ANALYSIS OF ABOVEGROUND CARBON FOR INDIGENOUS COMMUNITIES IN OAXACA, MX

by

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Analysis of aboveground carbon for indigenous communities in Oaxaca, MX

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Client: Integrator Campesino and Indigenous Communities of Oaxaca (ICICO)
EXECUTIVE SUMMARY
As the world races to combat the anticipated and actualized impacts of climate change, many are looking at the natural world as one of the many solutions – a natural climate solution (Turner 2018). One natural climate solution is to protect, conserve, or restore forest lands to allow the natural systems of carbon sequestration to aid in reducing global greenhouse gas emissions. But forests are being deforested at an aggressive rate due to host of reasons including agricultural expansion, urbanization, and changing climate (Bologna & Aquino, 2020) and quick actions must be taken to keep forest standing. Not only are the forests at risk, but also the livelihoods of nearby communities and biodiversity habitats are under threat. Places like Oaxaca, Mexico – the most biodiverse state in all of Mexico – contains critical habitats in need of conservation and indigenous peoples who rely on a healthy forest (Mittermeier et al., 1999).

One of many benefits forests supply is its ability to store carbon through carbon sequestration. The amount of carbon stored in a forest can be calculated and accounted for and used as a carbon offset. Carbon offset programs are gaining popularity as one of many viable solutions to combating climate change. For each unit of carbon stored in a tree, a carbon offset from that unit can be traded on the carbon market for an emitter elsewhere to purchase as an offset. This process is known as carbon offsetting and is available to all – governments, corporations, and the public. This solution not only provides for greater ecological benefits such as cleaner air, water, and suitable habitat for wildlife, but the carbon offsets produce a profit which can be funneled back into the communities managing the forest. This system creates an alternative sustainable livelihood opportunity for communities who mainly rely on agriculture for an income.

This Master’s Project has two components, one focused on carbon accounting and the other on identifying potential locations for carbon offsetting projects. I worked with 12 indigenous communities in Oaxaca to identify locations well suited for a carbon offset program to provide economic and ecological benefits. Currently, there are 5 participating communities and others interested, working with ICICO, a Oaxacan-based, non-profit focused on protecting and managing forests, and is the group leading the carbon offsetting program. Recognizing the importance of proper carbon accounting of the aboveground carbon present in the forest and therefore available for offsetting, I examined the allometric equations currently in use and identified any alternative equations. Through a literature review, I found a set of 478 allometric equations for Mexico. I cross referenced these with the equations currently employed by a third-party verification group, Climate Action Reserve, for the indigenous communities and found discrepancies between equations. I analyzed a subset of 20 species with the greatest amount of aboveground carbon to represent the study area. I found that 6 of the 20 species used a different equation resulting in a dramatic difference in the estimated aboveground carbon present. Given the sensitive nature of allometry and the variability of outcomes, it is evident that further consideration must be taken to identify the allometric equation best suited for calculating aboveground carbon based off the objectives of the project.

The second part of this project I produced a 20-meter resolution map estimating aboveground carbon for forests in the central area of Oaxaca for my client to use in the future to identify additional sites suitable for carbon offsetting programs. By using a variety of environmental, field, and remote sensing data to find significant indicators of aboveground carbon, I create a finer-resolution spatial map to help identify locations relatively high aboveground carbon within
the study area and the greater state of Oaxaca that could be considered to include in the carbon offsets program.

Combining my findings from the analysis of the allometric equations and the predictive modeling for aboveground carbon, I propose the following recommendations:

1. Further analysis should occur on the allometric equations currently in use to ensure the communities are receiving an accurate account for aboveground carbon in their forest.
2. The updated 20-meter resolution map should be considered when working in partnership with new or existing indigenous communities. It should be considered when evaluating if a carbon offset project is the right fit for the community based off the aboveground carbon in their community.
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1. Introduction

1.1. Overview of the project

Globally forested lands are under increasing pressure due to impacts of climate change, and deforestation – especially in tropical and subtropical places (Corona-Núñez et al., 2018). Biodiversity, habitats, and natural resources are diminishing as the need for these natural places becomes more critical as climate change intensifies. Global greenhouse gas (GHG) emissions are increasing, making it even more important to conserve forests. To limit global temperatures and warming to below the estimated threshold of 1.5°C by 2100, major scalable carbon removal initiatives must be put in place (Rockström et al., 2017). Carbon offsetting is one mechanism that can provide conservation value, emission reduction and an alternative sustainable livelihood.

