Mangroves in Ecuador: an application and comparison of ecosystem services valuation models

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1 Background

1.1 Ecuadorian Mangroves

1.1.1 General introduction to mangroves

Mangroves are woody plants that grow in tropical and subtropical climates in the presence of high and low salinity water (Kathiresan and Bingham, 2003). The area of intersection between freshwater and saltwater, known as an estuary, provides a perfect habitat for mangroves. Mangroves are very resilient organisms that can withstand high winds, extreme tides, and high temperatures.

Mangroves grow in different types of soil, ranging from wet mud and sand to other low elevation soils. Figure 1 shows typical groups of mangrove species found within Ecuador and elsewhere throughout the world. These varying habitat characteristics differentiate mangroves from other coastal ecosystems, which similarly provide ecosystem services such as fishery habitats and coastal protection to local communities, but grow in more restricted habitats. Mangroves face major challenges across the globe, as their removal seems to provide quick financial benefits without accounting for current and future benefits provided by the ecosystem. In order to combat this trend, scientists have begun to measure the ecosystem services of estuarine and coastal ecosystems in economic terms in order to capture their values (Barbier et al., 2011). This previous scientific research and many similar studies have shown the immense positive impact that stems from mangroves, from creating habitat for local animals to providing economic and social services to local communities.

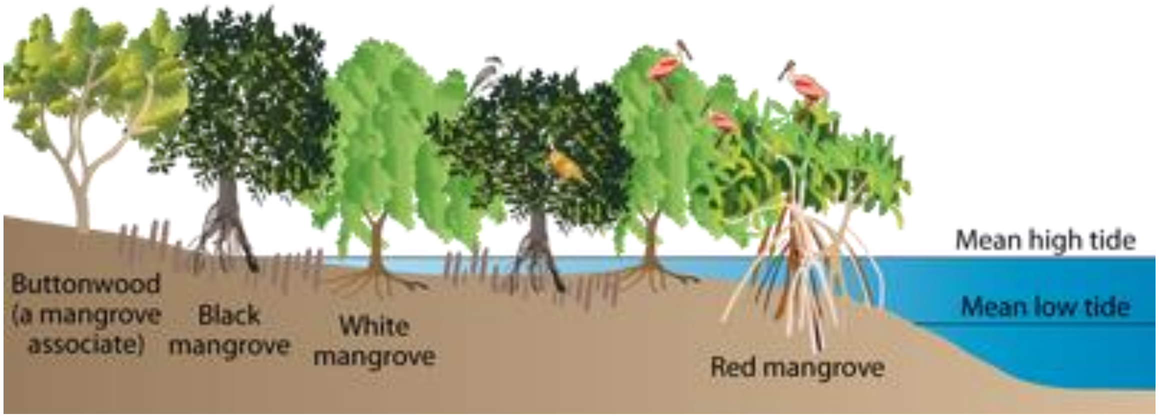

Figure 1. Dominant species of mangroves changes from red mangroves to white mangroves then black and buttonwood mangroves when getting away from the tidal zone. Picture retrieved from: http://ian.umces.edu/imagelibrary/displayimage-search-0-7614.html.

1.1.2 Ecuadorian mangroves

Ecuador's climate consists of three main regions: La Costa (Coastal), La Sierra (Andes Mountains), and El Oriente (Amazon River Basin). As the country lies on both sides of the equator, the lower elevation areas sustain a tropical climate with temperatures ranging from 68°F to 91°F (20°C to 33°C). Temperatures in the mountains of Ecuador range from 3°C to 26°C over the course of the year with sustained snow coverage on several peaks. The Andes Mountains consistently provide freshwater to rivers from snowmelt runoff that reaches the Pacific Ocean and Amazon River Basin. When these rivers approach the coast, they mix with the oceanic saltwater, providing opportune conditions for estuary habitats including mangrove areas.

The coastal landscape of Ecuador creates the perfect environment for mountainous rivers to run into the high-sodium oceans and facilitate the growth of mangrove roots. Mangroves benefit from large differences between low and high tides, which are present on the Ecuadorian coast, and the mixture of sand and mud provides opportune conditions for seed germination and plant growth.

Ecuador's mangrove areas center in three main provinces: Esmeraldas, Guayas, and El Oro. Mangroves in these areas contain the highest forest density and human-mangrove interactions. Therefore, these regions are the focus for a significant amount of research and studies (Beitl, 2011; Ocampo-Thomason, 2006)

For many years, the mangrove forests of Ecuador remained unharmed with high biodiversity and bountiful fishing opportunities; local citizens preserved the mangroves in recognition of the ecosystem services inherent to mangroves. Over the past 40 years, Ecuador's environment has undergone major changes in response to growing populations and changing economic frameworks. As a result, mangroves face threats from developers who may see the ecosystem as a barrier to development rather than a foundation.

1.1.3 Problems

Deforestation

At the global level, mangrove forests have decreased tremendously over recent years. It is estimated that nearly 35% of global mangrove forests no longer exist (World Wildlife Fund, 2015). The current global mangrove deforestation rate is greater than that of many tropical rainforests. In the case of Ecuador, mangrove forests are cleared mainly for the development of shrimp aquaculture sites (World Wildlife Fund, 2015). This pattern began in 1969, when the country's mangrove area began to decrease. By now, over 25% of the original mangrove area has been lost. The decline in mangroves coincides directly with the expansion of Ecuador's shrimp farm industry. As 20th century globalization expanded throughout South America, Ecuador found itself in a precarious situation: its mangroves were in peril due to the expansion of shrimp farms. The government initiated a permitting system for this industry to expand it at the expense of the mangrove forests, and development was highly successful. Ecuador's share of the global and regional shrimp trade rose quickly, and consequently the expansion was economically beneficial for private companies and national government. The element missing from these economic decisions was the social and environmental cost of losing the mangroves as an environmental entity that provides valuable and tangible ecosystem services to Ecuadorians. Shrimp farm development distances the local coastal community from the economy and distributes both goods and money to the larger cities.

Shrimp farm development drives the destruction of mangrove forests at an alarming rate. In a 2011 study, researchers calculated that nearly 90% of all mangrove deforestation resulted from the development of shrimp farms (Berlanga-Robles, Ruiz-Luna, & Hernández-Guzmán, 2011). The correlation between mangrove forest loss and shrimp farm growth represents a relationship that is currently benefiting the few at the expense of the many. According to FUNDECOL and C-CONDEM, a healthy mangrove system supports up to ten families for every one family a shrimp farm supports (Beitl, 2012).

By converting mangroves into shrimp farms, local Ecuadorian communities lose economic opportunities and food sources such as the cockle, a shellfish grown in the mangrove forests. The cockle is an important economic driver that enables the local communities to fish for their own families as well as trade with neighboring communities. The cockles are at a great risk from the loss of their habitat. The cockle supply is a local economic good directly affected for many years after the removal of mangroves (Beitl, 2011).

1.1.4 Introduction of local programs

In response to the alarming and precipitous decline of the mangrove forests, and the subsequent threats to local economies dependent on these ecosystems, certain programs like Socio Bosque and Socio Manglar were established within Ecuador's Ministerio del Ambiente

(MAE), or the Ministry of the Environment. The MAE is the entity within the national government responsible for managing all environmental resources and policies, and Socio Bosque houses the efforts to manage and conserve the nation's forested area in the best manner. Recently, the MAE and Socio Bosque created a new program called Socio Manglar, which specializes in the management and conservation of mangrove forests. Socio Bosque and Socio Manglar represent an opportunity to work toward sustaining the current mangrove areas in Ecuador, with Socio Manglar working solely with mangroves. Through these programs, the government and other institutions have begun to share data and knowledge to improve mangrove management strategies.

Through the initiation of Socio Bosque, beginning in the year 2000 local associations have been able to petition for 10-year sustainable management concessions. To improve their local mangrove areas, these community associations partner with external institutions. The external institutions provide maps, a copy of the association's agreement, a list of members, designated officers, and a management plan detailing the "sustainable use of resources" (Beitl, 2011).

1.2 The importance of conserving ecosystem services

1.2.1 Ecosystem services

Generally, ecosystem services represent the benefits provided by ecosystems to human beings. The term "ecosystem service" (ES) was first introduced in the 1960s (King, 1966; Helliwell, 1969), and its definition has been changing over time, based on different perspectives. Daily (1997) defined ecosystem services as "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life", which includes both "ecosystem goods", such as seafood and timber, and "life support" functions, such as "cleaning, recycling", and "intangible aesthetic and cultural benefits". The Millennium Ecosystem Assessment (2005c) (referred to as MEA) sustained this definition, and classified ecosystem services into four categories: "provisioning services", such as food and timber, which are identical to "ecosystem goods"; "regulating services" that have impact on climate, water quality, etc.; "cultural services", such as recreational and spiritual values; and "supporting services", such as nutrient cycling, etc.

However, the definitions of ecosystem services are diverse and are viewed from different perspectives (Vo et al., 2012). Some (De Groot et al., 2002; Boyd and Banzhaf, 2006; Chan et al., 2006; Kroeger et al., 2007) have argued that the MEA's definition is too broad and inefficient, with a mixture of ecosystem products, functions, processes, and benefits; whereas ecosystem services should be distinguished from ecosystem functions, since the former "require the explicit involvement of human beneficiaries". Boyd and Banzhaf (2006), especially, have integrated economic principles into the definition.

While ecosystem services can provide human beings with great benefits, they have suffered profound degradation over time (Millennium Ecosystem Assessment, 2005b; Boyd and Banzhaf, 2006; Kroeger et al. 2007). The obvious reasons are the increasing population and related consumption of human beings, which accelerates the transformation of ecosystems (Millennium Ecosystem Assessment, 2005a). More fundamentally, as Kroeger et al. (1997) indicated, the "unavoidable conversion of some lands" to provide goods for human needs may be rooted in the public goods nature of ecosystem services, and a lack of accurate values incorporating the services provided by ecosystems. Therefore, related decisions, policies, and markets do not efficiently protect ecosystems and their services; also, private individuals have reduced incentives to develop sustainable consumption habits.

It is important to estimate the values of ecosystem services, incorporate them into decision-making processes, and change people's perceptions. Currently, only "provisioning services" are likely to have direct values or prices, since they can be traded in markets. In the case of mangroves, examples of "provisioning services" are shrimp, fish, and timber. Other ecosystem services are hard to assign a monetary value directly because of their characteristics. For example, the coastal protection services of mangroves can save the property behind mangrove forests from damage by waves or tsunami, but there is no market for such services, hence no market value is directly observed. Therefore, it is important to carry out valuation for those ecosystem services that have value but no market. In addition, valuation is essential for comparing different values, conducting cost-benefit analysis, and calculating net present values of policies. For the past two decades, much research has been done in related fields, especially the value range of ecosystem services, and methods or tools to value them. For example, Eliasch et al. (2008) estimated that conserving forests could avoid greenhouse gas emissions, a valuation worth $3.7 trillion US dollars.

1.2.2 Mangroves provide tremendous ecosystem services

As one of the most productive ecosystems (Mitsch & Gosselink, 2007), mangrove forests provide a wide range of services, including "raw materials and food, coastal protection, erosion control, water purification, maintenance of fisheries, carbon sequestration, and tourism, recreation, education, and research" (Barbier et al., 2011). Generally, they can be categorized as (Vo et al., 2012):

(1) Use Values:

(a). Direct use value, such as wood products like timber and fuel, non-wood products like food, recreational uses, cultural uses, etc.

(b). Indirect use value, such as watershed protection, nutrient cycling, air pollution reduction, and carbon storage;

(c). Option value, such as future direct or indirect uses.

(2) Non-use Values

(a). Existence value, such as biodiversity, culture, heritage, and bequest values.

