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Quantifying carbon sequestration for riparian-zone restoration in Ecuador

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QUANTIFYING CARBON SEQUESTRATION FOR RIPARIAN-ZONE RESTORATION IN ECUADOR

An Abstract of a Thesis

Submitted

in Partial Fulfillment

of the Requirements for the Degree

Master of Arts

Paula Carvalho de Castro

University of Northern Iowa

July 2021

ABSTRACT

- Carbon sequestration supported by carbon pricing and carbon offset programs has the potential to mitigate the risks associated with environmental change. Riparian-zone restoration, beyond enriching degraded ecosystems, promotes carbon sequestration. With that premise, this study aims to estimate and compare how much carbon is captured and stored using six riparian-zone restoration scenarios for the Northwestern part of the Pichincha Province in Ecuador and the economic value of the respective carbon. The InVEST Carbon Storage and Carbon Sequestration Model which integrates land cover maps, carbon pools, and economic value of carbon in currency units was used to quantify the amount of carbon sequestered after restoration and its economic value. The six restoration scenarios were established by tracing two corridors (1 and 2) in three different widths: 60m, 90m and 120m along waterways. With a higher number of pixels converted into forest due to the region's land use map and carbon density pool, the proposed corridor 1 derived scenarios restored a larger area than their corridor 2 counterparts and also presented higher values as results when looking at carbon sequestration and financial return (economic value). By participating in the UN-REDD program, Ecuador is able to receive payments (through carbon pricing and carbon offset programs) for promoting conservation which have the potential to contribute to local livelihoods as financial capital. Considering its limitations (such as the assumption that the amount of carbon will only change if there is a

change in land use class) the InVEST Carbon Model showed itself to be a reliable to tool to quantify carbon sequestration and its economic value.

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This Study by: Paula Carvalho de Castro

Entitled: Quantifying Carbon Sequestration for Riparian-Zone Restoration in Ecuador

has been approved as meeting the thesis requirement for the

Degree of Master of Arts

Date	Dr. James Dietrich, Chair, Thesis Committee
Date	Dr. Mark Welford, Thesis Committee Member
Date	Dr. Alex Oberle, Thesis Committee Member
Date	Dr. Jennifer Waldron, Dean, Graduate College

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TABLE OF CONTENTS

PAGE

LIST OF TABLES

PAGE

LIST OF FIGURES

PAGE

LIST OF EQUATIONS

PAGE

INTRODUCTION

Human activities have already caused an approximate 1.0°C of global warming above pre-industrial levels and if the current rates continue, it is likely to reach 1.5°C between 2030 and 2052 (IPCC, 2019a). Through observation of land and sea temperatures, scientists noted that the 20 warmest years on the planet have occurred since 1981 and the 10 warmest years ever recorded have all occurred in the past 12 years (National Oceanic and Atmospheric Administration, 2021) .Changes on the planet's climate, which include a rise in the global temperature have direct consequences such as: sea level rise, draughts, and increased endangerment of plant and animal species (IPCC, 2019b; NASA, 2021). The Amazon Rainforest (which spreads over 9 countries in South America) has seen its average temperature rise by 1-1.5°C over the last 100 years and since 2005 the region has suffered from extreme weather variability, including severe droughts (Amigo, 2020). Globally, extreme weather events associated with the increase in temperature are being recorded more than ever (Wuebbles et al., 2017).

Climate change driven by global warming and its consequences affects human life as well as the atmospheric conditions that sustain every form of life on the planet (Amnesty International, n.d.; Rebeek, 2010). Rising emissions of carbon dioxide (CO_2) and other greenhouse gases (GHG) increases the level of heat-trapping of the Earth's atmosphere which causes temperature to rise (Robbins et al., 2014.). Increase in emissions of carbon related compounds such as CO_2 and Methane (CH_4) - both gases represent together 91% of all GHG emissions in the planet (United States Environmental Protection Agency, 2015b) - is associated with carbon being used as feedstock by industries for more than a century (Roberts, 2019). The relationship between carbon compounds and economic activity is such that imposing limitation factors to economic growth would impact directly on GHG emissions (Mardani et al., 2019).

The Biosphere is both a source and a sink of GHGs and plays a key role in the exchange of energy, water and aerosols between the planet's surface and atmosphere (IPCC, 2019a). Terrestrial ecosystems play a significant role as climate regulators with their ability to add and remove greenhouse gases from the atmosphere (Food and Agriculture Organization, n.d.-b). However, human induced carbon dioxide emissions have caused Earth's carbon sinks (CO_2 uptake mechanisms) to be insufficient to offset all the biosphere emitted carbon (Sundquist et al., 2009.). With that, the concept of carbon sequestration plays an important role as it has the potential to mitigate the risks associated with environmental change (Lal, 2008).Carbon sequestration is a term used to describe both natural (e.g. normal carbon uptake by flora), or human-induced (e.g. forest restoration, agriculture) process in which carbon dioxide is removed from the atmosphere by terrestrial systems such as soil, vegetation and geologic formations (Lal, 2008; Sundquist et al., 2009.).

Together with carbon sequestration, a mechanism for combating climate change and reducing GHG emissions is carbon pricing (Klenert et al., 2018). Carbon pricing is a strategy adopted by more than 40 countries (Worldbank, n.d.) aiming to lower greenhouse gasses emissions through setting actual monetary prices on carbon emissions in an attempt to limit global warming and follow the objectives of the Paris Agreement (Bataille et al., 2018; Union of Concerned Scientists, 2017.). Monetary value is established as a currency price per megagram (or metric ton) of CO_2 emitted by individuals and businesses in a country or subnational division (Carbon Pricing Leadership Coalition, n.d.; Hafstead, 2020). The Paris Agreement goal (among others) is to keep temperature rise under 2°C (Gao et al., 2017; Glanemann et al., 2020). A total of 189 countries that have ratified their participation in the Paris Agreement since 2016 (United Nations Framework Convention on Climate Change, 2021b). Widely established (as a market approach), cap-and-trade programs, such as the European Union Emissions Trading System, limit the amount of carbon dioxide that can be emitted by the use of allowances (or permits) (Environmental Defense Fund, n.d.; European Commission, 2015; Union of Concerned Scientists, 2017). Allowances are certificates issued to companies and organizations participating in carbon markets that represent the legal right to emit a megagram of a GHG (Cooper, 2017). Permits can be traded and the supply and demand drives a market price for allowances (Union of Concerned Scientists, 2017.). Emissions pricing produces the highest environmental benefits when the carbon social price (or carbon marginal price) is equal to the social damage of adding a megagram of CO_2 into the atmosphere (Hafstead, 2020). The social cost of carbon in this sense is suggested to range between 31 USD per megagram (Nordhaus, 2017) to 50 USD per megagram of CO_2 (United States Environmental Protection Agency, 2015b). Other methods, which assume that the cost of carbon should be equal to the cost alternative for sequestering it or vary in assumptions regarding the discounting of time in regards to carbon pricing, suggest that the social cost of carbon should range from 66 to 130 USD (Arkema et al., n.d.). However, no universal value has been determined and GHG emissions prices vary between countries. According to the New York Times in 2019, per a megagram of carbon emitted, Canada charges 15 to 30 USD, the United Kingdom charges 25 USD and the United States of America charges 5 to 15 USD depending on the State (with California charging 15 USD and states such as Connecticut, New York and Massachusetts changing 5 USD) (Plumer & Popovich, 2019). Stanford University through the Natural Capital Project suggests, based on literature regarding the social cost of carbon that values for emissions should range from 9.55 to 84.55 USD per megagram of CO_2 released into the atmosphere (Arkema et al., n.d.).

Carbon offset programs are yet another strategy to mitigate climate change. These programs allow individuals and industries to buy offsets that compensate for their GHG emissions by reducing emissions or increasing sequestration somewhere else (Anderson et al., 2017; Irfan, 2020) . What differentiates carbon offset projects from carbon pricing (and cap and trade programs) is the fact that they are designed specifically with the purpose of a reduction in emissions (Clark, 2011). Carbon offset projects usually include investments in clean energy development, planting trees and forest conservation (Cooper, 2017) and are usually based in developing nations (Clark, 2011). Offset purchases are voluntary and the price per megagram of GHG emitted varies widely, being the average price between around 3 and 14 USD (per megagram of carbon) (Mock & Tabuchi, 2019; Second Nature, n.d.).

To avoid extreme environmental change and its consequences, rapid decarbonization through prioritizing localized actions is strongly suggested (Goldstein et al., 2020). With the widely conceived premise that forest cover is environmentally desirable (Williamson, 2016), restoring degraded ecosystems along with reducing emissions of GHGs is key to reducing the vulnerability of natural (and societal) systems to the effects of climate change (Myers et al., 1997). Studies in China and Brazil suggest that the expansion of agricultural lands over natural vegetation results in decline of carbon stock (Chaplin-Kramer et al., 2015; Sun et al., 2017). Also, the implementation of restoration projects were found to be the most important factor leading to the increase of carbon stock and that land conservation practices, such as to control rapid built-up land expansion, can facilitate ecological processes in carbon storage oasis (Liang et al., 2017; Lu et al., 2018).