The world is losing its forests at an alarming rate of $2 \times 10^5$ Km² per year or 2.3 million Km² of forest were lost globally from 2000 to 2012 (Bologna & Aquino, 2020). This deforestation is due to human activities such as urbanization, agriculture expansion, population growth and changes to growing conditions due to climate change (Bologna & Aquino, 2020). Naturally, forests provide the planet with clean air, water, and resources and without forests, the planet will experience further negative effects of climate change (Bologna & Aquino, 2020). Deforestation removes the forests that would otherwise be removing in carbon dioxide from the atmosphere and storing it underground. With less forests, the effects of climate change will be exacerbated without natural systems to mitigate global emissions. As the threat of deforestation continues, opportunities to protect and conserve forests is increasingly important and innovation in this field
is necessary. The role forest play is critical for the future and stability of the planet with approximately 50% of the aboveground carbon stored in tropical forests, (Corona-Núñez et al., 2018) they are essential for storing carbon and thus reducing the impacts of climate change. Solutions to climate change come in a variety of forms – with one being forest as a natural climate solution (Turner, 2018). As a natural climate solution, the carbon stored in trees can be calculated and traded as a market commodity to provide income to the local people and increase the value of a standing tree verse a felled one. This type of climate solution is currently happening in Oaxaca as indigenous communities partner with groups like my client, the Integrator Campesino and Indigenous Communities of Oaxaca (ICICO), to implement carbon offsetting programs to provide ecological and economic benefits.

In this Master’s Project, I evaluate the current carbon accounting methodology and identify future opportunities for carbon accounting for indigenous communities in Oaxaca, Mexico to implement into their communal managed and owned forests. To do so, I evaluate different approaches to estimate aboveground carbon by looking at the allometry used and determine key indicators for suitable locations for a carbon offset program. This project will help inform future programmatic priorities set by ICICO to ensure the indigenous communities receive the highest and most accurate value on the carbon market from their forests. Currently, ICICO is working with a third-party group, The Climate Action Reserve, to calculate aboveground carbon in their forests. The indigenous communities working with ICICO, rely on opportunities such as carbon offsetting to provide livelihoods and conservation value to their forests.

1.2. The client and communities
The Integrator Campesino and Indigenous Communities of Oaxaca (ICICO), is an Oaxacan-based NGO founded in 2000 and currently serving 15 indigenous communities across the state to manage and protect their natural resources. ICICO spearheads efforts to enhance communally managed lands through market opportunities for ecosystem services. Through a holistic, community-based approach to land management, ICICO fosters sustainable livelihoods, land stewardship, and community-based forest management built on the premise that sustainable conservation efforts should include local communities for the sake of ecological and social well-being (Rivera et al., 2002).

The state of Oaxaca ranks as the most biodiverse state in Mexico. Located on the Pacific side of the country between the Sierra Madre de Oaxaca and Sierra Juárez mountain ranges, the “mega-diverse” state teems with biodiversity (Mittermeier et al., 1999; Duran et al., 2012). 60% of the 9.5-million-hectare state is covered by forest (Merino-Perez, 2004) and Oaxaca is home to half of the plant species (Oviedo, 2002) or almost 80% of the 32 main vegetation types in Mexico (Monroy-Gamboa et al., 2019), 40% of mammals and 63% of the birds found in Mexico (Oviedo, 2002). The forest ecosystems range from pine oak to mesopholic montane forests to dry, deciduous forests (García-Mendoza et al., 2004). The cultural diversity of the state is also impressive, with 16 distinct ethno-linguistic groups and one third of the 3.5 million population speaking an indigenous language (Duran et al., 2012). Of the land in Oaxaca, 72% of the territory is tenured by indigenous communities (Duran et al., 2012), meaning most of the forested land in the state is communally managed by local groups or peoples. As deforestation risk is ever-present for areas such as Oaxaca, this also threatens the livelihoods of indigenous groups who rely on the forests for their daily resources or income. With continued global
pressures on forested land and the role trees play in reducing global emissions, forests such as those found in Oaxaca are key for carbon sequestration as a means to protect the forest and reduce global GHG emissions (Corona-Núñez et al., 2018).

The study site includes 12 communities in Oaxaca, Mexico, each working in partnership with ICICO (Figure 1). The communities differ geographically, environmentally, and economically. The average population of these communities range from 900 – 5,000 people and is home to the Chatino and Zapotec indigenous groups (Mendoza Zuany, 2014). Subsistence farming is prevalent in Oaxaca, but the main economic industry is agriculture, coffee and honey production, and timber. Ecotourism activities and alternative livelihood opportunities like a water-bottling plant and small-scale aquaculture is also an industry for some of the communities (INEGI, 2020; Nickerson, 2017).

![Oaxaca Indigenous Communities](image)

**Figure 1:** Map of Oaxaca, MX highlighting the communities in partnership with ICICO. The communities’ range across the state from the Sierra Madre Del Sur, in the southwest, to the northern boundary.
1.3. Carbon credit and offsets

Through photosynthesis, plants use sunlight, water, and carbon dioxide (CO₂) to create chemical energy and oxygen used for plant function and wood growth. By absorbing CO₂ for their metabolic activities, plants remove or sequester that unit of CO₂ from the atmosphere. A carbon credit consists of a metric ton of CO₂ that has been taken out of the atmosphere. With the goal of reducing CO₂ emissions globally, carbon credit can be traded on the carbon market to offset or displace CO₂ emitted elsewhere. The location of the carbon sequestration is not necessarily significant if the same amount of carbon emitted is captured. Purchasing carbon offsets has become a new method for corporations to reduce their emissions. For example, companies like Apple and Tiffany & Co. are offsetting their carbon emissions by purchasing carbon credits in places like the Chyulu Hills, Kenya. Many companies are using carbon offsets as part of their approach to climate change in addition to reducing energy consumption or making changes in their supply chain. One benefit to this type of method to offset emissions, is the entry and accessibility of the system. Carbon credits are available for anyone to purchase to minimize their carbon emissions or footprint, this applies to the public, governments, or corporations.