Water filtration, biodiversity, carbon sequestration, tourism and recreation, coastal protection and soil erosion, fuel wood, and fisheries are among those that have been studied and valued the most (Vegh et al, 2014). Water filtration refers to the mangrove's ability to use nutrients from the water supply and thus create cleaner water. Biodiversity ecosystem services include habitat benefits to local fauna populations and the associated services to the local community. Carbon sequestration refers to mangroves' consuming more carbon dioxide than they emit. The tourism and recreation ecosystem service refers to the ecosystem's attracting local and foreign visitors to participate in activities or spend time within the mangroves. Mangroves also protect the coastline from soil erosion through strong roots in addition to physical protection of homes and communities from storms. In many places, firewood from mangroves is a major energy source; however, in Ecuador this practice is illegal. Fisheries and nursery services that derive from mangrove habitat could lead to larger and more abundant fish populations.

Fishery. Fishery value is linked to mangrove ecosystems in several different ways. Mangroves directly support production of certain fish, crustaceans, and mollusk species by serving as the habitat for those species (Rönnbäck, 1999). Considering the magnitude of the concha collecting business in Ecuador, this is an important services provided by Ecuadorian mangroves (MacKenzie, 2001). The ecosystem nursery site and refuge services to juvenile fish may also contribute to the production of offshore wild catch (Mumby, et al., 2004; Aburto-Oropeza, et al., 2008). In addition to the type and condition of mangrove forests, the value of fishery services highly depends on the intensity of fishery within the area, as well as effective fishery management practice. Presumably, mangrove forests with higher productivity but also accessible to anglers are likely to present a higher value of fishery service (Hutchinson, et al., 2014).

Coastal protection. Mangroves, together with other coastal habitats such as sea grass and coral reefs, play a great role in protecting coastal areas. For example, mangroves can reduce the surge from storms and cyclones, hence protect backshore areas from storms (Das & Vincent, 2009), and possibly protect from tsunamis, too (Dahdouh-Guebas, 2005). Through wave attenuation and sediment buildup, the ecosystem can potentially mitigate the impact of shoreline erosion (Spalding et al., 2014). Within the climate change adaption context, several studies discussed the effect of mangroves on maintaining the shoreline in the face of sea level rise (McKee et al., 2007).

Carbon Services. Mangroves, especially oceanic mangroves, contain larger per hectare stocks of carbon than seagrass meadows and salt marshes (Pendleton, et al., 2012). The carbon stock reflects the mangroves' ability to consume carbon dioxide as a service to the global environment.

1.2.3 Value of Mangrove Ecosystem Services

The economic values of ecosystem services provided by mangroves have been estimated by several researchers with different methods or models (Vo et al., 2012; Vegh et al, 2014). These methods or models include, but are not limited to, market-based valuation methods, stated preference valuation methods, revealed preference methods, and synthesis of existing literature.

The results from a recent survey of mangrove valuation studies by Barbier et al. (2011) can be seen in Table 1.

Table 1. Typical ecosystem services provided by mangroves

Ecosystem services	**Ecosystem processes and functions**	**Important controlling components**	**Ecosystem service value examples**
Raw material and food	Generate biological productivity and diversity	Vegetation type and density, habitat quality	US$484-585 $ha^{-1}*yr^{-1}$ capitalized value of collected products, Thailand (Barbier, 2007)
Coastal protection	Attenuate and/or dissipates waves and wind energy	Tide height, wave height and length, wind velocity, beach slope, etc.	US$8966-10821 ha^{-1} capitalized value for storm protection(Barbier, 2007)
Erosion control	Provides sediment stabilization and soil retention in vegetation root structure	Sea level rise, tidal stage, etc.	US$3679 $ha^{-1}*yr^{-1}$ annualized replacement cost, Thailand (Sathirathai and Barbier, 2001)
Water purification	Provides nutrient and pollution uptakes, as well as particle retention and deposition	Mangrove root length and density, mangrove quality and area	Estimates unavailable
Maintenance of fisheries	Provide suitable reproductive habitat and nursery grounds, sheltered living space	Mangrove species and density, habitat quality and area, primary productivity	US$708-$987 ha^{-1} capitalized value of increased offshore fishery production. Thailand (Barbier, 2007)
Carbon sequestration	Generates biological productivity, biogeochemical activity, sedimentation	Vegetation type and density, fluvial sediment deposition, subsidence, coastal geomorphology	US$30.5 ha^{-1} yr^{-1}
Tourism, recreation, education, and research	Provide unique and aesthetic landscape, suitable habitat for diverse fauna and flora	Mangrove species and density, habitat quality and area, etc.	Estimates unavailable

From the table we can see the great potential economic values mangroves hold. In addition, the estimates can be compared with household incomes, in order to get a clearer view of the role of mangroves to local people. For example, Barbier et al. (2011) report that the annual household income from mangroves in local villages ranged from $2626 to $6623, while excluding income from “collecting mangrove forest products” could increase the potential poverty incidence from 13.64% to 55.3%, compared to a survey of local coastal household income conducted in July 2000.

This evidence from other parts of the world suggests that the potential values of Ecuadorian mangroves could be high, with variation in locations with different geographic features. The loss of mangroves due to deforestation and degradation could exacerbate poverty and the sustainable development of local coastal communities.

1.3 Ecosystem services valuation models

While the majority of studies estimate the value of ecosystem services of mangroves monetarily, a growing amount of effort has been put into developing modeling tools to promote the integration of ecosystem services value into the decision-making process and assist management (Daily et al., 2009). These tools utilize publicly accessible environmental data, then model the amount of services provided by a target ecosystem according to known biophysical processes, and finally estimate the value of ecosystem services using coefficients obtained from other studies. Compared to economic valuation models, these tools can provide quick estimation at a large scale, while maintaining a relatively low cost in terms of both time and money. Therefore, they are expected to promote the implementation of ecosystem services valuation into planning and management. Examples of such tools are ARtificial Intelligence for Ecosystem Services (ARIES), Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), and Multi-scale Integrated Models of Ecosystem Services (MIMES) (Villa et al., 2014). Several studies have been conducted to compare the performance and outcomes of these tools, most of which focused on terrestrial systems or fresh water ecosystems (Nelson & Daily, 2010; Bagstad et al., 2013). Yet with a growing interest in coastal management, it is equally important to evaluate the possibility of applying the existing models to coastal ecosystems.

1.4 Scope and objectives of the study

This project takes as its point of departure an expression of interest from the Ecuadorian Government's Socio Bosque program, as well as interest from a range of conservation and development organizations in Ecuador. Socio Bosque, started by the Ministry of Environment of Ecuador, aims at achieving conservation of native forests and other ecosystems of Ecuador, reducing greenhouse gases caused by deforestation, and improving the living conditions of rural residents in those areas. As one sub-program of Socio Bosque, Socio Manglar establishes agreements and ownership of sustainable mangrove use with local communities, with aims of guaranteeing the living conditions of local populations and sustaining mangrove systems.

The present project aims to provide support to Socio Bosque and Socio Manglar by estimating potential values of mangrove ecosystem services with existing modeling tools and synthesis of research. Potential models include, but are not limited to, InVEST, AIRES, MIMES, MIDAS, Co$ting Nature, EcoServ, LUCI, and SolVES. These models and methods have been applied in multiple contexts regarding ecosystem services around the world. However, as we will be focusing on Ecuadorian mangrove systems, we would like to evaluate the models first, to see whether they are applicable to our context, and apply feasible models/methods to evaluate mangrove ecosystem services. In addition, we will compare the models with respect to aspects such as data availability, time consumption, applicability of results, etc., to identify the advantages and disadvantages of each model, and the potential applicability of our results with each model.

Since at the same time we will analyze specific scenarios, such as business as usual, mangrove loss and reforestation, the results could generate implications for mangrove protection. The results will provide both numerical and visual information, and will highlight the usefulness of each different modeling tool. Our intention is to provide suggestions and references for the government and other actors making decisions about mangrove management.

Among those mangrove-provided ecosystem services defined and examined by other studies, we confined our research to the following ecosystem services: fishery, recreation, coastal protection, and carbon sequestration. This decision developed through multiple conversations with stakeholders in both Ecuador and the United States. The Conservation Strategy Fund worked closely with the Ministry of the Environment, specifically Socio Manglar, to find those four ecosystem services as both important to decision-making and commonly evaluated services. Our research goals were influenced by data availability and the potential for ecosystem service valuation that would enable decisions by these stakeholders.

Apart from selecting, applying and evaluating ecosystem services valuation models, we also used a benefit transfer approach to generate reference monetary values for mangrove ecosystem services. Benefit transfer is a method that synthesizes the results from pre-existing research and studies, and applies the values or functions to ideal areas (Johnston and Rosenberger, 2010). The monetary results estimated by the benefit transfer method could help to justify the results generated by previously mentioned ecosystem services models.

Also, since the data we obtained are from different sources with potential variations, data comparison will be an extra scope of this study.

We expect that the potential mangrove ecosystem services values we estimated in this project could generate policy implications for:

Protection priorities. With a better understanding of the values of ecosystem services and the importance of mangroves, and a clearer view of the locations of mangroves with higher ecosystem services values, the government could apply the results in policymaking processes, and generate more efficient protection policies.

Potential protection programs. The results of the project may also provide ideas for economic incentive programs, such as the potential payment for ecosystem services (PES) programs with an emphasis on efficiency and the REDD+ initiatives (Reducing Emissions from Deforestation and Forest Degradation, which foster conservation, sustainable management of forests, and enhancement of forest carbon stocks). These programs could then be incorporated with other tools and programs such as a mitigation market, to encourage and increase the production and sustainability of ecosystem services (Farley, et al., 2010).

Public involvement. The results of the project may help to improve the public's consciousness of the broader values of mangroves, in sustainable development of mangrove systems, and in participating in governmental policymaking processes such as public hearings. This could accelerate and sustain the protection of mangrove systems.

2 Methods

2.1 Data and Scenarios

For historical and current coverage of Ecuadorian mangroves, we obtained statistics from the Informe De Manglar Unidad De Monitoreo (MAE, 2014). As a reference, we also calculated the area using map data: historical mangrove distribution in 1969 and 1999 created by C-

CONDEM (La Coordinadora Nacional para la Defensa del Ecosistema Manglar de Ecuador), and the current distribution (in 2012) and potential reforestation sites generated by el Ministerio del Ambiente de Ecuador (MAE, 2012). We also used several satellite images (30m resolution, classified, unpublished data from Dr. Chandra Giri, USGS). Since the satellite images were partially covered by clouds, the area of mangroves appears to be significantly lower than in the other two sources, but could still be used as a reference for the trend.

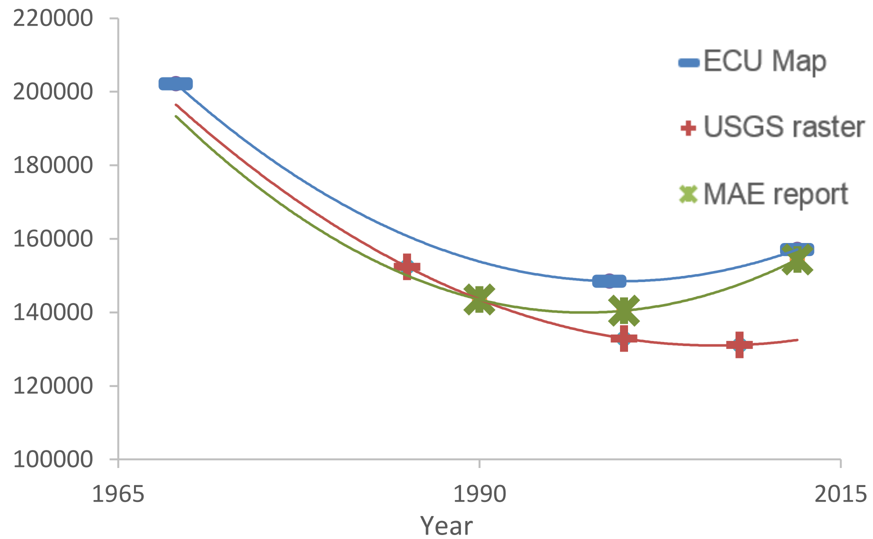

Figure 2.1 Historical and current coverage of mangrove forests in Ecuador, according to different sources.