In the same direction, one of the most frequent pieces of advice in the academic literature (Dios et al., 2007; Halpin, 1997; Scott et al., 2002) regarding conservation is the need to improve landscape connectivity so that species can move through them (Heller & Zavaleta, 2009). Riparian-zone restoration offers one avenue to enrich degraded ecosystems by increasing connectivity between systems and providing ways for species movement (Seavy et al., 2009). Riparian areas (or riparian buffers) are defined as lands that occur along waterways and water bodies that are managed to protect or enhance ecological health (American Rivers, 2016). It includes, typically, flood plains and streambanks (United States Department of Agriculture, 1996). Beyond alleviating flooding events, riparian vegetation improves water quality by trapping sediment and filtering pollutants. It also benefits the surrounding community's water supply by helping to recharge aquifers (American Rivers, 2016; Seavy et al., 2009). Historically, riparian areas reflect local and basin wide land use (National Research Council, 2002) and its narrowing is usually related to croplands expansion (Boudell et al., 2015). Restoring degraded riparian forests can contribute to maintaining (and improving) fresh water supply (American Rivers, 2016), to rapid CO_2 sequestration (Dybala et al., 2019; Seavy et al., 2009) and to increase the number of species being protected because they are biodiversity hotspots (Sabo et al., 2005). Although riparian buffers are an example of regulating ecosystem service which has its concept inherently based on its value or importance to society (Dybala et al., 2019; Zhu et al., 2010) and are demonstrated to have positive economic value because of the amenities they provide (American Rivers, 2016), setting actual monetary price to them is challenging and considerable disagreement between experts is observed when discussing environmental value (Norton, 2012).

In the effort of connecting climate change mitigation through carbon sequestration supported by carbon pricing/offset mechanisms and riparian zone restoration, my research aims to estimate and compare how much carbon is captured and stored using six different riparian-zone restoration scenarios for the Northwestern part of the Pichincha Province in Ecuador and the economic value of the respective carbon captured after restoration. Therefore, I seek to answer the following questions: (1) How much carbon is sequestered when non-forest areas are converted into forest in different restoration scenario? (2) For the cloud forests of Ecuador, what is the economic value of a restored riparian forest corridor? (3) Can carbon pricing or carbon offset programs be leveraged to incentivize ecosystem restoration?

STUDY AREA

Ecuador is a country located in the northwestern part of South America. It is one of the most biodiverse countries in the world containing around 23.056 taxonomic species of animals and plants (Biodiversity Finance Initiative, n.d.). Its territory on the mainland is divided into three main regions: the Costa (coastal) region, the Sierra (highland) region and the Orient. The coastal region stretches from the edge of the Andes Mountains to the Pacific Ocean. The Sierra region is characterized by two mountain chains and their foothills, the western and central ranges of the Andes. The Orient, the eastern part of the country, is located on the Amazon basin. Ecuador has an estimated population (2019) of 17,379,000 (MacLeod, n.d.). The establishment of grasslands and farmlands (together with timber extraction) are the main reason why, annually, Ecuador suffers the loss of 1.8% of its primary forests, the highest rate in Latin America (Food and Agriculture Organization, n.d.-a). The country does not have a “carbon tax” policy yet and its GHGs emissions are one of the lowest in South America (Worldbank, 2020). However, Ecuador participates in the UN - REDD program (United Nations, 2019). REDD stands for ‘reducing emissions from deforestation and degradation' and it is a program that allows developing countries to receive payments for preventing deforestation or ecosystem degradation. The funding comes from carbon trading, where other countries can offset their own emissions by transferring funds (carbon credits) to developing countries (International Institute for Environment and Development, 2009).

The Pichincha Province is situated in the Sierra region of Ecuador with a lowland fringe to the west. Its population is estimated (2010) at 2,576,287 and its main occupations are agriculture and cattle raising (Augustyn et al., n.d.). However, the Northwestern part of the Pichincha province has experienced rapid expansion of ecotourism and in the recent years touristic activity has largely replaced unsustainable agriculture and cattle ranching (M. R. Welford & Yarbrough, 2015).

My study area is situated in the Northwestern part of the Pichincha Province, most precisely around two corridors connecting three areas of interest for conservation determined by the Mindo Cloudforest foundation. These three areas (also listed on Table 1) are: Rio Silanche Bird Sanctuary, Mangaloma Reserve, Tatala River Mouth, which is a forested area in the mouth of the Tatala River that is connected to the forested riparian zone along the Mashpi River. The Mashpi river natural riparian zone connects the corridors to the Milpe Bird Sanctuary. The corridors both start at the Rio Silanche Bird Sanctuary and end at the Tatala River Mouth. Corridor 1 takes a northern route and corridor 2 runs to the south, both pass through the Mangaloma reserve and end at the Tatala River Mouth.

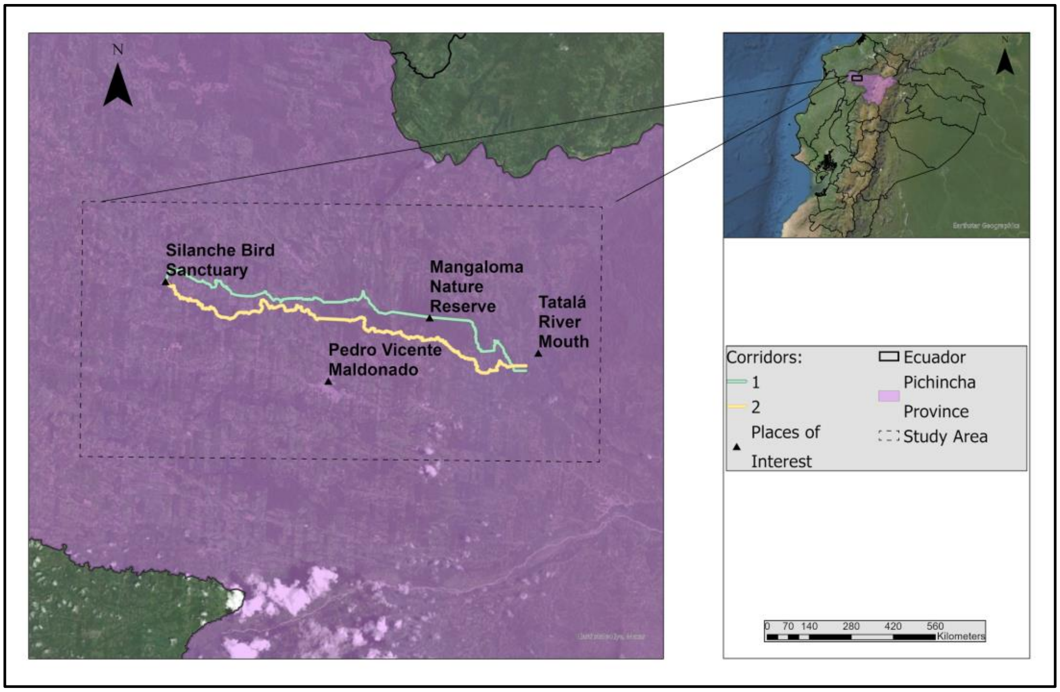
Table 1 Study Area Site

Site	Lat	Long	Elevation (Mean Sea Level)
Silanche Bird Sanctuary	0.146344	-79.142129	300-350m
Mangaloma Reserve	0.126206	-78.995568	700-900m
Tatala River Mouth	0.106644	-78.935239	900-1020m
Milpe Bird Sanctuary	0.035183	-78.870821	1020-1150m

Table containing latitude, longitude and elevation information on four relevant sites in the study area.

These areas are of specific interest to the Mindo Cloudforest Foundation (MCF) who aims to protect and restore forest connectivity on high conservation value regions and improve sustainability in the Northwest of the Pichincha region (mindocloudforest.org, n.d). Their specific goals are riparian forest restoration and reforestation. Our goal, through mutual collaboration, is to measure the carbon budget on their future projects sites. The quantification of carbon sequestration will help to monitor habitat quality and will aid and direct land purchase for tropical forest conservation. The Northwestern Pichincha region in Ecuador has suffered an intense loss of forest cover from land-use changes primarily to agriculture (Sierra, 2013) and pastures that are now exhausted (Welford & DeFalco, 2003). Restoring riparian-zone forest cover along important waterways that connect high interest areas for conservation is a strategy that can potentially be used by local government and stakeholders to mitigate the issues caused by the land cover changes (National Research Council, 2002). The map below (Figure 1Figure 1 Study Area) shows the study area with the proposed restoration corridors:

Figure 1 Study Area



Map representing the study area in the Northwestern Pichincha Province in Ecuador. The map also contains the two versions of the proposed corridors and places of interest as references.

METHODS

To answer my research questions, I propose two different corridors each having three different sizes (width) as restoration scenarios to connect the three different forest remnant reserves. The parameter values used to quantify the carbon economic value and the amount of time for the completion of the restoration were determined with collaboration from Mindo Cloudforest Foundation based on their conservation projects technical documentation and assessments.

With the goal of restoring as much riparian zone vegetation as possible, the two corridors were traced as line features type following major streams. When no stream was present, the path followed the shortest possible distance across non-riparian areas. To guide the tracing process, I have used ESRI's Worlds Imagery base map for reference and hydrologic and topographic vector data provided by Pedro Vicente Maldonado municipal government, a city located in the Pichincha Province. After the two corridors were established, each corridor received a 30m, a 90m and a 120m polygon buffer to establish six different restoration scenarios. (Figure 2).

Figure 2 Corridors and Buffers

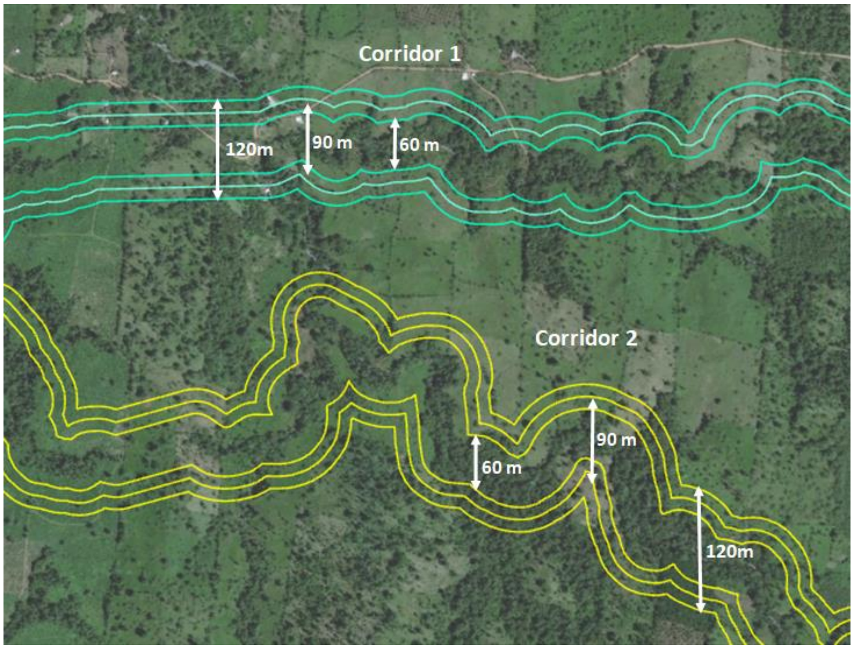


Figure representing the three buffers widths proposed for the two corridors on top of ESRI's World Imagery base map.