The concept of carbon offsetting was first proposed on the global scale by the United Nations Framework Convention on Climate Change at the Kyoto Protocol in 1997, where 192 countries joined forces to limit and reduce GHG emissions set by individual country targets. The Kyoto Protocol places a heavier weight and responsibility on developed countries to meet targets because they are historically and currently the biggest contributors to the GHG emissions. According to these UNFCCC gatherings, the global target from 37 developed countries, equaled
a 5 percent reduction in emissions compared to 1990 emissions level over a five-year period, from 2008 – 2012. Since the creation of the Kyoto Protocol, the Doha Amendment was adopted for the second commitment period from 2013 to 2020. The second commitment period aimed to reduce GHG emissions by 18 percent below 1990 levels, even though the make-up of Parties differed from the first commitment period. The inception of the Kyoto Protocol and the Paris Agreement, a new market has come about known as the carbon market – the platform to trade and sell carbon credits – creating a marketplace for this commodity.

As part of reaching these emission goals, the Kyoto Protocol outlined ways to meet the targets through a variety of methods such as International Emissions Trading, Clean Development Mechanism (CDM), and Joint implementation programs. International Emissions Trading refers to GHG emission as a commodity that can be traded or sold on the carbon market. The CDM refers to emission reduction as projects that limit, reduce or halt emissions in developing countries, such as using solar panels to bring electricity to rural areas. The Joint Implementation refers to allowing one country to earn emission reduction units from another country. This can be mutually beneficial if one country needs to meet a reduction goal and can provide financial or technological assistance to another country that may or may not need to reduce as much to meet the target.

The reduction options outlined by UNFCCC provide mechanisms by which countries can meet their emissions reductions targets through the stimulation of green investments in developing countries, employing cleaner development technologies, or opening market opportunities to trade carbon. A unit of carbon can be traded on the carbon market in three forms: 1. a removal unit
based on land-use, land-use change and forestry activities; 2. an emissions reduction unit created by a joint implementation project; or, 3. a certified emission reduction (CER) from a clean development mechanism project activity.

1.4. Carbon Market

There are two types of carbon markets, voluntary and compliance. The compliance market is a regulatory market created and monitored by carbon reduction regimes, like the Kyoto Protocol and the European Union’s Emission Trading Scheme (Maguire, 2011). The compliance market requires 100-year commitment from the landowners to ensure the forests remains standing to produce offsets being purchased today. This market is regulated and has a set of strict protocols that must be followed. Mechanisms to reduce global emissions such as the compliance market or carbon tax, useful as they are, alone are not meeting the demand needed to meet the reduction necessary and led to the creation of the voluntary market (Miltenberger et al., 2021).

Voluntary markets, like the California Cap-and-Trade market, operate independently of compliance markets, allowing both individuals and companies to purchase offsets. The benefits of voluntary markets are numerous from accessibility to innovation. Voluntary markets allow participation from unregulated countries and sub-national organizations like ICICO, to trade credits. The voluntary market is flexible in the types of projects included and provide a financially feasible entry point to multiple users (Maguire, 2011). Carbon offsetting also enables countries to develop and implement a low-carbon economy while providing livelihood opportunities and reducing global emissions.
Although carbon offsets projects can provide a wealth of benefits to local communities, I would be remised if I did not disclose the programs flaws and controversies. First and foremost, removing carbon through carbon sequestration and offsets is just part of the solution to combating climate change (Morrow et al., 2020). Globally, a reduction of carbon emissions in all sectors of society will be the long-term change that must occur (Morrow et al., 2020). Criticisms of such programs range from greenwashing to equity and social impact (Miltenberger et al., 2021b). There are also questions of the accuracy of the carbon accounting, verifications of offsets and longevity of the offsets (Miltenberger et al., 2021b), while others believe carbon programs can be barriers to industrialism for developing countries (Ciscell, 2010). In the past there were cases where the local communities were prohibited from accessing their traditional lands due to the carbon project which was benefiting a developed country and disadvantaging the local people (Beymer-Farris and Bassett, 2012). Since then, many verifiers have put in protocols to ensure that all communities are adequately benefitting from the programs (Miltenberger et al., 2021b).

1.5. Climate Action Reserve

The Climate Action Reserve (CAR) is a climate-oriented organization and voluntary offset program for GHG emission reduction projects. CAR launched in 2008 to create standards for quantifying and verifying GHG emissions for carbon offset projects in North America. This group serves as a supervisor to independent third-party verification groups as well as an issuer and tracker carbon credits. The credits are known and as Climate Reserve Tonnes (CRTs) (Nickerson, 2017).
In 2014, ICICO partnered with CAR to help develop CAR’s carbon offset program and Mexico Forest Protocol. CAR is certified under California’s Cap-and-Trade Program as an Offset Project Registry for the Compliance Offset Program. For groups such as non-governmental organizations, landowners or managers, CAR functions as a registry to market and sell carbon offsets. In this capacity, CAR helps collect the necessary project documentation and provides verification for each project. Next, they issue the offset credit through the Air Resource Board Compliance Offset Protocol. To ensure proper protocols are followed, CAR uses a set of protocols to provide guidelines for project eligibility. Protocols, such as the Mexico Forest Protocol, are created using the Program Manual as a guidebook, and expertise from the CAR staff, a stakeholder working group, a public comment period, and board approval. The input from these groups is all necessary to create a protocol that meets industry benchmarks to demonstrate its impact on climate and CRT potential.