In consideration of the inconsistency among data sources, we chose to build the analysis based on the government report data, i.e., the numbers from the 2014 MAE report.

2.1.1 Status quo (SQ)

We examined four scenarios to identify impacts of varying mangrove areas on ecosystem service valuation models. In the status quo scenario, mangroves maintain the same distribution as in 2012, with a total area of 154,424 ha according to MAE 2014.

2.1.2 Lose all (LA)

In the lose all scenario, we assumed a mangrove loss of 154,424 hectare, i.e., all the current distribution is lost.

2.1.3 Reforestation (RF)

According to MAE's 2014 report, the recovery rate of mangroves in Ecuador from 1990 to 2012 is 498 hectare per year. Therefore we built the reforestation scenario assuming that the mangroves will maintain the same rate of change for 20 years, ending up with a total of 164,365 ha.

2.1.4 Full recovery to historical range (FR)

In the full recovery scenario, we assume that by 2032 the mangroves will recover to their historical distribution as in 1969, ending up with a total of 235,374 ha. The distribution map was generated by merging the 2012 and 1969-mangrove distribution maps.

2.2 Specific models

Current ecosystem services models (Bagstad, 2013) can be roughly classified into four categories based on their site generality and spatial components. Site-specific models are built within the context of their case study areas, hence are not applicable to our case. In addition, as we are interested in map products, we narrowed our candidate models down to the general and spatially explicit models, i.e., ARIES, Co$ting Nature, LUCI, MIMES, InVEST, SolVES, and Ecoserv.

We then examined each of the seven models to decide 1) whether it is applicable to mangroves, 2) whether it estimates the ecosystem services of our interest, 3) whether it works with currently available data, and 4) whether it is currently ready for use so that the process can be completed within the time limit of this project. We then used those tools meeting all four requirements to conduct the analysis using Ecuadorian mangrove data.

2.2.1 InVEST

Developed by the Natural Capital Project, InVEST is a Python-based toolbox that includes 17 separate models focusing on different ecosystem services provided by terrestrial and coastal ecosystems (Sharp, et al., 2014). Two of them - Coastal Protection and Blue Carbon - are applicable to our study setting. The version of the software utilized in this study is 3.0.1, in which the Blue Carbon model has been updated for use as a stand-alone application (compiled Python script), while the Coastal Protection Model stays as an ArcGIS toolbox. GIS software is also needed to prepare the data and present the results for both models.

The models are developed to support decision making on natural resource management, and are completely free and open to the public (Sharp, et al., 2014). Available InVEST training resources include, but are not limited to: an online course through Stanford University, a series of free training videos (https://vimeo.com/album/1941452), a user guide, and a forum in which the model developers can answer questions.

InVEST is different from ecosystem coefficient valuation methods that directly associate the valued services to a certain type of ecosystem. Instead, InVEST estimates supply, service, and value separately (Sharp, et al., 2014). For each specific type of ecosystem (normally represented by land cover type), it first calculates the amount of biophysical “goods” the ecosystem can produce; then it estimates the social benefits generated from them; and finally it values the benefits according to market value, social preferences, or other coefficients adopted from existing studies. This framework allows the user to adjust and manipulate the assumptions used in the model, thereby allowing the measurement of ecosystem services under different natural or socio-economic conditions.

While it requires land use land cover (LULC) data from the area of interest, InVEST provides some global datasets as default inputs, which allows the user to perform a rough analysis without spending excess time on data acquisition and preparation. This approach allows the user to visualize the value of the ecosystem service on a map, and to compare the outcomes of different management plans by running models under different scenarios. The user can also increase the complexity of the model by adding more LULC sub-types or more habitat layers, as long as their coefficients of biophysical processes are appended to the input parameter matrix.

Compared with other tools we examined, a major advantage of InVEST is that the model develops a set of tools solely focused on coastal ecosystems (Guerry et al. 2012). Within the InVEST toolkit, we tested the coastal protection model and the blue carbon model using Ecuadorian data. The model allows the user to input mangrove distribution and provides estimates for the ecosystem services in which we are interested.

2.2.2 Co$ting Nature

Co$ting Nature is a web-based policy support system developed by King's College London (lead by Dr. Mark Mulligan), together with AmbioTEK CIC and other partners, based on policy support systems (developed by AmbioTEK) and SimTerra databases (developed by AmbioTEK and King's College London). It aims to "incorporate ecosystem service provision and benefits information into the conservation prioritization and planning", with specific focuses on water, carbon, and tourism, and taking into account current pressures, future threats, biodiversity, and conservation priority, at both the global and local levels (Co$ting Nature Version 2 Modules Model Documentation).

Co$ting Nature is one of the few models that is potentially able to provide results relevant to our work, which seeks to establish valuation of mangrove ecosystem services in Ecuador. The desired results for this model would be local ecosystem services value indices ranging from 0 to 1 for the “Relative total realized/potential bundled services index” in locations where mangroves exist, including water, carbon, tourism, and hazard mitigation services. The level of focus could range from the national, looking at Ecuador as a country, to the specific, examining gridded local areas.

2.2.3 Multi-scale Integrated Models of Ecosystem Services (MIMES)

MIMES is a modeling system developed at the university of Vermont by Roel Boumans and Robert Costanza in an effort to create a robust model for economic and ecosystem interactions. MIMES enables the user to generate multiple scenarios through user-defined processes in order to capture all components of the ecosystem (Boumans and Costanza, 2014). Across all MIMES ecosystem service valuations, a unique model is formed to combine environmental, social, and economic factors. MIMES relies heavily on user-developer synergy in order to create a functioning model (Bagstad, 2013). As a result, a model created for the ecosystem services of Ecuador’s mangroves would be a unique model for that specific comparison.

At this point, we are unable to implement the MIMES program under the necessary conditions outlined in the previous sections. The main constraint at this time is the lack of previous model development with the inclusion of spatial data to evaluate ecosystem services. Therefore, MIMES has yet to be used to evaluate the impact of mangroves in Ecuador’s coastal regions.

2.2.4 ARIES

ARIES is a platform using the Bayesian approach to model ecosystem processes, ecosystem services, and benefits (Villa, et al., 2014), and can address the level of uncertainty. Currently it has 8 developed modules including carbon sequestration and storage, flood regulation, coastal flood regulation, aesthetic views and open space proximity, freshwater supply, sediment regulation, subsistence fisheries, and recreation. Among them, the coastal flood regulation module takes mangrove distribution as one of the inputs, and the subsistence fisheries module uses a population distribution, a poverty map, and FAO catch data to estimate the spatial distribution of subsistence catch. We believe that these modules are applicable to ecosystem services assessment for mangrove-covered areas. However, they are not tested in our project because the only way to use the tool is to attend a training session held each spring, or through a co-developed case study, both of which require time and money that are outside the scope of our study.

2.2.5 LUCI

LUCI (Land Utilization & Capability Indicator) is another GIS based toolkit that looks at the potential supply of ecosystem services including production, carbon, flooding, erosion, sediment delivery, water quality, and habitat. It requires a minimum high resolution (5*5 - 10 *10) DEM, with land cover and soil information as its spatial input (lucitools, 2014). We excluded it from our pool, as the developer confirmed that the current version is built for terrestrial or freshwater ecosystems, hence is not suggested for use with mangrove ecosystems.

2.2.6 SolVES

SolVES, developed by the USGS, is a GIS application focusing on the social values of ecosystem services (Sherrouse & Semmens, 2015). However, as it is designed for "mapping and analyzing social survey response data," it does not suit our analysis, which is not survey-based.

2.2.7 Ecoserv-GIS

Ecoserv-GIS, also a GIS application, is a toolkit aimed at mapping ecosystem services on the county scale. It was developed for the Wildlife Trusts in England and funded by the Royal Society of Wildlife Trusts Strategic Development Fund and Dame Mary Smieton Fund (Bellamy, et al., 2014). EcoServ-GIS was developed to be used in any part of England, and includes designated sites and general countryside. The ecosystem services it covers include: provisioning services such as food provision and timber; regulating services such as carbon storage, local climate regulation, noise regulation, water purification, and pollination; and cultural services such as wildlife watching, accessible nature experience, and education/knowledge opportunities.

Although EcoServ-GIS can be used to provide information to local policy makers on where particular services could occur, the extent or value of these services for people, and the potential priority of certain services in the target area. It is hard to determine whether it is suitable to be applied to the Ecuadorian mangrove systems, since: (1) it uses local knowledge and data for England, and the model is not developed for other countries; and (2) the ecosystem services it focused on are not particularly related to mangroves.

2.3 Selection and evaluation criteria

The criteria for each model are summarized in Table 2. Application of these criteria revealed that only InVEST and Co$ting Nature satisfied all four criteria. We therefore focused on those two models for our quantitative evaluation of model performance using Ecuadorian mangrove data.

We also conducted a more limited, qualitative evaluation of two models (ARIES and MIMES) that are potentially applicable to mangrove ecosystems. The model evaluation criteria (adapted from Bagstad et al, 2013) are listed in Table 3.

Table 2. Model Selection criteria

	Applicable to coastal ecosystem	Open Access	Spatial component included	Mainly use public data	Type of estimates generated	Website
InVEST	Y	Y	Y	Y	Biophysical metrics and monetary value (require price as input)	http://www.naturalcapitalproject.org/InVEST.html
Co$ting Nature	Y	Y	Y	Y	Global and local level Index	http://geodata.policysupport.org/costingnature
MIMES	Y	Y	Y	N	Monetary and Biophysical	http://www.afordablefutures.com/home
ARIES	Y	N	Y	Y	Biophysical metrics and monetary value	http://www.ariesonline.org/
LUCI	N	N	Y	Y	Biophysical metrics and monetary value	http://www.lucitools.org/
SolVES	Y	Y	Y	N	Monetary Value	http://solves.cr.usgs.gov/
EcoServ	N	Y	Y	Y	Index	http://www.durhamwt.com/wp-content/uploads/2012/06/EcoServ-GIS-Executive-Summary-Only-WildNET-Jan-2013-9-pages.pdf

Table 3. Model Evaluation Criteria

	Helpful		Challenging
Development level	Stand-alone models, ready to use, well maintained and updated, can be applied to different regions and ES	More sites / modules under development	Only designed for a single type of ecosystem service, or a single region
Previous experience	No previous modeling or valuation experience needed	Programming / GIS / Modeling / Valuation experience will be preferred but not required	Programming / GIS / Modeling / Valuation experience required
Time requirements	Simple click and run	User Manual Based study	Over 200 hrs, may take extra time to collect data, test run, or analyze data
Data Acquisition	Data profile comes with models	Some data collection effort needed, with some built-in data	Solely depend on external data. Extensive data collection effort required
Documentation and training resources	Well documented model description and user guide available; video guide / online course / forum / developer's help accessible	General user manual or documentation, or detailed instruction on major modules, or available but not free	No or few resources documented and available with the tool
Type of ES valued	Deal with a bunch of ESs, or can run complicated combination of ESs	Have some major ESs, have some level of flexibility	Only a few ESs, no flexibility

In addition to its blue carbon and coastal protection models, InVEST does provide a Marine Fish Aquaculture model. However, it is specifically built for farmed salmon, hence not applicable to this study. Due to the high level of spatial heterogeneity, as well as its site- and species-specific characteristics, the fishery model has not been included at this time. Recent research released in January studied the rate of catch and necessary conditions for greater cockle growth. This study known “Mobility in the Mangroves: Catch Rates, Daily Decisions, and Dynamics of Artisanal Fishing in a Coastal Commons.” was carried out by Dr. Beitl of Maine University and published in *Applied Geography*. At this time, an analysis with this research in mind has not been applied.

