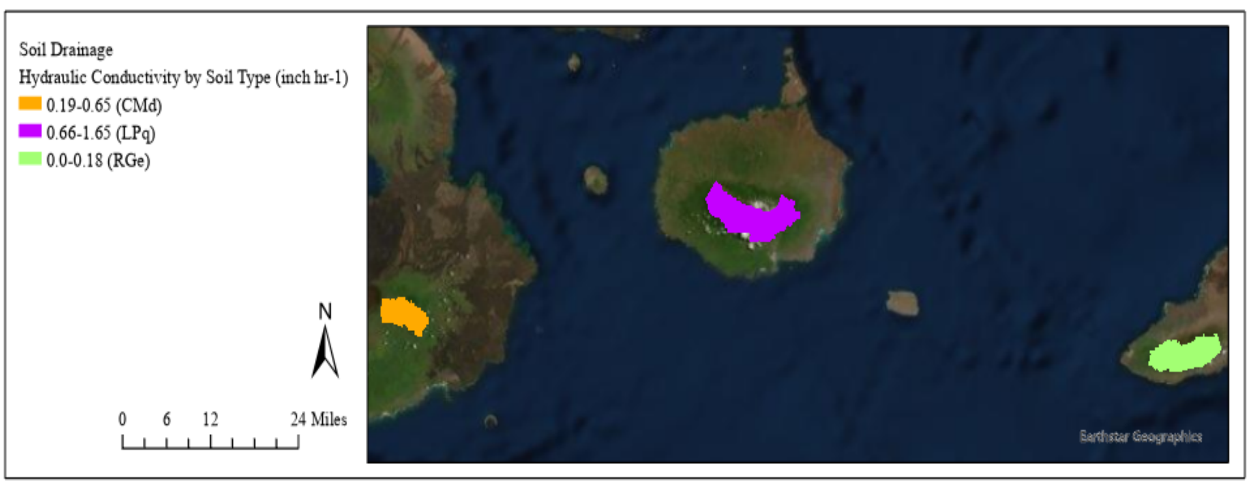

Figure 16. A visualization of the soil drainage class by the dominant soil type within the Galapagos Island study area.

The study classified this soil drainage variation within LPq, CMd, and RGe using a standard USDA-Natural Resource Conservation Service system of seven categories ranging from poorly drained to excessively drained and lastly into four categories of suitability using the suitability land evaluation system covered in chapter two. These soil drainage categories were associated with specific percentages and rates of hydraulic conductivity ranges for the given soil type across each of the three Islands.

Land Use Land Cover

The identification and consideration of existing LULC are important particularly within the Galapagos Island study area and built environment. This study area has experienced an increasing level of land cover or ecosystem disturbance due to an increase in tourism, the population of Galapagos residents, and invasive species arrival. Urban sprawl is creeping into the highlands (Epler, 2007). Population growth is out of control, the supply of drinking water heavily exploited, and more and more vehicles are required to meet demand (Epler, 2007). There is a limit to the built environment or urban expansion on the island due to land area. It's advantageous to utilize current utility infrastructure and land use for tourism development-scenario 2 before expanding the area of land use. Urban development regulations in the Galapagos assign a limited geographic extension of the municipal territory to the construction of new urban infrastructure (Pizzitutti et al., 2016). The study accounts for this built environment phenomena of limited expansion through the assessment and classification of LULC suitability.

This study utilized the ESA's established LULC system and classified suitability based on the degree of disturbance within scenario 2. The bare landscape or non-vegetated virgin ground was highly suitable (classes 200, 201, and 202), regions with a body of water or ice were not suitable (classes 0, 210 and 220), the urban regions were moderately suitable (class 190) and all land cover that was vegetated was classified as marginally suitable (class 160 to 180).

Average Annual Temperature

The component of annual temperature cycles within climate has a major effect on plants and animals within the terrestrial landscape, this includes most of the plant species and humans-people along with many other mammals.

These daily and monthly fluctuation in atmospheric temperature that generally equates to predictable yearly average temperatures is an important factor among others that determines the life cycle of plants and whether people can successfully inhabit a specific environment. This factor of temperature which is defined as the average annual temperature in this study also extends its influence on both scenarios of tourism development and agroforestry production.

The bioclimatic changes of plant diversity and quantity in combination with temperature as you move longitudinally across the globe or within a region maybe the clearest indication of the temperature effect on plant productivity. The warm humid tropics and semi-tropical zones of the globe hold more diverse plant growth and provide longer production periods for plant growth compared to your hot arid or cold tundra regions of the globe. These global and regional variations in temperature have a direct effect on the productivity of agroforestry systems across regions of the world and including the Galapagos Island study area (fig. 17).

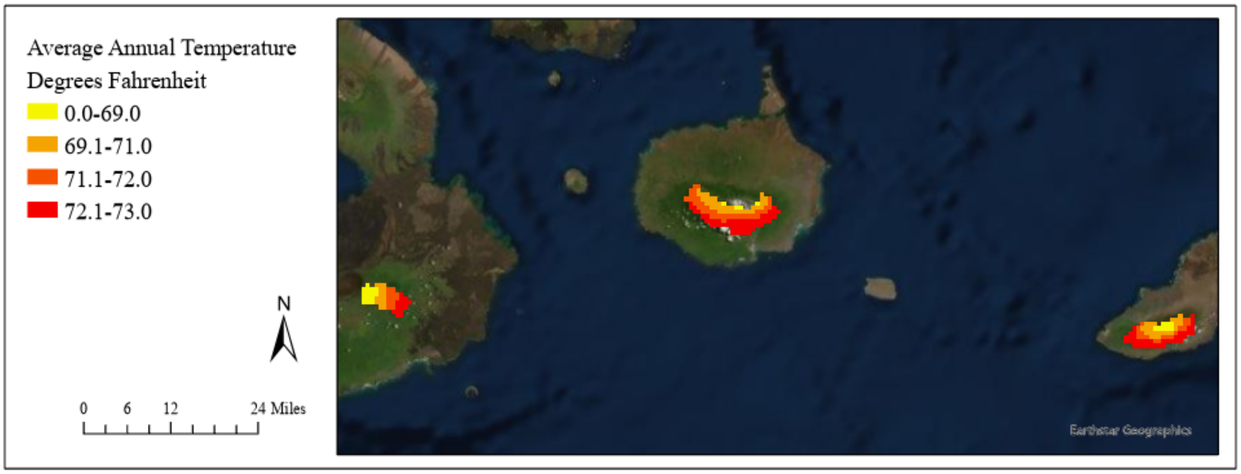

Figure 17. A visualization of the average annual temperature criteria for the year 2012 within the Galapagos Island study area.

The effect of temperature on plants influences people in a similar but more nuanced manner. This factor of temperature has been shown to affect people or the individual through thermal stress. The condition of thermal stress occurs when the temperature in a location becomes too extreme for the human body to handle. This condition of thermal stress is particularly important to consider in a recreational setting like tourism and its influence on visitation. Temperature is often used as one key variable to model tourist visitation (Hamilton and Tol 2007; Serquet and Rebetez, 2011) (Becken, 2012). This rate of tourist visitation can have a direct impact on the economic success of tourism and its development within the Galapagos Island study area.

The study measures this potential rate of tourist visitation in relation to thermal stress and potential plant productivity through an established index of thermal comfort which is in a similar range for both people and plants. This index is based on information about thermal comfort or thermal component, which are not based on human energy balance of individuals (Matzarakis, 2006) (Zaninovic, 2009). These thermal comfort ranges were classified within the study as 72.0 °F to 71.1 °F as highly suitable, 71.0 °F to 69.1 °F as moderately suitable, 72.1 °F to 73.0 °F as marginally suitable, and below 69.0 °F or above 73.0 °F as not suitable. However, regions above 73 °F do not exist within the study area for this criterion.