In 2011, CAR developed their protocol in Mexico. A member of the ICICO’s leadership assisted in the creation of CAR’s Mexico Forest Protocol. Later a partnership between CAR and ICICO was formed to develop a pilot project, selecting ICICO’s community partner, San Juan Lachao, in 2014 to become the pilot program for the Mexico Forest Protocol.

CAR developed the Mexico Forest Protocol 2.0 in March 2020 updating its 2011 protocol. Updates include clarification of project areas and definitions for communal, private, and non-federal lands, as well as separating small and large urban forestry to provide opportunities for a variety of management techniques and species requirements. The updated protocol now includes a section on improved forest management where forest restoration can be implemented to
enhance carbon sequestration. The restoration section, Environmental Safeguard for Reforestation, aims to maintain natural land cover in project areas, and change the standardized testing protocol to be more tailored to the type of forestry activity occurring (Climate Action Reserve, 2020). ICICO works with the indigenous communities of La Trinidad Ixltan, San Miguel Maninaltepec, and Santiago Xuicau, to update each community’s forest inventory, the Mexico Forest Protocol will provide guidance on best practices and compliance for entering carbon projects into CAR’s carbon registry.

1.6. Allometric equations

The aboveground biomass (AGB) of a forest stand – the weight of the trunk, branches, needles or leaves – is determined by the height and diameter of individual trees and the density of their wood, a species-specific characteristic. To accurately calculate AGB without having to destructively weigh each tree stem, allometric equations provide a formula to determine tree biomass from its attributes. Allometric equations are commonly used to estimate AGB from forest inventory data (Rojas-García, 2015). Because of species-specific differences in diameter, height, shape, and density, allometric equations are developed for species, although equations do not exist for all species. Equations are derived by a variety of agencies, organizations, and companies (Rojas-García, 2015; FAO 2013), and a dataset of 478 allometric equations has been compiled for Mexico (Rojas-García (2015), Návar (2009), De Jong et al., (2009)) (Table 1). In this project, I identify the equations that result in the highest estimates of aboveground carbon estimates (using a conversion from AGB to AGC) for the community forests working with ICICO.
Table 1. Extracted from Rojas-García 2015, this table shows the number of allometric equations by plant family in Mexico.

<table>
<thead>
<tr>
<th>Plant family</th>
<th>Number of equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinaceae</td>
<td>132</td>
</tr>
<tr>
<td>Fabaceae</td>
<td>73</td>
</tr>
<tr>
<td>Fagaceae</td>
<td>50</td>
</tr>
<tr>
<td>Euphorbiaceae</td>
<td>15</td>
</tr>
<tr>
<td>Poaceae</td>
<td>15</td>
</tr>
<tr>
<td>Asteraceae</td>
<td>11</td>
</tr>
<tr>
<td>Malvaceae</td>
<td>11</td>
</tr>
<tr>
<td>Burseraceae</td>
<td>10</td>
</tr>
<tr>
<td>Rutaceae</td>
<td>10</td>
</tr>
<tr>
<td>Remaining families</td>
<td>122</td>
</tr>
<tr>
<td>(45)</td>
<td></td>
</tr>
<tr>
<td>Equations for species of more than one family</td>
<td>29</td>
</tr>
</tbody>
</table>

2. Project Overview

Oaxaca is abundant in biodiversity and culturally vibrant with most of the land under communal management. This type of community-based management and land tenure has allowed for groups like ICICO to collaborate with indigenous groups to safeguard natural resources and develop opportunities to the locals, and environmental education. Sustainable alternative livelihoods for locals include timber harvesting, eco-tourism and coffee production and managing forest for carbon sequestration.

Duke and ICICO have worked together on a variety of projects since 2005. In 2020, Duke Master of Environmental Management and Forestry students laid the groundwork for siting a bi-community biological corridor. As part of the project, the group assessed alternative sustainable livelihood practices potentially available to communities of Oaxaca, including carbon offsetting. Although not all communities and land types are well suited for carbon offsetting, communities
containing forested areas could potentially join the program. San Juan Lachao, an ICICO community partner, pioneered the development of a carbon offsetting program through its partnership with the CAR and has joined the California Cap-and-trade market to sell carbon credits from their forests. Due to the potential sustainable livelihood benefits for the community and a method of forest conservation, ICICO is seeking other communities within the state to join the program.