2.4 Benefit Transfer

The benefit transfer approach includes value transfer and function transfer. Compared to other valuation methods, such as Market-based Valuation and Non-Market Valuation, benefit transfer is comparably more efficient with rather valid results. In this paper, we will use meta-analysis function transfer to value Ecuadorian mangrove ecosystem services, since it can reflect area variation and generate more applicable results. Also, since meta-analysis could combine the results of several other studies that are related to a certain topic, in this case, the fishery values of mangroves, and the values of the other 3 identified ecosystem services, and since it could generate potentially robust results (Vegh et al., 2014), it is an ideal way to perform estimation and valuation, which could save time and effort, and get high quality results. This approach does have restrictions; for example, the current research on mangrove fishery lies largely in Asia (Vegh et al., 2014), and the economic valuation methods may differ from MV to CV (Farber et al., 2002). However, based on the current situation, meta-analysis is the best way for us to evaluate fishery services and provide potential suggestions to policy makers.

Meta-analysis is a statistical analysis method based on evaluating several existing studies, which can provide statistical models that can be applied to other areas, based on the variables. In this paper we have identified two meta-analysis studies on mangrove ecosystem services around the world: Salem and Mercer (2012) and Brander et al. (2012). These two meta-analyses generate regression models to estimate values for mangrove ecosystem services; these could be used in Ecuador, where only a few studies have been done. A brief introduction to the two meta-analysis studies is shown in Table 4.

Table 4. Related facts of two meta-analysis models

	Salem and Mercer, 2012	**Brander et al., 2012**
Studies Included	73 examined studies, 44 selected studies. 352 examined observations, 145 selected.	48 examined studies, 41 selected studies. 130 observations.
Regression Methods	1. Ordinary Least Squares (OLS) 2. OLS with robust standard errors 3. OLS with robust standard errors and interaction variables	Ordinary Least Squares (OLS) with robust standard errors
Ecosystem Services Included	Fisheries, recreation, coastal protection, carbon sequestration, forestry, nonuse.	Coastal protection, fisheries, water quality, fuel wood.
Special Characteristics	Valuation methods and regions included.	Road density, population density included.
US$ value Base year	2010	2007

Both studies contain the ecosystem services we will be valuing. For Salem and Mercer's research, all four ecosystem services (fisheries, recreation, coastal protection, and carbon) are included, and their values can be estimated. For the Brander et al. model, coastal protection and fisheries are taken into consideration. Apart from ecosystem services, the regression models generated by the two meta-analysis studies contain other variables. For example, the regression model in Salem and Mercer contains as a variable the valuation methods that are used in the research. The variables contained in each analysis model are shown in Tables 5 and 6.

Table 5. Variables of Salem and Mercer, 2012

Variable	Definition and units
Study Characteristics	
Average value	Baseline category. It depicts when the value is taken as an average over the entire area of mangroves.
Marginal value	1 if the value was calculated per hectare and 0 otherwise.
Publication year	Year of publication
Monetary Price	Baseline category
Static production function	1 if a static production function was used and 0 otherwise
Dynamic production function	1 if a dynamic production function was used and 0 otherwise
Other regressions	1 if other regressions were used and 0 otherwise
Net factor income	1 if the net factor income method was used and 0 otherwise
Replacement cost	1 if the replacement cost method was used and 0 otherwise
Contigent valuation	1 if the contingent valuation method was used and 0 otherwise
Mangrove characteristics	
Log(area)	Area of the mangrove site in logarithm form
Local	Baseline category
Global	1 if exports or the contribution of foreign visitors represents a significant portion of value and zero otherwise
Thailand	Baseline category
Asia (excluding Thailand)	1 if in Asia but not Thailand and 0 otherwise
Middle East and Africca	1 if in the Middle East and Africa and 0 otherwise
Americas	1 if in the Americas and 0 otherwise
Other continent	1 if in Fiji or Micronesia and 0 otherwise
Protected	1 if site is designated as RAMSAR or provided any other legal protection by the state and 0 otherwise
Fisheries	Baseline category
Forestry	1 if a forestry product and 0 otherwise
Recreation	1 if tourism, recreation, or research and 0 otherwise
Coastal protection	1 if coastal protection and stabilization or flood control and 0 otherwise
Carbon sequestration	1 if carbon sequestration and 0 otherwise
Non-use	1 if a nonuse value and 0 otherwise
Water and air quality	1 if water and air purification or waste assimilation and 0 otherwise
GDP per capita	GDP per capita in logarithmic form

Table 6. Variables of Brander et al., 2012

Variable	Variable Definition
Constant	
Coastal Protection	Dummy variable for coastal protection ES
Water Quality	Dummy variable for water quality ES
Fisheries	Dummy variable for fisheries ES
Fuel Wood	Dummy variable for fuel wood ES
Mangrove Area	Area of wetland study site (ha; ln)
Mangrove Abundamce	Total area of mangroves within 50 km (km^2, ln)
Roads	Length of roads within 50 km (km, ln)
GDP per capita	GPD per capita (USD; ln)
Population	Population within 50 km (ln)

In order to use these meta-analysis functions for valuation, we first selected a focus area that could represent the mangrove conditions for the whole country. According to the characteristics of the region, we chose the binary variables as 0 or 1 and put them in the regression to generate the ultimate value: the average value of ecosystem services per hectare of mangroves.

Since both models include GDP per capita and mangrove area, we needed to find corresponding data for the valuation process. We used the Ecuadorian GDP from the World Bank, population data from the National Institute of Statistics and Censuses (INEC) of Ecuador, and a road shapefile from the Digital Chart of the World (DCW) as supplemental data. The other model input information was based on the meta-analysis models, and the characteristics of Ecuadorian mangroves.

3 Results

3.1 General comparison of the models

Based on the model comparison criteria we developed in section 2.3, we explored the four potential models that can be used on mangroves. InVEST and Co$ting Nature both provide pre-defined models with estimates synthesized from global averages, hence require much less time and effort to run the valuation, and thus meet the objective of quick assessment. MIMES and ARIES, however, required much more knowledge of both the biophysical and socio-economic process to build a model for a new study area (Table 7).

Table 7. Model Evaluation based on the 6 criteria

	INVEST	**CO$TING NATURE**	**MIMES**	**ARIES**
Development Level	Well maintained and kept updated. Current version: 3.1.1 Version used: 3.0.1	Current version: v.3. Version used: v.2	Current version is not well researched, but the level of development is very high	New stand-alone version under development
Previous Experience	No programming experience needed; Require GIS experience in pre/post analysis.	No programing or GIS experience needed. Nevertheless, require basic GIS knowledge in data preparation and analysis.	High levels of experience within the subject matter are needed to accurately map all services, stocks and flows.	Programing and GIS experience required for new case study
Time Requirements	Preparation time varies with study scope and accuracy. Program running time depends on data size.	Require more time in learning, less time in running the model.	Required time is very high. Suggestion to work with multiple people.	Required time is very high for new study area.
Data Acquisition	Y, user need to provide land cover and habitat maps. Some global data available as default	N, but user can upload more detailed or updated information to improve result	Data is user-defined and can be rather extensive.	Yes for new study area. Likely no for existing study area
Documentation And Training	Well documented, user manual and forum available, free online course and workshop videos available	Well documented, user manual and demo video available	Low. Not a great deal of documentation and limited training materials.	Training available each spring with a fee
Type Of ES Valued	Blue carbon and coastal protection are currently applicable. Recreation and fishery potentially usable with future model and data development.	Water, carbon and tourism, combined with current pressure, future threats, biodiversity and conservation priority	Evaluates all ecosystem services desired by the user.	8, among which coastal flood regulation and subsistence fishery may apply to mangroves

3.2 Model output comparisons

We conducted a valuation of all the mangroves in Ecuador under each scenario using the two models InVEST- Blue Carbon and Co$tingNature. However, the third model, InVEST – Coastal Protection, is a one-dimensional model. We applied it at a chosen sample site at Muisne instead of running it for the whole nation. As for meta-analysis, we picked two large parcels of mangroves in Guayaquil to meet the variable characteristics used to build the models.

3.2.1 InVEST – Blue Carbon

The Blue Carbon model of InVEST consists of two parts. Part 1 calculated the transition rate of land cover types between different years, and Part 2 used the land change information to calculate the change of carbon storage through time. It required a land use and land cover (LULC) map as the spatial input, and used carbon pool data associated with each land cover type, together with carbon half-life metrics to calculate carbon sequestration and storage through time. The model provides a default carbon pool table, which includes the parameters for mangroves (table 8). While we used the default data, the user may also customize the table for the local situation.

Table 8. Example of carbon pool information required by InVEST - Blue Carbon, shown with default values assigned to mangrove

Id	Name	Veg Type	Above (Mg / ha)	Below (Mg / ha)	Soil (Mg / ha)	Litter (Mg / ha)	Bio_accum_rate (Mg / ha / yr)	Soil_accum_rate (Mg / ha / yr.)
1	Mangrove	2	35	29	313	0	2	5.35

After calculating the carbon accumulation due to land transition, the Blue Carbon model can value the carbon stored by the mangroves in dollars per metric ton of either CO_2 or carbon, based on the carbon price provided by the user. One can either submit a price table, or set an initial value with an annual rate of change. In this analysis we used the default carbon “price” table, which shows the avoided social cost of per ton CO_2 according to the US Interagency Working Group on the Social Cost of Carbon (USIWGSCC, 2010; 2013), expressed in 2010 US$.

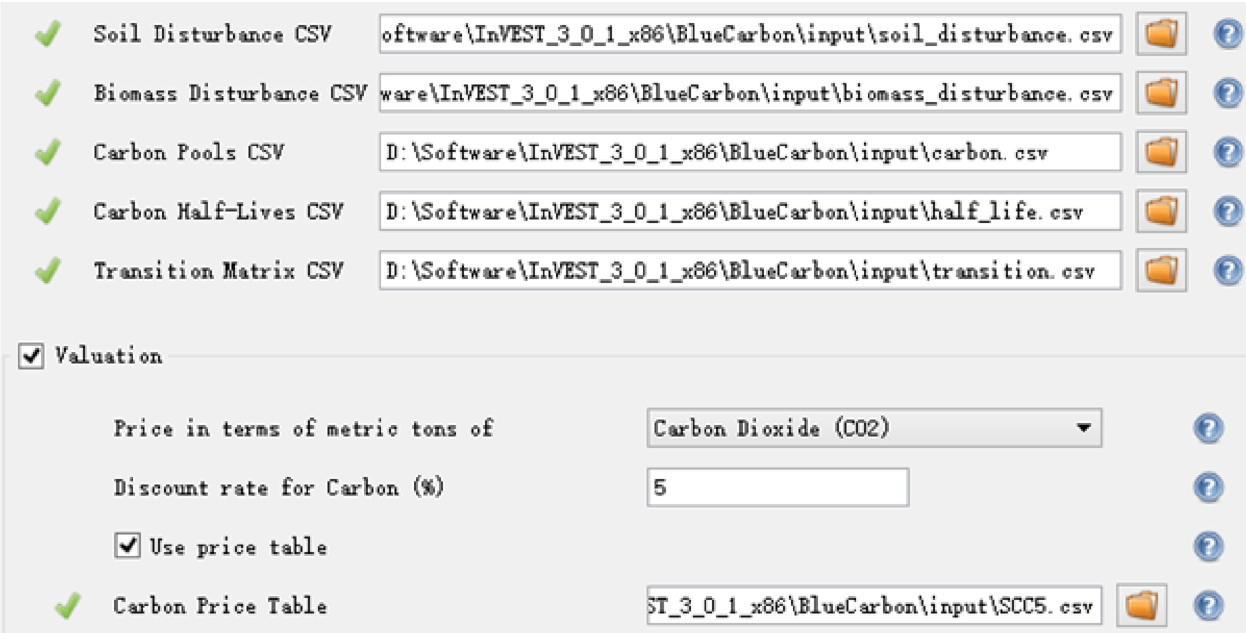

Figure 3.1 Input for InVEST blue carbon model. Except for the transition matrix that is calculated from the LULC, other inputs are available as global default datasets. However, the user can adjust the estimates to make the model better describe the local situation.