Aspect

Our understanding of the slope aspect is essential in determining the suitable and most advantageous location for agroforestry production or scenario 1. This geographic component of aspect plays a large part in the development of microclimates and by extension the habitat for certain plant communities. The slope aspect plays a vital role in determining soil moisture and solar radiation and thus soil heat flux between the soil and atmosphere (Bennie et al., 2008; Chesson et al., 2004). Generally, the slope aspect alters radiation and soil evaporation, and thus influences plant composition (Clifford et al., 2013; Deak et al., 2017). These variations considerably affect soil biogeochemical cycles and vegetation patterns (Zhao and Li, 2017) (Kong et al., 2019). This cascading effect of aspect is particularly important within the Galapagos Island study area which mostly exists on south or southeast facing slopes within the humid or transition vegetation zone (fig. 18). The humid zone extends from 200 to 450 m a.s.l. and was originally covered by the endemic Scalesia tree (Hamann, 1979) (Pryet et al., 2012).

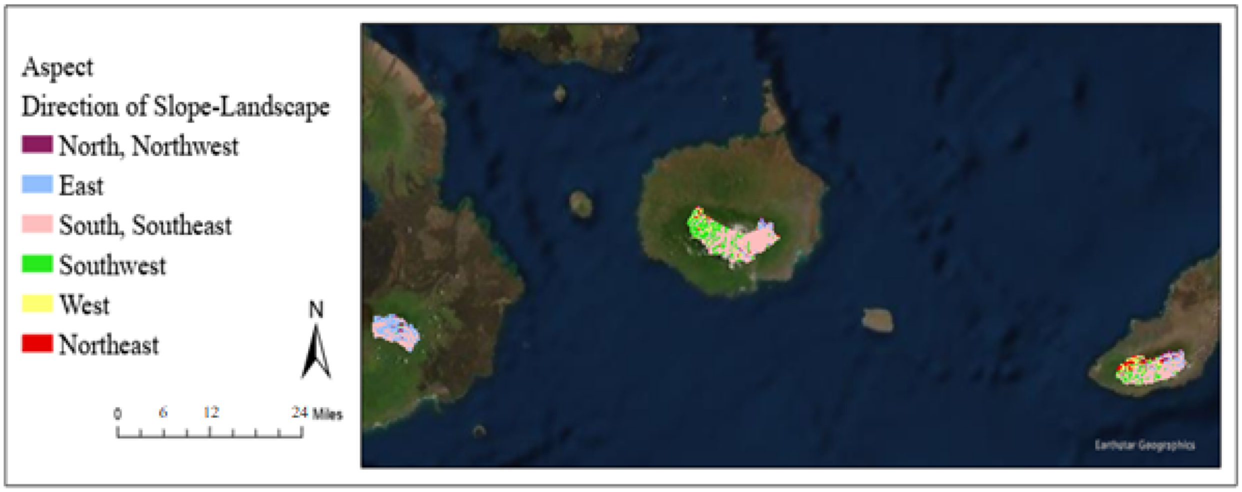

Figure 18. A visualization of the aspect criteria within the Galapagos Island study area.

The study measures aspect by the unit of slope direction ranging from 0 to 360. These measurements of slope direction are classified using the well-established understanding of directional variation in solar radiation levels in comparison to the historical vegetation zone phenomena within the study area. This slope direction between 202.5 and 247.5 was classified as highly suitable, 157.5 to 202.5 as moderately suitable, 247.5 to 292.5 or 67.5 to 112.5 as marginally suitable, and all other slope direction measurements as not suitable.

CHAPTER 4: Scenario-Based Suitability Framework Implementation

The chapter begins with an analysis of the fuzzy sub-model implementation results for scenario 1 followed by a section that discusses the final scenario 1 suitability result. Then, the fuzzy sub-model implementation results for scenario 2 are analyzed followed by a section discussing the final scenario 2 suitability result. The chapter ends with an analysis of the suitability interrelationship of both scenarios 1 and 2.

4.1 Scenario 1: Agroforestry Production

The section of scenario 1 discusses the fuzzy membership sub-model results for all six factors or categories of individual criteria discussed in chapter 3. This section also covers the modeling process, source layers, uncertainty in measurements, and the locations that were determined too definitely be suitable or unsuitable. The scenario 1 section concludes with a description of the agroforestry production site suitability findings, the resulting visualization, and an area measurement of site suitability by suitability class.

4.1.1 Agroforestry Production Sub Model Results

The sub-model execution of hydrology factors provided a variety of fuzzy membership results. These hydrology factors classified as major criteria include average annual precipitation-1b, potential evapotranspiration-1a, and potential aridity-1c. The sub-model output resulted in a higher membership value for the average annual precipitation and potential aridity phenomena within the San Cristobal Island region and a higher membership value for potential evapotranspiration within the Santa Cruz Island region (fig. 19).

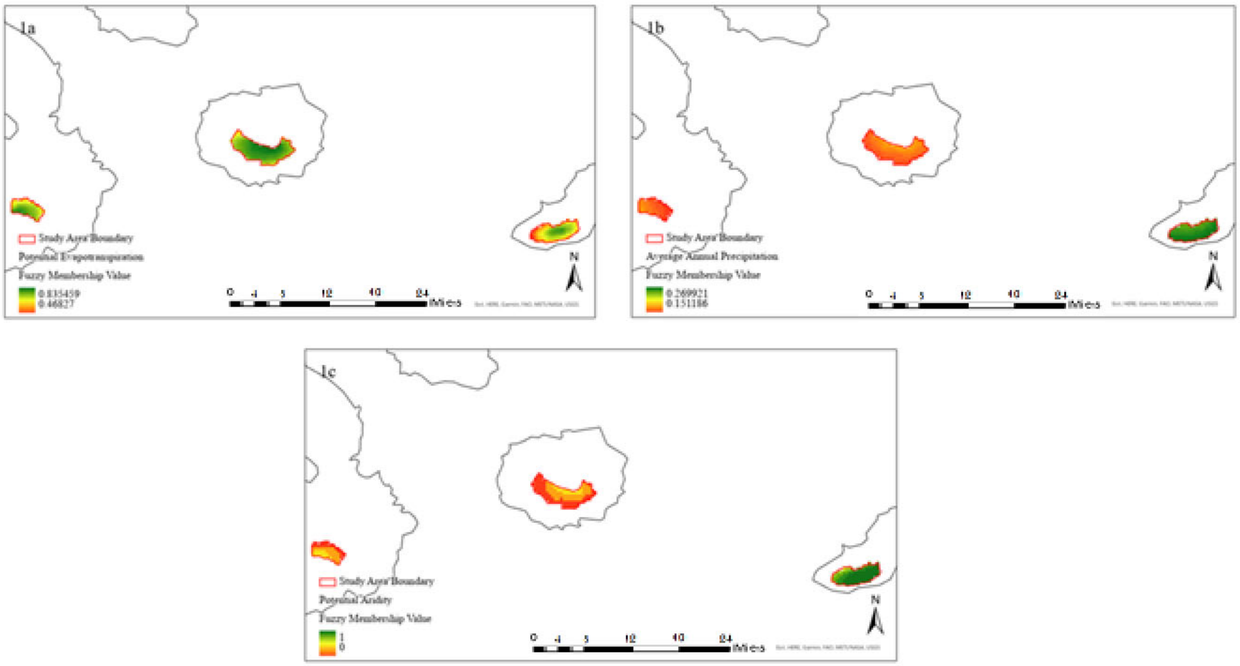

Figure 19. Map of fuzzy membership for criterion 1a, 1b and 1c.