### 2.3 Objectives

As ICICO expands its work, the objectives of this MP, directed by ICICO, aims to: (1) evaluate whether its methodology for carbon accounting is the most effective, and (2) determine which additional communities are best suited for carbon offset programs based on availability of aboveground carbon (AGC). AGC estimates exist for several the partner communities, collected in the field using a variety of allometric equations. Using existing field data from five indigenous communities, I will test different calculations for aboveground carbon at the community level as well as map and identify high carbon sites across the region (both inside and outside the current community boundaries), that could be well suited for carbon offsets programs. Currently, the most accurate spatial layer available for AGB is a country-wide biomass map (Rodríguez-Veiga et al. 2016). An Oaxacan-specific, fine-scale resolution map would allow for a greater understanding of the landscape and help ICICO identify new communities for carbon offset programs or forest conservation.

My Master’s Project will aim to address the following three questions:
1. What is the current carbon accounting methodology for Oaxaca? Are currently employed allometric equations the most accurate for the region and its tree species?

2. Does the Mexico-wide AGB map (Rodríguez-Veiga et al. 2016) accurately depict the AGB distribution across the ICICO project area compared to field data? Can the map be made more accurate for the Oaxaca area with additional remote sensing inputs?

3. Given finer-resolution AGC mapped representation:
   - Are current carbon plots located optimally for carbon offsetting for existing ICICO partner communities?
   - Are there additional communities in the region with high levels of AGC that ICICO should consider adding to its program?

To answer these questions, I plan to use the AGB measurements and allometric equations found in the literature to address the first question and I hypothesize the allometric equations will result in a range of values based off the equation in use. For the second and third question, I will use the existing state-wide AGB spatial layer, remote sensing inputs and environmental variables and I anticipate I will be able to create an updated, finer-resolution AGC map of Oaxaca by using the satellite-derived vegetation indices and radar data, along with a country-wide AGB map.

2.4 Methods

2.4.1 Data Sources

Community level:

ICICO provided data including the boundaries of 12 community partners (San Juan Lachao, Santa Maria Penoles, Capulapam de Mendez, San Bartolom Loxicha, San Juan Yagila, Santa
Maria Tlahuitoltepec, Santiago Xiacui, San Juan Metaltepec, La Trinidad Ixtlan, San Miguel Maninaltepec, Santa Maria Zoogochi, and Santiago Teotlaxco), a 15-meter digital elevation model (DEM), tree measurements and total CO$_2$ estimates (to be back transformed to AGC) for five carbon plots, and the CAR database (CALCBOSK) biomass calculations for three communities, La Trinidad Ixtlan, San Miguel Maninaltepec, Santiago Xiacui (Figure 2).

![Maps of communities](image)

**Figure 2.** There are 110 plots between the 5 communities that have carbon plots available. These plots will be used to answer the second and third research questions to determine locations of AGC.

Of the 12 communities, 5 (Capulapam de Mendez, Santiago Teoltexco, San Bartolome Loxicha, La Trinidad Ixtlan and San Miguel Maninaltepec) established 110 carbon plots with tree measurements and CO$_2$ uptake estimation (Figure 2). ICICO provided tree species, longitudes
and latitudes, height, diameter, CO$_2$ multipliers and CO$_2$ estimated totals on three communities (La Trinidad Ixtlan, San Miguel Maninaltepec, Santiago Xiacui) that will be joining the CAR offsetting program. For these 3 communities, ICICO and CAR used allometric equations in CALCBOSK to estimate total (Table 2).

Table 2. Breakdown of the ICICO partners and data available for each community. Not all partners have available data.

<table>
<thead>
<tr>
<th>ICICO COMMUNITY PARTNER</th>
<th>Carbon Offset Program with CAR</th>
<th>CO$_2$ estimates from CALCBOSK equations (objective 1)</th>
<th>AGB from field data (objective 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Juan Lachao</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Santa Maria Penoles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capulalpam de Mendez</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>San Bartolome Loxicha</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>San Juan Yagila</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Santa Maria Tlahuitoltepec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Santiago Xiacui</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>San Juan Maninaltepec</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Santiago Teotlaxco</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>San Juan Metaltepec</td>
<td></td>
<td></td>
<td>x –error in data</td>
</tr>
<tr>
<td>La Trinidad Ixtlan</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Santa Maria Zoogochi</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Regional geospatial data

To examine the representation of biomass across the study area, I used a regional biomass layer, Sentinel-2 multispectral data, and radar data from ALOS PALSAR – 2. I obtained a 250-meter resolution, AGB country layer derived from 16,000 field inventory plots (CONAFOR, INFyS), the Maximum Entropy (MaxEnt) algorithm, ALOS PALSAR (SAR) radar data (JAXA), optical data from NASA MODIS VI, and a digital elevation model (NASA, SRTM) (Rodríguez-Veiga et al., 2016). The country wide AGB layer represents AGB for all of Mexico at a 250-meter resolution. This map is a useful tool for large areas but is limited in the level of detail at the local
community level. For this project, I will refer to this map layer as the country wide AGB map (Figure 3).

Figure 3. The country wide AGB layer from Rodríguez-Veiga et al., 2016 at a 250-meter resolution. The white outlines are the project area community boundaries.