Carbon Modelling

To quantify the amount of carbon sequestered after restoration and its economic value, I used the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) Carbon Storage and Carbon Sequestration Model developed by the Natural Capital Project in Stanford University (Zaks, 2019). The software, through the model, integrates land cover/land use (LULC) maps, carbon pools, and economic value of carbon in currency units to calculate the output results. The InVEST Carbon Model needs the following data as inputs (Table 2 Input Data):

Table 2 Input Data

Input Data	Data Type
Current LULC	Raster map
Current LULC calendar year	Integer
Future LULC	Raster map
Future LULC calendar year	Integer
Carbon pools	Table - CSV File
Price of megagram of carbon (Mg of C)	Integer

Table listing the input data that InVEST Carbon Model needs to perform the intended computations.

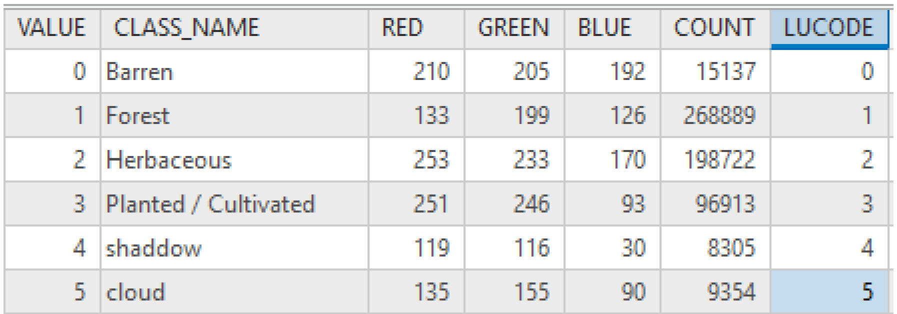
Current and Future Land Use

To quantify the amount of sequestered carbon (and subsequent economic value of the sequestered carbon) when non-forest areas are converted into forest, seven different land use raster maps were generated, one for the current LULC and six others representing the six restoration scenarios. One Landsat 8 scene from November, 20th

2016 was used to provide land cover data for the classification of current land use. The specific Landsat image acquired on November 20th, 2016 (LC08_L1TP_010060_20161120_20170318_01_T1) was chosen due to the lack of clouds covering the study area which allowed for classification. The LULC classes chosen for the study area were forest, herbaceous vegetation, cultivated lands, barren lands, clouds and shadow. With the combined Landsat 8 bands 6, 5 and 4 (standard for vegetation analysis (Butler, 2013)) I was able to obtain the 8 to 10 samples for each land use class needed to classify the image. I have used the Maximum Likelihood algorithm (which has its principles based on Bayes' theorem of decision making (ESRI, n.d.)) as a supervised classification method in ESRI's ArcGIS PRO software to classify the current LULC image. Landsat 8 imagery spatial resolution (bands 1 to 7) is 30 meters (NASA, n.d.) and for this reason the corridors size in this project were established to be 60m, 90m, and 120m wide. Each pixel value in the current LULC map corresponds to their class value after classification. To generate each of future LULC maps (six restoration scenarios in total), I have used the Pixel Editor tool in ESRI's ArcGIS PRO to select and convert all the pixels classified as a class other than forest into forest inside of each restoration corridor.

The LUCODE field in each of the LULC map's attribute table is needed in order to integrate the LULC maps to the carbon pools table. The Figure 3 below represents the attribute table of a classified LULC map used in this project.

Figure 3 Attribute Table of a Classified Image



VALUE	CLASS_NAME	RED	GREEN	BLUE	COUNT	LUCODE
0	Barren	210	205	192	15137	0
1	Forest	133	199	126	268889	1
2	Herbaceous	253	233	170	198722	2
3	Planted / Cultivated	251	246	93	96913	3
4	shaddow	119	116	30	8305	4
5	cloud	135	155	90	9354	5

Figure representing the attribute table of a LULC map containing the LUCODE field with its corresponding values for each LULC class.

As the calendar year for the Current LULC scenario, the date of 2021 was chosen to represent the current year, along with the 2051 date for all future LULC maps. The 2051 calendar year was chosen to accommodate a 30-year time frame for restoration, which is an averaged number between areas along small streams that would recover their natural function within a decade and large wood areas that would require between 50 to 100 years to recover (National Research Council, 2002). This 30-year period of time was also suggested by the Mindo Cloudforest Foundation as they understand that it is the time frame for plant growth and maturation in a restored area. The current and future land use maps information are listed below (Table 3) followed by Figure 4 to illustrate them.

Table 3 Land Use Maps:

Type of Corridor	Size (width)	Scenario and calendar year	Non-forest area to restore (ha)	Non-forest Pixels to restore
n/a	n/a	Current (2021)	n/a	n/a
1	60m	Future (2051)	212.22	2358
1	90m	Future (2051)	297.09	3301
1	120m	Future (2051)	339.15	4435
2	60m	Future (2051)	145.62	1618
2	90m	Future (2051)	234.63	2607
2	120m	Future (2051)	326.25	3625

Table listing all the restoration scenarios with their corridor type, size, calendar year, non-forested area and number of non-forested pixels.

Figure 4 LULCs

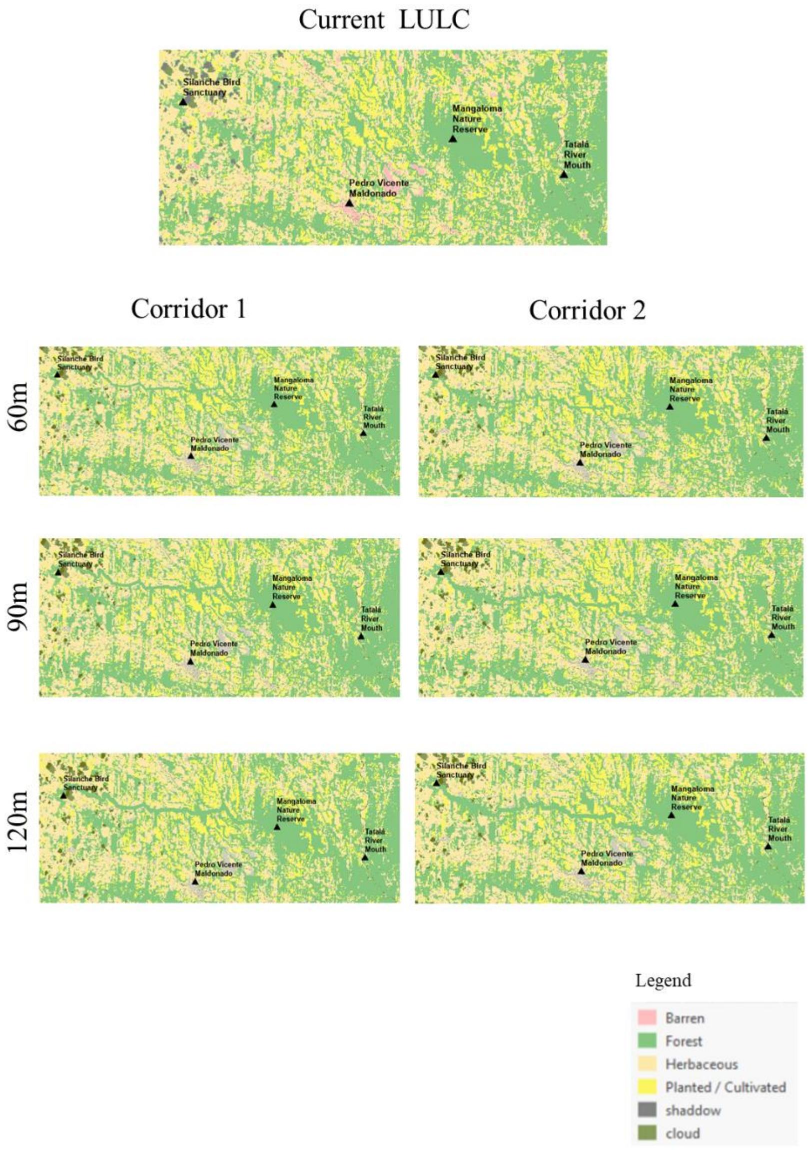


Figure representing the current and future LULCs scenarios with the LULC classes' legend for reference.

With the current and future LULC maps where each pixel is classified as a land use class, the InVEST model is able to calculate the amount of pixels that changed from non-forested or degraded (barren, herbaceous, planted / cultivated) to pixels classified as forest. Pixels classified as shadow and cloud were understood to be non-forested areas as well.

Carbon Pools

To quantify the change in carbon storage between future and current land use, the InVEST model requires data on the amount of carbon stored in four fundamental pools in the area of interest. The model needs values for the carbon density (megagrams per hectare) in aboveground biomass, in belowground biomass, and optionally the carbon density in soils and the carbon density in dead matter. These values are aggregated in a CSV table that associates each pool value to a LULC class by using the “lucode” field. With this table the model is able to quantify the total amount of carbon (by each pixel’s area) and the specific location (by the pixel’s coordinates) stored in each different land use class.

This way, InVEST generates eight raster maps where each pixel represents the amount of carbon stored in each corresponded land parcel. Four maps for current land use and four maps for future land use, being: 2 aboveground biomass maps (current and future), 2 belowground biomass maps (current and future), 2 maps of the carbon stored in soil (current and future), and 2 maps of the carbon stored in dead matter (current and future). These eight maps are considered “intermediate outputs” by the model. The input carbon pool table unit is megagrams per hectare, therefore the InVEST model converts the values based on the pixel size of the LULC maps.

Carbon pool data are available in literature and through the IPCC (Ruesch & Gibbs, 2008), the units in different sources are not consistent and conversions and other processing techniques are needed in order to obtain the correct measurements in megagrams of carbon (Mg of C). In this research, I was unable to find carbon pool values specific to Ecuador, therefore I have used the work of Miranda et al, (2014) that is the suggested data in the InVEST Model documentation for Brazil because of the similarity between the two countries in regards to biomes. Below is the carbon pool table (Table 4) used in this project (the units are in megagrams per hectare (Mg/ha)):

Table 4 Carbon Pools

lucode	c_above	c_below	c_soil	c_dead	LULC_Name
1	98	15.6	60	13.4	Forest
2	3	7.9	71	0.9	Herbaceous
4	0	0	0	0	shadow
5	0	0	0	0	cloud
0	0	0	0	0	Barren
3	0.015625	0.5	50.8	2.4	Planted / Cultivated

Table representing the Carbon Pool used in this research with data for the amount of carbon stored in aboveground biomass, belowground biomass, soil and dead matter.

Price of Carbon

In addition to the LULC inputs, the InVEST Model requires a price per megagram of elemental carbon emitted to calculate the economic value of the sequestered carbon. Because carbon emissions are usually priced as megagram of carbon dioxide emitted (Hafstead, 2020; Nordhaus, 2017; United States Government, 2010), the chosen price of 10 USD per megagram of carbon dioxide was converted into an elemental carbon price of 37 USD using the 44/12 ratio (the molecular weight of carbon dioxide to carbon (United States Environmental Protection Agency, 2015a). The price of 37 USD (based on the 10 USD per megagram of CO_2) was selected for this research because it approaches the average of the current prices charged for GHG emissions in the U.S (Plumer & Popovich, 2019). Also, this value is approximated to the ones currently used in MCF's restoration projects.

It is also possible to insert and use the market discount in price of carbon and the annual rate of change in the price of carbon. According to the InVEST Carbon documentation, the market discount in price of carbon is an integer percentage value that aims to reflect society's preference for immediate benefits of the sequestrated carbon over future ones. The United States government suggests the default value of 7% per year. However, this rate depends on each country's landscape and should be defined following local requirements (Arkema et al., n.d.). Because MCF does not account for that parameter in their restoration projects in Ecuador and therefore to follow guidelines, the value used in this research for this parameter was 0%. This means that monetary values were not discounted. Also, the annual rate of change in the price of carbon is an integer percentage value that adjusts the values of sequestered carbon as the impacts of emissions changes over time (Arkema et al., n.d.). Setting this parameter to a value bigger than 0% would suggest that the societal value of carbon in the future is less than the value of sequestration now. In the same direction, setting this value to anything less than 0% would suggest that society would benefit more from sequestration in the future rather than now. Due to the uncertainty of determining the change in value that carbon sequestration has to society the value of 0% was used.

For the penultimate calculation of the economic value of the sequestered carbon, InVEST uses the following equation (Equation 1)

Equation 1 Value of Sequestered Carbon

$$value\_seq_x = V \frac{sequest_x}{yr\_fut - yr\_cur} \sum_{t=0}^{yr\_fut-yr\_cur-1} \left(\frac{1}{\left(\left(1 \frac{r}{100}\right)^t\right) \left(\left(1 \frac{c}{100}\right)^t\right)} \right) \tag{1}$$

Equation to obtain the value of sequestered carbon (value_seq$_x$). Where: V represents the price per megagram of elemental carbon; sequest$_x$ is the total of sequestered carbon; yr_fut is the future calendar year; yr_cur is the current calendar year;r represents the market discount in the price of carbon; and c represents the annual rate of change in the price of carbon.

The input data described above allows the InVEST Carbon model to generate outputs that include (Table 5):

Table 5 Outputs

Output data	Data Type	Pixel value =
Current Landscape Scenario	Raster map	Mg of carbon stored
Restored Landscape Scenario	Raster map	Mg of carbon stored
Difference between restored and current scenarios	Raster map	Mg of carbon stored
Economic Value: carbon sequestered between the current and the restored (future) landscape dates.	Raster map	$ (currency)
Report	HTML	n/a

Table listing the output products of the InVEST Carbon Model

An HTML report file contains a summary of all data computed by the model including the following values:

1) Amount of carbon stored in Mg for the current scenario
2) Amount of carbon stored in Mg for the future scenario
3) The different between the current and future amounts of stored carbon
4) The total economic value of carbon sequestered between the current and the future scenario (in currency units)

With the outputs generated by InVEST, it is possible to quantify the carbon that is captured in each of the restoration scenarios and the economic value in currency of each restored scenario. The carbon budget and its value were estimated for the degraded areas (or non-forested areas) inside of each proposed corridor. By having the results of each restoration scenario, it is also possible to compare them with the actual financial budget of restoration undertaken by MCF to assess if the methodology used in this research provides results close to the reality of riparian zone restoration efforts.

The Foundation's projects budgets include: establishment and maintenance of plants, monitoring the sites, compensation for landowners, and other operational costs. The foundations uses the following schema (Equation 2) to calculate the financial budget for restoration per hectare:

Equation 2 MCF's budget schema

$$1\ ha = \left(\frac{22\ Mg\ of\ \mathrm{CO2e}}{year}\right)\ \times n\_years\ \times price\_carbon\_dioxide$$

MCF budget equation where: CO2e is carbon dioxide equivalent; n_years is the number of years for restoration (30 years in most cases) and price_carbon_dioxide is the price of carbon in U.S Dollars.

Carbon dioxide equivalents means that other GHG (e.g. methane, nitrous oxide, and sulphur hexafluoride) were converted into CO_2 values for better comparison and for being traded in carbon markets (Climate Change Connection, n.d.). Usually, MCF uses a 30 year time-frame for their restoration projects due to the time it takes for plants to grow and reach maturity. The foundation works with a range of 8.40 to 12 USD as the price of Mg of carbon dioxide.

RESULTS

The following table (

Table 6) summarizes the results obtained from running the InVEST Carbon Model for each restoration scenario.

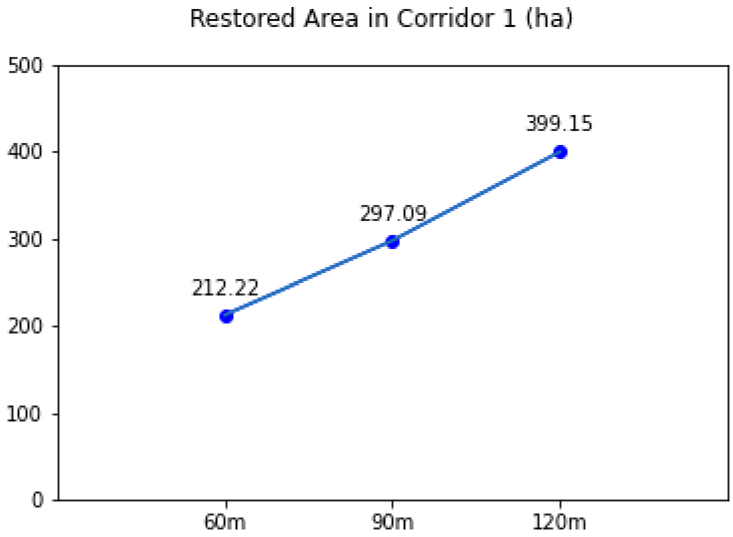
Table 6 Results

Corr	Size (m)	Delta Carbon (Mg of C)	Economic Value (U.S Dollars)	Restored Area (ha)	Pixels	MCF’s budget	Dif.
1	60	24697.82	$913,819.34	212.22	2358	$1,400,652.00	34.76%
1	90	34865.29	$1,290,015.73	297.09	3301	$1,960,794.00	34.21%
1	120	47194.23	$1,746,186.51	399.15	4435	$2,634,390.00	33.72%
2	60	17858.97	$660,781.89	145.62	1618	$961,092.00	31.25%
2	90	28908.79	$1,069,625.23	234.63	2607	$1,548,558.00	30.93%
2	120	40270.74	$1,490,017.38	326.25	3625	$2,153,250.00	30.80%

Table containing the results generated by the InVEST model and other assessments whew: Corr. is the corridor type; Size is the size of the corridors in meters; Delta Carbon is the amount of carbon that was sequestrated between current and future land use scenarios in megagrams of carbon; Economic Value: is the economic value of the sequestered carbon dioxide after non-forest pixels were converted into forest. The price of carbon dioxide was set to 10 USD per Mg of CO_2 which translates to 37 USD per Mg of elemental carbon (C); Restored Area is the area that was converted from non-forest to forest based on pixel size in hectares; Pixels is the number of pixels converted from non-forest (herbaceous, planted/cultivated, barren, cloud and shadow) into forest; MCF’s budget is the resulting amount after applying MCF’s budget schema in U.S Dollars; Dif. Is the difference in percentage of the amount between MCF’s budget schema and the economic value (financial return) of the (delta) sequestered carbon.