The sub-model of hydrology factors was comprised of spatial datasets from the CIGAR-CSI and WorldClime organizations and prepared for use within the ArcGIS Pro model builder platform. These datasets were computed through a series of geoprocessing algorithms starting with the clip operator followed by the reclassify operator, reclass operator, and lastly the fuzzy membership operator.

The fuzzy membership linear function was selected for use on all hydrology factors due to the maximum and minimum characteristics of the phenomena and source layer. All the hydrology criteria are standardized and visualized to the 30 arc seconds resolution which carries some inherent uncertainty in its accuracy of representation (appendix. A).

The second sub-model factor of topography provided unique fuzzy membership results. These topographic factors classified as major criteria include Elevation of Terrain-2a and Slope of Terrain-2b. The sub-model output resulted in a higher membership value for the elevation of terrain within the northern portions of Isabela, Santa Cruz, and San Cristobal Island while the slope of terrain holds higher membership values within the southern portion of Isabela and Santa Cruz and western portion of San Cristobal (fig. 20).

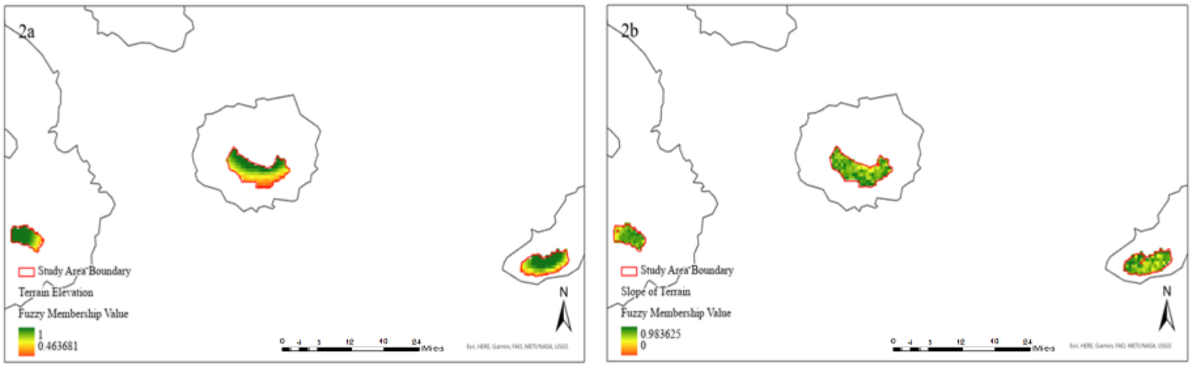

Figure 20. Map of fuzzy membership for criterion 2a and 2b.

The data and source layers for the topographic factor were acquired from the national aeronautics and space administration of the United States data portal and prepared for use within the ArcGIS Pro model builder platform. These datasets were computed through a series of geoprocessing algorithms starting with the clip operator followed by the reclass operator, reclassify operator, and lastly the fuzzy membership operator.

The fuzzy membership linear function was selected for use on both topographic factors due to the maximum and minimum characteristics of the phenomena and source layer. The elevation and slope of terrain criteria were resampled from its original resolution of 90m to 30 arc seconds resolution for standardization purposes which can cause some inherent uncertainty in its accuracy of representation (appendix. B).

The third sub-model built environment factors provided a variety of fuzzy membership results. These built environment factors classified as major criteria include LULC-3a and the Road Network-3b. The sub-model output resulted in a higher membership value for the road network phenomena within the western region of San Cristobal Island while the LULC resulted in a higher membership value within the southern regions of all three islands (fig. 21).

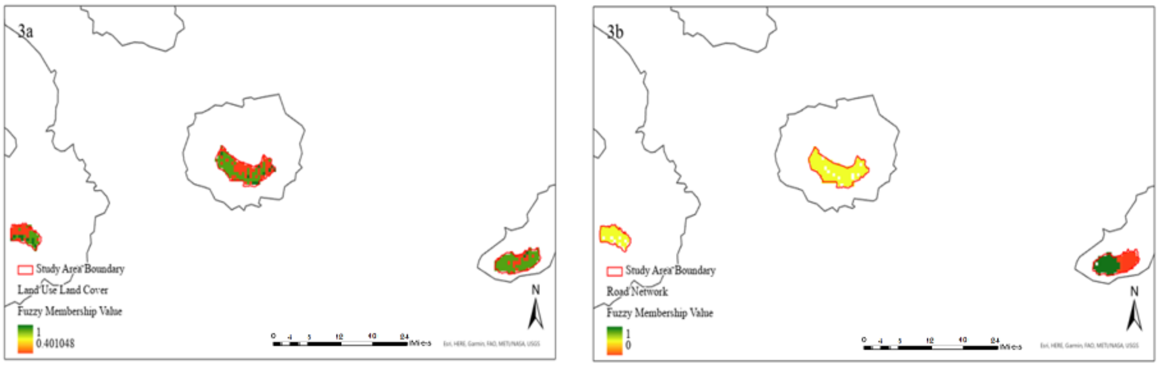

Figure 21. Map of fuzzy membership for criterion 3a and 3b.

The data and source layers for the built environment factors were acquired from the European Space Agency (ESA) and Open Street Map (OSM) organization's data portals and prepared for use within the ArcGIS Pro model builder platform.

The fuzzy membership linear function was selected for use within the model builder for both the road network and LULC criteria due to the maximum and minimum characteristics of the phenomena and source layer. The LULC criteria was remotely sensed and visualized at an original resolution of 30 arc seconds. This ESA's LULC classification system and standardization across a 30 arc seconds cell area was a cause of uncertainty due to the generalization of phenomena (appendix. C). The road network source layer in comparison carries some uncertainty due to the inherent positional accuracy of digitized OSM polylines.

The fourth sub-model factor of temperature provided a unique fuzzy membership result. The temperature factor or average annual temperature-4a was classified as a minor criterion within the study. The sub-model output resulted in a higher membership value for the criteria 4a phenomena within the southern region of all three islands (fig. 22).

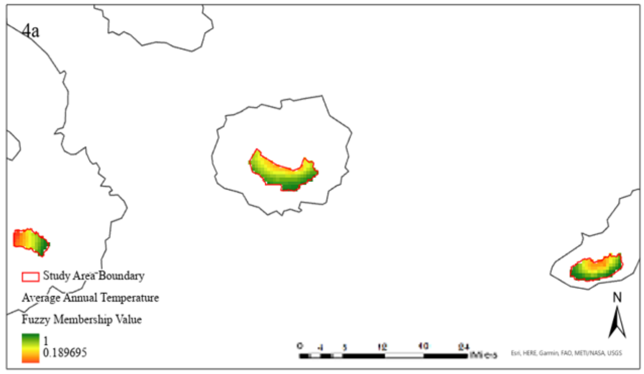

Figure 22. Map of fuzzy membership for criterion 4a.

The fuzzy membership near function was selected for use within the model builder for the average annual temperature criteria due to the midpoint and small range of temperature distribution of the phenomena and source layer. The average annual temperature criteria was standardized and visualized to the 30 arc seconds resolution which carried some inherent uncertainty in its accuracy of representation (appendix. D).