Cloud-free Sentinel 2 data were accessed from USGS Earth Explorer, for April 23, 2020. When using remote sensing to identify AGB, lidar is preferred for fine scale mapping of AGB (Jones & Vaughan, 2010), but due to the lack of lidar in the region, I opted to use 2018 radar. I supplemented the optical data with radar data using the Advanced Land Observing Satellite-2 Phased Array type L-band Synthetic Aperture Radar (ALOS-2/PALSAR-2) imagery from the Japan Aerospace Exploration Agency (EROC, JAXA). The data include horizontal transmit-vertical receive (HV) polarization and horizontal transmit-horizontal receive (HH) polarizations.
at a 25-meter resolution (Sarzynski et al., 2020). This sensor emits microwaves using L-band frequency to produce cloud-free images (EROC, JAXA). L-band is particularly useful because it is able to penetrate past the top layers of a forest and provide a more accurate representation of land cover (Sarzynski et al., 2020). Being its own source of light, the sensor can capture both the day and night producing cloud-free images (EROC, JAXA). The sensor’s H and V polarization measure the backscatter returning to the sensor from the earth’s surface (Frison, n.d.). These HH or HV polarizations can be used to analyze the earth’s surface such as forests cover or aboveground biomass because it is able to penetrate the forest canopy layers and provide a proportional relationship to density up to a certain saturation point (Behera et al., 2016). The long-wave bands from radar data (P and L bands) are useful for determining forest biomass, specifically using the HH and HV polarization band backscatter can determine the truck or canopy biomass (Behera et al., 2016).

2.4.2. Data processing:

**Sentinel – 2**

One project objective is to produce a finer-resolution spatial layer for aboveground biomass for the communities working with ICICO in Oaxaca. The Sentinel-2 imagery has 10-meter resolution, and eight images were required to cover the study area. The Sentinel-2 Level 1C data (USGS) is a top-of-atmosphere product. All the tiles contained less than 5% cloud cover, therefore it was not necessary to perform atmospheric correction (ESA, Sentinel). I used ENVI to process the data and calculated the Normalized Vegetation Difference Index (NDVI) (Sarzynski et al., 2020; Tucker et al., 1979) (Table 2).
### Table 3. NDVI and NDRE formulas for Sentinel-2 imagery.

<table>
<thead>
<tr>
<th>Vegetation Index</th>
<th>Formula</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized Difference Vegetation Index (NDVI)</td>
<td>$NDVI = \frac{NIR - RED}{NIR + RED}$</td>
<td>NDVI is a commonly used index that senses changes in greenness, making it good for vegetation and biomass (Sarzynski et al., 2020)</td>
</tr>
<tr>
<td>Red Edge Vegetation Index (NDRE)</td>
<td>$NDRE = \frac{NIR - Red Edge}{NIR + Red Edge}$</td>
<td>NDRE is commonly used for calculating leaf area index, chlorophyll and aboveground biomass (Castillo et al., 2017)</td>
</tr>
</tbody>
</table>

Once the NDVI was calculated, I completed the rest of the analysis in ArcGIS Pro 2.6.3. Using zonal statistics, I calculated mean NDVI for each plot (Figure 4).
Figure 4. NDVI values for existing carbon plots. Areas of green have higher NDVI values (i.e., more vegetation) than the areas in red shades. NDVI is used to show areas that have higher vegetation density. Amid the forests of the study area, the areas with higher NDVI typically have higher AGC.

Since the Sentinel-2 satellite provides a larger spectrum of light than other older satellites, I wanted to take advantage of this property. I used the Normalized Difference Red Edge Vegetation Index (NDRE) which tends to be able to measure further into a forest canopy because it is not as strongly absorbed by just the topmost layers of leaves (Table 3). Recent studies show that using the Red Edge band in Sentinel – 2 provided as a good predictor of aboveground biomass (Castillo et al., 2017; Sun et al., 2020). I followed a similar process from the NDVI, using ENVI to process the imagery and calculate the NDRE (Table 2), and used ArcGIS Pro
2.6.3 to complete the analysis and zonal statistics for each carbon plot (Figure 5).

Figure 5. Carbon plots shown in the Red Edge Vegetation Index and the community boundaries in the black boundaries. The areas of green are higher in vegetation than those in yellow or red (ArcGIS Pro 2.6.3).
Figure 6. Amount of AGB in each of the ICICO carbon project area shown in the NDVI and NDRE. The vegetation indices ranges from 0 - 1, with 1 being places with the most greenness. The NDVI values are higher relative to the NDRE values, but the overall pattern is the same, indicating that the inclusion of the red edge in the NDRE is not substantially contributing to showing higher vegetation.

**ALOS PALSAR-2**

To cover the study area, I used five ALOS PALSAR-2 radar tiles from 2018 to cover the range of the ICICO project area. I used ENVI to process these data and then completed the analysis using ArcGIS Pro 2.6.3. The tiles were corrected for terrain upon download. I opted not to perform speckle reduction given I planned to average the HH and HV values across each carbon plot which has a similar effect of speckle reduction. I created sets of 100 random points to sample each of the carbon plots and their corresponding HH and HV values. I averaged across all the points to get the mean of the radar data in each location.

**Digital Elevation Model**

The National Institute of Statistics and Geography’s (INEGI) 15-meter Digital Elevation Model (DEM) dataset provided the necessary data for me to create the elevation and the slope layer for the region and for the carbon plot boundaries.