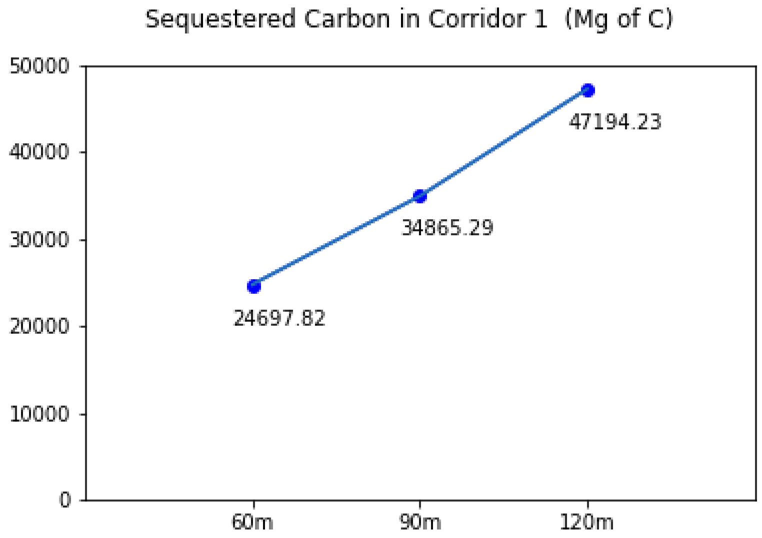
When looking at corridor 1, the 120m version restored an area 25.37% larger than the 90m wide version, which in its turn restored 28.57% more than the 60m version. On carbon sequestration, the 120m version of the restored corridor captured 26.12% more than the 90m version, which sequestrated 29.16% more carbon than the smaller version of the corridor, the 60m one. When comparing the economic value, since it is directly proportional to the amount of carbon that was captured, the percentage values are the same as the ones for Mg of Carbon sequestered. The following graphs (Figure , 6 and7) illustrate the results for corridor 1.

Figure 5 Restored Area in Corridor 1



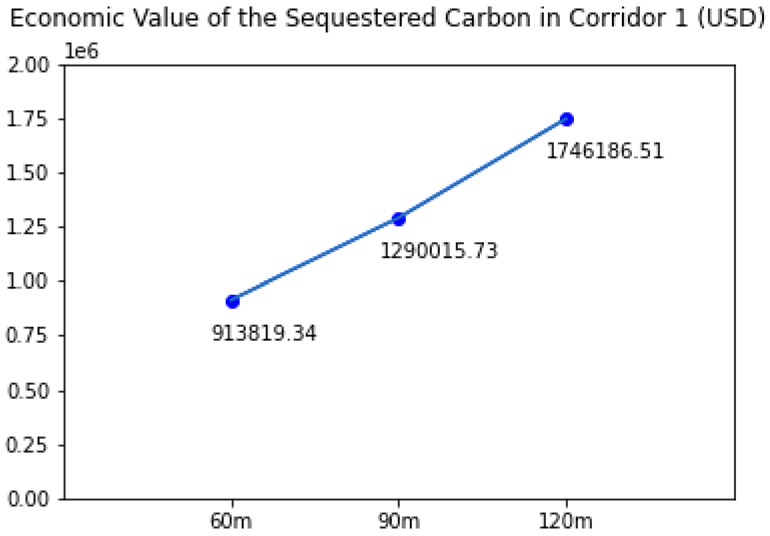
Graph representing the amount of area restored in the three versions of corridor 1.

Figure 6 Sequestered Carbon in Corridor 1



Graph representing amount of sequestered carbon in the three versions of corridor 1

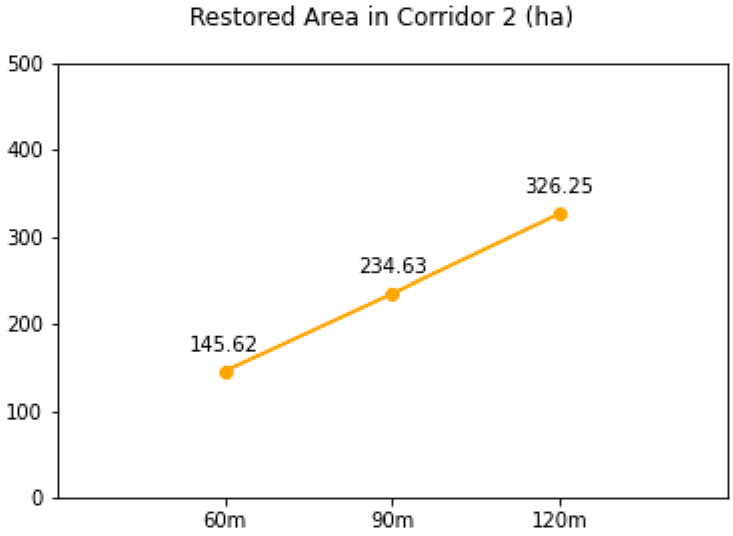
Figure 7 Economic Value of the Sequestered Carbon in Corridor 1



Graph representing the economic value of the sequestered carbon in the three versions of corridor 1

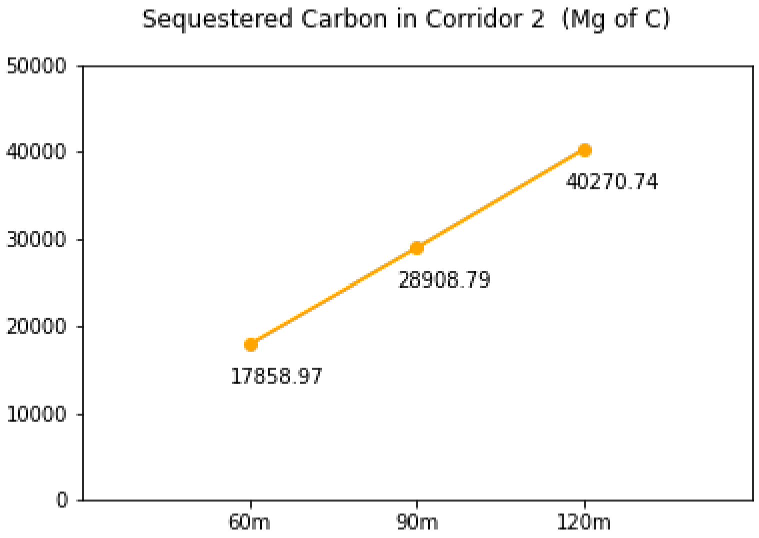
Corridor 2 in its different sizes showed the following results for the amount of area restored: the 120m version restored 28.08% more than the 90m one, which restored 28.57% more than the 60m wide version. When analyzing carbon sequestration, the 120m wide version resulted in 28.21% of carbon being sequestered while the 90m version captured 38.22% more of the smaller 60m version. As a direct consequence of the count of Mg of C per pixel restored, the same percentage is observed for the economic value of the captured carbon. The following graphs (Figure 8, Figure 9 and Figure 10) illustrate the results for corridor 2.

Figure 8 Restored Area in Corridor 2



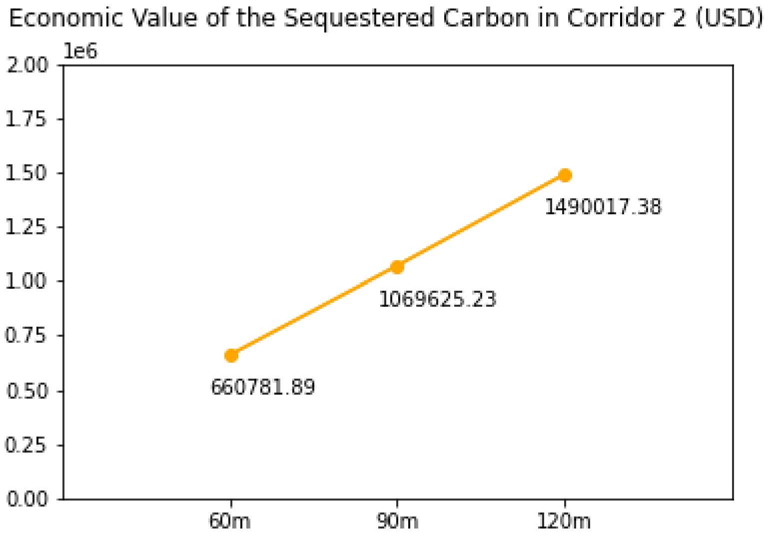
Graph representing the amount of area restored in the three versions of corridor 2

Figure 9 Sequestered Carbon in Corridor 2



Graph representing amount of sequestered carbon in the three versions of corridor 2

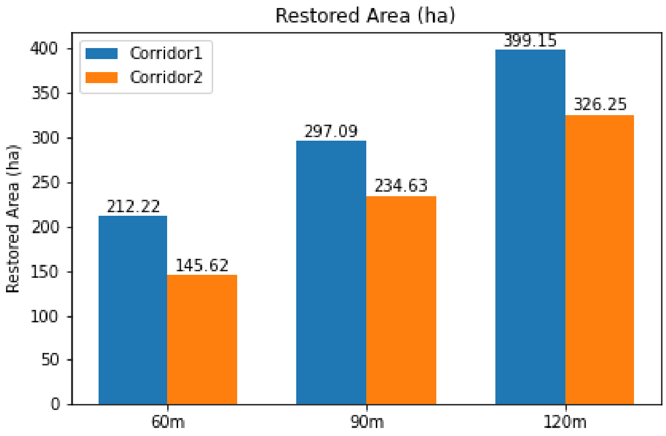
Figure 10 Economic Value of the Sequestered Carbon in Corridor 2



Graph representing the economic value of the sequestered carbon in the three versions of corridor 2

With a higher number of pixels converted into forest due to the region's land use, the proposed corridor 1 restores a larger area than corridor 2. The 60m version restores 31.8% more in area than its counterpart in corridor 2. The 90m version restores 21.02% more than its corresponding in corridor 2 and finally, the 120m corridor buffer restores 18.26% more than its version in corridor 2. The graph below (Figure 11) illustrates this differences:

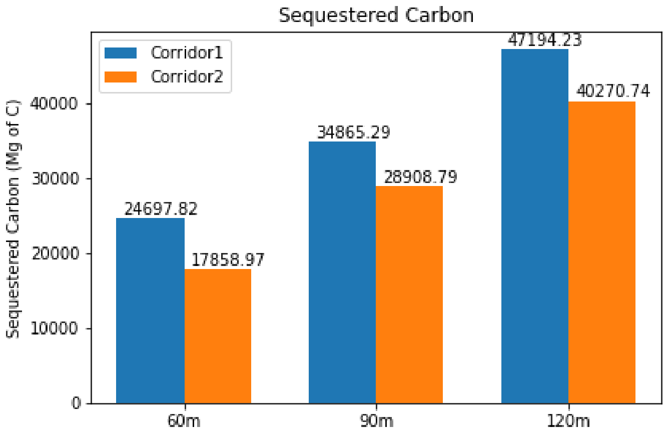
Figure 11 Restored Area



Graph representing the restored area in the three versions of the two proposed corridors

Because of the difference in restoration area as shown in Figure 10, as well as because of differences in the land use, corridor 1 also presents higher results when looking at carbon sequestration. Between current and future (restored) landscape scenarios, corridor 1 with 60m of width results in 27.69% more of sequestration. The 90m version sequesters 17.08% more than its counterpart while the 120m version of corridor 1 results in 14.67% more in sequestration. Figure 12 illustrates these amounts.

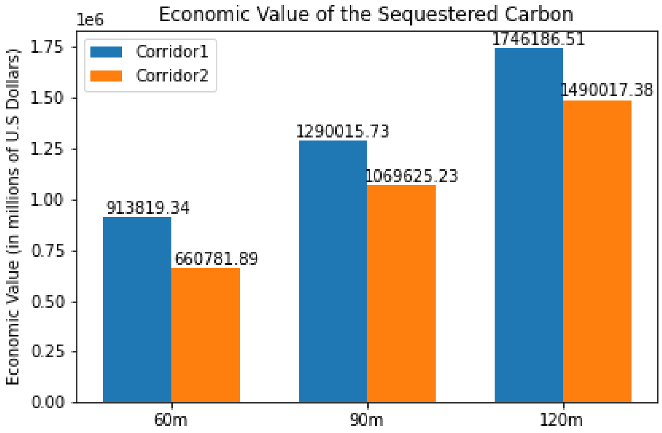
Figure 12 Sequestered Carbon



Graph representing the amount of carbon that was sequestered in the three versions of the two proposed corridors

Directly linked to the amount of carbon captured, the economic value (or the financial return) obtained from restoration was also higher in corridor 1. The 60m wide version of corridor 1 returns 27.69% more than the same width in corridor 2. The 90m corridor returns 17.08% more than its counterpart, while the 120m one returns 14.67% more. Figure 13 shows the comparison for the economic value between the proposed corridors.

Figure 13 Economic Value of the Sequestered Carbon



Graph representing the value of the sequestered carbon in the three versions of the two proposed corridors

Finally, initiatives like Mindo Cloudforest Foundation show that the tropical forests in Ecuador can benefit from international carbon pricing systems and carbon offset programs. Ecuador also became the first country to receive Green Climate Fund co-financing to implement Reducing Emissions from Deforestation and Degradation (REDD) policies and measures in 2017 and it is considered a leader in the effort to reduce deforestation (Guay & Guedez, 2018; United Nations, 2019). Alongside Brazil, the country completed all requirements under the Warsaw Framework for REDD+ (Guay & Guedez, 2018). The framework includes the development of strategies and actions plans, implementation of national policies and sequentially the establishment of result-based payments for fulfilling the commitment to climate actions in the forest sector (United Nations Framework Convention on Climate Change, 2021a). The implementation of the framework and its resulting actions involves the private and public sector as well as institutions, government agencies, NGO's and local stakeholders (which include local communities) (Guay & Guedez, 2018). With that, the country is able to receive payments for promoting conservation which have the potential to contribute to local livelihoods as financial capital (Bremer et al., 2014).

DISCUSSION

The results presented in this article are directly related to the data that was computed by the InVEST Carbon Storage and Sequestration model and therefore are impacted by the data gathering process and the limitations and simplifications of the model. According to the model’s documentation, there are three main causes (simplifications) that lead to its limitations. 1) The model assumes that none of land use classes are losing or gaining carbon over time, in turn, it assumes that the amount of carbon will only change if there’s a change in land use class. 2) InVEST Carbon relies on the estimates for carbon stock in each land use class for its results and for this reason the values are only as detailed and reliable as the land use classification is. 3) The model’s economic valuation assumes that the carbon storage changes linearly over time instead of following a non-linear path. This tends to undervalue the carbon sequestration as the image below (Figure 14) illustrates (Arkema et al., n.d.).

Figure 14 Sequestration Path

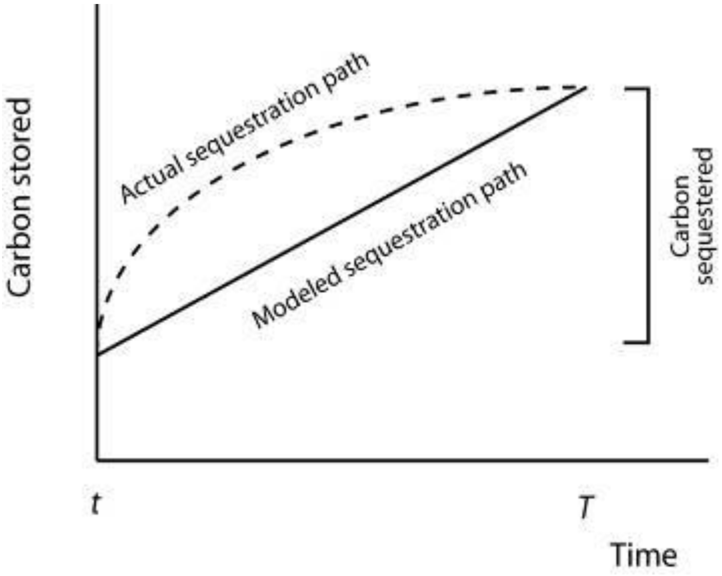


Figure removed from the InVEST Carbon Model Documentation by Arkema et al. (n.d.)

The limitations related to the data gathering include: the classification process and the carbon pool values that were selected from literature. It is important to stress that the image used in this article is from November 20th 2016 and therefore reflects the landscape of that time and may not reflect the landscape in 2021. Because of this, the land use classes resulting from the classification process (which has its own constraints) represent the November 2016 land cover. The values related in the carbon pools table (that represent the amount of carbon stored in each land class) were established for Brazil and therefore may not reflect the study area’s carbon pools accurately. I chose to work with the presented carbon stock values because these values were related in the official documentation of the used model and were collected in South America, in contrast with the more generic values provided by the IPCC (where the carbon stock was generalized to accommodate North and South America's tropical forests) (Ruesch & Gibbs, 2008).

The sequestered carbon and its economic value calculated in this project is, in essence, the difference in carbon stock between the current and the future scenarios. The current scenario represents the landscape before the conversion of pixels classified as a land use class other than forest into forest. The future scenarios represent versions of the landscape where, inside of each proposed corridor, all non-forest pixels were converted to the forest class. For this reason, the resulting values should be further added to the current carbon stock of natural forests in the areas of interest to obtain the total carbon stock in each corridor. In doing that, it will be possible to assess the value of the restored corridors in their totality.

Applying the equation (schema) used by Mindo Cloudforest Foundation for their restoration projects budgets, it was possible to compare the costs of restoration allocated in their budget to the financial return obtained solemnly by the economic value of capturing carbon (which results directly to the price established for Mg of C). The costs in such a project include operational costs, seed and plant maintenance and financial compensation for land owners in order to incentivize their participation and engagement. When looking at Table 6, the costs undertaken by MCF when averaged are 32 % higher than the financial return of the sequestered carbon.

This difference between cost and return can be explained when the baseline used by MCF and the one used in this project are analyzed. The Foundation uses a baseline of 0 (or close to 0) for the carbon pools in degraded areas that need restoration. In this project, all land use classes (apart from barren, shadow and cloud) have significant carbon stock values as baseline. For this reason, the amount of carbon sequestered between current and future restored scenarios (which means the difference between them) in the present research is smaller than when compared to a baseline of 0 that MCF uses.

Using the same methods and parameters described in the methods section of this article but setting all carbon pools (apart from the forest carbon pools needed for calculation) to 0, I can simulate what the results using MCF's baseline would look like (Table 7).

Table 7 Carbon Pools (Simulation)

lucode	c_above	c_below	c_soil	c_dead	LULC_Name
1	98	15.6	60	13.4	Forest
2	0	0	0	0	Herbaceous
4	0	0	0	0	shadow
5	0	0	0	0	cloud
0	0	0	0	0	Barren
3	0	0	0	0	Planted / Cultivated

Table simulating the carbon pool values with a baseline of 0 for the LULC classes other than forest.

Using corridor 1 with a 60m wide buffer as an example, when applying MCF's carbon pool method, an amount of 39,673.28 Mg of C is sequestered between current and future land use scenarios. The economic value of such an amount of carbon being sequestered is $1,467,911.36 USD. This value is 37.75% higher than the one calculated using the current present carbon pools values. Therefore, this methodological difference can be understood as the main factor (among others previously discussed in this section) driving the difference in budget and financial return between my research and MCF's budget schema.

Originally, on-site field work was planned in order to collect and verify essential information to the research project. Data collection would include high precision GPS coordinates, which would increase the accuracy and precision of the land use maps used to run the carbon model and ground truth data to validate land-cover information obtained from remote satellite imagery. However, due to the present COVID-19 pandemic, it was not possible to conduct on-site field work and my project was limited to the data collected through literature research, remote sensing and geoprocessing techniques.

CONCLUSION

Carbon sequestration driven by carbon offset programs and carbon pricing mechanisms can aid in the efforts of slowing global warming through decreasing the amount of GHG in the atmosphere. Riparian zone restoration, beyond contributing to carbon sequestration, also improves landscape connectivity which enhances habitat quality for local flora and fauna. The two restoration corridors proposed in this research were shown to impact significantly both in the amount of carbon that would be sequestered through them and its economic value for stakeholders. Corridor 1 (which followed a northern route from the Silanche Bird Sanctuary to the Tatala River Mouth) restores a higher number of pixels and therefore results a higher amount of carbon being captured which directly causes a higher financial return when carbon pricing or carbon offset programs are in place. Ecuador is at a strategic position to leverage carbon offset programs once it participates in the UN-REDD program and is able to receive payments for promoting conservation through restoration projects or through lowering forest degradation and helping local communities manage their natural assets.

The InVEST Carbon model was effective in generating results that come close to the ones observed in real restoration projects by Mindo Cloudforest Foundation in the study area. The model showed itself to be a reliable to tool to quantify carbon sequestration and its sub sequential economic value. It can be leveraged to further aid in conservation efforts once it allows for the proposition of different scenarios that can be compared and analyzed. Projects aiming to improve habitat quality through restoring degraded areas can benefit from the InVEST model as its results can be used as indicators.

REFERENCES

American Rivers. (2016, April 28). New report: The economic value of riparian buffers. *American Rivers*. https://www.americanrivers.org/conservation-resource/new-report-economic-value-riparian-buffers/

Amigo, I. (2020). When will the Amazon hit a tipping point? *Nature*, *578*(7796), 505–507. https://doi.org/10.1038/d41586-020-00508-4

Amnesty International. (n.d.). *Climate Change: The biggest human rights violation in history?* Retrieved February 1, 2021, from https://www.amnesty.org/en/what-we-do/climate-change/

Anderson, C. M., Field, C. B., & Mach, K. J. (2017). Forest offsets partner climate-change mitigation with conservation. *Frontiers in Ecology and the Environment*, *15*(7), 359–365. https://doi.org/10.1002/fee.1515

Arkema, K., Bernhardt, J., Bierbower, W., Chaumont, N., Denu, D., Douglass, J., & Fisher, D. (n.d.). *Carbon Storage and Sequestration—InVEST 3.8.0.post5+ug.h0ca37b798303 documentation*. Retrieved February 23, 2020, from http://releases.naturalcapitalproject.org/invest-userguide/latest/carbonstorage.html#introduction

Augustyn, A., Zeidan, A., & Zelazko, A. (n.d.). *Pichincha Province, Ecuador*. Encyclopedia Britannica. Retrieved April 25, 2020, from https://www.britannica.com/place/Pichincha-province-Ecuador

Bataille, C., Guivarch, C., Hallegatte, S., Rogelj, J., & Waisman, H. (2018). Carbon prices across countries. *Nature Climate Change*, *8*(8), 648–650. https://doi.org/10.1038/s41558-018-0239-1

Biodiversity Finance Initiative. (n.d.). *Ecuador BIOFIN*. Retrieved April 25, 2020, from https://www.biodiversityfinance.net/ecuador

Boudell, J. A., Dixon, M. D., Rood, S. B., & Stromberg, J. C. (2015). Restoring functional riparian ecosystems: Concepts and applications. *Ecohydrology*, *8*(5), 747–752. https://doi.org/10.1002/eco.1664

Bremer, L. L., Farley, K. A., Lopez-Carr, D., & Romero, J. (2014). Conservation and livelihood outcomes of payment for ecosystem services in the Ecuadorian Andes: What is the potential for ‘win–win’? *Ecosystem Services*, *8*, 148–165. https://doi.org/10.1016/j.ecoser.2014.03.007

Butler, K. (2013, July 24). Band Combinations for Landsat 8. *ArcGIS Blog*. https://www.esri.com/arcgis-blog/products/product/imagery/band-combinations-for-landsat-8/

Carbon Pricing Leadership Coalition. (n.d.). *CPLC - Who we are*. Carbon Pricing Leadership Coalition. Retrieved April 18, 2020, from https://www.carbonpricingleadership.org/who-we-are

Chaplin-Kramer, R., Sharp, R. P., Mandle, L., Sim, S., Johnson, J., Butnar, I., Canals, L. M. i., Eichelberger, B. A., Ramler, I., Mueller, C., McLachlan, N., Yousefi, A., King, H., & Kareiva, P. M. (2015). Spatial patterns of agricultural expansion determine impacts on biodiversity and carbon storage. *Proceedings of the National Academy of Sciences*, *112*(24), 7402–7407. https://doi.org/10.1073/pnas.1406485112

Clark, D. (2011, September 16). A complete guide to carbon offsetting. *The Guardian*. https://www.theguardian.com/environment/2011/sep/16/carbon-offset-projects-carbon-emissions

Climate Change Connection. (n.d.). *CO2 equivalents*. Retrieved February 15, 2021, from https://climatechangeconnection.org/emissions/co2-equivalents/

Cooper, J. (2017, December 5). Differences between carbon offsets & carbon allowances. *Native Energy*. https://native.eco/2017/12/carbon-offset-vs-carbon-credit/

Dios, V., Fischer, C., & Colinas, C. (2007). Climate change effects on mediterranean forests and preventive measures. *New Forests*, *33*, 29–40. https://doi.org/10.1007/s11056-006-9011-x

Dybala, K. E., Matzek, V., Gardali, T., & Seavy, N. E. (2019). Carbon sequestration in riparian forests: A global synthesis and meta-analysis. *Global Change Biology*, *25*(1), 57–67. https://doi.org/10.1111/gcb.14475

Environmental Defense Fund. (n.d.). *How cap and trade works*. Environmental Defense Fund. Retrieved February 1, 2021, from https://www.edf.org/climate/how-cap-and-trade-works

ESRI. (n.d.). *How maximum likelihood classification works—ArcGIS Pro | Documentation*. Retrieved March 16, 2021, from https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-maximum-likelihood-classification-works.htm

European Commission. (2015). *EU ETS hanbook*. https://ec.europa.eu/clima/sites/default/files/docs/ets_handbook_en.pdf

Food and Agriculture Organization. (n.d.-a). *Global forest resources assessment*. Retrieved March 24, 2020, from http://www.fao.org/forestry/fra/fra2010/en/

Food and Agriculture Organization. (n.d.-b). *Regulating services*. Food and Agriculture Organization of the United Nations. Retrieved April 21, 2020, from http://www.fao.org/ecosystem-services-biodiversity/background/regulating-services/en/

Gao, Y., Gao, X., & Zhang, X. (2017). The 2 °C global temperature target and the evolution of the long-term goal of addressing climate change—From the united nations framework convention on climate change to the Paris agreement. *Engineering*, *3*(2), 272–278. https://doi.org/10.1016/J.ENG.2017.01.022

Glanemann, N., Willner, S. N., & Levermann, A. (2020). Paris Climate Agreement passes the cost-benefit test. *Nature Communications*, *11*(1), 1–11. https://doi.org/10.1038/s41467-019-13961-1

Goldstein, A., Turner, W. R., Spawn, S. A., Anderson-Teixeira, K. J., Cook-Patton, S., Fargione, J., Gibbs, H. K., Griscom, B., Hewson, J. H., Howard, J. F., Ledezma, J. C., Page, S., Koh, L. P., Rockström, J., Sanderman, J., & Hole, D. G. (2020). Protecting irrecoverable carbon in Earth's ecosystems. *Nature Climate Change*, *10*(4), 287–295. https://doi.org/10.1038/s41558-020-0738-8

Guay, B., & Guedez, P. Y. (2018, September 4). *Ecuador's Pioneering Leadership on REDD+;A Look Back at UN-REDD Support Over the Last 10 Years*. Un-Redd-Website. https://www.un-redd.org/post/2018/09/04/ecuadors-pioneering-leadership-on-redda-look-back-at-un-redd-support-over-the-last-10-yea

Hafstead, M. (2020, August 10). *Carbon pricing calculator*. Resources for the Future. https://www.rff.org/publications/data-tools/carbon-pricing-calculator/

Halpin, P. N. (1997). Global climate change and natural-area protection: Management responses and research directions. *Ecological Applications*, *7*(3), 828–843. https://doi.org/10.1890/1051-0761(1997)007[0828:GCCANA]2.0.CO;2

Heller, N. E., & Zavaleta, E. S. (2009). Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biological Conservation*, *142*(1), 14–32. https://doi.org/10.1016/j.biocon.2008.10.006

International Institute for Environment and Development. (2009, May 14). *REDD: Protecting climate, forests and livelihoods*. International Institute for Environment and Development. https://www.iied.org/redd-protecting-climate-forests-livelihoods

IPCC. (2019a). *Summary for policymakers—Global warming of 1.5 ^{o}C*. https://www.ipcc.ch/sr15/chapter/spm/

IPCC. (2019b). *Summary for policymakers—Special report on climate change and land*. https://www.ipcc.ch/srccl/chapter/summary-for-policymakers/

Irfan, U. (2020, February 27). *Can you really negate your carbon emissions? Carbon offsets, explained.* Vox. https://www.vox.com/2020/2/27/20994118/carbon-offset-climate-change-net-zero-neutral-emissions

Klenert, D., Mattauch, L., Combet, E., Edenhofer, O., Hepburn, C., Rafaty, R., & Stern, N. (2018). Making carbon pricing work for citizens. *Nature Climate Change*, *8*(8), 669–677. https://doi.org/10.1038/s41558-018-0201-2

Lal, R. (2008). Carbon sequestration. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1492), 815–830. https://doi.org/10.1098/rstb.2007.2185

Liang, Y., Liu, L., & Huang, J. (2017). Integrating the SD-CLUE-S and InVEST models into assessment of oasis carbon storage in northwestern China. *PLOS ONE*, *12*(2), e0172494. https://doi.org/10.1371/journal.pone.0172494

Lu, F., Hu, H., Sun, W., Zhu, J., Liu, G., Zhou, W., Zhang, Q., Shi, P., Liu, X., Wu, X., Zhang, L., Wei, X., Dai, L., Zhang, K., Sun, Y., Xue, S., Zhang, W., Xiong, D., Deng, L., … Yu, G. (2018). Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010. *Proceedings of the National Academy of Sciences*, *115*(16), 4039–4044. https://doi.org/10.1073/pnas.1700294115

MacLeod, M. J. (n.d.). *Ecuador | history, geography, & culture*. Encyclopedia Britannica. Retrieved February 25, 2020, from https://www.britannica.com/place/Ecuador

Mardani, A., Streimikiene, D., Cavallaro, F., Loganathan, N., & Khoshnoudi, M. (2019). Carbon dioxide (CO2) emissions and economic growth: A systematic review of two decades of research from 1995 to 2017. *Science of The Total Environment*, *649*, 31–49. https://doi.org/10.1016/j.scitotenv.2018.08.229

Mindo Cloudforest Foundation. (n.d.). *Mindo Cloudforest Foundation*. Retrieved February 20, 2020, from https://mindocloudforest.org/

Miranda, S. do C. de, Bustamante, M., Palace, M., Hagen, S., Keller, M., & Ferreira, L. G. (2014). Regional variations in biomass distribution in Brazilian savanna woodland. *Biotropica*, *46*(2), 125–138. https://doi.org/10.1111/btp.12095

Mock, J., & Tabuchi, H. (2019, July 24). How to buy carbon offsets. *The New York Times*. https://www.nytimes.com/2019/07/24/climate/nyt-climate-newsletter-carbon-offsets.html

Myers, J. P., Reichert, J., Postel, S., Bawa, K., Kaufman, L., Peterson, C. H., Carpenter, S., Tillman, D., Dayton, P., Alexander, S., Lagerquist, K., Goulder, L., Matson, P. A., Mooney, H. A., Naylor, R., Vitousek, P., Harte, J., Schneider, S. H., & Buchmann, S. L. (1997). *Nature's services: Societal dependence on natural ecosystems* (M. G. C. Daily, Ed.; 1st Edition edition). Island Press.

National Aeronautics and Space Administration. (n.d.). *Landsat 8 overview | landsat science*. Retrieved February 10, 2021, from https://landsat.gsfc.nasa.gov/landsat-8/landsat-8-overview

National Aeronautics and Space Administration. (2021, March 8). *Climate change evidence: How do we know?* Climate Change: Vital Signs of the Planet. https://climate.nasa.gov/evidence

National Oceanic and Atmospheric Administration. (2021, March 12). *Global climate change Indicators | monitoring references | national centers for environmental information (NCEI)*. https://www.ncdc.noaa.gov/monitoring-references/faq/indicators.php#warming-climate

National Research Council. (2002). *Riparian areas: Functions and strategies for management*. https://doi.org/10.17226/10327

Nordhaus, W. D. (2017). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(7), 1518–1523. https://doi.org/10.1073/pnas.1609244114

Norton, B. (2012). *Valuing ecosystems | learn science at scitable*. https://www.nature.com/scitable/knowledge/library/valuing-ecosystems-71373110/

Plumer, B., & Popovich, N. (2019, April 2). These countries have prices on carbon. Are they working? *The New York Times*. https://www.nytimes.com/interactive/2019/04/02/climate/pricing-carbon-emissions.html, https://www.nytimes.com/interactive/2019/04/02/climate/pricing-carbon-emissions.html

Rebeek, H. (2010, June 3). *Global warming* [Text.Article]. NASA Earth Observatory. https://earthobservatory.nasa.gov/features/GlobalWarming

Robbins, P., Hintz, J., & Moore, S. A. (2014). *Environment and society: A critical introduction* (2 edition). Wiley-Blackwell.

Roberts, D. (2019, September 4). *Pulling CO2 out of the air and using it could be a trillion-dollar business*. Vox. https://www.vox.com/energy-and-environment/2019/9/4/20829431/climate-change-carbon-capture-utilization-sequestration-ccu-ccs

Ruesch, A., & Gibbs, H. K. (2008). *New IPCC tier-1 global biomass carbon map for the Year 2000*. https://cdiac.ess-dive.lbl.gov/epubs/ndp/global_carbon/carbon_documentation.html#tables

Sabo, J. L., Sponseller, R., Dixon, M., Gade, K., Harms, T., Heffernan, J., Jani, A., Katz, G., Soykan, C., Watts, J., & Welter, J. (2005). Riparian zones increase regional species richness by harboring different, not More, species. *Ecology*, *86*(1), 56–62. https://doi.org/10.1890/04-0668

Scott, D., Malcolm, J. R., & Lemieux, C. (2002). Climate change and modelled biome representation in Canada’s national park system: Implications for system planning and park mandates. *Global Ecology and Biogeography*, *11*(6), 475–484. https://doi.org/10.1046/j.1466-822X.2002.00308.x

Seavy, N. E., Gardali, T., Golet, G. H., Griggs, F. T., Howell, C. A., Kelsey, R., Small, S. L., Viers, J. H., & Weigand, J. F. (2009). Why climate change makes riparian restoration more important than ever: Recommendations for practice and research. *Ecological Restoration*, *27*(3), 330–338. https://doi.org/10.3368/er.27.3.330

Second Nature. (n.d.). *Purchasing Carbon Offsets FAQs*. Retrieved April 26, 2020, from https://secondnature.org/climate-action-guidance/purchasing-carbon-offsets-faqs/

Sierra, R. (2013). *Patrones y factores de deforestacionen el ecuador continental, 1990T2010. Y un acercamiento a los próximos 10 años.* Conservación Internacional Ecuador y Forest Trends. https://www.forest-trends.org/wp-content/uploads/2013/03/rsierra_deforestacionecuador1950-2020_180313-pdf.pdf

Sun, J., Twine, T. E., Hill, J., Noe, R., Shi, J., & Li, M. (2017). Effects of land use change for crops on water and carbon budgets in the Midwest USA. *Sustainability (Switzerland)*, *9*(2), 225. https://doi.org/10.3390/su9020225

Sundquist, E., Burruss, R., Faulkner, S., Gleason, R., Harden, J., Kharaka, Y., & Tieszen, L. (2009, January). *CarbonFS.pdf*. https://pubs.usgs.gov/fs/2008/3097/pdf/CarbonFS.pdf

Union of Concerned Scientists. (2017, January 8). *Carbon pricing 101*. https://www.ucsusa.org/resources/carbon-pricing-101

United Nations. (2019). *UN-REDD programme*. Un-Redd-Website. https://www.un-redd.org

United Nations Framework Convention on Climate Change. (2021a). *What is REDD+?* https://unfccc.int/topics/land-use/workstreams/redd/what-is-redd

United Nations Framework Convention on Climate Change. (2021b). *What is the Paris Agreement?* https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement

United States Department of Agriculture. (1996, August 11). *Riparian areas environmental uniqueness, functions, and values*. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/?cid=nrcs143_014199

United States Environmental Protection Agency. (2015a, August 10). *Greenhouse gases equivalencies calculator—Calculations and references* [Data and Tools]. US EPA. https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

United States Environmental Protection Agency. (2015b, December 23). *Overview of greenhouse gases* [Overviews and Factsheets]. US EPA. https://www.epa.gov/ghgemissions/overview-greenhouse-gases

United States Government. (2010, February). *Scc_tsd_2010.pdf*. https://www.epa.gov/sites/production/files/2016-12/documents/scc_tsd_2010.pdf

Welford, M., & DeFalco, S. (2003). Early successional habitats and bird-related ecotourism in the ecuadorian andes. *Lyonia*, *4*(1), 97–102.

Welford, M. R., & Yarbrough, R. A. (2015). Serendipitous conservation: Impacts of oil pipeline construction in rural northwestern Ecuador. *The Extractive Industries and Society*, *2*(4), 766–774. https://doi.org/10.1016/j.exis.2015.07.005

Williamson, P. (2016). Emissions reduction: Scrutinize CO2 removal methods. *Nature News*, *530*(7589), 153. https://doi.org/10.1038/530153a

Worldbank. (n.d.). *Pricing carbon* [Text/HTML]. World Bank. Retrieved April 18, 2020, from https://www.worldbank.org/en/programs/pricing-carbon

Worldbank. (2020, November 1). *Carbon pricing dashboard | Up-to-date overview of carbon pricing initiatives*. https://carbonpricingdashboard.worldbank.org/map_data

Wuebbles, D. J., Easterling, D. R., Hayhoe, K., Knutson, T., Kopp, R. E., Kossin, J. P., Kunkel, K. E., LeGrande, A. N., Mears, C., Sweet, W. V., Taylor, P. C., Vose, R. S., Wehner, M. F., Wuebbles, D. J., Fahey, D. W., Hibbard, K. A., Dokken, D. J., Stewart, B. C., & Maycock, T. K. (2017). *Ch. 1: Our globally changing climate. climate science special report: fourth national climate assessment, volume I*. U.S. Global Change Research Program. https://doi.org/10.7930/J08S4N35

Zaks, I. (2019, May 29). *Our home at Stanford University* [Text]. Natural Capital Project. https://naturalcapitalproject.stanford.edu/who-we-are/our-home-stanford-university

Zhu, Z., Bergamaschi, B., Bernknopf, R., Clow, D., Dye, D., Faulkner, S., & Forney, W. (2010). *2010—Scientific investigations report.pdf*. https://pubs.usgs.gov/sir/2010/5233/pdf/sir2010-5233.pdf

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