The fifth sub-model factor of soils provided a unique fuzzy membership result. The soils factor or soil drainage-5a is classified as a minor criterion within the study. The sub-model output resulted in a higher membership value for the criteria 5a phenomena within the Santa Cruz Island region (fig. 23).

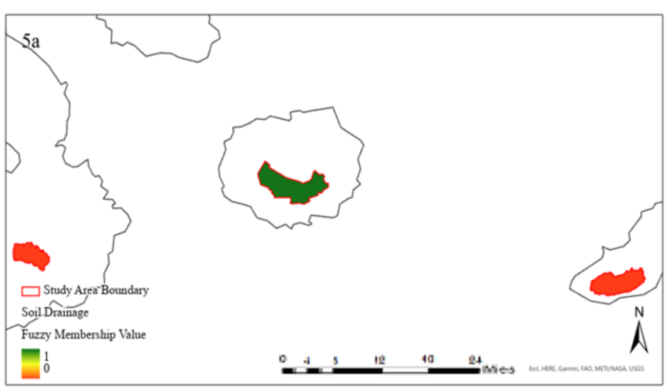

Figure 23. Map of fuzzy membership for criterion 5a.

The fuzzy membership linear function was selected for use within the model builder for the soil drainage criteria due to the maximum and minimum characteristics of the phenomena and source layer. The soil drainage criteria is standardized using an established USDA soil drainage classification system and visualized to the 30 arc seconds resolution which carried some inherent uncertainty in its accuracy of representation (appendix. E).

The sixth sub-model factor of aspect provided a unique fuzzy membership result. The aspect factor or aspect criteria-6a is classified as a minor criterion within the study. The sub-model output resulted in a higher membership value for the criteria 6a phenomena in isolated regions at the individual cell area level of Santa Cruz and San Cristobal Island (fig. 24).

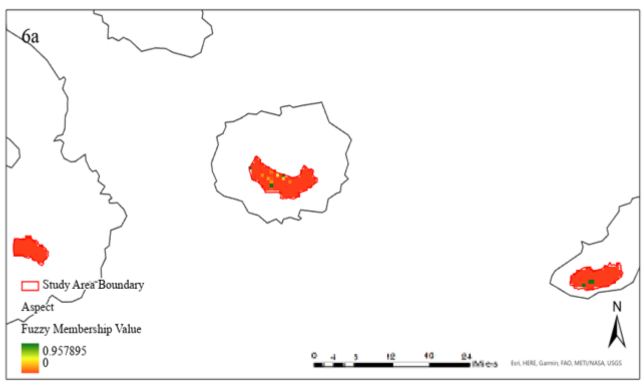

Figure 24. Map of fuzzy membership for criterion 6a.

The fuzzy membership linear function was selected for use within the model builder for the aspect criteria due to the maximum and minimum characteristics of the phenomena and source layer. The aspect criteria were resampled from its original resolution of 90m to 30 arc seconds resolution for standardization purposes which caused some inherent uncertainty in its accuracy of representation (appendix. F).

4.1.2 Agroforestry Production Scenario

The fuzzy overlay *And* operator was used to combine the fuzzy membership layers of scenario 1. This *And* operator assigns the minimum values from all the input fuzzy membership layers to the output cell. The operator identifies the least common denominator of the membership criteria, producing a more conservative result with smaller overall membership values. This allows cells with a membership of a specific minimum value of a criterion to be identified. The fuzzy overlay execution and analysis resulted in clear visualization of site suitability for agroforestry production classified under the categories highly suitable-S1, moderately suitable-S2, marginally suitable-S3, and not suitable-N (fig. 25).

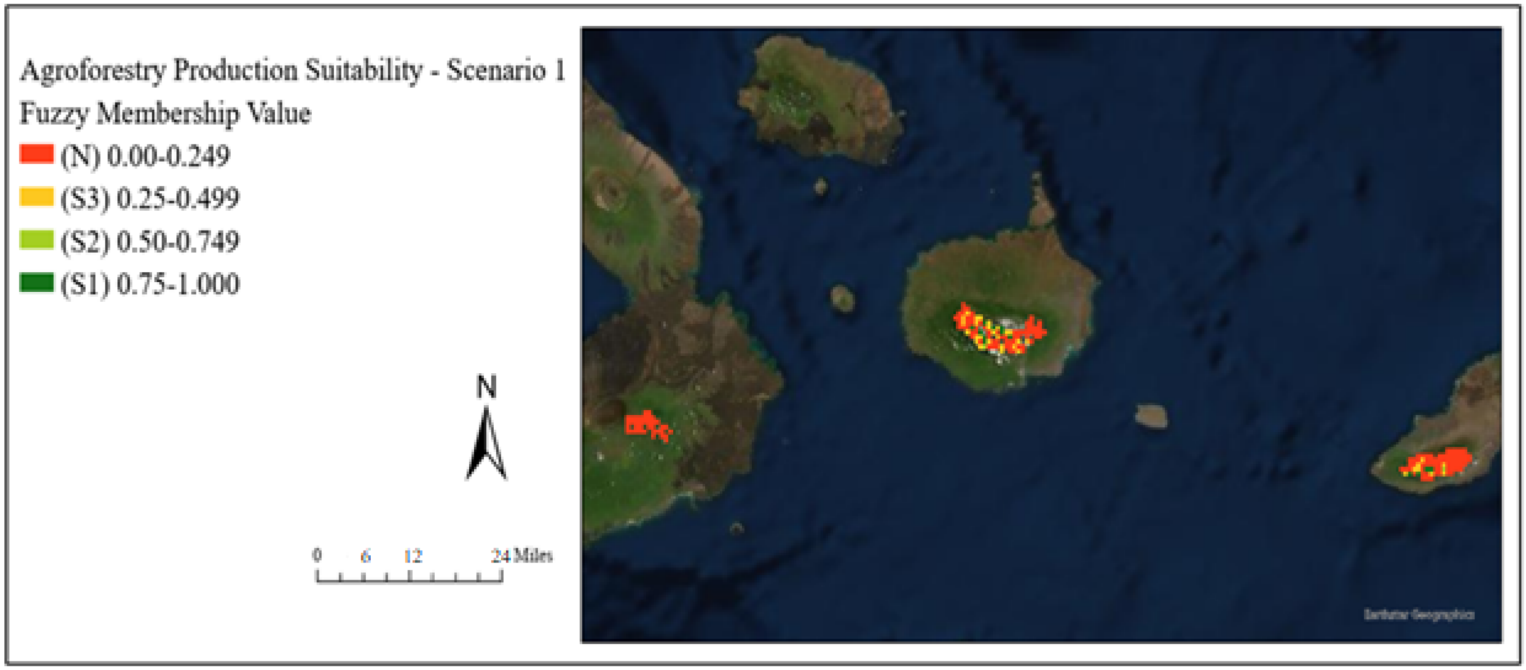

Figure 25. The fuzzy overlay suitability result of scenario 1or agroforestry production within the study area-agricultural zone of the Galapagos Islands.

This exclusive geoprocessing *And* function within the fuzzy overlay operator have disqualified or classified major areas to be not suitable due to the geoprocessing method of assigning values based on the lowest common denominator for all criteria. The exclusive function of the fuzzy overlay operator was beneficial because it removed major parts of the region from consideration allowing for more focused site surveying.

While much of the study area is not suitable, it is not as exclusive as it appears given that each individual raster cell in the visualization equates to 0.56 by 0.56 miles or approximately 285.4 acres. The site suitability membership class S1 was measured at 4 percent, S2 at 0 percent, S3 at 16 percent, and N at 80 percent across the entire study area (table. 6).

Table 6. The suitable area measurement and membership class results of scenario 1.

Membership Range	Membership Class	Overall Suitability	Approximate Acres
0.75-1.00	Highly Suitable	4%	2,477.28
0.50-0.749	Moderately Suitable	0%	0
0.25-0.499	Marginally Suitable	16%	9,909.12
0.0-0.249	Not Suitable	80%	49,545.60

These highly suitable and marginally suitable sites were in the central region of Santa Cruz Island and western region of San Cristobal Island equating to a sum of 12,386.4 acres.

4.2 Scenario 2: Tourism Development

The section of scenario 2 discusses the fuzzy membership sub model results for the two factors or categories of individual criteria discussed in chapter 3. This section also covers the modeling process, source layers, uncertainty in measurements and the locations that are determined too definitely be suitable or unsuitable. The scenario 2 section concludes with a description of the tourism development site suitability findings, the resulting visualization, and an area measurement of site suitability by suitability class.

4.2.1 Tourism Development Sub Model Results

The sub-model factors of the built environment provided a variety of fuzzy membership results. These built environment factors classified as major criteria include the Road Network-3c, Market Center-3d, LULC-3e, and the Coastal Port Routes-3f. The sub-model output resulted in a higher membership value for the road network phenomena within the western region of San Cristobal Island while the LULC resulted in a higher membership value within the northern regions of all three islands (fig. 26). The 3d criterion is similar to 3c as it resulted in a higher membership value within the western portion of San Cristobal Island while criterion 3f resulted in a higher membership value across most of Santa Cruz Island, western San Cristobal Island, and eastern Isabela Island.

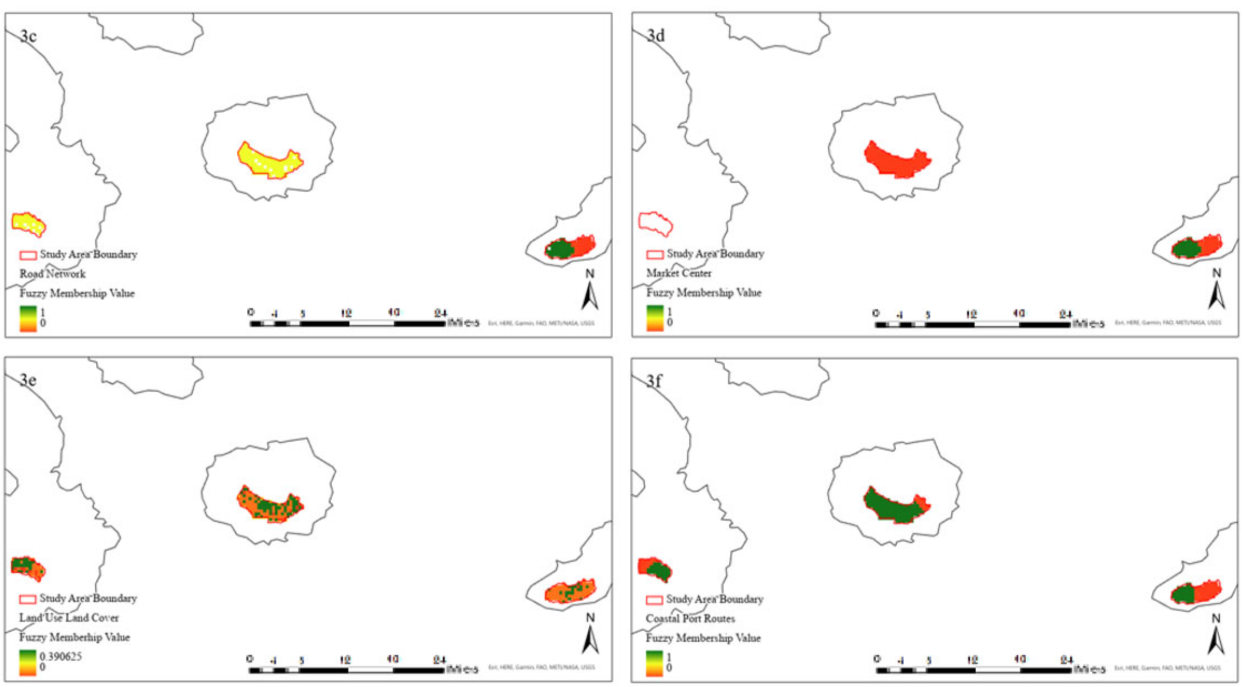

Figure 26. Map of fuzzy membership for criterion 3c, 3d, 3e and 3f.

The data and source layers for the built environment factors were acquired from the ESA's data portal, OSM data portal, and digitized from the OSM remotely sensed imagery. These source layers were prepared for use within the ArcGIS Pro model builder platform.

The fuzzy membership linear function was selected for use within the model builder for all the built environment criteria due to the maximum and minimum characteristics of the phenomena and source layer. The road network, coastal port routes, and market center source layer carried some uncertainty due to the inherent positional accuracy of digitized OSM polylines and central points. The LULC criteria in comparison were remotely sensed and visualized at an original resolution of 30 arc seconds. This ESA's LULC classification system and standardization across a 30 arc seconds cell area was also a source of uncertainty due to the generalization of phenomena (appendix. G).

The second sub-model factor of temperature provided a unique fuzzy membership result. The temperature factor or average annual temperature-4b was classified as a minor criterion within the study. The sub-model output resulted in a higher membership value for the criteria 4b phenomena within the southern region of all three islands (fig. 27).

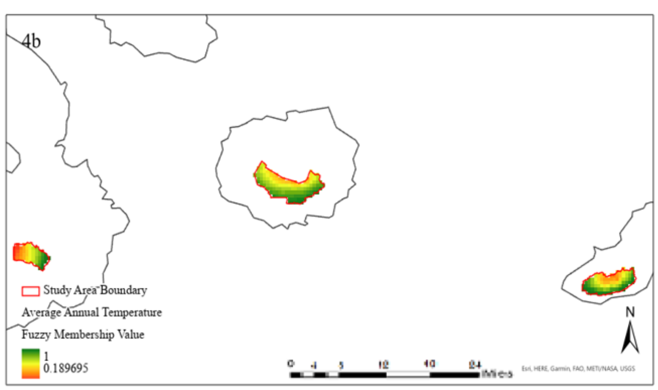

Figure 27. Map of fuzzy membership for criterion 4b.

The fuzzy membership near function was selected for use within model builder for the average annual temperature criteria due to the midpoint and small range of temperature distribution of the phenomena and source layer. The average annual temperature criteria was standardized and visualized to the 30 arc seconds resolution which carried some inherent uncertainty in its accuracy of representation (appendix. H).

4.2.2 Tourism Development Scenario

The fuzzy overlay *And* operator were used to combine the fuzzy membership layers of scenario 2. This *And* operator assigns the minimum values from all the input fuzzy membership layers to the output cell. The operator identifies the least common denominator of the membership criteria, producing a more conservative result with smaller overall membership values. This allows cells with a membership of a specific minimum value of a criterion to be identified. The fuzzy overlay execution and analysis resulted in clear visualization of site suitability for tourism development classified under the categories of highly suitable-S1, moderately suitable-S2, marginally suitable-S3, and not suitable-N (fig. 28).