The regional AGB map values were extracted for the carbon project area. The AGB raster size was too large and not conducive for using zonal statistics, therefore, I created point data to extract a value for each pixel within the carbon plots. I used a spatial join to overlay the polygon features to the point values and used the mean value for each carbon plot.

**2.4.3. Allometric equations**
CAR uses a proprietary database (CALCBOSK) to calculate the potential AGB estimates for La Trinidad, Santiago Xuicui and San Miguel Maninaltepec. I was not given permission to examine calculations with CALCBOSK, but the allometric equations used are readily available online. I accessed these equations and cross-referenced each with the species found in the carbon plots. Carbon offset locations were determined by my client and future potential locations were predicted based off the environmental conditions of the current locations. I used the allometric equations from San Miguel Maninaltepec and created a subset of the 20 species with the highest AGB estimates. I used this subset to compare to the allometric equations found in Rojas-García et. al (2015) as the most up to date collection of allometric equations.

2.5. Analysis

2.5.1. Analysis Part One

To address the first part of this study, I looked at the current carbon accounting methodology to determine the accuracy and if there were additional allometric equations that could be used to produce a higher amount of AGC. Once I had created the subset of species of about 3,200 individual trees, I used a function in R Studio to read through each equation to pick the equation producing the max amount of AGB. Since the equations in the literature and in CALCBOSK were calculated to AGB, I used this to compare equations. Once I had a total for each equation, I converted the totals using a multiplier of ~ 0.47 to result in Mg AGC.

3.2. Analysis Part Two

To determine locations with high levels of AGC within the greater project area and throughout the rest of the state of Oaxaca, I used the remote sensing variables, AGB state-wide map, and
environmental variables as predictor variables for AGC. The data provided from ICICO had calculated CO$_2$ equivalent (CO$_2$e) for each of the carbon plots. I back transformed the CO$_2$e to AGC for ease and clarity. This was calculated by dividing the CO$_2$e by 3.67 as instructed by the CAR Mexico Protocol 2.0. I examined the relationships between AGC amounts and all predictor variables to assess potentially important predictors of AGC and to avoid multicollinearity. To ensure a normal distribution of data the assumptions of a linear model, I log transformed the AGC. (Figure 7).

![Heat map of the correlations between variables. The areas in green have a higher correlation than those in yellow. The high correlation is ~90%, medium is ~30%, and low is ~12%.

Figure 7. Heat map of the correlations between variables. The areas in green have a higher correlation than those in yellow. The high correlation is ~90%, medium is ~30%, and low is ~12%.

Next, I created a multi-variate linear model assess the effects of slope, aspect, AGB, HH polarization, HV polarization, NDVI, NDRE on AGC. After running this model, I reduced the model in a stepwise manner to eliminate the variable with the least significance. I ran an ANOVA test to choose the best option. The ANOVA identified the key variables based off their
significance to AGC and used these variables in ArcGIS Pro to predict locations across the project area and the state of Oaxaca with medium to high amounts of AGC. The model residuals were evaluated visually to ensure that they met the assumptions of linear models and were normally distributed residuals.

3. Results

3.1 Results from Part One

The results of the allometric equation analysis showed that there is a significant difference in the amount of AGC available based on the different equations. Even though all the equations used were derived from Mexican species, the sensitivity of these equations is evident when examining difference in the total Mg CO$_2$. The allometric equations found in the literature totaled ~6,100,000 Mg CO$_2$ compared to the total from CALCBOSK was ~1,600 Mg CO$_2$ (Figure 8). The literature equations were looking to maximize Mg CO$_2$ and the total resulted in 381,000% over the total used in the CALCBOSK system. This shows that changing the equation can dramatically affect the about of aboveground carbon estimate and therefore amount to sell as a credit. The focus of this study was to determine the maximum total amount of Mg CO$_2$ available, but these totals do not necessarily reflect the amount of carbon that should be sold as credits.
Figure 8. The top panel shows the AGB totals from the equations found in Rojas-Garcia et. al 2015 (top), the middle panel shows the AGB totals from the CALCBOSK database (middle), and the bottom panel shows the difference between the two equations totals plotted on a log-transformed y-axis.

Given the range of outputs from the equations, I wanted to further investigate, which species were responsible for the change. I found that only six of the twenty species’ equations were using a different equation than the original CALCBOSK equations, meaning those six species had the biggest influence on the total AGC (Figure 9).
Figure 9. The boxplots with the black asterisk next to them are the 6 species that are using a different equation than the CALCBOSK equation. These 6 species are PIDU (Pinus durangensis), PIPA (Pinus patula), PIPS (Pinus pseudostrobus), PITE (Pinus teocote), QULA (Quercus laurina), and QURU (Quercus rugosa).