According to the estimation, the current existing mangroves in Ecuador can sequestrate over 23,000,000 metric tons of carbon over 20 years, which will avoid a social cost of $378 million. In contrast, in the Lose All scenario, 43,000,000 metric tons of carbon will be emitted during the 20 year time frame, resulting in a significant social cost of $574 million.

Due to the settings of the model, the biophysical metrics and dollar value of blue carbon under different scenarios are directly associated with the area of mangroves. As we expected, since we provided only one land cover type, the blue carbon output showed no spatial

Table 9. Estimates of carbon storage, sequestration, and benefits provided by Ecuadorian mangroves under different scenarios. Benefit= NPV by 2032 with 5% discount rate (InVEST default).

Scenario	Total area of mangroves (ha)	Sequestration (megaton C) (Metric Ton *10^6)	Benefit (million $)	Comparison to status-quo (million $)
Status-quo	154,424	23	378	
Lose All	0	-43	-574	-952
Reforestation	164,365	24	402	24
Fully-Recovered	235,374	35	576	198

heterogeneity within the mangrove coverage. An alternative approach is to classify mangroves into different categories based on their dominant species / location / condition or other applicable criteria to maintain the heterogeneity; however. collecting the carbon pool information for each new category is outside the scope of our study.

3.2.2 InVEST – Coastal Protection

The coastal protection model also consists of two parts. Part 1 generates the cross-shore profile of the bathymetry, habitat locations, and wind/wave information; Part 2 then calculates the protection to the shoreline and backshore properties provided by the coastal habitats under certain wave level and storm conditions. As it is a one-dimensional model, the change of land cover will not be calculated from the land use map, but rather read from a background information sheet as user input.

According to the model output, the presence of mangroves can significantly attenuate the wave heights and protect the backshore area from erosion. The monetary value of coastal protection services is calculated by multiplying the area protected from erosion by the property price. While the wave data were obtained from the World Wave Watch database that InVEST provided by default, the backshore property price was taken from user input. We skipped the final step in the current study; however, once we have the backshore infrastructure or property price, that piece of information is easily implementable and can generate a reasonable valuation result.

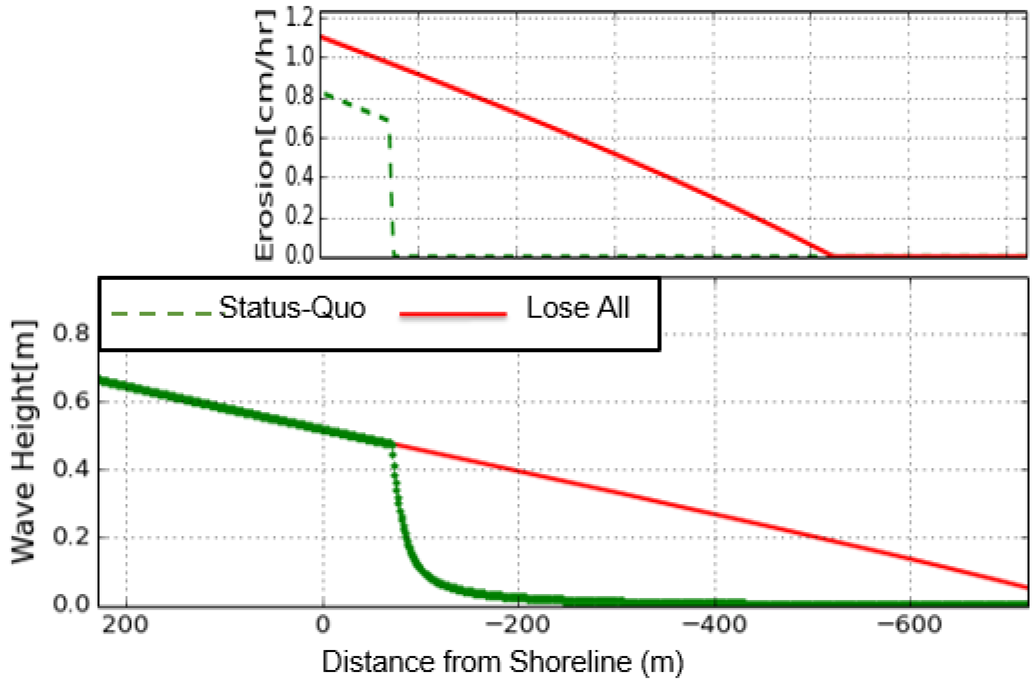

Figure 3.2. The change of wave heights and erosion caused by the removal of current mangroves at the Muisne sample site. The current mangrove forest can significantly reduce wave energy by 98.54%, and protect 112 ha of backshore area behind a 2.5km length of shoreline.

At this sample location the mangroves under the Reforestation and Fully-Recovered scenario provide same level of wave attenuation, but potentially for a longer shoreline, hence demonstrating a higher value of ecosystem services.

3.2.3 Co$ting Nature

Co$ting Nature cannot generate monetary values for Ecuadorian mangrove ecosystem services. However, based on our observation, Co$ting Nature has several characteristics that can be applied to Ecuadorian mangroves, and be used in our paper:

(1) It contains a mangrove layer. The default mangrove layer is the distribution map (Figure 3.3) generated by UNEP World Conservation Monitoring Center and International Society for Mangrove Ecosystems (Spalding et al., 1997). It is different from the USGS data and Ecuador data. However, since it only contains data for one year, the trend of changing mangrove distribution over time is hard to compare. With this layer, we can generate a relative ecosystem services value index within the country, ranging from 0 to 1. However, since Co$ting Nature has around 133 input maps, and mangroves only account for one layer, the function or role that mangroves played in this model is low. The ecosystem services calculated using the mangrove layer is mainly “hazard mitigation”, which can be interpreted as “coastal protection”.

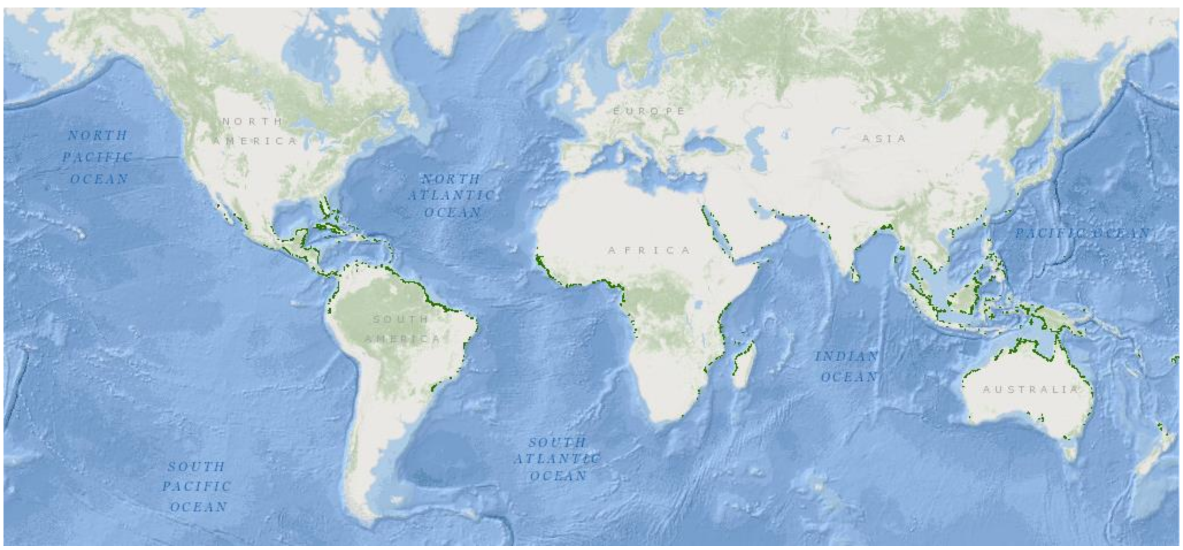

Figure 3.3. World mangrove distribution map 2007, UNEP WCMCIS

(2) Default results are usable. The default simulation results and corresponding priority indices represent in some way the different aggregate values of ecosystem services of mangroves. For example, the relative total potential bundled services index could offer us a perspective on the total value of potential services of mangrove systems, including water, carbon, tourism, and hazard mitigation. For this case in Ecuador, the values mainly address the hazard mitigation or coastal protection services value of mangroves.

(3) The comparison of values or protection priorities is visible. The results of valuation have a visual version that can be shown on a map, which could help us to deliver messages in an easier way.

(4) Easy access. It is an online-based model, which can be accessed through the Internet, without a requirement of a type of computer or software that needs to be downloaded. However, currently only the basic level (scientist and policy analyst) can be accessed at no charge. The higher levels (superuser, hyperuser and megauser) with more functions, analyses and results can only be accessed through building a partnership with model developers, or by purchasing licenses.

The interface and potential results of Co$ting Nature

In order to run Co$ting Nature, the model area has to be defined first, as shown in Figure 3.4. However, one restriction is that if the user level is low, the user cannot model Ecuador as a whole country; but even if a high level user can model the whole country, the resolution becomes too low, changing the pixel size from 1ha*1ha to 1km*1km.

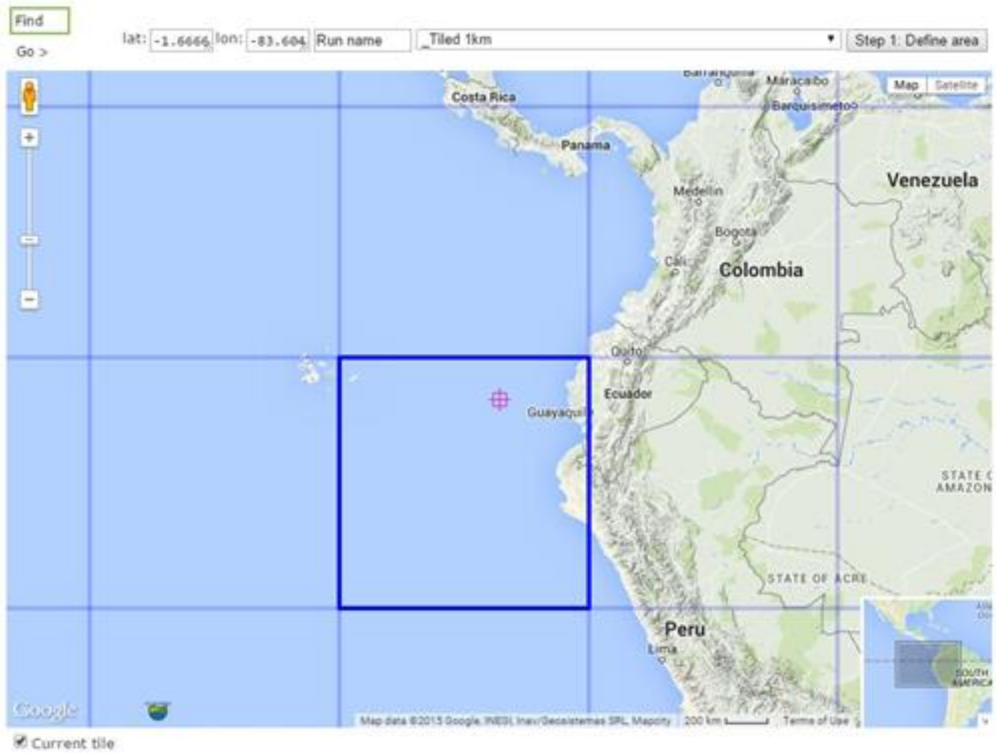

Figure 3.4. Not adjustable default Ecuador model area

After default data preparation, uploading scenario maps, and simulation, the model can be used to generate result maps for different scenarios. The relative potential ecosystem services value index of the status-quo scenario is shown in Figure 3.5, with minor changes of colors compared to the default map online.

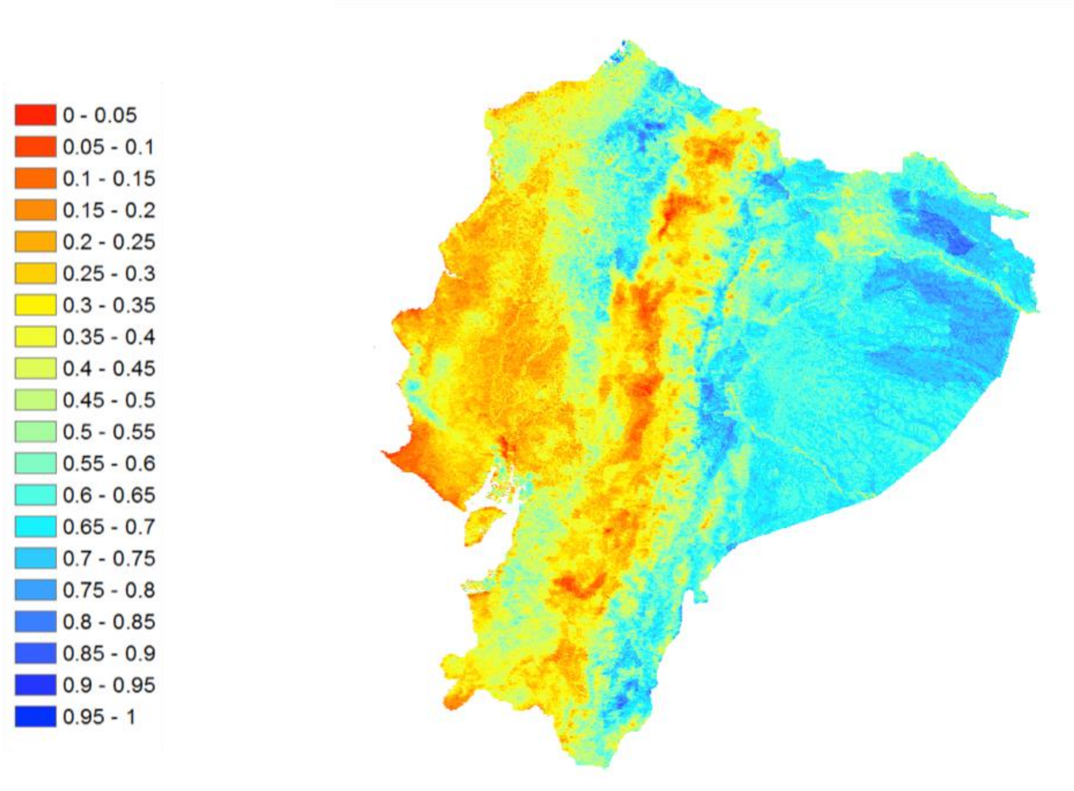

Figure 3.5. Co$ting Nature result on relative ecosystem services valuation index of Ecuador.

In Figure 3.5, the index ranges from 0 to 1, with red representing lower relative values of ecosystem services and blue representing higher values, based on total ecosystem services values for the whole country.

However, it is hard to tell the values of mangroves, when they are combined with so many layers of other ecosystems. Therefore, we conducted a scenario analysis, by combining two scenarios and deducting the effects of one scenario from the other, to generate potential values of mangrove ecosystem services. The comparison results zoomed into one region of the country coastline can be seen in Figure 3.6.

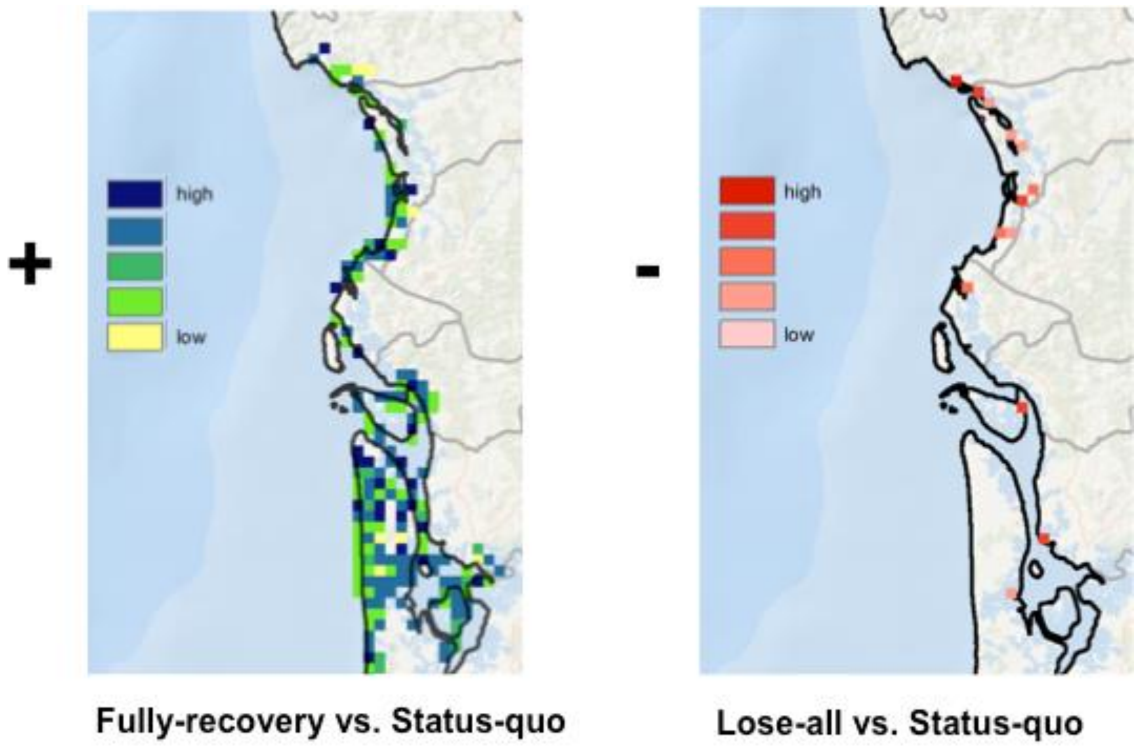

Figure 3.6. Scenario analysis between deforestation and status-quo, and reforestation and status-quo

It is clear from the above figure that, with more mangroves, the relative value index will increase, and vice versa. The green and red areas are places where values increase or decrease because of the existence of mangroves. Since hazard mitigation is the main service estimated in this model, the colored areas lie very near to the sea. Also, the variation of colors represents the differences of values of the ecosystem services: the darker the areas are, the more value they hold.

In order to get a clearer view of the index, a scatterplot containing the values of 500 randomly selected dots is shown in Figure 3.7. The x-axis represents the index value under the status-quo scenario, and the y-axis represents the index value under the full-recovery and deforestation scenarios. The dots lying on the line in the middle represent no value change, and the dots lying on either side of the line represent an increasing or decreasing value.

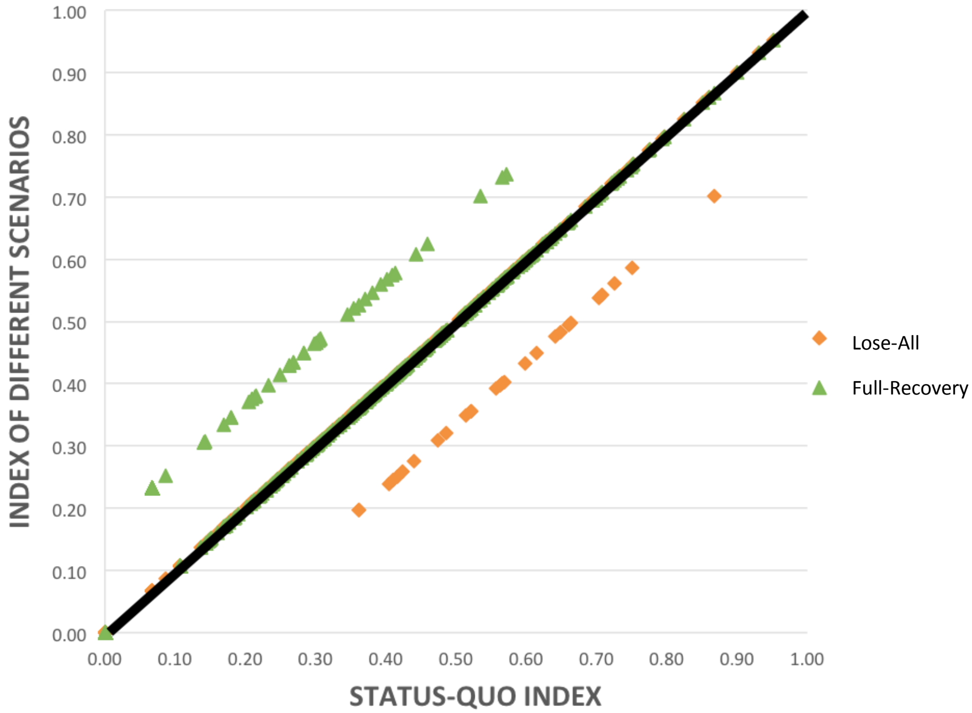

Figure 3.7 Values of scenario comparison between status-quo, lose-all, and full- recovery.

The contribution mangroves can make to the total ecosystem services values in all of Ecuador is around 16.5%, which is the distance from each dot above or below the middle line to the line. The values are slightly different for each point, indicating differences of mangrove ecosystem services at different points, as seen in Figure 3.6. However, the differences are too small under the national level index, and could thus be omitted when considering national policies and conservation programs.

3.3 Benefit transfer

Results under the previous models and scenarios express the valuation for Ecuadorian mangroves within their constraints. Previous research provides an additional perspective on valuation for

Ecuadorian mangroves through a benefit transfer process known as meta-analysis, a study of studies. The sample regions for benefit transfer analyses are shown in Figure 3.8:

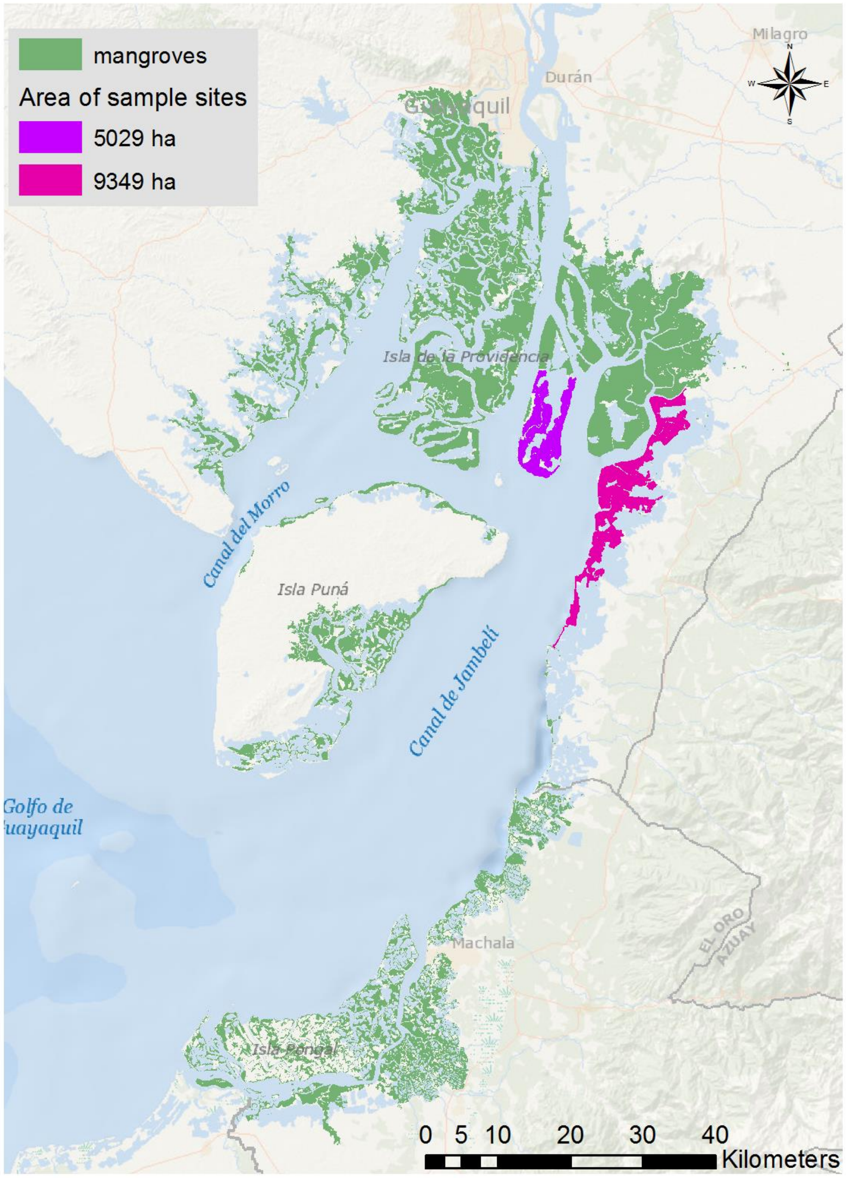

Figure 3.8 Sample regions for benefit transfer models.

The smaller region (purple) is the sample region for the Salem and Mercer model, with an area equal to 5029 hectares; the larger one (dark pink) is for the Brander et al. model, with an area equal to 9349 hectares. The two regions are chosen based on the average area value for both meta-analysis models; whereas in the Salem and Mercer model, the mean area value is 5710.15

hectares, in the Brander et al. model, the mean area value is 10938.02 hectares. However we also ran the Brander et al. model on the first site for comparison.

The value for each variable based on local characteristics is input into each model to estimate the values of each service. For example, in the Salem and Mercer model, the fishery service is contained in the baseline model, with the following binary variables: average value (1 for this estimation), monetary price (1 for fishery), local (1, since the valuation is for Ecuador only), and Thailand (0, since Ecuador lies in South America). For study characteristics, since each service may be estimated by several methods, and each method has been applied to several ecosystem services, we are using the average values reported for the "study characteristics" in the model. For mangrove characteristics, we chose 1 for "Americas" (as Ecuador lie in the Americas), "protected" (as Ecuadorian mangroves are currently under protection), with the area equal to 5029 hectares, and GDP per capita equal to $3578.44. As for the Brander et al. model, we also needed to calculate the area of mangroves, population, and length of roads within a 50km neighborhood of the study site. According to the analysis, the fishery value varied significantly among sites and models, while the coastal protection was relatively consistent (Table 10).

Table 10. Valuation of mangrove ecosystem services by two meta-analysis models

ES Values (US$ $ha^{-1}\cdot yr^{-1}$)	**Salem and Mercer, 2012***	**Brander et al., 2012***	**Brander et al., 2012***
(Site Area)	(5029 ha)	(5029 ha)	(9349 ha)
Fishery	577	960.18	1285.14
Coastal protection	3,946	1356.66	1815.19
Carbon sequestration	1,631		
Recreation	-133		* 2010 US dollar value

From the above tables we can see that the unit values generated by the Salem and Mercer model and the Brander et al. model are within the same interval.

Since the variables of the Salem and Mercer model are the same throughout the country except for the mangrove areas, we can simplify the method of generating national values of each service under different scenarios, by multiplying the unit value by the corresponding areas of mangroves (Table 11). The drawback of this approach is that it sacrifices the uniqueness of each single mangrove area. However, as the mean values used in both models are comparatively large for mangrove areas in Ecuador, where only seven areas in the range from 4063 hectares to 9349 hectares among 3343 areas with a mean of 47 hectares. It is difficult and potentially inaccurate to estimate the value of each single area and summarize to generate a national value.

However, we cannot use this approach with the Brander et al. model, as the input variables vary among sites.

Table 11. Valuation of mangrove ecosystem services by Salem and Mercer's meta-analysis models under different scenarios

Scenario	ES Values (2010US$*yr^{-1})	Salem and Mercer, 2012*	
		Value	Difference to SQ
Status-quo	Fishery	89,107,861	-
	Coastal protection	609,330,942	-
	Carbon sequestration	251,880,233	-
	Recreation	-20,606,915	-
Reforestation	Fishery	94,884,154	5,736,293
	Coastal protection	648,556,443	39,225,502
	Carbon sequestration	268,094,950	16,214,717
	Recreation	-21,993,479	-1,316,564
Full-recovery	Fishery	135,818,744	46,710,883
	Coastal protection	928,745,927	319,414,985
	Carbon sequestration	383,917,383	132,037,150
	Recreation	-31,409,185	-10,802,270

The results from Table 11 indicate that, compared to the status-quo scenario, the other two scenarios with higher mangrove distribution areas have higher annual values for each mangrove ecosystem service. With mangrove areas fully recovered to the 1969 level in 2032, they can bring $46,710,883 more value to fishery nursery and production; $319,414,985 more value by protecting the coastal areas; and $132,037,150 more value for carbon sequestration by avoiding potential harm done by extra carbon.

However, the recreation value is negative, which may indicate the bias of the paper. In the Salem and Mercer paper, the recreation value is computed as “the revenues that accrue to the community by visitors”. The negative results imply that mangroves could not bring benefits to local communities in tourism and recreation.

As for the deforestation scenario, as the mangrove area variable is in natural logarithm form, it is impossible to put a “0” area value in the model, therefore, no potential values could be estimated under the deforestation scenario. Also, it is clear that even without mangroves, the area that used to be mangrove forests may not have a 0 ecosystem services value. But if only the mangrove forests themselves are taken into consideration, the loss of mangroves will be followed by the disappearance of related ecosystem services, which leaves the value at 0.

4 Discussion and conclusion

To sum up, the InVEST model is a built-up framework, a set of equations modeling the amount of ecosystem services. However, it is cannot do “valuation” when there are no input values. Rather, it requires value as the input, and projects the distribution of the value provided onto the map. Co$ting Nature could provide only relative values and protection priorities, but no monetary values. Therefore, we conducted two meta-analysis function transfers to estimate the monetary values and provision of ecosystem services of Ecuadorian mangroves.

4.1 Limitations of models

4.1.1 Simplified and lack of monetary values

While the InVEST models used biophysical processes to estimate the amount of services, it requires the user to provide the “price” for per unit services or goods, hence it does not really do valuation. To obtain more accurate values, it is necessary to conduct a focused study within a local area for the true “price”. For other tools that do simulate the whole process to value ecosystem services (e.g. ARIES and MIMES), expertise on the process and knowledge of how the community utilizes the services are required to build the model. Hence these models may not suit the quick assessment requirement.

For Co$ting Nature, the results are focused on relative values, as conservation indices, or protection priorities, but not focused on dollar values.

4.1.2 Time consumption

The models are general; therefore, time consumption increases if we want to model a specific area, or a specific ecosystem service.

4.1.3 User friendly

The models are not extremely user friendly to the point of a point and click valuation. Rather, the models take a great deal of research and understanding in order to maximize their abilities. For example, Co$ting Nature takes quite a short time to generate results.

4.2 Limitations of current analysis

Mangrove forests are commonly classified into different kinds according to the species composition, or based on the location and function type, such as Riverine, Fringe and Basin mangroves (Twilley & Day, 2012). Riverine mangroves have the highest productivity, and hold the most important role in sediment retention and food supply, while fringe mangroves serve most in coastal protection. Basin mangroves, while the least productive among the three types, sequestrate and hold carbon and nutrients as they have less exchange with their environment (Ewel et al, 1998). In addition, a study in coastal Ecuador shows that the carbon sequestration rate of natural mangroves is significantly higher than that of restored mangrove sites (DelVecchia et al., 2014). Therefore, putting all the mangroves into one habitat layer risks losing important information about the condition of the mangroves.

4.3 Possible extensions in the future

In addition to the impacts related to shrimp farm developments, Ecuador's expansion of their oil and gas exploration should be considered. Mangrove areas could potentially lie within new oil and gas reserves. As a result, future decisions should encompass the ecosystem services while considering oil and gas expansion within the mangrove forests.

4.3.1 Improve data input for better estimate

For Co$tingNature, the input is restricted to a 1km or 100m resolution, single category mangrove map. However, for InVEST, users are allowed to improve both the spatial resolution and the biophysical process resolution, hence the output of each model depends on the accuracy and sufficiency of the input data.

4.3.2 Customize mangrove information to estimate supply and service

A desired future output includes a more primary data collection strategy to calculate a valuation that is more accurate. Calculating ecosystem service components in the field provides more robust scientific evidence for establishing unique models for the study area.

4.3.3 Include socio-economic elements into scenarios

Current scenarios use only the distribution of mangroves as the variable, while the value of ecosystem services will depend on local economic activity.

We also need to define how concessions affect the value of ecosystem services.

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Appendix

1. InVEST

1.1 Carbon output table

Table A.1. Estimates of carbon storage, sequestration, and benefits provided by Ecuadorian mangroves under different scenarios. Benefit= NPV by 2032 with 5% discount rate (InVEST default).

Scenario	Total area of mangroves (ha)	Sequestration (megaton C) (Metric Ton *10^6)	Benefit (million $)	Comparison to status-quo (million $)
Status-quo	154,424	23	378	
Lose All	0	-43	-574	-952
Reforestation	164,365	24	402	24
Fully-Recovered	235,374	35	576	198

1.2 Coastal protection output example

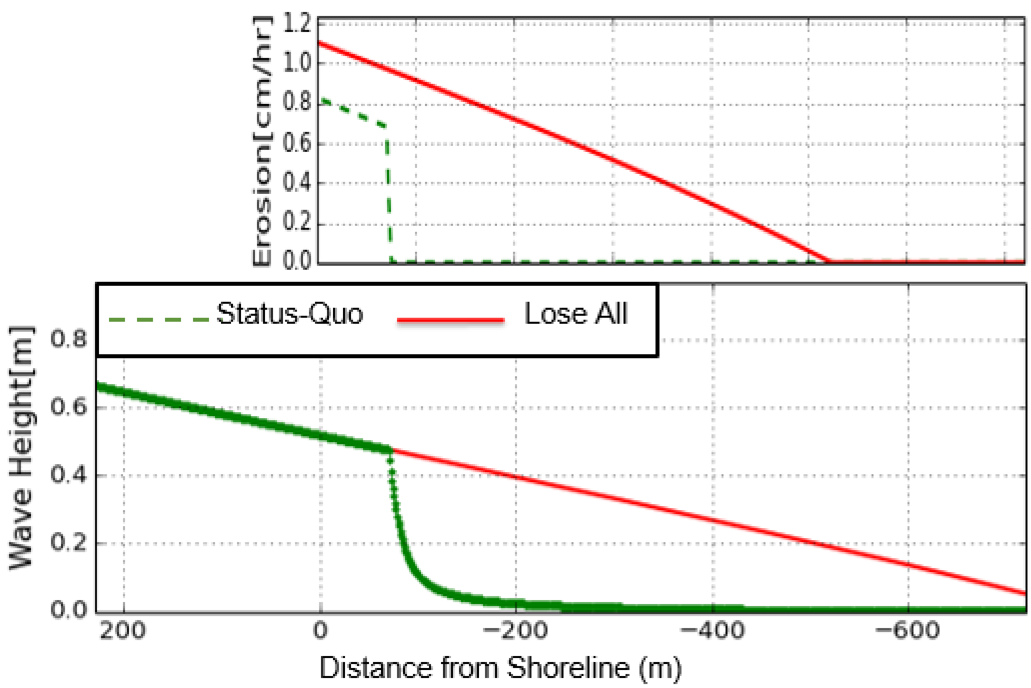

Figure A.1. The change of wave heights and erosion caused by the removal of current mangroves at the Muisne sample site. The current mangrove forest can significantly reduce the wave energy by 98.54%, and protect a 112 ha backshore area behind a 2.5 km length of shoreline.

2. Co$ting Nature

2.1 Single scenario map

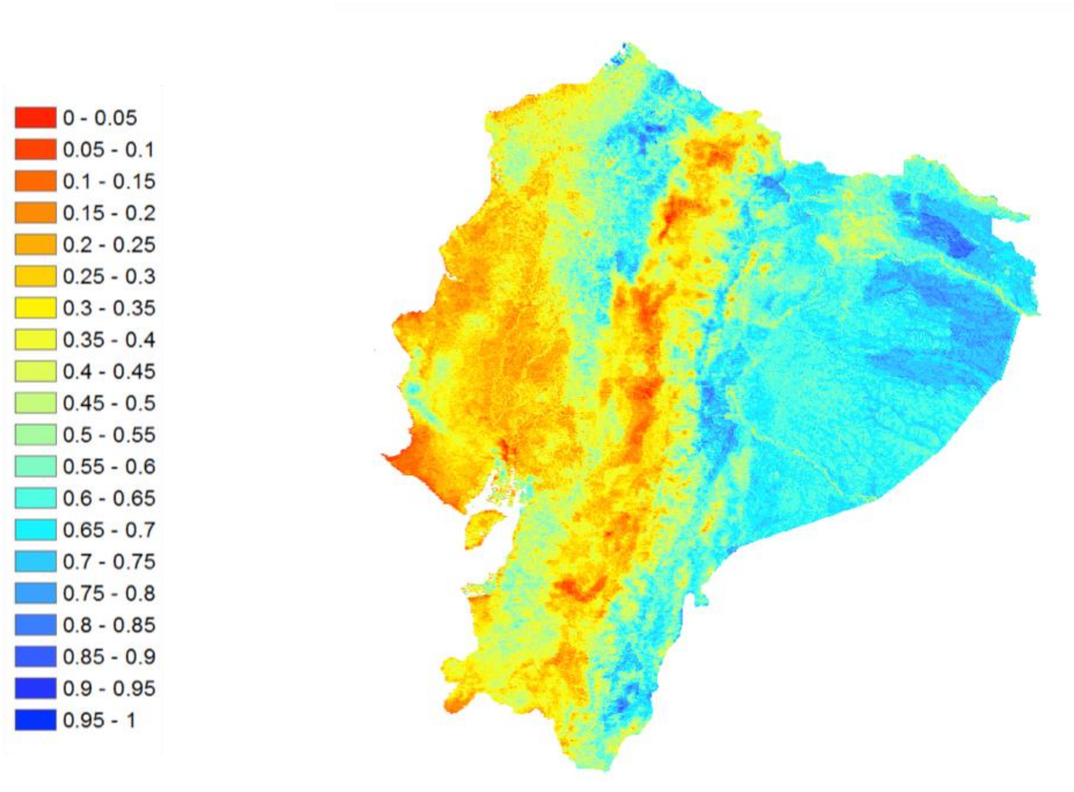

Figure A.2. Co$ting Nature result on relative ecosystem services values index of Ecuador, Status-quo scenario.

2.2 Comparison maps

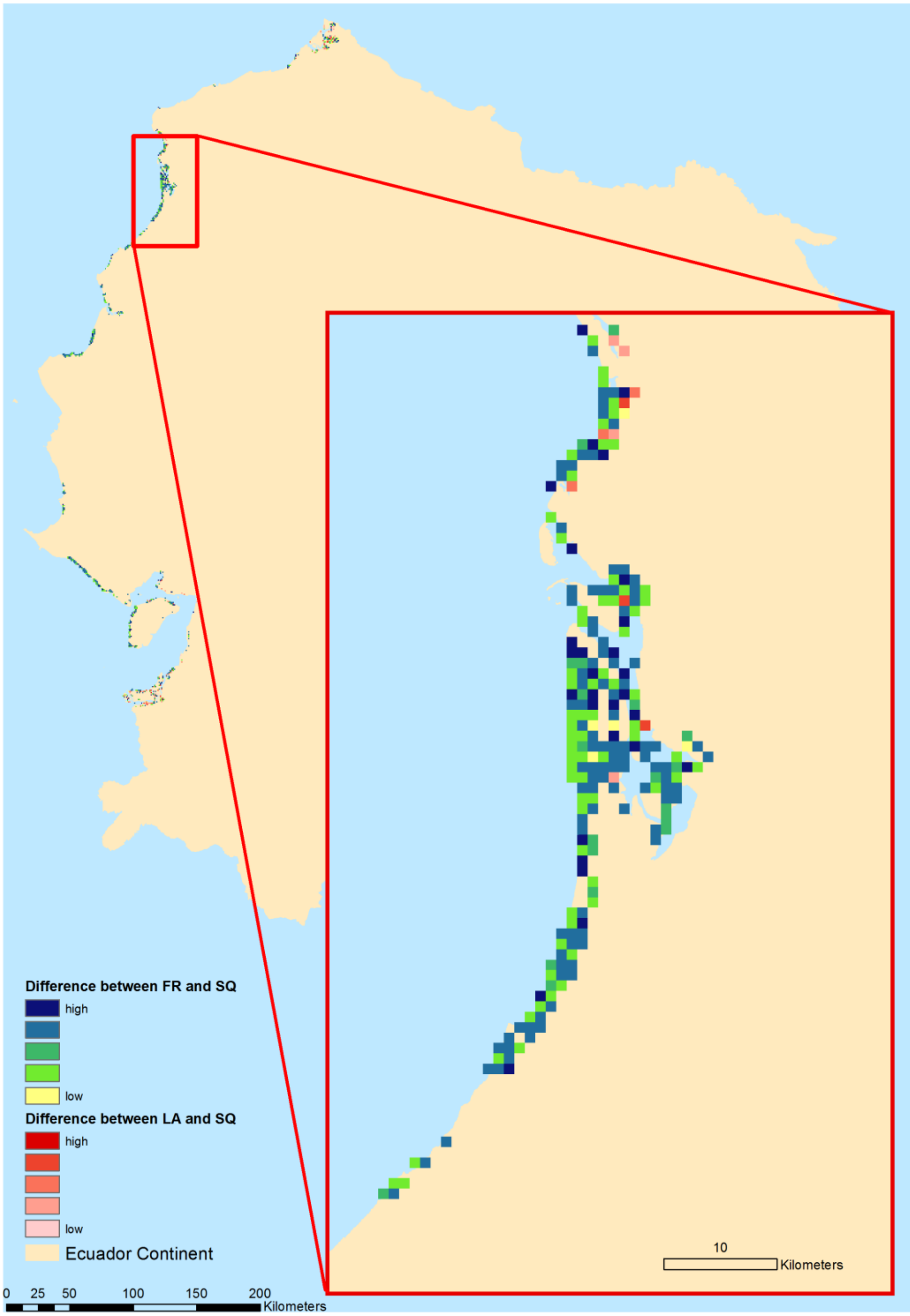

Figure A.3. Comparison between scenarios: based on Co$tingNature Output.

3. Meta-analysis tables

3.1 Meta-Analysis models from Salem and Mercers

Site Area: =5029 ha

Meta-Analysis models and results					
Marwa E. Salem and D. Evan Mercer					
	Model 2				
Variable	**Estimation results**	**Fishery only**	**Fishery + Coastal protection**	**Fishery + Carbon sequestration**	**Fishery + Recreation**
Average value		1	1	1	1
Monetary Price		1	0	0	0
Local		1	1	1	1
Thailand		0	0	0	0
Fisheries		1	0	0	0
Study Characteristics					
Marginal value	-1.066	0	0	0	0
Static production function	-0.437	0.014	0.014	0.014	0.014
Dynamic production function	1.148	0.068	0.068	0.068	0.068
Other regressions	3.705	0.034	0.034	0.034	0.034
Net factor income	-0.618	0.192	0.192	0.192	0.192
Replacement cost	-0.791	0.212	0.212	0.212	0.212
Contigent valuation	-2.421	0.068	0.068	0.068	0.068
Mangrove characteristics					
Log(area)	-0.0774	8.52	8.52	8.52	8.52
Global	0.674	0	0	0	0
Asia (excluding Thailand)	-0.833	0	0	0	0
Middle East and Africca	1.043	0	0	0	0
Americas	-0.581	1	1	1	1
Other continent	0.977	0	0	0	0
Protected	0.845	1	1	1	1
Forestry	-0.455	0	0	0	0
Recreation	-0.263	0	0	0	1
Coastal protection	2.059	0	1	0	0
Carbon sequestration	1.342	0	0	1	0
Non-use	5.809	0	0	0	0
Water and air quality	3.027	0	0	0	0
Log(GDP)	0.866	8.18	8.18	8.18	8.18
Forestry_GDP per capita		0	0	0	0
Recreation_GDP per capita		0	0	0	3574.88
Coastal protection_GDP per capita		0	3574.88	0	0
Carbon sequestration		0	0	3574.88	0
Non-use_GDP per capita		0	0	0	0
Water and air quality_GDP per capita		0	0	0	0
Constant	-0.0787	1	1	1	1
Ln(Annual per hectare mangrove values in 2010 US$)					
Model 2		6.357902469	8.416902469	7.699902469	6.094902469
Values (US$ ha–1·yr–1)					
Model 2		577	4,523	2,208	444
		Fishery only	**Coastal protection**	**Carbon sequestration**	**Recreation**
Values (US$ ha–1·yr–1)		577	3,946	1,631	-133

3.2 Meta-Analysis model from Brander

Site 1: Area = 9349 ha

Variable	Coefficient	S.E.	Input	Excluded use only	Fisheries	Coastal Protection
Constant	-0.59	2.193		-0.59	-0.59	-0.59
Coastal Protection	1.456	0.491		0	0	1.456
Water Quality	1.714	0.752		0	0	0
Fisheries	0.86	0.355		0	0.86	0
Fuel Wood	-1.085	0.437		0	0	0
Mangrove Area	-0.343	0.065	9349	-3.13606	-3.13606	-3.13606
Mangrove Abundance	0.248	0.082	1096	1.735857	1.735857	1.735857
Roads	-0.312	0.175	579	-1.98473	-1.98473	-1.98473
GDP per capita	0.785	0.174	3574.88	6.422624	6.422624	6.422624
Population	0.284	0.149	1613878	4.059539	4.059539	4.059539
Value	US$/ha/year; 2007 prices (ln)			6.507236	7.367236	7.963236
	US$/ha/year; 2007 prices			669.972	1583.251	2873.356
	(- Excluded use)				**913.2795**	**1290.104**

Site 2: Area=5029 ha

Variable	Coefficient	S.E.	Input	Excluded use only	Fisheries	Coastal Protection
Constant	-0.59	2.193		-0.59	-0.59	-0.59
Coastal Protection	1.456	0.491		0	0	1.456
Water Quality	1.714	0.752		0	0	0
Fisheries	0.86	0.355		0	0.86	0
Fuel Wood	-1.085	0.437		0	0	0
Mangrove Area	-0.343	0.065	5029	-2.92338	-2.92338	-2.92338
Mangrove Abundance	0.248	0.082	1076	1.731289	1.731289	1.731289
Roads	-0.312	0.175	525	-1.95418	-1.95418	-1.95418
GDP per capita	0.785	0.174	3574.88	6.422624	6.422624	6.422624
Population	0.284	0.149	1939573	4.111746	4.111746	4.111746
Value	US$/ha/year; 2007 prices (ln)			6.798098	7.658098	8.254098
	US$/ha/year; 2007 prices			896.1415	2117.726	3843.345
	(- Excluded use)				**1221.585**	**1725.618**