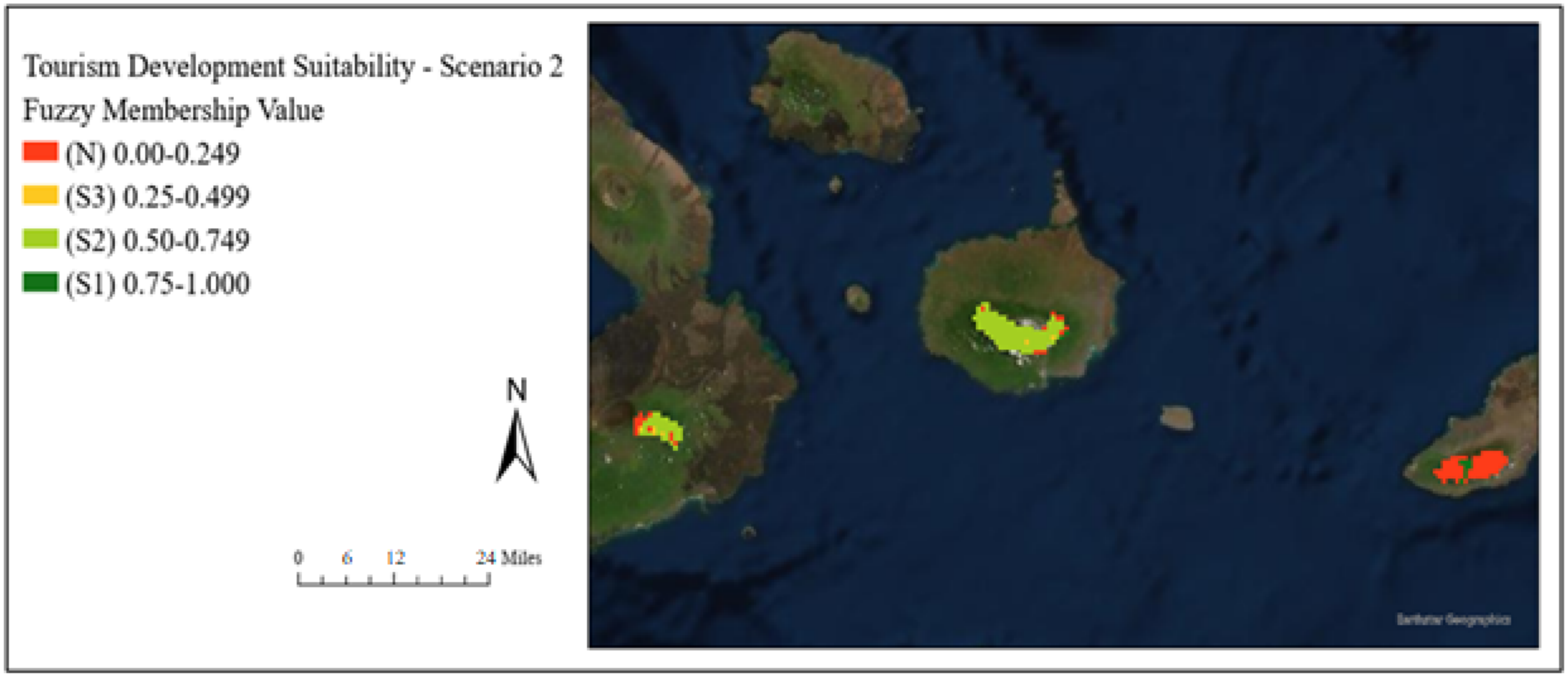

Figure 28. The fuzzy overlay suitability result of scenario 2 or tourism development within the study area-agricultural zone of the Galapagos Islands.

This exclusive geoprocessing *And* function within the fuzzy overlay operator have disqualified or classified major areas as not suitable particularly within San Cristobal Island due to the geoprocessing method of assigning values based on the lowest common denominator for all criteria. The exclusive function of the fuzzy overlay operator was beneficial because it removed major parts of the region from consideration but also determined major areas to be moderately suitable allowing for more focused site surveying.

While a good portion of the study area was not suitable, it was not as exclusive as it appears given that each individual raster cell in the visualization equates to 0.56 by 0.56 miles or approximately 285.4 acres. The site suitability membership class S1 was measured at 5 percent, S2 at 50 percent, S3 at 3 percent, and N at 42 percent across the entire study area (table. 7).

Table 7. The suitable area measurement and membership class results of scenario 2.

Membership Range	Membership Class	Overall Suitability	Approximate Acres
0.75-1.00	Highly Suitable	5%	3,096.60
0.50-0.749	Moderately Suitable	50%	30,966.00
0.25-0.499	Marginally Suitable	3%	1,857.96
0.0-0.249	Not Suitable	42%	26,011.44

These highly suitable sites were located predominately in the center of San Cristobal Island. While the moderately suitable and marginally suitable sites were located across the majority of Santa Cruz and Isabela Island. All the suitable sites of S1, S2 and S3 combined equate to 35,920.6 acres.

4.3 Interrelationship of Scenarios

The fuzzy membership classes for both scenarios 1 and 2 were defuzzified to produce quantifiable crisp binary results of suitable and unsuitable (not suitable) sites. Both scenarios were assessed within the study area to determine the percentage of suitable and unsuitable sites. The points of spatial overlap for both scenarios were also assessed and measured in acres of both suitable or both unsuitable sites (table. 8).

Table 8. The defuzzification percentage of suitable area verse unsuitable area for both scenario 1 and 2 compared with area percentages that contain overlap of both scenarios.

	Suitable	Unsuitable	Both Suitable	Both Unsuitable
Scenario One	20%	80%	21%	42%
Scenario Two	58%	42%		
Approximate Acres:			12,843.00	25,971.00

This assessment of spatial overlap of suitable scenarios was determined to be 21 percent of the study area or 12,843.0 acres and can be beneficial for more focused site surveying and on the ground investigation of scenario interrelationships or compatibility. The defuzzification of scenarios also provided a clear quantitative measure of regions or sites that can be removed or disqualified from immediate surveying. This unsuitable area for both scenarios or region of disqualification equates to 42 percent of the study area or 25,971.0 acres.

CHAPTER 5: Summary and Conclusion

This study developed a general framework to identify the suitable sites for where risks of agroforestry production and tourism development are minimized, and benefits are maximized within the agricultural zone of the Galapagos Islands. In summary, the research had a threefold purpose of building upon current research on agroforestry production potential, scenario-based land use planning in relation to biodiversity conservation, and fuzzy methods of suitability analysis; creating a suitability framework that could be implemented by governments and NGOs throughout the humid highland ecosystems while also developing a refined model that applies the framework to the specific context of the Galapagos Islands, Ecuador. This research included a review of relevant literature on the risks to biodiversity along with conservation solutions, a means to evaluate criteria, and developing methods to analyze the criteria in a GIS.

5.1 Assessment of Model

Fuzzy logic was an effective method for this application because it eliminated a false appearance of certainty in the data. This fuzzy logic allowed for low certainty to be captured. Fuzzy methods were utilized to represent the fuzziness that was inherent in the data. These techniques were especially useful for data layers that needed to be resampled to ensure compatibility for multi-criteria analysis.

5.2 Future Work

While the model implementation showed good performance, it can be further improved. Field research and further investigation into the regions that scored as not suitable-unsuitable on the membership scale are needed. This can provide more information about why regions were deemed unsuitable and their biodiversity significance. Field research can also help to identify inappropriate criteria in the general framework.

Once a field check is completed, the results of a model, such as the suitability map created in this scenario-based study, can be used as a decision support tool for biodiversity conservation planning. The model was able to identify unsuitable areas for scenario 1 and scenario 2 or regions of development risk to biodiversity based on multiple criteria. These criteria can be modified and improved as higher resolution data and more types of data become available. The general framework and the implemented model outlined here are intended to serve as a foundational tool that local governments and NGO practitioners can continue to improve and utilize for the valuation of land specific to scenarios or for general planning.

The economic and ecological valuation of land is contextual and can be assessed through a market-based approach, ecosystem services approach or using simple cost-benefit analysis but the suitability of locations is a first step that must be understood. This scenario-based framework and study was intended to provide this multicriteria modeling perspective and first step of land evaluation for further in-depth land assessment.

The framework was developed remotely and can therefore continue to be improved with local knowledge and the addition of other scenarios important to the Galapaguenos. It is likely that as research continues more criteria and scenarios will be added to the framework to account for the rich and complex planning environment. A user on the local field level with an understanding of the complexity may also be able to acquire higher resolution data that will likely improve model performance.

5.3 Applicability of Research

Since many of the risks to biodiversity also exist outside of the Galapagos Islands, the framework can be used in other regions. The fifteen criteria were developed by researching universal risks to biodiversity, geographic requirements, and socioeconomic requirements specific to scenario 1 and scenario 2 within the Galapagos Island study area. Using the general framework, a user is easily able to select only relevant scenario-based criteria and parameter requirements as it relates to biodiversity risk and to add additional ones that may be appropriate.

The use of the fuzzy membership function is an important part of the framework because it allows a user to set membership ratings based on whether or not a scenario-based criterion is intended to decrease risk to biodiversity or provide socioeconomic benefit. The shape of the membership function can be selected for each criterion based on knowledge about the uncertainty. This study utilized a mix of near, gaussian, and predominantly linear functions due to the type of uncertainty in criterion. The framework included suitability factors that carry a risk, and/or a benefit to biodiversity therefore the ability for a user to set each membership value uniquely with a positive or negative slope based on input values or the major minor hierarchy of criterion using hedges was critical. The choice of the fuzzy membership function was a key component of the framework during implementation.

When the framework is implemented, it can improve the workflow used by government or NGOs to determine where a tourism development or agroforestry production enterprise should be located to ensure the conservation of biodiversity. The framework allows users to disqualify locations for consideration that have a higher risk to biodiversity or do not provide high socioeconomic benefits. The framework also demonstrated how a GIS-based tool can be used to evaluate several criteria with one suitability map.

The scenario-based model and tool does not however capture all the dimensions involved in deciding where an agroforestry production or tourism development enterprise should be located. As mentioned earlier, there are several cultural, political, and social factors that influence the decisions made. The framework can, however, be used to supplement decision-making as a macro-level tool.

The work in this project lays the foundation for scenario-based assessment in future development. These general framework measurements used in the model and criteria can continue to be refined by users as they customize the model for their context. While the model performed at an adequate level, the study itself offers some suggestions for how a GIS scenario-based conceptual framework can be used by governments and NGOs to improve land use planning in regions with limited access to data that ensure the conservation of biodiversity and meets SDGs in the long-term.

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Appendices

Appendix A. Analysis of the scenario one hydrology category of criteria factors.

Criteria	Source Layer	Values in source layer	Source of Uncertainty	Definitely Suitable	Definitely Unsuitable	Membership Function
1a-Should not be established within low potential evapotranspiration zones	CGIAR-CSI, Potential Evapotranspiration	The layer consists of an average millimeter per year of potential evapotranspiration for years 1982 to 2012 (values converted to inches).	The values are continuous with no breakpoint and the layer is visualized in 30 arc sec resolution. This scale of visualization and with no breakpoint or boundary lines holds some inherent uncertainty.	The 20 cells to the north on Santa Cruz Island, 5 cells to the south on Isabela and 8 cells in the central core of San Cristobal are suitable.	The western region of the San Cristobal Island study area is definitely unsuitable.	The linear function was used. The unsuitable locations with a minimum value of 1499 were assigned a membership value of 0. Then a membership rating of 1 was assigned to the maximum value of 1001.

1b-Should not be established on terrain that receives a low quantity of precipitation	NASA-WorldClim, Average Annual Precipitation	The layer consists of raster data in millimeters per year of average annual precipitation for the year 2018 (values converted to inches).	There is uncertainty about how accurately the layer represents the phenomena. The layer is visualized in 30 arc sec resolution which can cause most inherent uncertainty.	The entire Santa Cruz, Isabela and San Cristobal Island study area are definitely suitable	No locations of unsuitability	The linear function was used. The unsuitable locations with a minimum value of 0 were assigned a membership value of 0. Then a membership rating of 1 was assigned to the maximum value of 700.
1c-Should not be established in areas of high aridity	CGIAR-CSI, Potential Aridity	The layer contains aridity index values comprised of ten classes: high aridity of 0.03 as arid to a low aridity of 1.75 as tundra.	The values are standardized within the aridity index and visualized in 30 arc sec resolution. This scale of resolution and data standardization holds some inherent uncertainty in its accuracy of representation.	The southern and eastern regions of San Cristobal Island are definitely suitable.	The northern regions of Isabela Island and southern regions of Santa Cruz are definitely unsuitable.	The linear function was used. The unsuitable locations with a minimum value of 0.03-class 1 were assigned a membership value of 0. Then a

						membership rating of 1 was assigned to the maximum value of 1.75-class 10.

Appendix B. Analysis of the scenario one topographic category of criteria factors.

Criteria	Source Layer	Values in source layer	Source of Uncertainty	Suitable Location(s)	Unsuitable Location(s)	Membership Function
2a-Should be established within the optimum altitude where the humid and transition zone exists.	SRTM-DEM, layer	The layer contains landscape altitude measurements in meters (values converted to feet).	The layer was originally in 90 m resolution and resampled to 30 arc sec. This causes the total cell area measurement accuracy of altitude to be uncertain.	The western region of Isabela, northern region of Santa Cruz and the northern region of San Cristóbal Island are definitely suitable.	The area of three cells in the southern region of Santa Cruz Island is definitely unsuitable.	The linear function was used. The unsuitable locations with a minimum value of 459 were assigned a membership value of 0. Then a membership rating of 1 was assigned to the maximum value of 1444.
2b-Should not be established on steep slopes greater than 30 percent that are difficult to access, plant or harvest	SRTM-DEM, layer	The layer contains landscape altitude measurements in meters (values converted to feet). These altitude values were converted into percent slope using geoprocessing tools.	The layer was originally in 90 m resolution and resampled to 30 arc sec. This causes the total cell area measurement accuracy of altitude to be uncertain.	The eastern region of Isabela, western region San Cristobal and southern region of Santa Cruz Island are definitely suitable.	The raster cell area of a location in the western region of Isabela, northern region of Santa Cruz and southern region of San Cristobal Island are definitely unsuitable.	The linear function was used. The unsuitable locations with a minimum value of 0 were assigned a membership value of 0. Then a membership rating of 1 was assigned to the maximum value of 30.

Appendix C. Analysis of the scenario one built environment category of criteria factors.

Criteria	Source Layer	Values in source layer	Source of Uncertainty	Suitable Location(s)	Unsuitable Location(s)	Membership Function
3a-Should not be established within the urban land use.	ESA, Land use land cover layer	The layer is comprised of land use land cover area measurements that correspond to a standard ESA classification system of landscape types and numerical codes.	The ESA's remotely sensed data is visualized at the 30 arc sec resolution. This generalization of the land use land cover phenomena across a 30 arc sec cell area is a cause of uncertainty.	The southwestern region of Santa Cruz, eastern region of Isabela and the majority of San Cristobal Island is definitely suitable.	The western region of Isabela, northern region of Santa Cruz and northern region of San Cristobal Island are definitely unsuitable.	The linear function was used. The unsuitable locations with a minimum value of 153 were assigned a membership value of 0. Then a membership rating of 1 was assigned to the maximum value of 10.
3b-Should not be established within primary and secondary roads	Layer digitized from the OSM secondary source	The layer is comprised of road network polylines in association with euclidean distance measurements at 5 miles, 6 miles and greater than 6 miles.	There is uncertainty in the positional accuracy of digitized road networks and the exact alignment of these polylines with the phenomena of primary and secondary roads.	The western region of San Cristobal Island is definitely suitable.	The eastern region of San Cristobal Island is definitely unsuitable.	The linear function was used. The unsuitable locations with a minimum value of 6 were assigned a membership value of 0. Then a membership rating of 1 was assigned to the maximum value of 5 (all roads-polylines containing a buffer of 1312.0 feet of no data).

Appendix D. Analysis of the scenario one temperature category of criteria.

Criteria	Source Layer	Values in source layer	Source of Uncertainty	Suitable Location(s)	Unsuitable Location(s)	Membership Function
4a-Should not be established in regions with high or low annual temperature	WorldClim Group, Average Annual Temperature layer	The layer is comprised of numerical temperature values in degrees Celsius (values converted to Fahrenheit).	The raster layer is visualized in 30 arc sec resolution. This representation of average annual temperature at the 30 arc sec scale is a cause of uncertainty.	The eastern region of Isabela, southern region of Santa Cruz and western region of San Cristobal Island is definitely suitable.	The western region of Isabela Island is definitely unsuitable.	The near function was used. A membership rating of 1 was assigned to the value of 73.4 degrees Fahrenheit as the midpoint and membership decreases on either side of the midpoint to an assigned value of 0 for the value 62.6 and 95.0 degrees Fahrenheit.

Appendix E. Analysis of the scenario one soil category of criteria.

Criteria	Source Layer	Values in source layer	Source of Uncertainty	Suitable Location(s)	Unsuitable Location(s)	Membership Function
5a- Should be established in soils with an optimal drainage class range	ISRIC-FAO, Soils layer for the South American region	The layer contains qualitative values of soil type and area that are then assigned standard measurements- conductivity of water in millimeters per hour (values converted to inches) of drainage based on soil type.	The layer value of dominant soil type is assigned its corresponding hydraulic conductivity property value and classified using a standard drainage class system of six categories. This generalization of dominant soil type and its associated drainage class is a cause of uncertainty.	The soil drainage within Santa Cruz Island is definitely suitable.	The soil drainage within Isabela and San Cristobal Island is definitely unsuitable.	The linear function was used. The unsuitable locations with a minimum value of 0.16 were assigned a membership value of 0. Then a membership rating of 1 was assigned to the maximum value of 4.92.

Appendix F. Analysis of the scenario one aspect category of criteria.

Criteria	Source Layer	Values in source layer	Source of Uncertainty	Suitable Location(s)	Unsuitable Location(s)	Membership Function
6a-Should not be established on aspects with low annual sunlight	SRTM-DEM, layer	The values of slope direction from 0 to 360.	The layer was originally in 90 m resolution and resampled to 30 arc sec. This causes the total cell area of aspect-slope direction to be uncertain.	Three separate cell locations in the western portion of Santa Cruz Island and two cell locations within southern San Cristobal Island are definitely suitable.	A large portion of Santa Cruz Island, San Cristobal and all of Isabela are definitely unsuitable.	The Gaussian function was used. A membership rating of 1 was assigned to the value of 202.5 as the midpoint and membership decreases on either side of the midpoint to an assigned value of 0 for the value 0.0 and 360.0.

Appendix G. Analysis of the scenario two built environment category of criteria factors.

Criteria	Source Layer	Values in source layer	Source of Uncertainty	Suitable Location(s)	Unsuitable Location(s)	Membership Function
3c-Should be developed near primary and secondary roads	Layer digitized from the OSM secondary source	The layer is comprised of road network polylines in association with euclidean distance measurements at 5 miles, 6 miles and greater than 6 miles.	There is uncertainty in the positional accuracy of digitized road networks and the exact alignment of these polylines with the phenomena of primary and secondary roads.	The western region of San Cristobal Island is definitely suitable.	The eastern region of San Cristobal Island is definitely unsuitable.	The linear function was used. The unsuitable locations with a minimum value of 6 were assigned a membership value of 0. Then a membership rating of 1 was assigned to the maximum value of 5 (all roads-polylines containing a buffer of 1312.0 feet of no data).

3d-Should be developed in proximity to a market center	Layer digitized from the OSM secondary source	The layer is comprised of market center points in association with euclidean distance measurements at 5 miles, 6 miles and greater than 6 miles.	There is uncertainty in the positional accuracy of market center points (centers of commerce and population) and the exact alignment of these points with the center plaza or node of commerce and population .	The western region of San Cristobal Island is definitely suitable.	The eastern region of San Cristobal Island is definitely unsuitable.	The linear function was used. The unsuitable locations with a minimum value of 6 were assigned a membership value of 0. Then a membership rating of 1 was assigned to the maximum value of 5.
3e-Should be developed near or within the existing urban land use	ESA, Land use land cover layer	The layer is comprised of land use land cover area measurements that correspond to a standard ESA classification system of landscape types and numerical codes.	The ESA's remotely sensed data is visualized at the 30 arc sec resolution. This generalization of the land use land cover phenomena across a 30 arc sec cell area is a cause of uncertainty.	The western region of Isabela, northern region of Santa Cruz and portions of northern San Cristobal are definitely suitable.	The most southern region of Santa Cruz and Isabela Island are unsuitable.	The linear function was used. The unsuitable locations with a minimum value of 10 were assigned a membership value of 0. Then a membership rating of 1 was assigned to the maximum value of 202.

3f-Should be developed in proximity to a coastal port	Layer digitized from the OSM secondary source	The layer is comprised of coastal route access points in association with euclidean distance measurements at 5 miles, 6 miles and greater than 6 miles.	There is uncertainty in the positional accuracy of coastal route access points and the exact alignment of these points with the primary roads.	The western region of San Cristóbal, eastern region of Isabela and majority of Santa Cruz Island is definitely suitable.	The western region of Isabela, eastern most region of Santa Cruz and eastern region of San Cristobal Island are definitely unsuitable.	The linear function was used. The unsuitable locations with a minimum value of 6 were assigned a membership value of 0. Then a membership rating of 1 was assigned to the maximum value of 5.

Appendix H. Analysis of the scenario two temperature category of criteria.

Criteria	Source Layer	Values in source layer	Source of Uncertainty	Suitable Location(s)	Unsuitable Location(s)	Membership Function
4b-Avoid regions that contain higher or lower than average temperature for the majority, of the year	WorldClim Group, Average Annual Temperature layer	The layer is comprised of numerical temperature values in degrees Celsius (values converted to Fahrenheit).	The raster layer is visualized in 30 arc sec resolution. This representation of average annual temperature at the 30 arc sec scale is a cause of uncertainty.	The eastern region of Isabela, southern region of Santa Cruz and western region of San Cristobal Island is definitely suitable.	The western region of Isabela Island is definitely unsuitable.	The near function was used. A membership rating of 1 was assigned to the value of 73.4 degrees Fahrenheit as the midpoint and membership decreases on either side of the midpoint to an assigned value of 0 for the value 62.6 and 95.0 degrees Fahrenheit.