3.2. Results from Part Two

The final model accounts for 25.3% (adjusted R2) of the variation in the data. The results showed variation in AGC was significantly determined by the NDRE (effect: -9.13, p-value: 0.027), AGB state-wide map (effect: 0.009, p-value: 0.003), and elevation (effect: -0.003, p-value: <0.001) (Figure 10). I used these variables’ back transformed coefficients to predict AGC locations in Oaxaca.
In ArcGIS Pro, I calculated the coefficients found from the linear regression to find locations of AGC within the project area and across Oaxaca (Figure 1). This map, now a 20-meter resolution of the area, shows some of the locations of the current carbon plots are well suited, while others are in the Medium to Low ranges. It further shows that there is potential outside of the current project area, that could be good for carbon offsets. The accuracy of the locations of the aboveground carbon will improve with the higher resolution because it provides more detail and with added spatial data is a more accurate representation.
4. Discussion

Forests around the globe are seeing high rates of deforestation and are increasingly threatened by urbanization, agriculture, and a changing climate (Corona-Núñez et al., 2018). As global emissions continue to rise, the impacts of climate change will also become more severe. To combat climate change, a variety of solutions are urgently needed to alleviate the worst outcomes. One viable natural solution to climate change is to protect and conserve forested areas. Forests need to be seen as having as having more value standing than cut down and to achieve this goal, programs such as the carbon offsetting provide this opportunity. Carbon offsetting
programs provide financial resources while keeping forests intact and allow for alternative livelihoods for the local communities. This nature-based solution is innovative and provides a method for capturing carbon thus reducing global emissions. The results of my Master’s Projects demonstrates the usefulness of carbon offsetting programs, the methodology behind carbon accounting, and identifies forested areas in Oaxaca, MX which are potential suitable locations for future carbon projects.

As demonstrated in the results, the viability of carbon accounting is highly sensitive to which allometric equation was implemented. For landowners and groups working in the carbon offsetting space, it is important to understand and educate the communities involved on how the AGC is calculated. Accurately accounting for forest carbon determines how much value and credits are available for the market. The results show the range of AGC possible for accounting carbon which indicates further research and analysis should take place to understand what makes the currently employed equations the right fit. Each allometric equation is tailored to the species and location, therefore, to determine the best fit equation will take a deeper dive into the equations. As carbon offsetting becomes a more common use in the management of forests, selecting allometric equations best suited to accurately account for carbon is imperative to the future of carbon programs especially since this has been a point of criticism for the program (Miltenberger et al., 2021). If this type of nature-based solution continues to be implemented, accurate accounting carbon in the forest is important for financially supporting the landowners but also to not double-count credits.
As ICICO continues to work with communities in Oaxaca, having a finer-resolution AGC map will help in identifying locations with the potential to join the program. With additional inputs from remote sensing satellites and focusing in on the local level, allowed for a 20-meter resolution map to be possible. It was also evident that the state-wide AGB map does not accurately depict AGC in all locations. This map allows ICICO to find other indigenous communities who could work to conserve their forests while still providing for a sustainable livelihood. A goal of ICICO is to be able to bring more indigenous communities into this program, and now being able to identify areas with adequate AGC, will accelerate the process to have communities look at carbon programs as a useful resource for their forest.

Although this map provides greater insight into AGC in Oaxaca, it does have its shortcomings. Due to the lack of lidar data, we currently must rely on optical and spatial data. NDRE, a significant predictor of AGC, was used instead of the commonly used NDVI, but the NDRE still did not fully capture biomass estimates to the level desired. Cloud-free satellite data was not available across all of Oaxaca for my study period and therefore does not provide a full state-wide map, so I had to narrow my study area. Another opportunity would be to explore using an alternate vegetation index such as the Enhanced Vegetation Index (Pandapotan Situmorang et al., 2016) or the Ratio Vegetation Index (Clerici et al., 2016) used in studies in Indonesia and Peru, respectively. More promising are NASA’s new space-based missions (waveform LiDAR- GEDI, https://gedi.umd.edu/) as well as future missions (e.g. L-band radar: NISAR, https://nisar.jpl.nasa.gov/) that will provide more accurate and finer-scale biomass mapping over the globe. Future projects for local communities will likely be able to validate and better extrapolate field measurements with these new technologies.
The updated AGC map, with more spatial inputs, does provide more detail information on the level of AGC compared to the coarse AGB map, yet it does not encompass the entire state of Oaxaca.

As carbon sequestration and offsetting programs continue to gain momentum, working with the local people should continue to be at the forefront of the program. In cases like Oaxaca, the forests capturing the carbon are owned and managed by indigenous groups. This type of community-based management is critical for the longevity of such programs and for the forest which they call home. This is the case for carbon offsetting programs but also for any nature-based solution to climate change – the people of the forests must be a part of the solution as well.

5. Conclusion

The results of this study provide further insight into the carbon offsetting programs, opportunities and areas of further investigation. One is for further study is the allometric equation accounting and decision for using the equations that are currently in practice. This study was solely focused on understanding if there were alternative equations available for use, and if so, what is the most about of AGC possible for the communities. I found a wide range of outputs and future work should deep dive into the nuances of each equation to know which would be best suited for ICICO’s partner communities based off their objectives. The second conclusion is that a finer-resolution map is possible by using additional inputs. Although the original map is helpful for a large scale, when working at the local level, this updated map, will allow ICICO to more accurately identity future partner communities and areas of Oaxaca well-suited for carbon offset work.
6. References:


