PROJECTIONS OF FUTURE CROPLAND ABANDONMENT:

IMPACTS TO BIODIVERSITY & CARBON SEQUESTRATION

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A Group Project submitted for the degree of
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The Bren School of Environmental Science & Management produces professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principle of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

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Executive Summary

Socioeconomic and environmental changes are likely to drive shifts in the distribution of global agriculture, resulting in large-scale abandonment of croplands. Abandonment is driven by ecological, socioeconomic, and climatic factors that vary considerably by region. Without strategic management, abandonment can cause soil erosion, inhibit nutrient cycling, increase wildfire risk, threaten local food security, and negatively impact species adapted to human agricultural landscapes.

However, abandoned lands can also be reforested or rewilded, though the optimal environmental outcomes generally require incentives for land managers. If managed strategically, the rewilding of abandoned lands can serve as a powerful natural climate solution, as revegetation sequesters carbon in the form of plant biomass. Moreover, allowing abandoned land to reforest can preserve biodiversity in some regions, including in the tropics.

Patterns of future cropland abandonment, as well as strategies for making use of abandoned lands, are not well-researched. Understanding where and to what extent cropland abandonment will occur can inform conservation planning. The first stage of this project examines where croplands are projected to be abandoned globally under various climate change scenarios using future global land cover data. These projections are then overlaid with spatially explicit carbon sequestration potential and biodiversity data. We find that cropland abandonment will be widespread in 2050, but the amount and location of abandoned croplands vary by climate scenario. Projected abandoned croplands consistently overlap with areas of high importance to biodiversity and carbon sequestration, highlighting where these abandoned lands can offer valuable conservation opportunities.

The next stage of the analysis focuses on Brazil. Brazil is home to 13% of the world's biota and has immense potential for carbon sequestration, making its abandoned lands essential for climate change mitigation and biodiversity preservation. We conduct an optimization analysis to identify regions of Brazil where projected abandoned lands can be managed on a given budget to maximize benefits for biodiversity and carbon sequestration. Our findings indicate that while patterns of cropland abandonment are highly regional, conservation goals can be met by leveraging abandoned lands and local restoration efforts.

Ultimately, understanding where and to what extent cropland abandonment will occur in the future is crucial for informed conservation strategies and land use planning. Through our research, we hope to inform effective policies and management strategies that balance the need for agricultural production with goals for climate change mitigation and biodiversity preservation.

Objectives

This analysis projects cropland abandonment and highlights regions where the natural or assisted recovery of abandoned land can sequester carbon and enhance biodiversity. The science-based recommendations produced through this project can inform conservation and policy investments that best use available resources to restore abandoned croplands while maximizing social and environmental benefits.

This project supports Conservation International in setting global priorities for conservation investment by completing the following objectives:

1. Generate global projections of abandoned cropland under different climate scenarios in the near future to investigate the impact of abandonment on biodiversity and carbon sequestration.

2. Within projected abandoned cropland in Brazil, identify regions where the conservation of abandoned land can generate the highest benefits to biodiversity and carbon sequestration.

3. Identify and evaluate policies to maximize benefits from the active restoration of projected abandoned croplands.

Project Significance

In the 21st century, population growth and global warming are projected to drive large-scale land use change, altering the distribution of croplands across the planet. Degraded, less productive croplands are expected to be abandoned, while higher-quality parcels will be cultivated more intensely (Stoate et al., 2009). Abandonment is driven by socioeconomic and environmental factors that render agriculture unsustainable and no longer economically viable on certain lands (Li & Li, 2017).

However, if managed strategically, these abandoned lands can offer numerous environmental benefits. Abandoned lands hold significant potential for carbon sequestration and climate change mitigation (Bell et al., 2020). Additionally, they can recover habitat that supports species richness and biodiversity (Queiroz et al., 2014). Finally, reverting former croplands to natural states can improve ecosystem services that directly benefit local communities (Quintas-Soriano et al., 2022).

While historical patterns of cropland abandonment are well documented, more research needs to be conducted on future abandonment trends and the influence of climate change on abandonment. Additionally, most research on abandoned cropland management explores methods to recultivate the land with little research on the potential benefits of rewilding the land (Navarro and Pereira, 2015).

This project with Conservation International (CI)–a global nonprofit dedicated to natural climate solutions, biodiversity, and human well-being–investigates how abandoned croplands can be managed to promote carbon sequestration and biodiversity worldwide. We employ a prioritization analysis to illustrate how abandoned croplands may be strategically protected at the national and ecoregion scales to maximize future benefits to carbon sequestration and biodiversity. Ultimately, this project contributes to the growing body of research that attempts to unlock the conservation potential of land abandonment (Corbelle-Rico et al., 2022; Du et al., 2019; Fayet et al., 2022b).

This research will directly support the UCSB-CI Climate Solutions Collaborative project, Spatial Planning for Area Conservation, Land Use, and Energy in Response to Climate Change. UCSB-CI aims to identify where strategic land allocation for area-based conservation, agriculture, and energy can support humans and biodiversity in a warming world. Understanding where cropland abandonment will occur and where it will overlap with areas of high environmental importance will support conservation and land use planning. CI will share results with national-level planners to support programmatic decision-making.

1. Introduction

1.1 Background

Agriculture dominates global land use, with pastures and cropland covering 26% and 12% of ice-free terrestrial areas, respectively (Foley et al., 2011). While economically productive farmland has trended towards intensification, several economic, social, geological, and cultural drivers have resulted in other agricultural lands being abandoned (Beilin et al., 2014). Globally, the area of abandoned agricultural land that has not been restored or developed is estimated at 385 million to 472 million hectares, a larger land area than India (Yang et al., 2020). This phenomenon of abandonment has been observed extensively in Europe (Keenleyside & Tucker, 2010), Latin America (Munroe et al., 2013), Asia (Subedi et al., 2022), Africa (Leal Filho et al., 2017), and North America (Meyfroidt & Lambin, 2011).

Land abandonment has mixed environmental and socioeconomic impacts. On the one hand, abandoned land can lead to the loss of soil nutrients and the release of soil carbon into the atmosphere (Yang et al., 2020). Abandoned land is also vulnerable to soil erosion, lower water availability, and increased wildfire risk (Estel et al., 2015). In dry regions, the revegetation of abandoned lands can also reduce soil water content and river flows as plant biomass consumes a limited water supply (Ustaoglu & Collier, 2018). Moreover, abandonment on low-intensity and historic farmland can negatively affect local biodiversity adapted to human-managed landscapes and open spaces (Beilin et al., 2014). The loss of farmland can also harm food security and livelihoods in rural, low-income communities (Khanal & Watanabe, 2006).

However, abandoned land can be strategically managed to benefit nearby human and ecological communities. Abandoned land can function as a carbon sink if native vegetation recovers and through regenerative agricultural practices that capture and store atmospheric carbon in the soil (Yang et al., 2020). Restoring abandoned farmland can also enhance biodiversity and promote habitat connectivity, nutrient cycling, soil recovery, and water retention, ultimately providing local communities with key ecosystem services that can improve human well-being (J. Benayas et al., 2007).

1.2 Drivers

Many factors contribute to agricultural abandonment, ranging from geological constraints to economic and social pressures (Terres et al., 2015). Drivers also vary depending on location (Beilin et al., 2014). Differences in terrain, along with social, economic, and cultural factors result in significant regional variation in the drivers of abandonment (Osawa et al., 2016). Scholars identify differing numbers of drivers that contribute to abandonment, but these drivers can generally be split into three categories: socio-economic, ecological, and land mismanagement (J. Benayas et al., 2007).

1.2.1 Socio-Economic Drivers

One major socio-economic driver of agricultural abandonment is the migration of rural populations into urban centers due to industrialization and urbanization (Leal Filho et al., 2017). Economic conditions have led workers to relocate away from rural areas in search of manufacturing and service industry jobs, reducing the agricultural labor force in many countries (Díaz et al., 2011; Li & Li, 2017; Ustaoglu & Collier, 2018).

Other socio-economic factors driving land abandonment include declines in market prices for crops due to shifting demand and foreign-trade developments (Li & Li, 2017), agricultural policies and land management systems (Ustaoglu & Collier, 2018), and agricultural intensification and commercialization (van Vliet et al., 2015). Lower crop prices and higher input costs drive abandonment in some regions as farmers give up their land in search of more profitable endeavors (Prishchepov et al., 2021).

1.2.2 Ecological/Geographic Drivers

Ecological and geographic characteristics of the land are important factors contributing to abandonment. Agricultural activity tends to continue on the parcels that generate high yields, while abandonment occurs on marginal lands with lower-quality soils (Grau & Aide, 2008). Regional case studies provide useful insights into commonalities between abandoned agricultural lands. In Nepal, farmland was abandoned primarily in less fertile areas, further from villages and population centers, and closer to forested areas (Paudel et al., 2014). In Europe, spatial land use models predicted that agricultural lands will be abandoned in high-latitude regions such as Finland and Sweden, as well as in mountainous and hilly areas in the Alps (Keenleyside & Tucker, 2010). Other studies have also highlighted topography and parcel isolation as key determinants of where abandonment occurs, with mountainous regions, sloped parcels, and more isolated farmlands experiencing higher abandonment rates (Müller et al., 2009). Water stress and drought are other important causes of abandonment (Terres et al., 2015). Climate change can exacerbate these conditions in certain regions, as declines in precipitation in the Mediterranean regions have contributed to the abandonment of cereal cropland and pastures (Lasanta et al., 2017).

1.2.3 Land Mismanagement

The mismanagement of agricultural land can also be a driver for abandonment. Overexploitation and unsustainable farming practices can result in a loss of productivity, soil degradation, erosion, and flooding, ultimately leading to abandonment (J. Benayas et al., 2007). Mismanagement of soil and unsustainable agricultural practices can result in high rates of soil erosion, which can eventually result in desertification, especially in arid regions (MacDonald et al., 2000). In Central and Eastern Europe, soil degradation due to intensive agriculture and a gradual water shortage due to heavy irrigation are critical drivers of abandonment (Lasanta et al., 2017). Moreover, global economic and political pressures have incentivized agricultural intensification (Díaz et al., 2011; Osawa et al., 2016; Ustaoglu & Collier, 2018). This shift from extensive agriculture to mismanaged intensive agriculture has resulted in abandonment (Pinto-Correia & Godinho, 2013; van Vliet et al., 2015).

1.3 Post-Abandonment Land Use

Agricultural land abandonment is a gradual process that often begins with a reduction in land management, followed by a decline in farming intensity (Leal Filho et al., 2017). Abandonment can also be temporary or permanent, presenting another source of uncertainty in defining where abandonment has occurred (Keenleyside & Tucker, 2010). Former farmlands can follow several trajectories after abandonment. Land abandonment owing to the expansion of urban centers can result in the development of former agricultural land (Pandey & Seto, 2015). Land can also undergo revegetation, either through natural succession or active restoration (Lasanta et al., 2015). In other cases, abandoned land is cultivated years after being fallowed (Fayet et al., 2022a).

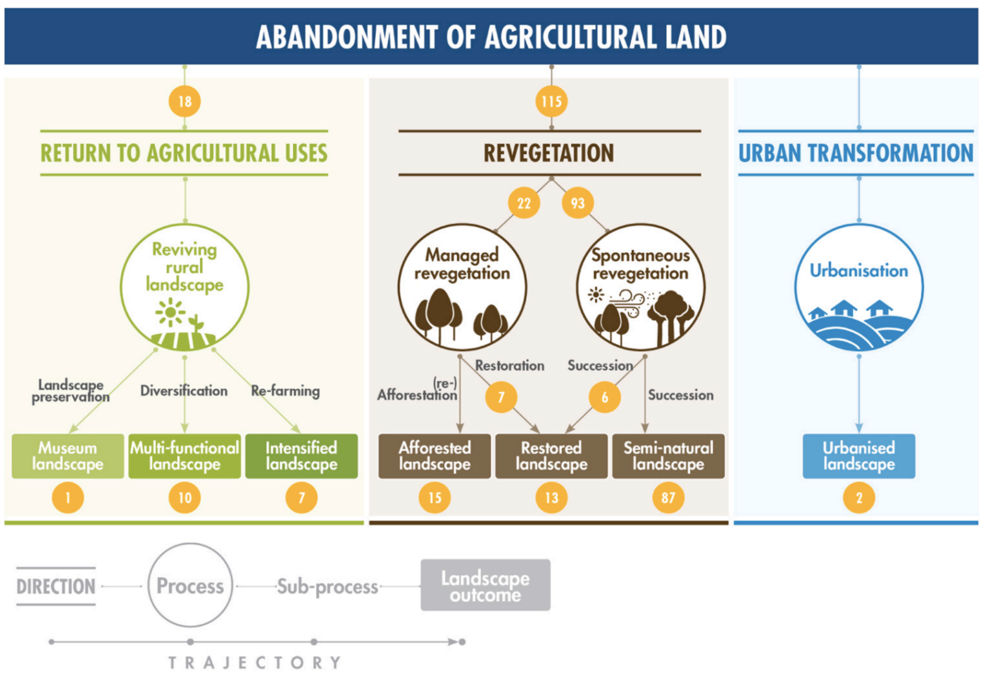

Figure 1-1. Post-abandonment trajectories of farmland in Europe. Of the 135 parcels examined as part of the study, 115 were eventually revegetated, largely through natural succession processes (Fayet et al., 2022a).

1.3.1 Passive Restoration/Spontaneous Revegetation

Passive restoration involves the natural succession of abandoned land by surrounding plants and wildlife. The outcome of passive restoration largely depends on the local climate (Benayas et al., 2007) and past land use (Meli et al., 2017). Natural succession can be a slow process in drier regions with low primary productivity (Benayas et al., 2007). In tropical regions, canopy height and basal tree area similar to primary forests can be seen in abandoned lands after 40 to 50 years of natural succession (Muñiz-Castro et al., 2006). While vegetation may recover its structure and diversity in this 50-year time frame as well, it can take over a century for species composition and aboveground biomass to return to their pre-land use levels (Poorter et al., 2021).

Passive restoration has also been shown to improve soil quality; the quantity of nutrients like nitrogen, phosphorus, and organic carbon can decrease in the period immediately following abandonment due to the halting of fertilizer inputs, but levels of these nutrients can exceed those of agricultural land within 30 years of succession (Zhang et al., 2016). However, nutrient levels on abandoned agricultural land undergoing natural succession are still lower than those surrounding native forests after 50 years (Wang et al., 2011). The semi-natural landscapes that result from succession can vary in quality. Some areas may experience successful restoration, while others may be prone to invasive species (Fayet et al., 2022a). Proponents of natural regeneration tout its cost-effectiveness and simplicity. Natural regeneration can also provide numerous benefits, including critical habitat for native species, carbon sequestration, and ecosystem services (Chazdon & Guariguata, 2016).

1.3.2 Afforestation/Managed Revegetation

Afforestation or managed revegetation is another common outcome on abandoned agricultural lands. This approach involves the planting of trees or native species to assist regeneration. There has been substantial debate on the effectiveness of active versus passive restoration. Some studies argue that managed revegetation does not provide substantial benefits over natural succession (Fayet et al., 2022a; Meli et al., 2017). However, site selection bias has hindered many of these studies supporting passive restoration. It is common for research on natural regeneration to occur at sites already undergoing secondary succession, while those addressing active restoration often occur at fully degraded sites (Reid et al., 2018).

Active restoration has been supported as a way to restore ecosystem services (Benayas et al., 2009) and increase biodiversity on degraded lands (Curran et al., 2014). Afforestation has also been adopted to prevent soil erosion and encourage regrowth while maintaining the economical use of the land (Campo et al., 2019; Segura et al., 2020). In Europe, subsidies encourage plantings on abandoned agricultural land to boost tree cover (Keenleyside & Tucker, 2010). In areas with degraded soil quality due to intensive agricultural use, assisted recovery through direct plantings and reforestation efforts have been shown to shorten recovery times (Chazdon, 2008).

1.3.3 Alternative Agricultural Uses

Through management and restoration, abandoned lands can also potentially return to agricultural use. One pathway for agricultural use on these lands is the adoption of low-impact or regenerative activities (Fayet et al., 2022a). In China, rural regions have explored land consolidation in traditional agricultural areas to protect farmland, support food demand, and benefit livelihoods (Li et al., 2014). These efforts have revitalized rural areas experiencing high migration to urban centers and have resumed traditional, extensive farming operations (Zhou et al., 2020). Community farms can also use abandoned agricultural land, as has occurred in the Italian Alps (Varotto & Lodatti, 2014).

1.4 Environmental Factors of Interest

1.4.1 Carbon Sequestration

Earth's soils and vegetation store approximately five times more carbon than the atmosphere (Lal, 2004). Preserving current carbon sinks and increasing sequestration in vegetation and soils are essential solutions to mitigating climate change. Two forms of carbon pertinent to agricultural abandonment are gaseous carbon dioxide (CO_2) and carbon stored as soil organic matter (SOM) (Weng, et al., 2021). While land conversion to cropland emits gaseous CO_2, increasing carbon storage as SOM and plant biomass over time through restoration practices provides a low-cost and high-yield way to provide local and global environmental benefits (Chazdon et al., 2016).

Carbon sequestration rates can increase through conservation methods such as active restoration, passive restoration, reforestation, and varying land use management practices (Griscom et al., 2017). Of these natural climate solutions, reforestation has the highest carbon sequestration potential (Griscom et al., 2017).

Rates of carbon capture and capacity for carbon storage vary depending on land use and location. Brazil has the highest potential for carbon storage, followed by Colombia, Venezuela, and Mexico (Cook-Patton et al., 2020; Friedlingstein et al., 2021; Global Carbon Project, 2018). In a secondary tropical forest located in Minas Gerais, Brazil, 35.23% of carbon is stored in aboveground biomass, while 63.22% is in soil (Dantas et al., 2020). Other studies of forest carbon suggest a nearly even split in aboveground and belowground carbon storage, but carbon storage rates vary greatly depending on the region (Dantas et al., 2020; Dixon et al., 1994). Carbon storage allocation also varies with stand age; primary forests hold more biomass aboveground than belowground, while secondary forests display the opposite trend (Dixon et al., 1994; Ngo et al., 2013). Within the first 20 years following the abandonment of agricultural land in the tropics, aboveground biomass accumulation rates increase much more quickly on average (6.2 MgC/ha/yr) than belowground biomass (1.4 MgC/ha/yr) (Silver et al., 2000). Thus, following abandonment in the tropics, most gains in carbon sequestration occur aboveground (Rovai et al., 2022).

1.4.2 Biodiversity

Biodiversity is an important indicator of biome health and function. The impacts and benefits of agricultural land abandonment on biodiversity are still debated and can vary based on several factors (Quintas-Soriano et al., 2022). A literature review of 276 studies on biodiversity and abandoned agricultural lands that received no restoration interventions found that geographic region, study metrics used, and taxa assessed all significantly affected abandonment-related impacts on biodiversity (Queiroz et al., 2014).

Countries in Eurasia have mainly reported negative effects of abandonment without intervention on biodiversity, while countries in the Americas have mostly reported positive effects (Queiroz et al., 2014). This may be attributed to historical land use. In Central and South America, habitat has recently been converted into agricultural land; thus, extensification primarily threatens biodiversity. In Europe, many species and landscapes have co-evolved with human intervention. European forests typically have lower biodiversity, likely due to long-term habitat fragmentation (Haddad et al., 2015). As a result, the succession of agricultural land to a more homogeneous forested landscape reduces total biodiversity in Europe (Queiroz et al., 2014). Land abandonment typically promotes the population decline of species adapted to open spaces and favors the populations and diversity of species of alternative habitats such as wooded vegetation; however, this is regional and crop-dependent (Otero et al., 2015).

Native biodiversity recovers from disturbances, such as agriculture, more slowly than species richness (Hamilton, et al., 2005). Early in natural succession, species richness can be high, with a wide variety of species coexisting until one type of species (shade-tolerant for example) becomes more prevalent (Falster et al., 2017). It takes time for competition to create more equal species abundance. Species diversity recovers in tropical forests after 25-60 years, while species composition can take 120+ years to fully recover after agricultural uses (Poorter et al., 2021).

Global research on abandonment's impact on biodiversity informs management strategies for alternative post-abandonment trajectories. Studies from the Cedar Creek Ecosystem Science Reserve in Minnesota reveal that plant diversity recovers incompletely, and plant productivity does not significantly recover from natural succession on abandoned lands (Isbell et al., 2019). In their sample grassland ecosystem, after 91 years of abandonment, formerly plowed fields had only three-quarters of the plant diversity and half of the plant productivity of nearby ecosystems that have never been plowed (Isbell et al., 2019).

Low-intensity farming, such as cacao agroforests or milpas in South America, can promote high species and habitat diversity; abandonment of these areas reduces biodiversity and landscape heterogeneity if a smaller subset of species dominates the region without active management (Queiroz et al., 2014). Invasive species can also impact biodiversity recovery on abandoned agricultural land if they have competitive advantages to grow more quickly and thus limit opportunities for other species to become established (Benayas et al., 2007).

Positive impacts include improvements to biodiversity from abandonment in areas classified as, or adjacent to, biodiversity hotspots. Additionally, where diverse, woody vegetation exists (e.g., tropical forests), abandonment can facilitate biodiversity recovery. Some studies have found a positive correlation between plant and invertebrate species richness and time since abandonment (Benayas et al., 2007).

1.5 Agricultural Abandonment Policy

Few countries have existing policies explicitly discussing the management of abandoned lands (Fayet et al., 2022b). As agricultural abandonment persists in Europe, North America, and parts of Asia, policies from these regions can offer insight into optimizing agricultural abandonment policies to prioritize biodiversity, carbon sequestration, and human well-being (Calaboni et al., 2018; Corbelle-Rico et al., 2022).

To date, most policies that address land abandonment aim to prevent abandonment and sustain agricultural production. The EU's Common Agricultural Policy (CAP) aims to prevent agricultural land abandonment through income support for farmers, rural development programs, and market measures (European Commission, 2022; Keenleyside & Tucker, 2010; Renwick et al., 2013). Agricultural policy in the neotropics rarely considers the impacts of abandoned cropland. Failing to consider land abandonment in policymaking increases these countries' abandonment rates (Calaboni et al., 2018).

Brazil's agricultural policies have led to the consolidation of farmland and resulted in pockets of abandoned croplands at the margins of active agricultural land, facilitating reforestation. Brazil's Forest Code promoted reforestation by requiring landowners to maintain a percentage of their properties in native vegetation (Navarro, 2010). However, policies promoting agricultural and industrial development can also negatively impact the well-being of small farmers and the environment (Du et al., 2019; Fayet et al., 2022b). Studies from China, where they have tried to mitigate these impacts, have shown that microfinancing can be more successful than institutional support in preventing agricultural abandonment (Hua et al., 2016). In conclusion, policies must complement one another to benefit biodiversity and carbon sequestration substantially. For an extended discussion on agricultural abandonment policy and implications, see Chapter 4 of this report.

1.6 Shared Socio-Economic Pathways (SSPs)

Socioeconomic pathways and representative concentration pathways (SSP-RCP) explore alternative climate futures under different global responses to climate change through 2100 (O'Neill et al., 2017). The five SSP scenarios outlined in Figure 1-2 represent distinct narratives describing various climate mitigation and adaptation challenges. These narratives cover various potential futures and incorporate socio-economic, political, demographic, technological, and lifestyle trends. SSP1, "Sustainability," depicts a gradual global shift towards environmentally friendly, inclusive development emphasizing human well-being instead of economic gain. SSP 5 on the other hand, depicts continued global economic development powered by fossil fuels and resource exploitation. SSP2 represents the "Middle of the Road" scenario, where slow progress is made toward sustainable development goals and income inequality persists (Riahi et al., 2017). We will project and analyze abandoned lands under each SSP to understand how climate change impacts abandonment.

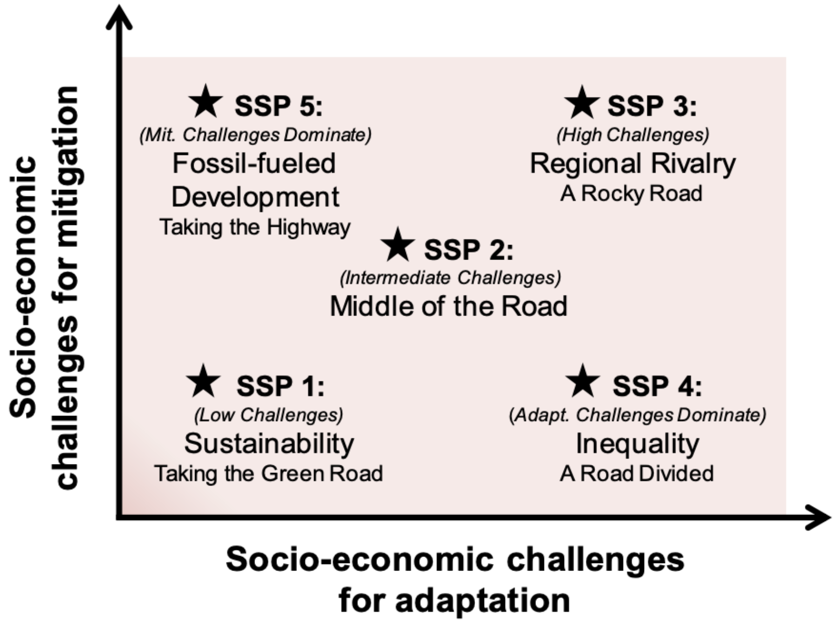

Figure 1-2. The relative mitigation and adaptation challenges for the five SSP scenarios (O'Neill et al., 2017).

2. Global Projections of Cropland Abandonment

Limited research has been conducted to project the future distribution of abandoned lands under climate change. Several other studies have projected land abandonment, but none on a global scale in accordance with the IPCC's SSP scenarios. One study conducted in Europe examined socioeconomic, geographical, and ecological factors to predict which lands would be newly abandoned by 2030 (Perpina et al., 2021). A regional study in Japan projected abandonment using biophysical and socioeconomic indicators according to two scenarios: high economic growth and low economic growth (Estoque et al., 2019). In February of 2023, another study projected global cropland abandonment based on its proximity to other abandoned lands (Gvein et al, 2023).

This project complements this growing body of research by projecting global abandonment based on the five SSPs. Our global abandonment projections are the first of their kind to employ a robust land demand model that considers both the physical and social environments, and how humans interact with each (Chen et al., 2022). This analysis is especially useful in the context of biodiversity preservation and carbon sequestration, since strategic use of abandoned lands can help make progress towards these conservation goals. Therefore, the global analysis also highlights areas where our projections of cropland abandonment overlap with areas of importance for biodiversity and carbon sequestration.

2.1 Methods

To determine where cropland abandonment may occur, we compared current and future global land use and land cover projections under different SSP scenarios. For the purposes of this analysis, any current cropland that has a different land use classification in future projections is assumed to be abandoned, with the exception of land that has been urbanized. Urbanized land is excluded from this analysis since croplands converted to urban use do not support our project goals of maximizing benefits to carbon sequestration and biodiversity. Finally, we overlaid carbon sequestration data and biodiversity data to visualize abandoned lands with high conservation potential. Spatial analyses were performed using the *terra* package (version 1.6-41) in R. Data sources and code used to perform this analysis are provided in Appendix D.

2.1.1 Identifying cropland abandonment

1. **Examine current global cropland distribution**
   Current cropland data are from the year 2015 (Chen et al., 2022) and provide a baseline for the abandonment analysis.

2. **Examine future global cropland distribution**
   Projected cropland data (Chen et al., 2022) are based on SSPs from the IPCC's 6th Assessment Report. This set of analyses analyzed cropland projections for 2050 under each of these five climate scenarios.

3. **Perform raster calculations to determine abandonment**
   The 2015 baseline cropland raster was subtracted from the future cropland raster to determine where current cropland is projected to be abandoned in 2050 (Figure 2-1). This analysis was conducted for five of the SSP-RCP coupled scenarios (SSP1/RCP2.6, SSP2/RCP4.5, SSP3/RCP7.0, SSP4/RCP6.0, and SSP5/RCP8.5) at the 2050 time horizon, producing five global rasters of abandonment at 1km resolution.

4. **Remove urbanized cropland from abandonment projections**
   To determine the potential carbon and biodiversity benefits of abandoned land we removed from our projections any abandoned cropland that is classified as urban under future scenarios.

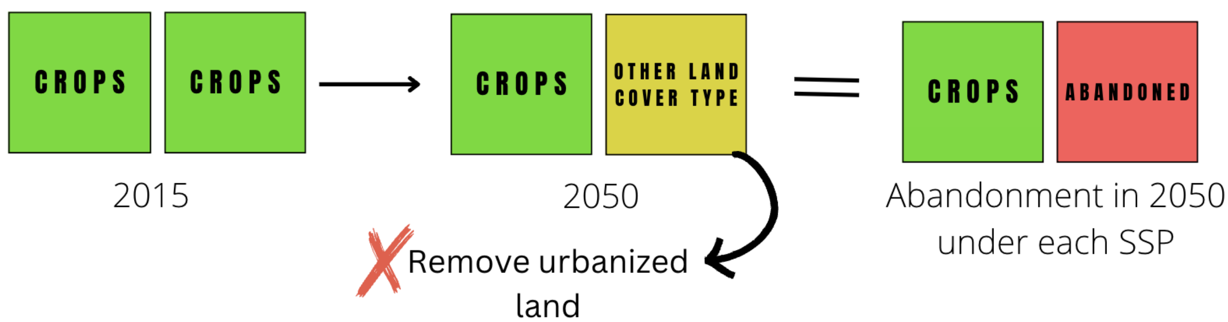

Fig 2-1. The methodology for projecting a future abandonment layer for a single climate scenario.

2.1.2 Visualize abandonment projections in R Shiny

An R Shiny web application was created to visualize major trends in projected abandonment overlaid with carbon sequestration and biodiversity data. Conservation International's SPARC conservation priority spatial data were utilized for global biodiversity. To estimate the carbon sequestration potential of abandoned lands, we used potential accumulation rates, a measure of how much carbon an area can sequester in 30 years of reforestation following anthropogenic disturbance (Cook-Patton et al., 2022). Due to computational limitations, projected abandonment, carbon, and biodiversity data were upscaled to 50 km resolution using the cell mean values when aggregating. As a result, the abandonment raster represents the proportion of abandonment (value between 0-1) within each cell.

2.1.3 Calculating total abandonment in 2050 by climate scenario

To quantify global trends in abandonment, the projected abandonment rasters were used to calculate the total area of abandoned cropland by SSP scenario. These values were compared against the total amount of cropland in 2015 to determine the percentage of global cropland that becomes abandoned under each SSP. Croplands that became urbanized were excluded from this analysis. These results are presented in Figure 2-4 below.

2.1.4 Calculating global net cropland change in 2050

To further explore global agricultural shifts, another raster calculation using the same land use data from Chen et al., 2022 determined the amount of new cropland in 2050. New cropland was defined as any cropland in 2050 that was not cropland in the 2015 baseline layer. This analysis was conducted for each of the five SSP scenarios. The total amount of projected new cropland was subtracted from projected abandonment to determine the net cropland change in 2050 for each SSP. These results are presented in Table 2-1 below.

2.2 Results

2.2.1 Identifying and visualizing land abandonment

Results from the global abandonment analysis are presented in an interactive R Shiny App. The following figures show a sample of the visualizations of cropland abandonment (Figure 2-2), as well as overlays with carbon sequestration rates and biodiversity values (Figure 2-3). As displayed in Figures 2-2 and 2-3, many high abandonment areas have the potential to sequester carbon quickly and are crucial areas for preserving global biodiversity. For more granular visualizations, interested parties should use our R Shiny application.

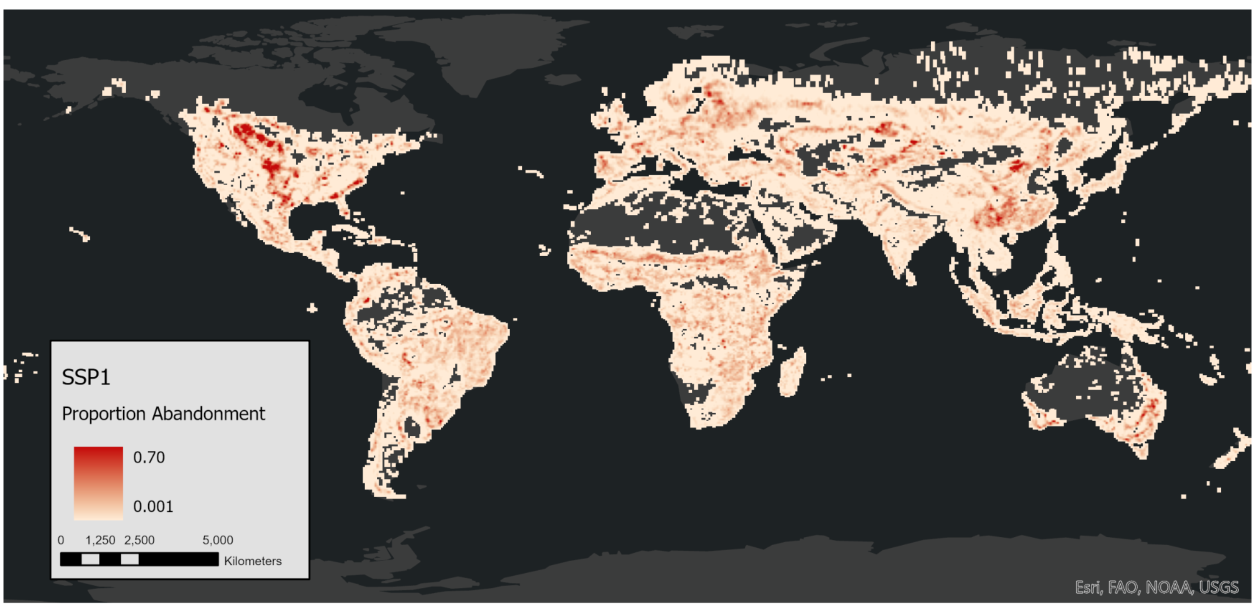

Figure 2-2. Cropland abandonment at 50 km resolution in 2050 based on SSP1. Coloring reflects the proportion of cropland abandoned within each pixel; dark red represents pixels with a higher proportion of abandonment, while lighter colors show regions with less abandonment. Areas with no pixels are locations that either have no current cropland or don't have any projected abandonment.

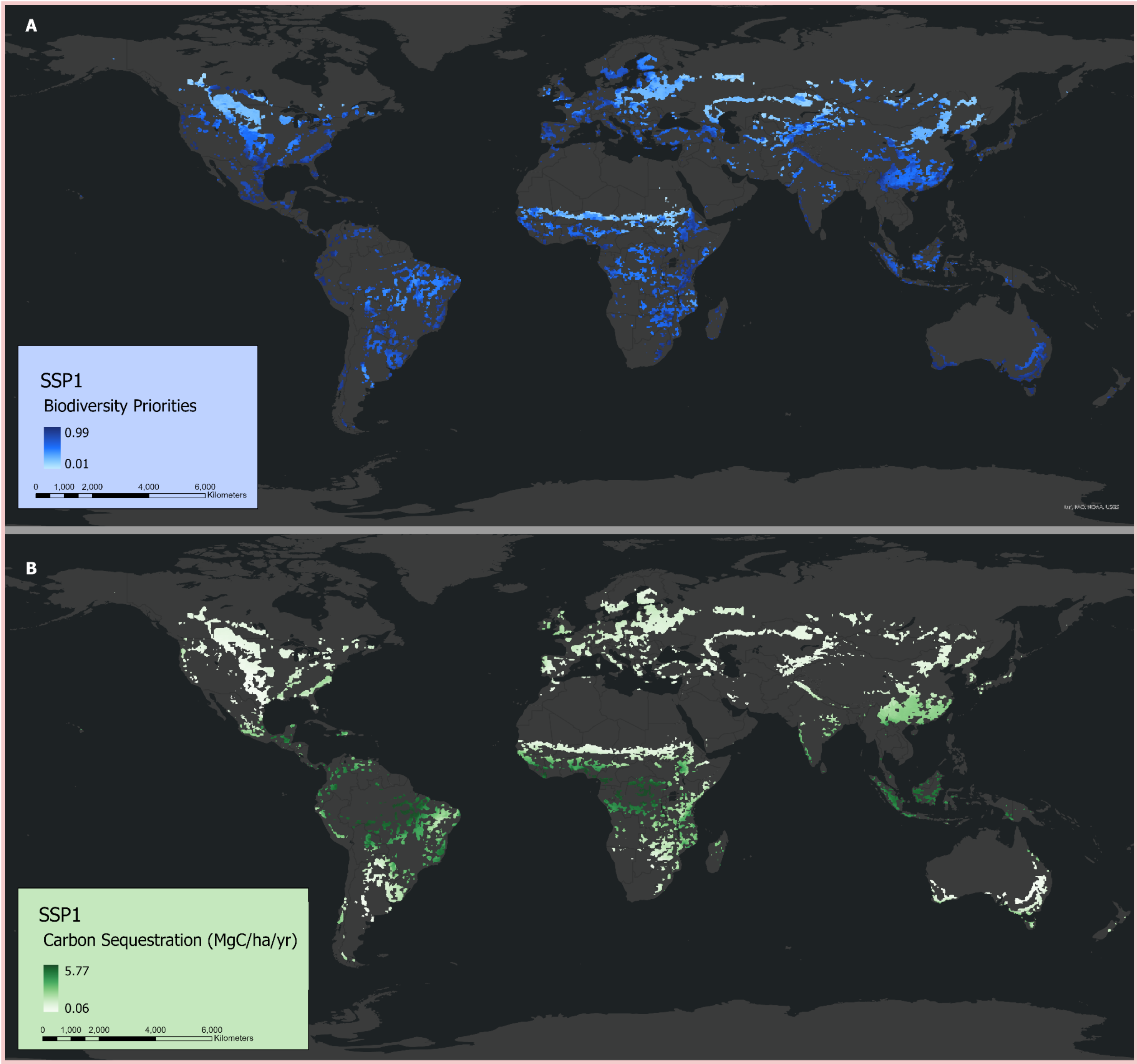

Figure 2-3. Biodiversity and carbon values within areas of high cropland abandonment at 50 km resolution. Only pixels in the top 20% of projected abandonment by 2050 in SSP1 are included in the figure. Figure 2-3a (top) shows SPARC Conservation Priorities biodiversity indicator, where darker blue indicates areas of greater importance to preserving biodiversity. Figure 2-3b (bottom) shows the same areas of high abandonment overlaid with carbon sequestration potential, with darker green indicating greater carbon sequestration rates.

2.2.2 Total abandonment by climate scenario (excluding urbanized land)

Cropland abandonment is projected to be widespread in 2050 and differs across SSPs, both in the total volume of abandonment and spatial distribution. SSP1, the "Sustainability" scenario, has the largest amount of projected cropland abandonment (3,163,707 km^2, or 14.5% of current cropland), while SSP2, dubbed the "Middle of the Road", has the smallest amount (1,748,083 km^2, or 8% of current cropland) (Figure 2-4).

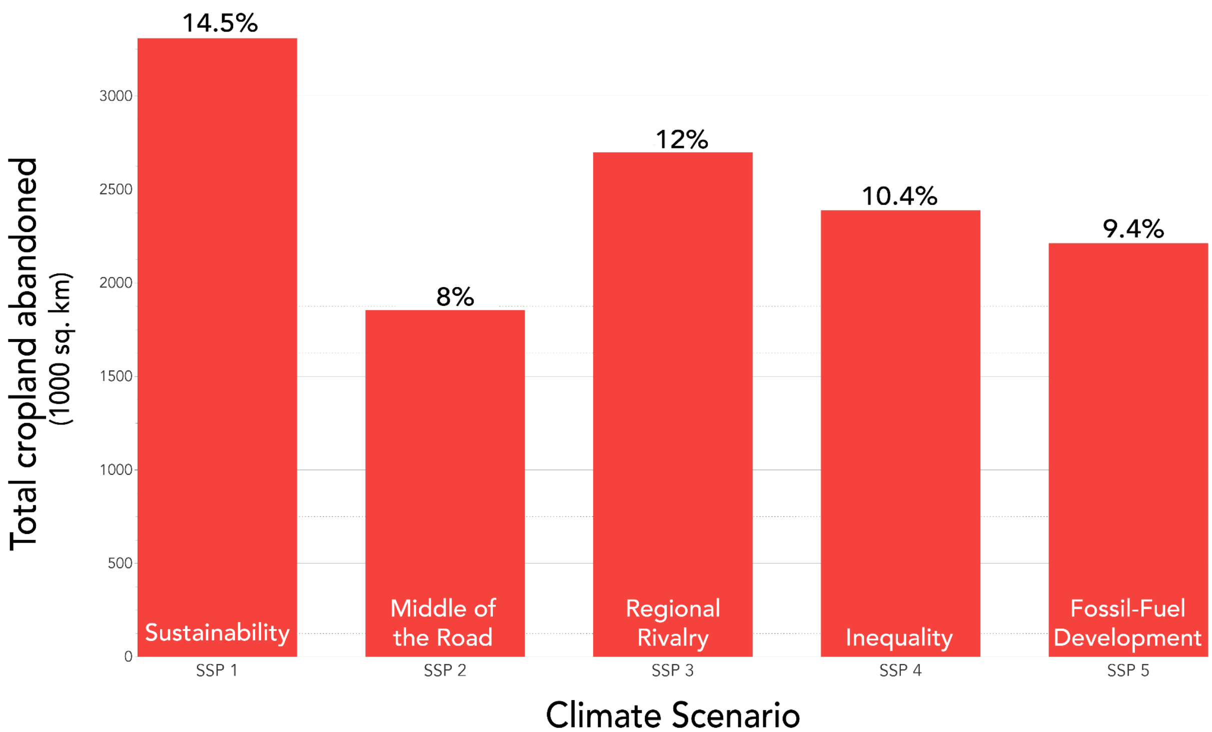

Figure 2-4. Total abandoned cropland globally in 2050 (km^2) by climate scenario. Percentages indicate the proportion of current cropland that is projected to be abandoned. Cropland which was urbanized is not included in this analysis.

2.2.3 Net cropland abandonment by climate scenario

SSP1 was the only climate scenario in which there was more abandoned cropland than newly cultivated cropland in 2050 (a net loss of 158,894 km^2). Despite widespread abandonment projected under each SSP, all other climate scenarios projected net increases in total cropland greater than 175% by 2050. As displayed in Table 2-1, the largest amount of new cropland is generated under SSP3. New cropland in this analysis includes the migration of cropland to new lands that were not previously under agricultural production; the recultivation of croplands abandoned between 2015 and 2050 are not considered as new cropland.

Table 2-1: Abandoned and new cropland in 2050 by climate scenario. Urbanized cropland is included in calculating the total cropland abandonment to gain a more complete understanding of global shifts in agricultural land use.

Climate scenario	Non-urbanized cropland abandonment (km^2)	Urbanized cropland abandonment (km^2)	Total cropland abandonment (km^2)	New cropland (km^2)	Net cropland (km^2)
SSP1	3,163,707	145,607	3,309,314	3,150,420	-158,894
SSP2	1,748,083	107,687	1,855,770	3,356,630	1,500,860
SSP3	2,627,198	71,850	2,699,048	4,986,243	2,278,195
SSP4	2,262,644	125,502	2,388,146	4,304,894	1,916,748
SSP5	2,056,045	156,884	2,212,929	4,442,760	2,229,831

2.3 Discussion

Global projections of cropland abandonment, and their overlap with areas of high biodiversity and carbon sequestration potential, can provide useful insight to policymakers and scientists. By allowing stakeholders to visualize these features, our interactive R Shiny App can be a powerful and versatile tool to inform further research and conservation decision-making.

This analysis indicates that high rates of cropland abandonment are projected to occur on lands that are important to preserve global biodiversity (Figure 2-3). For many countries, conserving the land made available by cropland abandonment can help them meet targets set at the Conference of the Parties (COP) 15, the UN biodiversity conference held in Montreal in 2022. At COP 15, nations agreed to four targets and 23 goals to accomplish by 2030 in an effort to reverse biodiversity loss by the end of the decade. These targets include a commitment to protect 30% of the world's lands and waters and for the restoration of at least 30% of degraded lands by 2030 (Kunming-Montreal Global Biodiversity Framework, 2022). Investing in the restoration and protection of abandoned croplands can be an important strategy for nations to reach these targets.

Additionally, this analysis indicates that cropland abandonment will only outpace the development of new cropland under SSP1. All other climate scenarios show a net gain of global cropland, with new agriculture exceeding losses to abandonment (Table 2-1). This could be explained by several factors such as the prevalence of sustainable intensification under SSP1, or its assumption of an accelerated demographic transition, allowing the global population–and therefore food demand–to level off faster than under other SSPs (Riahi et al., 2017). Many other factors incorporated into SSP1 can also explain how more food will be grown on less land. Along with slowing population growth, technological advances, a reduction in food waste, and shifting dietary preferences contribute to a decrease in overall cropland in production (Fitton et al., 2019). Meanwhile, other SSP scenarios must grapple with a rise in food demand of anywhere from 35-56%, 60%, or 100-110% (van Dijk et al., 2021, Alexandratos & Bruinsma, 2012, Tilman et al., 2011). Without the sustainable development trends present in SSP1, this rise in food demand results in an expansion of land area under agricultural production.

Although crop yields will need to rise to meet rising food demand by 2050, the rapid development of new croplands projected in Table 2-1 raises conservation concerns. With rising food demand, an increase in abandoned croplands will mean that new agricultural land must be developed elsewhere at the cost of existing ecosystems (Fitton et al., 2019). Agricultural production is expanding quickly, especially in the tropics of South America and Sub-Saharan Africa (Laurance et al., 2014). This expansion of croplands is a primary cause of deforestation, with 90-99% of deforestation in the tropics occurring in regions where the main driver of tree cover loss is agriculture (Pendrill et al., 2022).

While the analysis shows that some projected abandoned lands have high value for biodiversity and carbon sequestration, other areas with less conservation value may be able to better benefit global environmental health through recultivation or remaining in agricultural production. Revitalizing these projected abandoned lands could reduce the demand for new cropland and deforestation by using already disturbed landscapes to meet food demand.

Certain regions, particularly in the tropics, offer an excellent opportunity for carbon sequestration through the restoration of abandoned lands; there are also areas where very little carbon will accumulate post-abandonment (Cook-Patton, 2020). These regions, which include the central U.S., Central Asia, and parts of Southern Europe, among others (Figure 2-3b), may be ideal candidates to remain under agricultural production so that restoration resources can be directed towards regions where carbon and biodiversity benefits are greater.

Moreover, the commitments made at COP 15 call for reducing the loss of areas of high importance to biodiversity to near zero (Kunming-Montreal Global Biodiversity Framework, 2022). This project can help protect valuable cropland at risk of abandonment by allowing decision-makers to locate and revitalize these lands for agriculture, therefore avoiding deforestation for new agriculture in other areas.

However, avoiding cropland abandonment and revitalizing previously abandoned croplands come with potential complications. As discussed in Chapter 1 of this report, abandonment is caused by many drivers, including socioeconomic considerations such as urban-rural migration and crop price shifts, as well as environmental factors including water availability, topography, and soil quality. While environmental drivers of abandonment may be difficult to overcome, incentive-based programs have the potential to keep croplands in production.

3. Maximizing Benefits of Brazilian Abandoned Cropland

The second stage of our analysis focuses on abandoned cropland in Brazil. Brazil is a crucial contributor to climate resilience due to its vast carbon storage capacity and significance to biodiversity. To support global efforts to safeguard critical regions like the Amazon, we have singled out Brazil as an ideal location to pinpoint areas of projected abandonment that can provide maximum benefits in terms of carbon sequestration and biodiversity if actively restored. Furthermore, President Da Silva's commitment to halting deforestation in Brazil by 2030 further amplifies the importance of our work, as it enables the identification of regions that are most suitable for restoration and where investments in recultivation will be most effective in preventing future deforestation.

3.1 Brazil Background

Brazil is the fifth largest country in the world, spanning 852 million hectares (Mha) across the northern and southern hemispheres (United Nations Statistic Division, 2020). Brazil hosts several distinct biomes: the Amazon (tropical rainforest), Atlantic Forest (coastal rainforest), Caatinga (semi-arid dryland), Cerrado (savanna), Pampa (grassland), Pantanal (wetland), and the coastal area (Fonseca & Venticinque, 2018). These ecosystems are home to 9.5% of the world's total biodiversity, including 19% of the world's flora (Giulietti et al., 2005; Lewinsohn & Prado, 2005). Brazil is also home to the largest portion of the Amazon, which holds 31.5 Gt of irrecoverable carbon–the largest reserve of its kind (Noon et al., 2022).

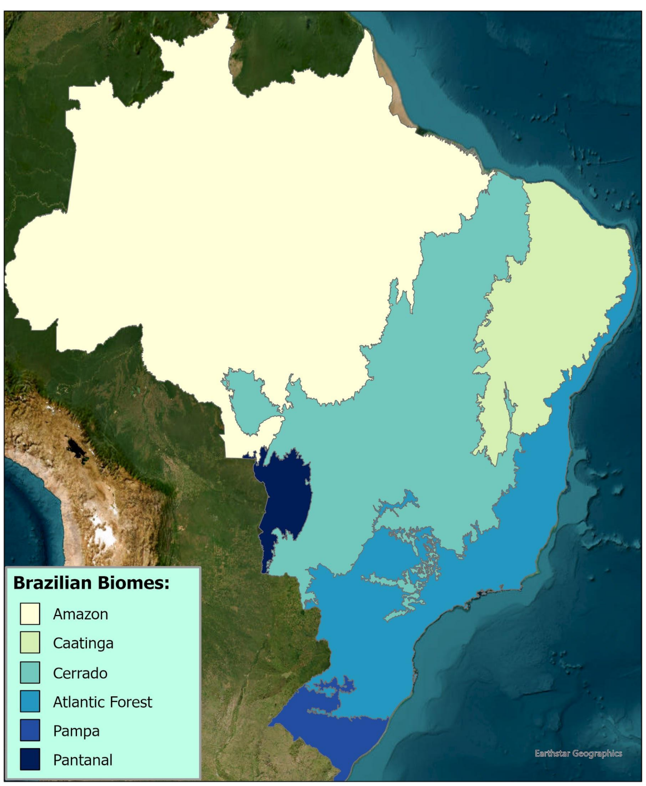

Figure 3-1. Boundaries for Brazil's six biomes.

At the same time, Brazil faces large-scale deforestation, with forest land cover decreasing from 65.9% in 2000 to 59.7% in 2018 (Food and Agriculture Organization, 2018). Most of this land is deforested to establish new fertile agricultural land to replace abandoned degraded parcels (Navarro, 2010). The primary drivers of native vegetation loss in Brazil are conversion to pasture and farmland (Nepstad et al., 2009; Pendrill et al., 2019; Silveira et al., 2022). From 1996 to 2005, Brazil cleared an average of 1.95 Mha of forest annually, releasing an estimated 0.7 to 1.4 billion tons of CO_2 equivalent per year (Nepstad et al., 2009). While the Amazon region lost 44.53 Mha of native forest cover from 1985 to 2020, there is evidence that the pace decreased significantly due to government agency intervention (Silveira et al., 2022). In 2004, trends reversed with the rate of afforestation surpassing deforestation. This is largely attributed to restrictions on credit for illegal deforestors, establishing public registries of properties and municipalities with illegal deforestation, the Soybeans Moratorium, and the Meat Conduct Adjustment Agreement (Nepstad et al., 2014; Rocha et al., 2015; Silveira et al., 2022). The Soy Moratorium in Brazil is an agreement among soybean traders not to buy soybeans produced on newly deforested lands in the Amazon (Nepstad et al., 2014). The Meat Conduct Adjustment Agreement is a similar agreement among meatpackers to avoid sourcing cattle from suppliers engaged in illegal deforestation in the region (Silveira et al., 2022). However, in 2015 deforestation once again increased to surpass afforestation rates. Projections from SSP2 and SSP3 estimate that the Amazon biome will lose an additional 67 Mha of forest cover by 2050. In contrast, SSP1 projects an addition of about 45 Mha of forest vegetation (Bezerra et al., 2022).

As of 2018, 28.3% (237 Mha) of Brazil was cultivated (Food and Agriculture Organization, 2018). In 2020, most high-value crops in Brazil were grown in the Central-West and South of Brazil (Instituto Brasileiro de Geografia e Estatística, n.d.). Despite that, agricultural production in Brazil is a growing industry that impacts all of its biomes. For example, 43% of the Brazilian Cerrado has been converted to agricultural lands as of 2013 (Sano et al., 2019). The Amazon biome saw a dramatic increase in agricultural land from 0.08 Mha in 1985 to 6.06 Mha in 2020 (Silveira et al., 2022). It also saw a 38.1 Mha increase in pastureland due to cattle breeding for beef production, resulting in 13.5% of the biome being occupied by pasture (Silveira et al., 2022; Bergier et al., 2018).

Brazil's snippets of success in preventing deforestation can be credited to its extensive history of federal conservation units, codified by the National System of Conservation Units Law (SNUC) of 2000. Brazil's first protected area, the Parque Estadual de Capital, was established in 1896. Now, federal conservation units cover 8% (69.5 Mha) of the country (Drummond et al., 2009). There are two groups the conservation units fall under: "fully protected" units, dedicated to preserving nature and allowing only indirect use of natural resources, and "sustainable-use" units, combining conservation and the sustainable use of natural resources (Drummond et al., 2009). From the 1980s to the 2000s, 247 of the 287 conservation units were established, protecting some 62 Mha of land (Drummond et al., 2009). Most of these conservation units are in the Amazon biome, and only 3.13% of conservation units protect species-rich transition areas between biomes (Alves Oliveira Silva & Barbosa, 2019). Despite its history of deforestation, Brazil has many existing policy mechanisms that can protect abandoned croplands so they are rewilded without the potential of being degraded again.

3.1.1 Status of Brazilian Environmental Policies

With a complex history of environmental policy dating back to the 1960s, Brazil has a robust system of policies to protect and recover native vegetation in its diverse biomes. However, recent political changes brought damaging reforms to these historic policies. In the past decade, environmental policies like the Forest Code have decreased the amount of private land that must be protected as native vegetation. These policy changes mean that just one individual region of Brazil, the Cerrado, now has about 39 Mha of native vegetation that is not protected from conversion to agriculture; this is more than 3 times larger than Brazil's Nationally Determined Contribution to restore 12 Mha of forest (Soares-Filho et al., 2014). These changes mean less native vegetation is protected under historic laws and could be protected through new protected units or policies.

Other threats to environmental policy come from a lack of international trust following the election of President Jair Bolsanaro in 2019. Countries like Germany and Norway have ended their contributions to the Amazon Fund–a REDD+ mechanism that has disbursed $592 million USD to restoration projects in the Amazon (Bo, 2019). The fund, which currently has $678 million USD, was frozen after Bolsanro removed the fund's governing committee and overseers. The Bolsonaro administration also oversaw the passage of 57 legislative acts that aimed to weaken environmental protections. Additionally, fines for violating environmental laws decreased by 72% during the pandemic, despite an increase in deforestation during this time (Vale et al., 2021). With the reelection of President Lula da Silva in 2022, one of his first actions was to announce Brazil's renewed commitment to ending deforestation by 2030, as well as soliciting countries like the US, UK, and Canada to become contributors to the Amazon Fund once again (Spring, 2022).

3.1.2 Brazil's Environmental Commitments

Table 3-1. An overview of Brazil's environmental commitments and their status.

Policy/Agreement	Target
PLANAVEG (federal)	12 million hectares by 2030
NDC to Paris Climate Agreement	12 million hectares by 2030
Bonn Challenge	12 million hectares
Aichi Target 15 of the Convention on Biological Diversity	Restore 15% of all degraded ecosystems by 2020 (43 mha)
Atlantic Forest Restoration Pact	15 mha of native forest in Atlantic Forest biome by 2050*
COP27	End deforestation by 2030

*Registered 60,000 ha of restoration projects from 2009 to 2018; 1.206 Mha of natural regeneration

3.2 Methods

To determine priority restoration areas in Brazil, we first determined where cropland is projected to be abandoned under the five SSP scenarios. These locations then served as the available planning units for the spatial prioritization of restoration efforts. Along with these planning units, the prioritization software requires the input of the features and cost to be evaluated for each planning unit, specific targets for how much of each feature should be represented in the solution, and a primary objective for solving the problem. Figure 3-2 provides a broad, visual overview of the processes and data inputs used for this analysis. Greater details on how these data were processed and how the spatial prioritization was formulated are outlined below. An additional analysis evaluating the accuracy and precision of the utilized future land use data is included in Appendix C. Sources for publicly available data as well as the code generated to perform this analysis are provided in Appendix D.

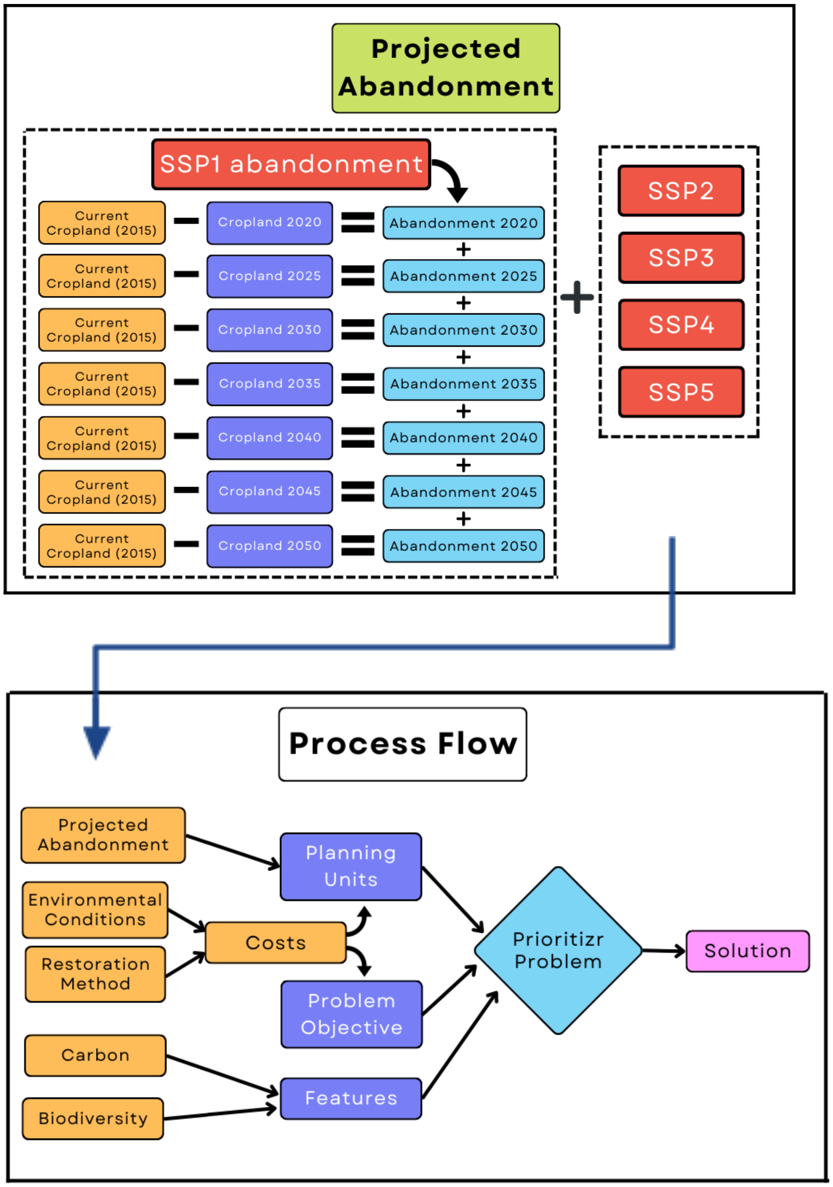

Figure 3-2. The workflow diagram for the overall methods in this study includes a simplified process for generating the final results, as well as an in-depth look into the projected abandonment layer used to create planning units.

3.2.1 Planning Units

1. Determine areas of cropland abandonment:

The planning units represent locations where current cropland is projected to transition to another non-urban use by 2050. As with the global projections of cropland abandonment, these areas were determined using the dataset of projected global land use rasters from 2015 to 2050 at 1 km resolution (Chen et al., 2022). Each SSP scenario contains spatial rasters of projected land use at five-year intervals; unlike the global analysis, the calculation of Brazilian cropland abandonment utilized all seven rasters for each climate scenario to identify any parcel of cropland projected to be abandoned between 2020-2050. Along with the 2015 raster representing “current'' land use, a total of 36 land use rasters were utilized to determine the planning units across five SSP-RCP scenarios.

Using the *terra* package (version 1.6-41) in R, rasters for each SSP scenario between 2020 and 2050, as well as the baseline 2015 land use raster, were clipped and masked from their original global extent to Brazil using boundary data from the Brazilian Institute of Geography and Statistics (IBGE). Each raster was then reclassified to isolate pixels representing cropland and urban land use. All future land use rasters were individually subtracted from the baseline 2015 raster to determine where current cropland will become abandoned.

Because we are interested in identifying abandoned cropland optimal for restoration efforts, planning units cannot represent cropland that becomes urbanized by 2050. Another series of raster calculations and reclassifications removed any projected urban areas from our cropland abandonment rasters. The seven rasters of non-urbanized abandonment for each SSP scenario were then added together; the final result was one raster for each climate scenario representing all parcels of projected cropland abandonment between 2020 and 2050.

In addition to these five rasters, a sixth planning unit raster representing consistent abandonment was generated. This “consistent” climate scenario was calculated by overlaying the five rasters described above and selecting only parcels projected to be abandoned in all five SSP scenarios.

2. Cost:

The value assigned to each planning unit represents the cost of actively restoring that parcel. Restoration cost data were sourced from a report by the Nature Conservancy that calculates the mean price of six different restoration methods depending on location (Brazilian biome) and environmental condition of the land (de Miranda Benini & Adeodato, 2017). This file was first filtered to return only costs for the “conducting natural regeneration” restoration method in unfavorable environmental conditions. This method was selected for most closely mimicking natural vegetation regrowth, which the carbon sequestration data represents. It takes into account important measures such as the removal of invasive species and treatment against pests. Additionally, abandoned cropland tends to be more degraded, fragmented, and small-scale, which reflects the higher restoration costs in the unfavorable environmental conditions scenario. Table 3-2 displays these costs.

The filtered cost data were spatially joined with Brazilian biome shapefiles (IBGE, 2019). These shapefiles were then rasterized and masked to the planning units for each SSP-RCP scenario. The final output was a planning unit raster file for each of the five climate scenarios with pixel values indicating the restoration cost.

Table 3-2. Cost in Brazilian Reals and U.S. Dollars of conducting natural regeneration in unfavorable environmental conditions by Brazilian biome.

Biome	Cost ($R/ha)	Cost ($USD/ha)
Amazon	2,385	449
Caatinga	2,521	474
Cerrado	3,188	600
Atlantic forest	2,940	553
Pampa	2,629	495

3.2.2 Restoration Features

Our prioritization simultaneously evaluates the potential benefits each planning unit provides to protecting biodiversity and sequestering carbon. Data for both features were reprojected, resampled, clipped, and masked to each SSP's planning units to ensure the same resolution and spatial extent. Biodiversity and carbon layers for each SSP were then combined into a raster stack to be utilized as the feature input in the *prioritizr* problem.

1. Biodiversity:
Biodiversity data was sourced from a study mapping global conservation priorities at 5 km resolution based on current and future species distribution models. These models evaluated over 17,000 terrestrial vertebrate species and future bioclimatic variables under the RCP2.6 and RCP8.5 climate scenarios (Roehrdanz et al., 2021). Aggregate extinction risk values were calculated based on the proportion of a species' range conserved, then summed and normalized across all species (Hannah et al., 2020). To maximize the benefits to present and future biodiversity, and therefore reduce the risk of extinction, parcels with higher extinction risk values were prioritized for restoration.

2. Carbon:
The carbon dataset, originally created by Cook-Patton et al. and updated by Global Forest Watch, estimates the carbon sequestration rate in aboveground and belowground biomass during the first 30 years of natural forest regeneration. Spatial sequestration estimates include all forest and savanna biomes in units of MgC/ha/yr at 1 km resolution. Carbon data are missing for most of the Pantanal biome, a large, mainly freshwater wetland in the southwestern portion of Brazil. As a result, this biome was removed from all other feature and planning unit layers.

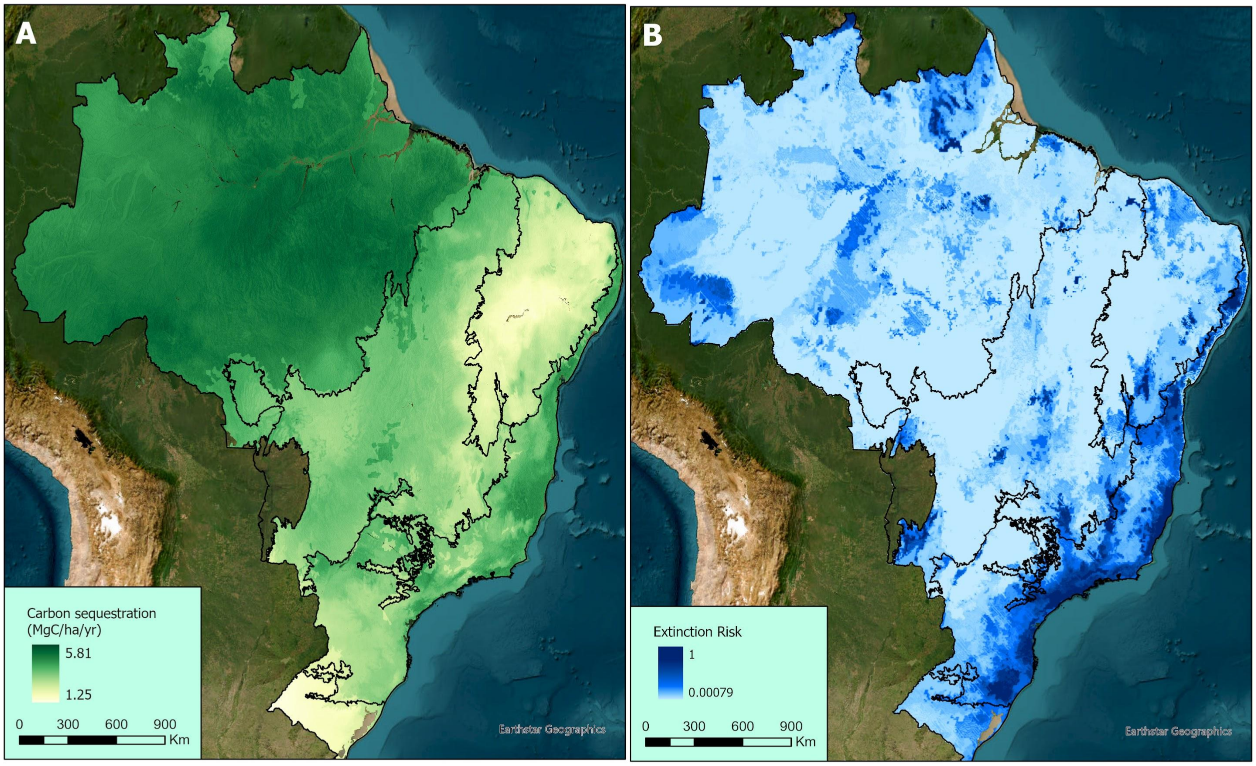

Figure 3-3. Carbon and biodiversity data utilized as features in the spatial prioritization of cropland restoration. Figure 3-3a (left) displays carbon sequestration rates (MgC/ha/yr) which range from 1.25 (light yellow) to 5.81 (dark green). Figure 3-3b (right) displays extinction risk values that range from 7.9e-04 (light blue) to 1 (dark blue).

3.2.3 Budget scenarios

The restoration prioritization model was run under various budget scenarios. The low-end budget was determined by evaluating past allocation and spending by Brazil's Ministry of the Environment. In 2022, the Ministry only utilized 85.8% of its environmental management budget, including restoration costs and associated activities. By applying this ratio to the 2023 budget, restoration efforts could be financed by the potentially unused 455 million Brazilian Reals. The high-end budget scenario of 3.4 billion Reals reflects the current balance of the Amazon Fund. The Amazon Fund can be utilized by nonprofits, universities, international, and government projects that prevent, monitor, and combat deforestation in Brazil.

3.2.4 Prioritization model

The spatial restoration prioritization was computed using the *prioritizr* package (version 7.2.2) in R. This software uses mixed integer linear programming and provides greater flexibility in building and solving spatial planning problems than similar conservation tools, such as Marxan (Beyer et al., 2016). A separate problem was formulated for each SSP scenario and their associated planning units and features data. Because this analysis only considers areas of non-urbanized abandoned cropland for restoration, no planning units were locked in or out of the solution.

Each problem utilized a minimize shortfall objective, in which the solution minimizes the overall target shortfall across all features while not exceeding a specified budget. Biodiversity and carbon were weighted equally, and relative targets were set to 0.5 each (50% feature conservation). Each SSP problem was run under both low and high-budget scenarios. After formulation, each problem was solved using Gurobi Optimizer (version 9.5.2) with a 0.05 "gap to optimality"; this value represents a 5% accepted deviance from the optimal solution, reducing computational requirements.

3.3 Results

The number of parcels predicted to be abandoned (available planning units), the number prioritized for restoration, the percent of targets met per climate scenario, and budget are presented in Table 3-3. Across the five SSP scenarios, the average amount of projected abandonment in Brazil is 271,830 km^2 ± 46,743 km^2 (mean ± standard deviation) with a range of 139,398 km^2 between the highest (SSP4) and lowest (SSP2) projections. The mean number of parcels prioritized for restoration with a high-end budget is 11,754 km^2 ± 83 km^2, while the low-end budget resulted in an average of 1,577 km^2 ± 2 km^2 (mean ± standard deviation).

The bottom row of Table 3-3 indicates our sixth "consistent" climate scenario, in which 123,883 km^2 of cropland are projected to become abandoned by 2050 regardless of SSP. The number of these parcels selected for restoration with a high budget is 12,188 km^2, greater than any individual climate scenario. Figure 3-4 graphically displays the amount of projected abandonment and restoration from Table 3-3. Additionally, Figure 3-5 illustrates where abandonment is consistently projected to occur by 2050 in comparison to current cropland.

Table 3-3. Counts of planning units available, those selected for restoration, and feature values held in each climate scenario. Planning units are 1 km^2 in size.

Climate Scenario	Planning units available (n)	Budget	Planning units selected (n)	Carbon		Biodiversity	
				carbon held (MgC/ha/yr)	percent total	biodiversity held (avoided extinction risk)	percent total
SSP1	268,654	Low	1,576	6,344	0.64%	815	6.49%
		High	11,746	43,687	4.39%	3,641	29.00%
SSP2	214,596	Low	1,575	6,264	0.78%	780	7.67%
		High	11,883	44,755	5.57%	3,405	33.50%
SSP3	242,908	Low	1,579	6,285	0.69%	812	7.05%
		High	11,790	43,973	4.86%	3,589	31.20%
SSP4	353,994	Low	1,576	6,238	0.48%	858	5.31%
		High	11,630	42,324	3.25%	3,921	24.30%
SSP5	278,997	Low	1,581	6,264	0.61%	845	6.35%
		High	11,720	43,214	4.19%	3,797	28.50%
Consistent	123,883	Low	1,573	6,120	1.28%	713	11.50%
		High	12,188	47,416	9.90%	3,111	46.10%

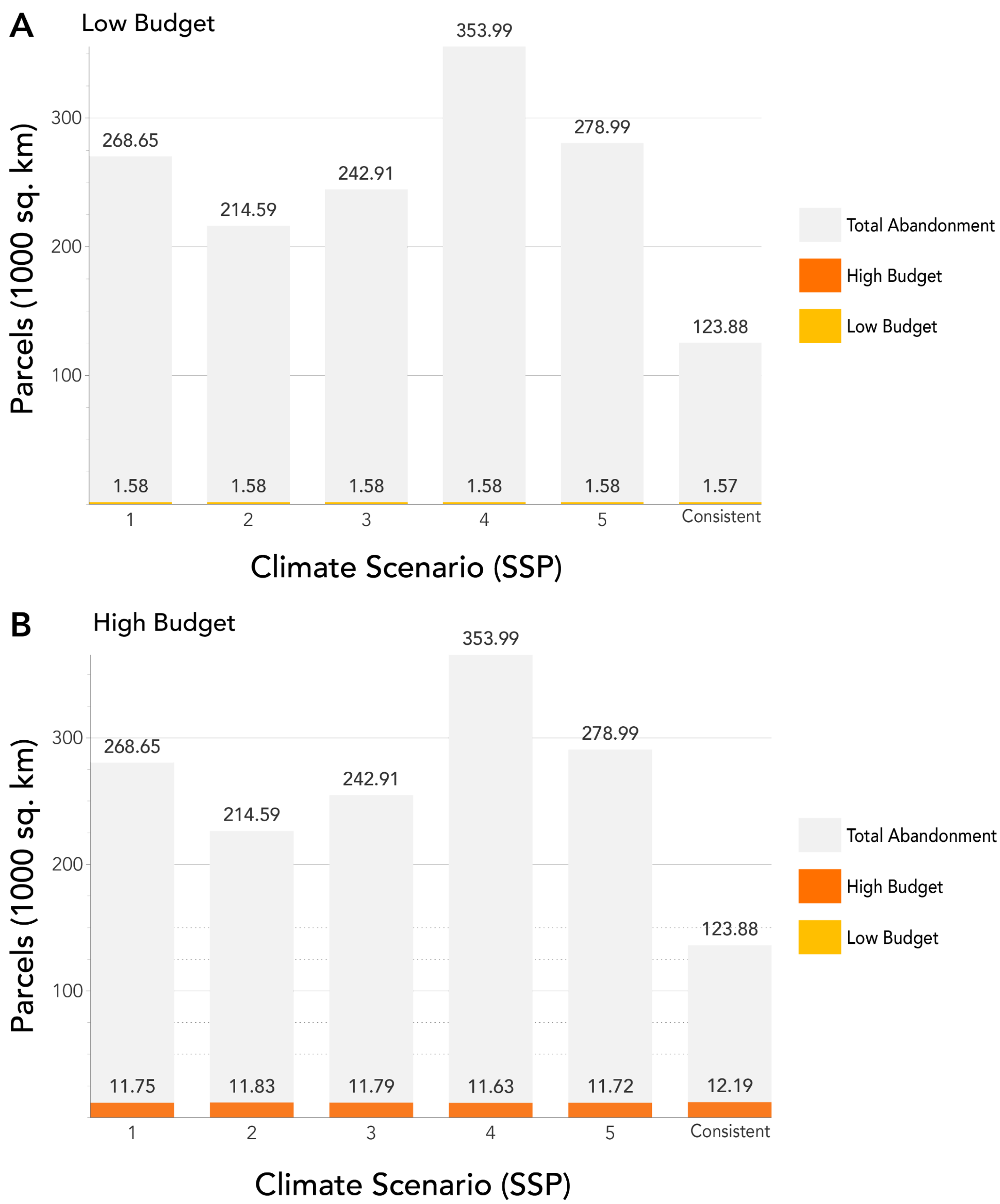

Figure 3-4. Projected cropland abandonment and number of parcels selected for restoration for each climate scenario. Figure 3-4a (top) shows the number of parcels prioritized for restoration with a low budget in yellow, while Figure 3-4b (bottom) shows the number of parcels selected with a high budget in orange.

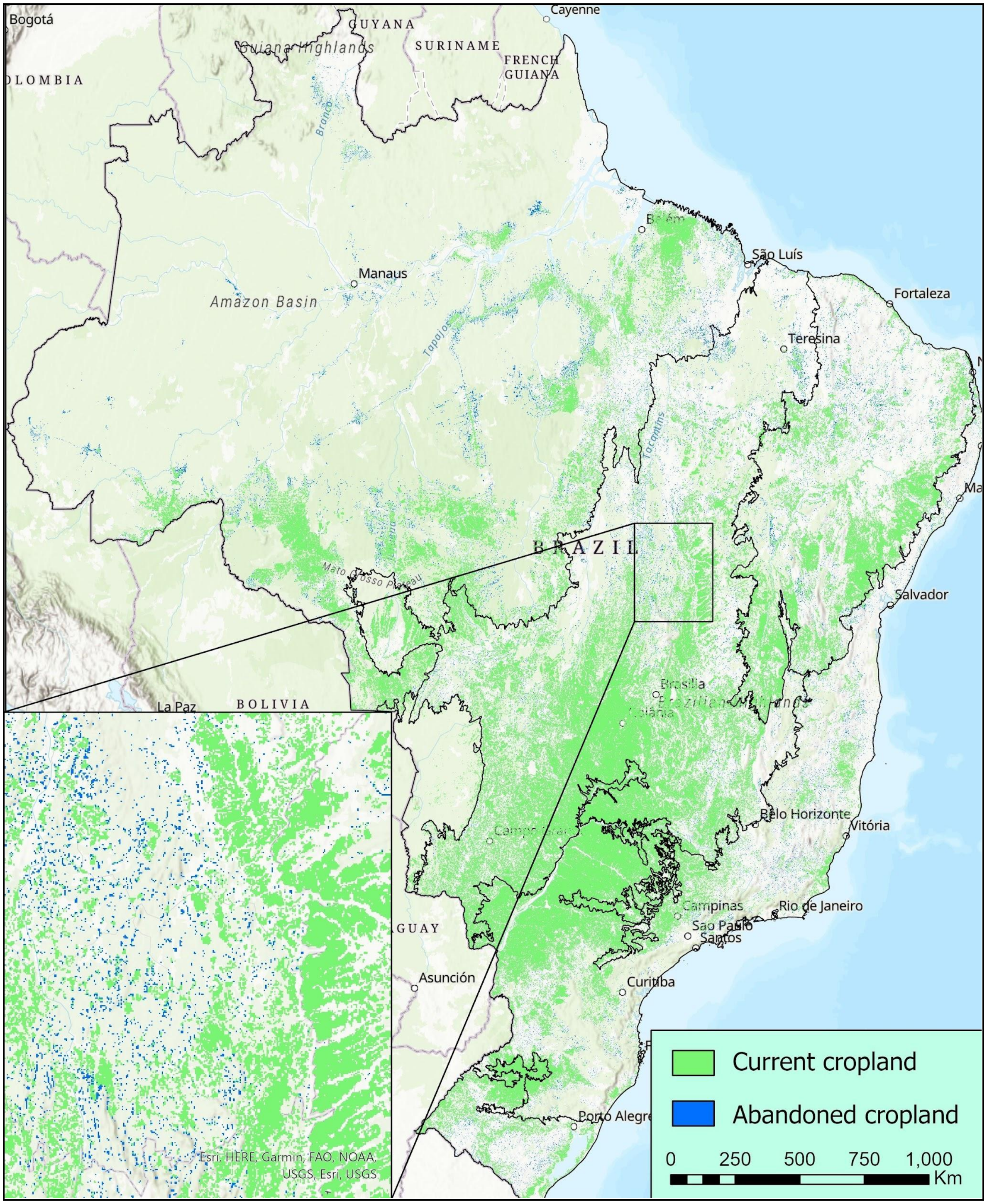

Figure 3-5. Current cropland (green) and projected cropland abandonment (blue) between 2020-2050 for the Consistent climate scenario. The inset map highlights cropland within the Cerrado biome.

Considering variation by biome, Tables 3-4 and 3-5 provide greater context for the spatial variation of projected abandonment and where parcels were prioritized for restoration, respectively. Figure 3-6 displays the difference in parcel fragmentation between the Amazon and Atlantic Forest, the two biomes with the highest numbers of projected abandonment and prioritized restoration.

Table 3-4. The number of planning units available in each biome by climate scenario.

Biome	SSP1	SSP2	SSP3	SSP4	SSP5	Consistent
Amazon	97,992	82,506	91,636	126,438	102,521	53,401
Caatinga	43,471	34,571	39,701	58,719	48,533	18,841
Cerrado	77,673	59,092	67,266	105,339	74,824	29,576
Atlantic Forest	39,763	31,501	35,982	50,746	43,159	18,587
Pampa	9,755	6,926	8,323	12,752	9,960	3,478
Total	268,654	214,596	242,908	353,994	278,997	123,883

Table 3-5. The number of planning units selected as a restoration priority by climate scenario and biome under a high-end budget.

Biome	SSP1		SSP2		SSP3		SSP4		SSP5		Consistent	
	high	low	high	low	high	low	high	low	high	low	high	low
Amazon	1,205	259	1,791	246	1,366	262	691	235	926	266	3,007	269
Caatinga	864	141	856	149	891	155	862	183	914	170	869	116
Cerrado	2,041	107	1,782	104	1,919	105	2,255	129	1,795	112	1,093	126
Atlantic Forest	7,603	1,069	7,367	1,076	7,587	1,057	7,795	1,029	8,062	1,033	6,991	1,062
Pampa	33	0	87	0	27	0	27	0	23	0	228	0
Total:	11,746	1,576	11,883	1,575	11,790	1,579	11,630	1,576	11,720	1,581	12,188	1,573

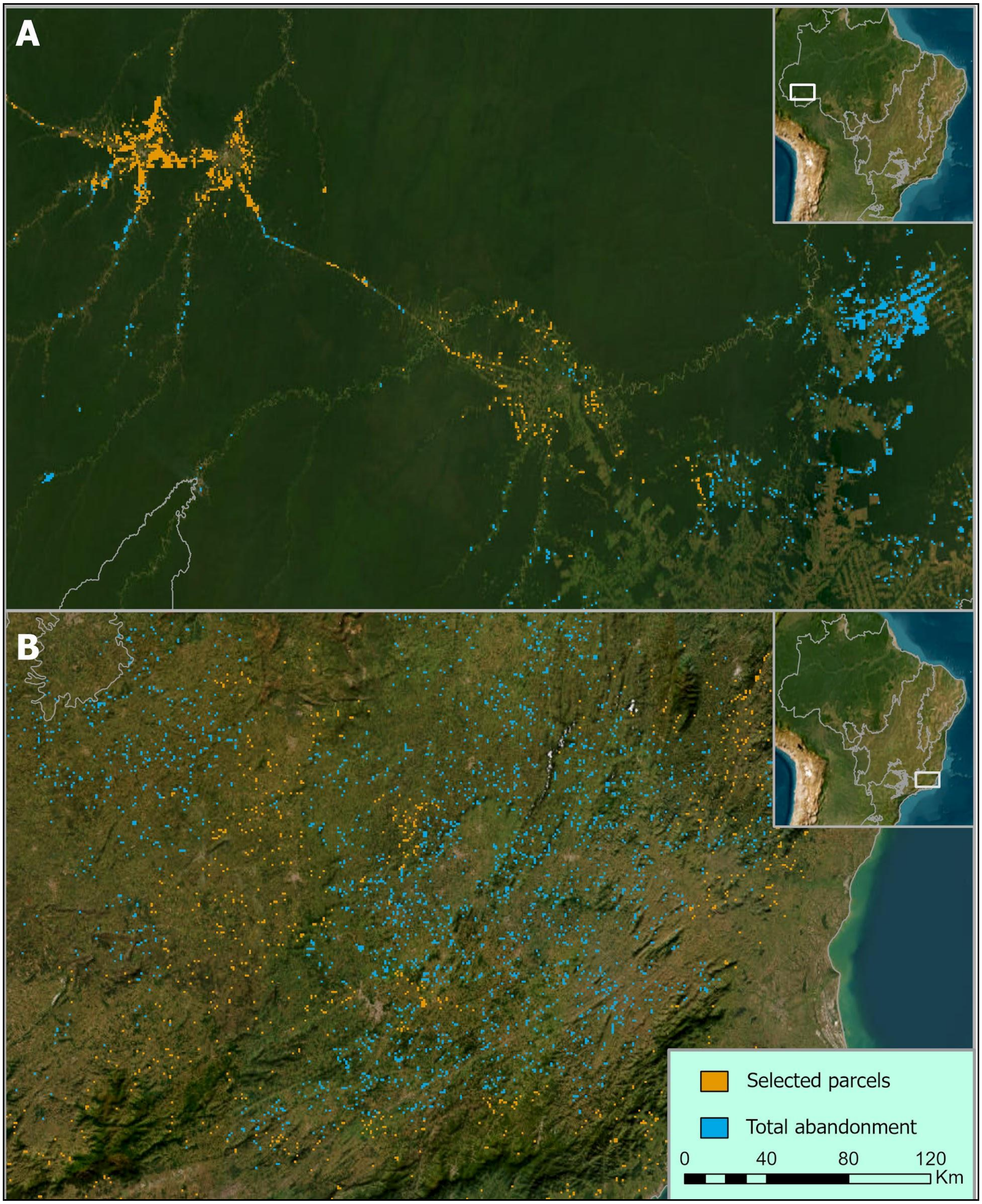

Figure 3-6. Parcels projected to be abandoned between 2020-2050 under the Consistent climate scenario. Orange pixels represent parcels prioritized for restoration with a high budget, and blue pixels are unselected abandoned parcels. Figure 3-6a (top) highlights an area of the Brazilian Amazon where restoration priorities and projected abandonment are relatively concentrated. Figure 3-6b (bottom) highlights the more fragmented parcels available within the Atlantic Forest biome.

3.4 Discussion

The prioritization model results indicate that budget constraints limit the potential restoration of abandoned croplands. Across all SSP scenarios, an average of 271,830 km^2 of cropland is projected to be abandoned–more area than the country of France. The high-end budget scenario examined in our model can only facilitate the restoration of about 11,750 km^2, 10% of Brazil's 12 mha goal for restoration. Our prioritization tool can serve as a framework for restoration decision-makers to inform which areas offer the highest value to carbon sequestration and biodiversity. It is paramount that policies discussed in Chapter 4 be used to revitalize and incentivize projected abandoned lands to remain under agricultural production where possible. While it may be difficult to overcome the drivers of abandonment in some regions, encouraging projected abandoned lands to remain as croplands where possible can help limit deforestation for new agricultural production elsewhere. Meanwhile, the results from this prioritization model can identify areas that may be better used for conservation rather than continued agricultural use. This is especially important considering the risk of continued land conversion in ecosystems essential to global carbon sequestration and biodiversity, like the Amazon and Atlantic Forest.

Table 3-3 shows that the amount of projected cropland abandonment differs significantly among SSP scenarios. SSP2 contains the least abandoned parcels (214,596 km^2), while SSP4 contains the greatest (353,994 km^2). The 65% increase in projected abandonment from SSP2 to SSP4 may be explained by how land use projections vary between climate scenarios. SSP2, or the "Middle of the Road" pathway, envisions a future where socioeconomic and technological trends remain similar to current and historical patterns (Popp et al., 2016). SSP4, dubbed a "Road Divided," predicts a future fraught with increasing socioeconomic inequalities both within and between countries; this leads to increases in crop yield in high-income countries but unproductive agriculture and increased deforestation in lower-income countries (Popp et al., 2016). Despite this variance in available planning units (standard deviation of 46,743 km^2), the number of parcels selected for restoration in each SSP solution remains much more consistent (standard deviation of 83 km^2 and 2 km^2 for high and low budgets, respectively). This displays how monetary constraints largely limit restoration goals, as the number of parcels selected for restoration remain low under all SSPs regardless of the total area of available land.

The restoration of abandoned lands in Brazil offers opportunities to maximize the benefits of rural land conservation, carbon sequestration, and biodiversity conservation. However, policies that provide long-term protection of projected abandoned lands are crucial to ensure these benefits, and mechanisms like the private natural heritage reserve program can be utilized to ensure long-term protection. Nonprofits can also promote expanding this program to include more conservation planning and monitoring. The prioritization model results indicate that the budget constraints limit the potential restoration of abandoned croplands, but the prioritization tool can serve as a framework for restoration decision-makers to inform which areas offer the highest value to carbon sequestration and biodiversity. These policies and mechanisms can help Brazil achieve its climate targets while maintaining biodiversity and other ecological attributes.

4. Agricultural Abandonment Policies

Agricultural land abandonment is a global phenomenon with significant implications for biodiversity, climate mitigation, and human well-being. While some policies, such as the European Union’s Common Agricultural Policy (CAP), acknowledge the threat of agricultural land abandonment, few policies or frameworks aim to find beneficial uses for these lands. This chapter will discuss the current landscape of global policy regarding abandoned agricultural lands and the tradeoffs in designing environmental and agricultural policies that complement one another to benefit biodiversity, carbon, and human well-being.

4.1 Global Policy Comparisons

The EU has several policies, including CAP, that intend to minimize agricultural abandonment. In the case of CAP, the policy supports farmer livelihoods to prevent agricultural land abandonment through income support for farmers, rural development programs, and market measures (European Commission, 2022; Keenleyside & Tucker, 2010; Renwick et al., 2013). Despite efforts to prevent abandonment, the EU is projected to lose 3% (4.8 Mha) of its 2015 agricultural land by 2030 (Perpiña Castillo et al., 2021). EU policies only acknowledge the potential of abandoned agricultural lands for climate mitigation but do not provide frameworks for beneficial land use in these areas (Fayet et al., 2022b).

The lack of land planning tools, communication with local populations, and economic uncertainties contributed to the failure of CAP to prevent land abandonment (Fayet et al., 2022b). In contrast, policies that promote biodiversity, such as the EU's Birds and Habitats Directives, have facilitated nature conservation more effectively than agricultural policy (Fayet et al., 2022b). Expert interviews also suggest recognizing the value of public goods that farmers and landowners provide for nature protection. EU policies like CAP currently hinder conservation initiatives by providing large economic incentives for agriculture, disincentivizing other programs that promote biodiversity and carbon sequestration. This reveals that land-owning farmers are primarily motivated by these economic policy mechanisms (Fayet et al., 2022b). To promote optimal land use for agriculture, policies like CAP could provide less support to large-scale farming and the acquisition of chemical products and instead finance rural citizens to dedicate parts of their land to nature.

However, studies from China have demonstrated that institutional support can be unsuccessful in preventing agricultural abandonment. In contrast, informal finance from relatives and friends can successfully incentivize farmers not to abandon their lands (Du et al., 2019). Agricultural credits provided by banks and loan institutions struggled to reach rural Chinese populations, while informal microfinancing significantly negatively affected farmland abandonment (Du et al., 2019).

Unlike the EU, Brazil has agricultural policies that have unintentionally resulted in the abandonment of marginal croplands. While EU policy attempts to support the preservation of small-scale farming, countries like Brazil employed policies in the 1960s that consolidated large amounts of farmland to a small group of owners (Calaboni et al., 2018; Navarro, 2010). Brazil experienced deforestation in the mid-20th century, followed by reforestation in rural areas largely because of agricultural policy. The creation of programs like the Rural Credit Subsidy System (RCSS) and the National Program of Alcohol (Proálcool) instigated the consolidation of farmland in rural parts of São Paulo. RCSS prioritized export crop production, which excluded small and medium farmers from agricultural modernization. Proálcool reinforced the exclusion of staple crop farmers by funding research on the development of biofuels (Navarro, 2010).

Due to increased access to agricultural intensification technology, São Paulo's rural population decreased from 43% to 14% between 1950 and 1980 (Calaboni et al., 2018). The consolidation of land for agro-industry led to rural-urban migration and further isolated communities from development (Calaboni et al., 2018). While agricultural policy impacted rural livelihoods, it also set the scene for an agricultural transition in São Paulo from extensive to intensive agriculture. This change created space for reforestation, where agricultural land was abandoned (Calaboni et al., 2018). This transition is described as "forest transition theory"–deforestation rates slow or even reverse when development becomes less dependent on the primary sector (Mather & Needle, 1998). Agricultural policy in the state of São Paulo negatively impacted small and medium farmers' well-being but facilitated reforestation on land that consolidated farms left to natural succession.

Brazil restored native habitats in abandoned marginal agricultural areas through agricultural policy and laws that establish environmental protections and simultaneously drive the creation of new cropland. Forest transitions are often driven by industrialization policies that promote rural-urban migration, the concentration of modern agriculture on flatter and fertile lands, and the abandonment of marginal lands (Rudel et al., 2005). The transition to reforestation in Brazil's state of São Paulo was also supported by the Brazilian Forest Code (BFC). Adopted in 1965, BFC promoted reforestation by requiring landowners to maintain a percentage of their properties in native vegetation and preserve native vegetation on slopes steeper than 45°, hilltops, and riparian areas (Calaboni et al., 2018). Despite secondary forest growth on abandoned lands, primary forests continued to be deforested for new agriculture (Calaboni et al., 2018; Ferraz et al., 2014). Primary forest loss is largely attributed to increased sugarcane production in which farmers burn fields before cultivation, leading to large-scale forest fires that degrade old-growth forest health (Ferraz et al., 2014). The policy that led to reforestation in São Paulo also led to environmental degradation that impeded ecosystem service demands. These tradeoffs reveal the importance of designing environmental and agricultural policies that complement one another to substantially benefit biodiversity, carbon, and human well-being when considering abandoned lands.

China's Grain for Green Program (GFGP) is the world's largest reforestation program. Instituted in 1999 to control soil erosion, GFGP provides direct cash payments to rural households to re-establish forests and grasslands on sloped croplands. By 2013, GFGP led to 27.8 million hectares of regrown forests at the cost of $46.9 billion USD. GFGP forests are largely monocultures or simple mixed forests. These forests are often timber, tree fruits, or other cash crops planted with production as the intended use (Hua et al., 2016). While active restoration under the GFGP was not conducted with conservation as the primary goal, the program has increased carbon sequestration in southern China, with the magnitude dependent on a region's specific land use land cover change (Hu et al., 2021). However, due to the tendency for GFGP forests to be monocultures, the biodiversity of bird species has shown net losses (Hua et al., 2016).

Europe, China, and Brazil's ecological policies have led to varied reforestation levels over the past few decades. Moreover, the predominantly non-forest ecosystems in many European regions facing abandonment require more active management to increase biodiversity (Fayet et al., 2022a; Isbell et al., 2019; Renwick et al., 2013). Importantly, agricultural abandonment is often influenced by a positive feedback loop: the relative decline of working opportunities leads to out-migration, which causes diminishing levels of public and commercial services, leading to further migration and further decreases in services. Due to this positive feedback and the need for active management in most ecosystems, policies that consolidate agricultural land into areas that are the least attractive for carbon sequestration and biodiversity while other policies promote the value of public goods from natural systems lead to the best optimization of agricultural abandonment.

4.2 Potential Policy Mechanisms in Brazil

Considering the budget limitations of restoration projects, several recommendations can be made for nonprofits to promote the development of existing restoration mechanisms. Programs in Brazil for rural land conservation, expanding protected areas, and improving native nursery infrastructure offer opportunities to maximize the benefits of restoring abandoned lands. Policies that provide long-term protection of projected abandoned lands chosen for restoration are also important to ensure benefits to biodiversity and carbon sequestration occur, considering the need for abandonment to persist for at least 50 years to see benefits to carbon sequestration and potentially longer for biodiversity (Crawford et al., 2022; Rozendaal et al., 2019). To maximize the potential benefits, there are several mechanisms that nonprofits can utilize to ensure long-term protection.

One of the most attractive protection methods for private lands is the private natural heritage reserve program (reserva particular do patrimônio natural) in the Brazilian Forest Code. This program creates tax incentives (i.e., exemption from the Rural Territorial Tax) for private landowners to convert their lands to permanent private areas. This system could be successful in regions like the Atlantic Forest, where projected abandonment and selected parcels for conservation occur in a fragmented pattern. While large protected areas offer many benefits to carbon sequestration and biodiversity, private reserves would require little governmental investment, allowing environmental management budgets to focus on protecting areas with concentrated potential benefits, like the Amazon forest. These private reserves allow the sustained use of renewable environmental resources while maintaining biodiversity and other ecological attributes.

Many current reserves are private from the public but open for research and conservation efforts. The largest number of these reserves are found in the state of Bahia, in the Atlantic Forest–emphasizing their success at conserving land in the areas the program can be most effective. However, our projections also revealed that cropland persists within these existing reserves and that some of these lands may be abandoned. This likely concerns the lack of cohesive conservation plans required by the private natural heritage reserve system (Rodrigues et al., 2011; Joly et al., 2014). Nonprofit organizations can promote expanding the private natural heritage reserve program to include more conservation planning and monitoring to ensure private reserves do not illegally cultivate crops on their lands. There also is an opportunity to target selected parcels with high carbon sequestration and biodiversity potentials to join the private natural heritage reserve program.

An additional obstacle arises from limited native species seed stocks–an important issue considering the high levels of endemic species found in Brazil's diverse biomes. There is limited availability of native species nurseries outside of the Atlantic Forest, posing issues for active restoration efforts in other regions. These challenges to improving biodiversity are exacerbated by a focus on commercial reforestation in many projects, which produces limited biodiversity through monocultures (Melo et al., 2013; Moreira da Silva et al., 2017). Areas like the Amazon have significantly less diversity of native seedling resources compared to the Atlantic Forest, which is exacerbated by seed collection in protected areas being illegal. Previous research has shown that hiring local landowners in the Amazon to procure native seedling stock is highly effective, with locals producing 78 native tree species for nurseries. In contrast, commercial operations were limited to 9 species (Moreira da Silva et al., 2017). The Atlantic Forest, in contrast, has the most robust stock of diverse, native species thanks to the Atlantic Forest Restoration Pact, which built out more diverse nurseries by connecting local seed collectors, nonprofits, and commercial companies.

Finally, it's important for nonprofits to persuade foreign governments to invest in the Amazon Fund and similar restoration efforts to increase opportunities for conservation. The solutions from our prioritization favor concentrated restoration of lands in the Amazon. However, bringing future abandoned cropland into healthy protected areas will require long-term planning and management, as well as sufficient funds–demonstrated by the budget limitations of the model. Increasing investments in restoration and resilience can bring Brazil closer to the climate targets they are committed to.

Nonprofits can be essential in promoting the empowerment and expansion of existing restoration mechanisms to maximize the benefits of restoring abandoned lands in Brazil. The private natural heritage reserve program offers an attractive protection method for private lands. Meanwhile, improving native nursery infrastructure and promoting foreign investment in restoration funds can help increase the availability of native species and secure long-term protection. Implementing these recommendations can help Brazil achieve its climate targets while maintaining biodiversity and other ecological attributes.

4.3 Conclusion

This chapter highlights the potential of agricultural policies to lead to land abandonment as well as the challenges to minimizing abandonment through policy. The EU's policies, like CAP, intend to prevent agricultural abandonment but do not always succeed. Moreover, the policies lack frameworks to leverage abandoned lands for their potential benefits to biodiversity and carbon sequestration. Meanwhile, Brazil's history of agricultural policy from the 1960s demonstrates the potential for policy to produce marginal cropland abandonment without considering the phenomenon. The history of agricultural land abandonment policies emphasizes the importance of designing environmental and agricultural policies that complement each other to provide substantial benefits to biodiversity, carbon, and human-wellbeing while considering the potential of abandoned lands. Bringing attention to the scale of cropland abandonment and existing policies that can bolster the strategic use of those lands are necessary to support sustainable land use transitions.

5. Conclusion

5.1 Limitations

Our global projections of cropland abandonment examined the difference between a baseline 2015 cropland layer and a future projection layer in 2050. However, it is possible that land became abandoned sometime between 2015 and 2050 but was re-cultivated for crops before 2050. This would not show up in our global projections. Additionally, the analysis does not show when in that 35-year window the cropland became abandoned.

In some regions, our future projections of cropland abandonment were highly fragmented, with very little connectivity between parcels projected to be abandoned. This lack of connectivity limits the efficacy of prioritizing lands for conservation goals, especially preserving biodiversity. If an abandoned parcel is reforested but is surrounded by lands still being used for agricultural processes, there may be no way for native species to move back into and repopulate newly restored land. Moreover, this limits the potential to create new conservation networks, or to expand existing protected areas, since fragmented parcels will often be isolated by private croplands.

Additionally, our data coverage for carbon sequestration rates had incomplete coverage within Brazil. The Pantanal region, which contains high levels of irrecoverable carbon, is missing from our carbon accumulation potential dataset. This discourages the Prioritizr model from selecting parcels within the Pantanal for restoration, even if they may have high value for carbon sequestration.

Finally, an original intention of our research was to incorporate the impacts of cropland abandonment on human well-being. While the effects of abandonment on people are imperative to understand, it was not feasible to responsibly incorporate a quantitative measurement of human well-being that added valuable insights to our projections and prioritization. Considerations regarding human well-being are explored further in our literature review in Appendix A.

5.2 Future Research

Many unanswered questions remain about agricultural abandonment and its implications for biodiversity and carbon sequestration. This analysis focused only on croplands, given that our land cover data (Chen et al., 2022) did not distinguish between grasslands and pasture. The inability to distinguish between the natural and altered land uses means we removed the effects of pasture entirely from the analysis. With the availability of future land cover data sets, all agricultural land, including both cropland and pasture, could be included in a similar prioritization. Additionally, future research should analyze potential trends and differences in abandonment rates by crop type. Depending on the dominant pre-abandonment crop type, soil quality and restoration costs may vary.

Moreover, future work could also include inputs into the Prioritizr model that consider the connectivity of parcels when making selections. This would place heightened value on habitat connectivity, since restoring isolated parcels may not be as meaningful as the restoration of lands adjacent to already existing reserves.

Our global projections of cropland abandoned focused on a single time horizon (2050). Future research should examine how abandonment differs in the near term (2030) and the long term (as late as 2100), for which data coverage exists. This would give a more complete picture of the progression of abandoned land over time, and provide more insight for land managers attempting to prioritize specific parcels of abandoned land based on their goals.

5.3 Abandoned Cropland's Role in Conservation

Abandoned cropland can play an essential role in meeting global conservation goals, with a range of 1.8 to 3.3 million km^2 of land projected to be abandoned depending on the climate scenario. How cropland abandonment is addressed will vary regionally, as the amount of projected abandonment differs by SSP and area of interest. Globally, SSP1 ("Sustainability") had the highest amount of projected abandonment and was the only climate scenario with a net loss of cropland by 2050. All other scenarios project net cropland growth, which emphasizes the importance of targeting regions threatened by abandonment to decrease land use change from native vegetation to cropland.

Within Brazil, however, SSP4 resulted in the highest projected abandonment. This underscores the socioeconomic nature of the SSP-RCP coupled climate scenarios and its influence on future land use changes. The scale of "consistent" abandoned parcels across all SSPs is roughly the same amount of land Brazil set to restore (12 Mha), indicating that regional restoration and conservation goals could potentially be met by leveraging cropland abandonment.

Additionally, the net effect of cropland abandonment differs between regions. In Europe, abandonment has largely negative effects as gains to biodiversity are slim to none as wildlife there has co-evolved with human-altered landscapes, and carbon sequestration potential is low. However, in the neotropics, abandonment can help restore more recent losses to biodiversity and carbon.

Our Brazil case study's prioritization model found that budget constraints limit the potential restoration of abandoned croplands. Policy should target lands to remain as agriculture while also using the results from this prioritization model to identify areas that may be better used for conservation than continued agricultural use. Nonprofits can pursue restoration by promoting the expansion of existing restoration mechanisms to provide long-term protection of restored abandoned lands, like Brazil's program for rural land conservation, expanding protected areas, and improving native nursery infrastructure. Additionally, nonprofits can build capacity for restoration by encouraging foreign governments to invest in the Amazon Fund and similar restoration funds.

Existing policies and movements to increase funding for restoration offer opportunities to bring these lands into preserved status. There also is a need to improve the monitoring and enforcement of strategies that rely on community and private landowner cooperation to ensure conserved lands are not disturbed by further land use change.

Appendices:

A. Human well-being

It is essential to consider human well-being when discussing agricultural lands and their potential use change into restoration and conservation areas. Productive agricultural lands are necessary to feed the world's people. Land abandonment and the restoration of abandoned land has the potential to contribute to nature-based ecosystem services such as carbon sequestration. In many regions across the globe, the well-being of present and future generations depends on the continuous flow of these ecosystem services (Pereira et al., 2005). Thus, the many tradeoffs between continued cultivation and land abandonment are complex and situational, and depend on the human well-being factors considered. A systematic review in the Mediterranean region found abandoned lands had mostly mixed or negative impacts on quality of life metrics such as food security, social relations, and property rights (Quintas-Soriano et al., 2022). With uncertain results, there remains a knowledge gap in land abandonment's impact on human well-being. However, other metrics defined in landmark human well-being studies such as Nature Dependent People and Nature's Contribution to People offer insight into the impact land abandonment may have on socio-economic factors (Fedele et al., 2021, Quintas-Soriano et al., 2022).

Revegetation of abandoned cropland can impact human well-being in different ways. Two pivotal studies have quantified natural lands' impacts on human well-being. In both studies, rewilding of abandoned lands was used to restore interactions between nature and humans. Eighty-seven percent of the global population benefits from local critical natural assets such as nitrogen retention, fuelwood production, and access to nature. In Brazil, 98.7% of people benefit from significant natural assets (Chaplin-Kramer et al., 2022). Ecosystem services such as coastal protection, water quality regulation, coastal risk reduction, and crop pollination were additional natural assets that benefit human well-being when intact (Chaplin-Kramer et al., 2019; Fedele et al., 2021).

One method to measure the importance of the health of the local environment and human well-being is to consider the level of dependence individuals have on the environment for livelihood and survival. A study on "nature dependent people" finds that 1.2 billion people in tropical countries–30% of their population–are highly dependent on nature for fulfilling basic human needs such as housing materials, drinking water, fuel for cooking, and for a main occupation (Fedele et al., 2021). This study can inform specific regions in the Neotropics to focus on the impacts of land abandonment by identifying localized concentrations of nature-dependent communities. It is estimated that 5.2% of the Brazilian population, or 11,489,639 people, rank as high or very high in nature dependence indicators (Fedele, et al., 2021). This study also claims that high nature dependent countries tend to have lower human development ranking. This aligns with other studies that demonstrate that high direct use of natural resources is usually associated with communities of people who have limited market access, high poverty rates, and strong cultural ties to nature (Berkes et al., 2001; Angelsen et al., 2014). Considering these studies, reforesting abandoned lands and restoring nature to people who depend on it can address global environmental justice issues.

The assessment on nature dependent people across the tropics provides a foundation for human well-being metrics in three categories: universal need satisfiers (Gough, 2015), basic materials for good life (Millennium Ecosystem Assessment, 2005), and social foundations (Raworth, 2012). Respectively, these indicators include factors for adequate nutritional food and water, protective housing, economic security (Gough, 2015), adequate livelihoods and income, access to energy (Millennium Ecosystem Assessment, 2005), and sanitation (Raworth et al., 2012).

B. Reforestation Reflections in Monteverde, Costa Rica

Regardless of where future projections on agricultural land abandonment are, human impact considerations are essential to consider and evaluate. One way to evaluate potential human impacts associated with agricultural land abandonment is to assess the characteristics and values of farmers who voluntarily have decided to reforest (and therefore retire part of their agricultural land). With the knowledge that agricultural abandonment will occur in the future, understanding the institutions that influenced those who already abandoned their agricultural land is invaluable.

With this in mind, our group sought to investigate the motivations, costs, and benefits farmers have for participating in a voluntary reforestation program with the Monteverde Institute in Costa Rica. The results show that increased participation in the program may be correlated to farmers who own relatively flat land, rely minimally on their land for their main income, and farmers who seek to block wind and preserve their natural water resources. These findings provide trends that can inform best practices for future restoration projects with similar demographic and geographic characteristics, as well as advise the Monteverde Institute on how to improve their program participation and better meet the interests of their active participants. Additionally, this case study promotes the importance of understanding the needs of a community and working with local individuals to create restoration programs that benefit both the environment and the people whose livelihoods are intertwined with the land.

Figure B-1. Report author Michelle Geldin speaking to a farmer in front of the voluntarily reforested plot of their land near Monteverde, Costa Rica.

B.1 Background

Demographic History of Monteverde

Indigenous peoples lived in the Monteverde region for thousands of years until European contact, colonization, and war waged by European settlers largely decreased their population. In the early 1900s, a small number of Costa Rican settler families arrived in the Monteverde area. They cleared forests to create areas for cattle farms and small-scale croplands (Davis, 2009).

In 1951, a group of 41 Quakers migrated from the United States to the sparsely populated Monteverde region. These Quakers were seeking refuge from a home country whose participation in war went against their beliefs. As Costa Rica had recently abolished their military, the group decided Costa Rica would be their new home. Similar to the Costa Ricans in the area, the Monteverde Quakers raised cattle and crops (Davis, 2009).

Though the Costa Ricans had partially cleared land in the area, the Quakers continued to cut down forests to make room for their farms and settlements. However, the Quakers specifically left about a third of each of their land plots to be natural forest. Their reasoning was not for modern conservationist reasons such as to protect biodiversity of endangered species (though their beliefs would lend themselves easily into the later-developed conservation movement in Costa Rica), but was to functionally preserve resources such as water (Davis, 2009).

In the 1960s, scientists enticed by the English-speaking community in Monteverde began to descend into the region to study the unique ecology and biodiversity in the cloud forest ecosystem. Many of these scientists moved into Monteverde and their dedication to conservation sparked the beginning of a cultural ethic of conservation in the local area (Davis, 2009).

Between the 1960s and 1980s, Costa Rica experienced accelerated deforestation due to increased cattle raising, agricultural production, and human population growth. Monteverde scientists began noticing the impacts this was having on the wildlife there, including on iconic birds such as the Three-wattled Bellbird and the Resplendent Quetzal. This concern led to the formation of a community group known as the Monteverde Conservation League (MCL) which spearheaded reforestation projects in the region (Davis, 2009).

The MCL worked with farmers in the 1980s and learned that the high winds that came for part of the year to Monteverde “stressed cattle and pasture grasses” which “negatively affected milk production” (Davis, 2009). The MCL used this information to successfully campaign for reforestation programs complete with free trees for farmers who would care for them and in turn receive the benefits of wind blockage as they grew. By 1994, “500,000 trees had been planted by 263 farmers” (Davis, 2009).

Scientists documented that these windbreaks provided essential habitat connections for many bird species. Further research into the migratory patterns of the Three-wattled Bellbird demonstrated that the birds rely on many life zones during the course of one year–including protected forest as well as "small forest fragments on private farms". This underscores the importance of small-scale reforestation projects on farmland in supporting key habitat zones for this vulnerable species (Davis, 2009).

In the late 1990s, an organization with similar interests and goals as the MCL, the Costa Rican Conservation Foundation (FCC) was established and began reforestation program work to protect the Pacific Slope region around Monteverde that is important for Bellbirds.

The Bellbird Biological Corridor (BBC or CBPC) was founded in 2005 by the FCC, the Monteverde Institute, and four other local organizations out of the recognition that Three-wattled Bellbirds were declining due to habitat loss and fragmentation in the region. The BBC spans over 164 acres and strives to connect critical habitat for several species of concern between the cloud forests of Monteverde and the coastal mangroves on the Gulf of Nicoya in northwestern Costa Rica (Newcomer et al., 2022).

The Monteverde Institute, a "non-profit educational organization founded in 1986" (Burlingame, 2019), has hosted the Monteverde Institute Reforestation Program since the late 1990s. This program is similar to the MCL's original program, as it grows trees native to the BBC and distributes them to local community members at no cost.

While there are many conservation initiatives and reforestation programs in the region, the long-standing recognition and success of the Monteverde Institute's Reforestation Program render it the target of this investigation. Understanding the dynamics and successes of this program can help improve this program as well as inform and create other successful reforestation programs in other parts of the world.

B.2 Description of Project

Research Overview

This project included interviews with 22 farmers who have participated in the Monteverde Institute Reforestation Program at least one time between the years 2000 and 2022. Twelve of the interviewed farmers had participated in the reforestation program and created one designated area of reforestation while the remaining ten interviewed farmers had participated in the program multiple times and had created more than one designated area of reforestation.

Each farmer was asked the same 87 questions pertaining to the following categories:

- General Information
- Household Information
- Biophysical, Land Use, and Land Dependence Information
- Experience in the Community and with the Monteverde Reforestation Program
- Opinions on the benefits and drawbacks of reforesting land
- Open Ended Questions

Farmers were additionally asked questions pertaining to their Reforestation Parcel Characteristics for each parcel they reforested. As mentioned previously, twelve farmers reforested once, and thus were each asked one set of 26 questions pertaining to their parcel. On the other hand, the remaining ten farmers reforested between two and four parcels in total. These “multiple-reforester” farmers were asked one set of additional 26 questions for each relevant parcel.

Farmers were interviewed in either Spanish or English, according to their language preference. The main researcher, Michelle Geldin, and a local bilingual translator conducted all interviews. Interviews took place at the location of preference for the interviewees which included locations that were both on and off of the farm sites in question.

Selection Methodology

A stratified cluster sampling method was used to create two groups from which to select participants. The two groups to be selected from were farmers who had reforested once and farmers who had reforested more than once. All chosen participants were farmers who had participated in the Monteverde Institute Reforestation Program. Geographically, the participant pool was restricted to the upper BBC watershed in the Monteverde region in order to minimize cost and travel constraints. Available data were provided by the Monteverde Institute’s staff members and included farmer name, farmer phone number, and approximate geographic locations of the farm. Participants were sampled from the divided data pool and were called or texted a consistent script asking for their interest in participating in an approximately 50-minute interview.

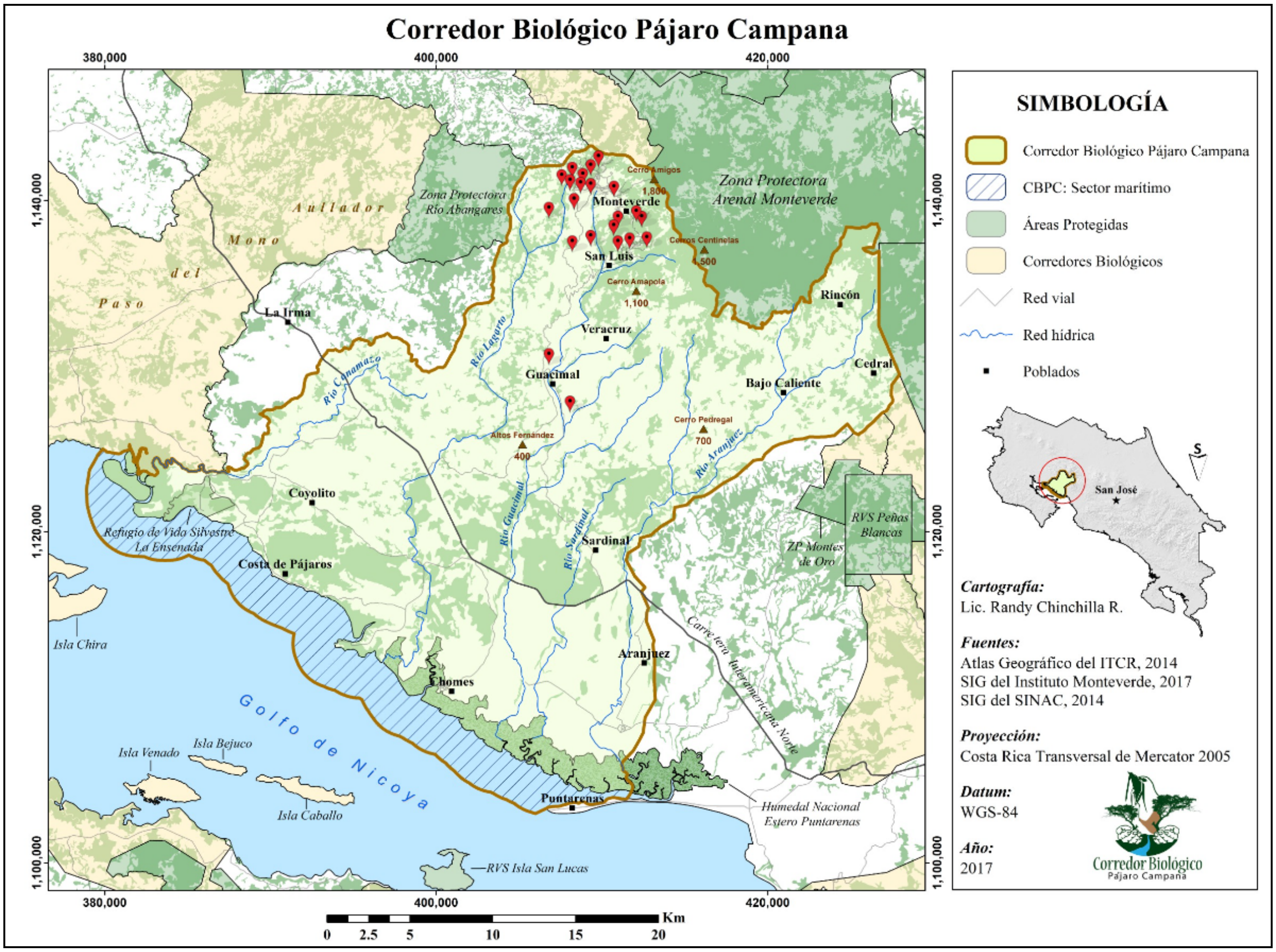

Figure B-2. This map illustrates the extent of the Bellbird Biological Corridor (gold border in the larger left map), the relative size of the Bellbird Biological Corridor within Costa Rica (red circle in the country legend map on the right), and the approximate locations of the 22 interviewed farms (red points). (MVI Digital Collections, 2017).

B.3 Study objectives

1. To understand why farmers reforest their land and how they decide where to reforest.
    a. To identify the social, economic, and biophysical factors associated with farmers who decide to reforest.
2. To document farmers' perceptions of the costs and benefits of reforestation overall. To compare these perceptions between those who participate multiple times and those who participate once.
3. To explore why some farmers choose to participate in the program for multiple years while others only participate once.
    a. To identify the social, economic, and biophysical factors associated with farmers who decide to reforest more than one parcel/project on their land.

4. To identify how the Monteverde Institute's Reforestation Program could increase the number of farmers who reforest or the total area of land reforested.

B.4 Results

Objective 1

Exploring the first objective, we can identify trends in motivations as well as physical, social, and economic incentives factors associated with all participants of the program.

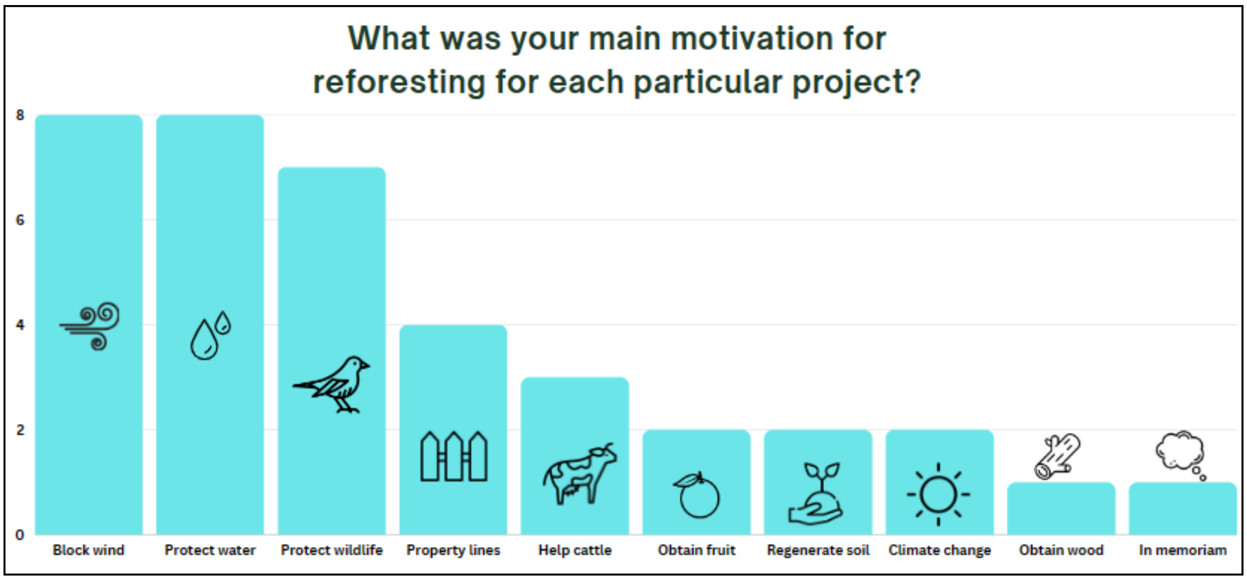

Figure B-3. The prevalence of various motivations for 38 total reforestation projects discussed by interviewees. The largest motivators for reforestation projects were to block wind on the property and the desire to protect natural water sources.

There is a wide variety of motivations to reforest land in this case study. Focusing on the strongest motivators, we see that knowledge of wind protection for both the health of crops and cattle, as well as protection for the home itself, is of large significance. Additionally, those who reforested were aware of the benefits reforestation has to protect the short and long-term availability of natural water sources on their property for both human and animal usage.

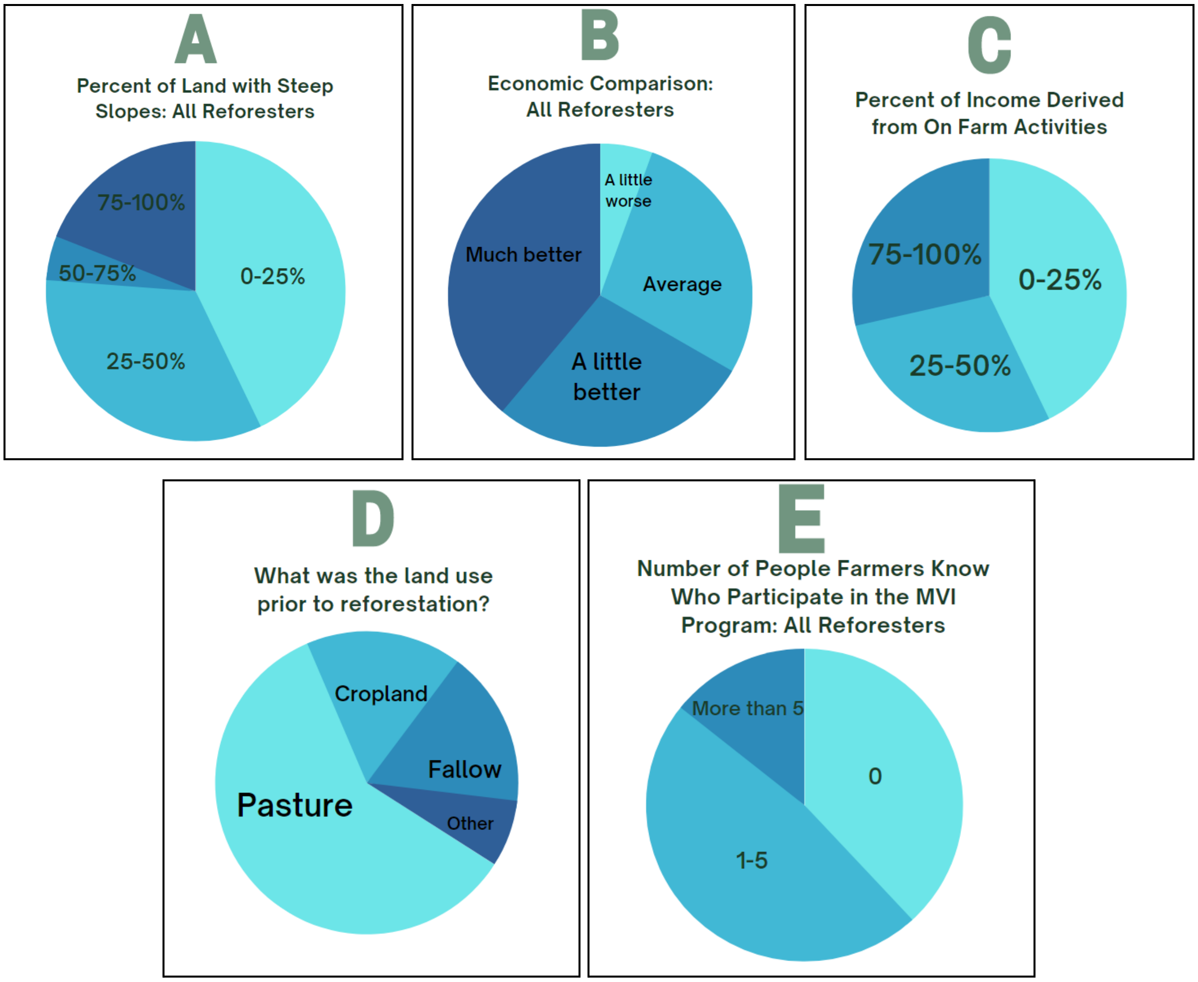

Figure B-4. Proxies for the social, economic, and biophysical factors associated with all farmers who participated in a reforestation project. Chart A shows how the steepness of the physical property plays a role in reforestation decisions. Charts B and C demonstrate economic factors associated with reforestation decisions. Chart D shows physical use prior to the restoration project's implementation. Finally, Chart E demonstrates social factors relevant to reforestation decisions.

Chart A in Figure B-4 displays that around 43% of participating farmers' land is only between 0-25% steep whereas 19% of participating farmers' land is classified as almost completely steep, or 75-100% steep. Chart B depicts farmers' comparison of their current economic situation to that of the community at large. Chart C displays the percent of income for farmers that are dependent on farm products. About one-third (29%) of farmers have a high proportion of income derived from their on-farm activities while around 43% rely relatively little (0-25%) on their income from their farm. Chart D shows the breakdown of previous land uses: 60% of land for reforestation work was transitioned from pasture land, while 17% was cropland and another 17% was fallow. Chart E displays that most participants knew at least one to five others participating in the Institute's Reforestation Program (48%).

Objective 2

This objective seeks to compare the costs and benefits perceived between those who conducted one reforestation project versus those who conducted multiple reforestation projects on their land. Interviewees were asked open ended questions related to whether they experienced any personal costs or benefits related to participating in the Program, if any. For example, a perceived cost could be that the reforestation effort was "labor and time intensive" while a perceived benefit could be that the reforestation effort "increased natural fruit production". For respondents who gave a reason for which they perceived some type of cost or benefit, they were recorded as a "Yes" in the figure below. For respondents who explicitly said they did not have a reason to believe they experienced any type of cost or benefit, they were recorded as a "No" in the figure below.

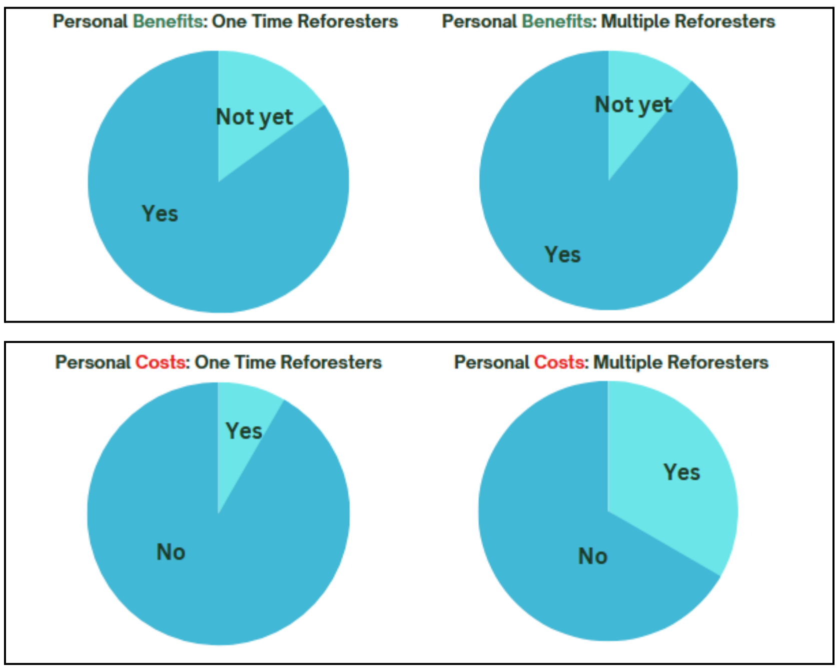

Figure B-5. The first two charts in the top box demonstrate the existence of perceived personal benefits between one-time-reforesters and multiple-reforesters. The latter two charts on the right demonstrate the existence of perceived personal costs between one-time-reforesters and multiple-reforesters.

While one-time-reforesters and multiple-reforesters perceived a similar amount of personal benefits, multiple-reforesters reported perceiving more costs than one-time-reforesters.

Objective 3

This objective explores the social, economic, and biophysical factors associated with farmers who decide to reforest more than one project on their land and how they compare to farmers who decide to reforest only once. Asking interviewees about their generated income is regarded as invasive and may lead to unreliable results. Therefore, the interviewee's perceived economic status is asked for as a proxy for economic status. Interviewees compared their personal economic situation with that of their general community and indicated whether they felt they were “much worse off”, “a little worse off”, “average”, “a little better off”, or “much better off” than others.

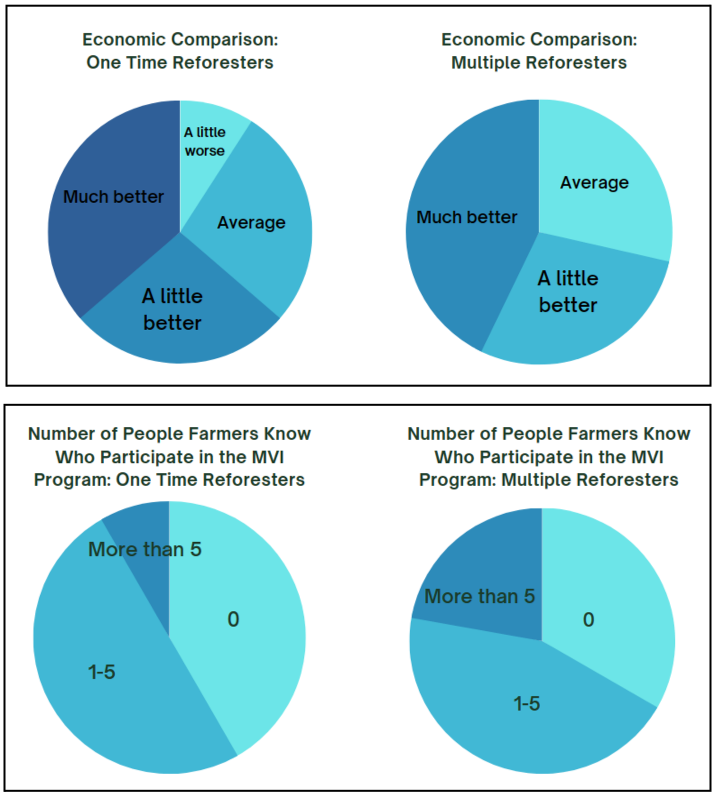

Figure B-4. The first two charts on the top demonstrate the perceived economic status between one-time-reforesters and multiple-reforesters. The latter two charts on the bottom demonstrate the role of knowing other people involved in the project between those who were one-time-reforesters and those who were multiple-reforesters.

Economic comparisons between the two groups in question were quite similar, though one-time-reforesters were the only group to choose the category “a little worse” economically relative to other people in their community.

Multiple-reforesters were more likely to know of other people involved in the Reforestation Program and were more likely to know larger numbers of people as compared to one-time-reforesters.

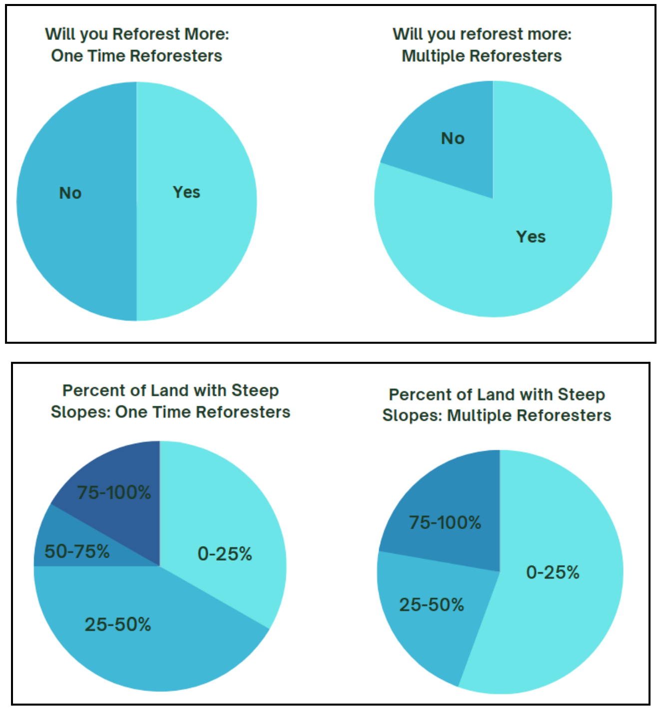

Figure B-5. The first two charts on the top demonstrate the motivation for one-time-reforesters and multiple-reforesters to choose to reforest again in the future. The latter two charts on the bottom show the physical difference of farms for one-time-reforesters and multiple-reforesters in regard to land steepness.

The chart on the top demonstrates that multiple-reforesters are much more likely to wish to reforest more plots of their land in the future.

For one-time-reforesters, one-third of farms had property that was minimally steep (0-25% steep), whereas multiple-reforesters had 56% of farms with property that was minimally steep (0-25% steep).

Objective 4

This objective seeks information on how to encourage more participants to both join the Monteverde Institute's Reforestation Program, and to encourage those who have already participated once to continue to participate. The list below highlights key suggestions provided by farmer interviews to support both of these goals.

In order to encourage increased participation, farmers suggested:

- Educating farmers on the benefits to production that are possible. If farmers can be shown that sustainable agricultural activities and planting trees can provide economic payoffs, there may be increased participation (whether that be in the form of receiving fruit, wood, increased milk production, or in other ways).

- Seeking methods for direct economic incentives to plant trees. Government-run Payment for Ecosystem Service Systems were not used by any of the interviewees, partly due to the slow, bureaucratic process. Finding localized methods for direct economic payments may increase participation.
- Increase the number of tree species offered. The Reforestation Program hosts nurseries that grow plants from seed and then freely distributes them as young seedlings. In this way, the Institute controls what native species are grown. However, some farmers believe that there should be more diversity in native tree species provided and that they would be more interested in planting trees that provide more functional benefits to their farm. These farmers encourage the Institute to consider offering additional tree species that are both functional to the farmers and beneficial to improving the ecosystem.
- Educating farmers through active workshops or in ways that demonstrate the benefits and functionality of reforesting instead of just talking about it. It is crucial to consider who is educating and promoting the program to farmers as some individuals may be more trusted than others (farmers may trust other farmers more than non-farmers).
- Discuss the ways in which reforestation can provide increased outlets for income such as through tourism.
- Provide supplies such as fencing materials to farmers in addition to trees to limit outside costs that the farmers will incur related to caring for the trees.

B.5 Discussion

The voluntary active reforestation efforts on agricultural land undertaken through the Monteverde Institute benefits native habitat for wildlife in the region and the livelihoods of those who have participated. The motivations, costs and benefits, and the social, economic, and biophysical characteristics of participants and their farms provide insight into the best practices for program improvement.

Motivations

Blocking wind, preserving water sources, and protecting wildlife were the top three primary motivations mentioned by participants of this project. These motivations can be generally distilled into improving productivity and protecting property, protecting natural resources, and preserving the natural ecosystem, respectively. Understanding the driving forces for participation in this reforestation program illustrates the specific needs and interests of the community. While these motivations may be common for other regions or for current Institute participants, human behavior is dynamic and unpredictable and these results serve as reflective information rather than a blanket ruling for other potential farmers.

Costs and Benefits

Both one-time-reforesters and multiple-reforesters indicated low levels of personal costs with high levels of benefits incurred from participation in the program. Interestingly, multiple-reforesters more commonly stated that they incurred some type of cost from participating. However, multiple-reforesters were more likely than one-time-reforesters to want to reforest again in the future. Farmers pointed to various perceived benefits and costs associated with participating in the reforestation program. Some of the benefits frequently mentioned were the prevention of erosion, improved living conditions for livestock and increased production from livestock, increased perceived property value, and elevated emotional satisfaction with their land. On the other hand, perceived costs included the time and labor intensity for reforesting, decreased available land for agricultural activities, and occasional lack of success rates with planting. These results can inform the Institute in directly addressing perceived costs, and incentivizing pathways to achieve more of the benefits mentioned.

Characteristics

Social dynamics are important to consider when investigating participation. Knowing other people who are involved in the Institute's Reforestation program is correlated to more consistent participation in reforestation projects. This emphasizes the importance of social networks and pressure for participating communities to continue reforesting.

Perceived economic status as well as true economic status can play a role in determining program participation. The majority of participants relied minimally (0-25%) on their farm for their income, which may indicate that farmers who have less at stake when decreasing productive land are more likely to participate.

Biophysical factors related to farmland may dictate reforestation participation. From this study, farmers who had flatter land were more likely to reforest multiple times than those who had steeper land. This is initially a surprising result as it was originally hypothesized that those with more steep land would generally find the steeper portions of their land more ideal to reforest and thus create multiple reforestation projects. However, it is possible that steeper land may be more inaccessible and thus harder to actively reforest.

Next Steps

Farmers provided key insights into what actions the Institute can take to increase participation in the program. Among these insights are increasing appropriate education on the benefits of the program and considering compromising conservation goals and the needs of farmers when choosing what tree species to offer.

The insights provided by farmers to improve participation in the Institute's program can be incorporated into future updates to the program, as well as taken into account for other reforestation programs with similar goals in other places to consider.

The trees planted by farmers and community members through the Monteverde Institute's Reforestation program can support habitat for native flora and fauna in the Bellbird Biological

Corridor. In addition to nurturing the environment, active reforestation on farmlands can create a plethora of benefits for the farmers themselves. Promoting best practices to improve participation in reforestation initiatives will be important as we adapt and coexist with nature in an ever changing world.

B.6 HSC Protocol Information and Acknowledgements

This Costa Rica Case Study was completed with the approval of the Human Subjects Committee within the UCSB Office of Research. The Human Subjects Committee's Institutional Review Board completed the approval of this research on September 9th, 2022, with interviews taking place after this date. The approved protocol number is 2-22-0538.

This research was made possible with the guidance of Dr. Celia A. Harvey, supportive staff of the Monteverde Institute, countless kind community members, and with the generous support of donors to the Bren School of Environmental Science and Management.

C. Accuracy assessment of projected cropland abandonment

Using remote sensing derived Brazilian land cover data from MapBiomas (Souza et al., 2020), we created a series of confusion matrices comparing the abandonment projected under Chen et al. in 2020 to abandonment observed in 2020. This allowed us to evaluate the performance of our abandonment projection methodology.

MapBiomas (Collection 6) uses Landsat mosaics to classify LULC at 30m resolution for the spatial extent of Brazil. First, the resolution of the 2020 LULC MapBiomas data was aggregated to 1km and resampled to match the resolution and spatial extent of Chen et al.'s land cover projection data. Next, the MapBiomas data was reclassified only to include categories of cropland. Finally, we created a confusion matrix to compare the sensitivity (true positive rate) and specificity (true negative rate) of Chen 2020 projections against MapBiomas 2020 cropland data. The accuracy and precision are also reported, where accuracy is defined as how often the predictor is correct overall, and precision is defined as how often "true" predictions are correct. Table C-1 displays how to interpret the confusion matrix results. The link to code used for this analysis is provided Appendix D (Table D-2).

$$Accuracy = \frac{(true\ pos + true\ neg)}{(pos + neg)} \qquad Precision = \frac{true\ pos}{(true\ pos + false\ pos)}$$

Table C-1: Confusion matrix format used to report observed vs predicted data, where the numbers reported in each cell are the raw count and ratios are reported within parentheses.

		Predicted	
		Positive	Negative
Observed	Positive (p)	true pos (tp/p)	false neg (fn/p)
	Negative (n)	false pos (fp/n)	true neg (tn/n)

Table C-2: Chen 2020 (SSP1) vs MapBiomas 2020 (cropland) confusion matrix. Accuracy = 0.890, precision = 0.344

		Predicted (Chen)	
		Positive	Negative
Observed (MapBiomas)	Positive	329541 (0.518)	306508 (0.482)
	Negative	629588 (0.080)	7223321 (0.920)

Table C-3: Chen 2020 (SSP3) vs MapBiomas 2020 (cropland) confusion matrix. Accuracy = 0.887, precision = 0.339

		Predicted (Chen)	
		Positive	Negative
Observed (MapBiomas)	Positive	341437 (0.537)	294612 (0.463)
	Negative	664845 (0.085)	7188064 (0.915)

Table C-4: Chen 2020 (SSP5) vs MapBiomas 2020 (cropland) confusion matrix. Accuracy = 0.867, precision = 0.315

		Predicted (Chen)	
		Positive	Negative
Observed (MapBiomas)	Positive	415557 (0.653)	220492 (0.347)
	Negative	904644 (0.115)	6948265 (0.885)

Overall, Chen et al.'s data is above 86% accurate for the three SSPs tested against MapBiomas cropland. The precision, however, hovered between 31.5% - 34.4%. This emphasizes that high true negative rates (accurately classifying what is not cropland) is driving the overall model's accuracy.

While the Chen et al.'s plant functional type classifications do not include pasture land, the MapBiomas data includes a classification for both "pasture" and "mosaic agricultural and pasture land". Additional confusion matrices were created to examine how including mosaic agriculture and pasture affected the accuracy of Chen et al.'s global land use projections.

Table C-5: Chen 2020 (SSP1) vs MapBiomas 2020 (crop + mosaic agriculture) confusion matrix. Accuracy = 0.874, precision = 0.420

		Predicted (Chen)	
		Positive	Negative
Observed (MapBiomas)	Positive	402249 (0.439)	514157 (0.561)
	Negative	555279 (0.073)	7017273 (0.927)

Table C-6: Chen 2020 (SSP3) vs MapBiomas 2020 (crop + mosaic agriculture) confusion matrix. Accuracy = 0.872, precision = 0.414

		Predicted (Chen)	
		Positive	Negative
Observed (MapBiomas)	Positive	417220 (0.455)	499186 (0.545)
	Negative	589678 (0.078)	6982874 (0.922)

Table C-7: Chen 2020 (SSP5) vs MapBiomas 2020 (crop + mosaic agriculture) confusion matrix. Accuracy = 0.858, precision = 0.390

		Predicted (Chen)	
		Positive	Negative
Observed (MapBiomas)	Positive	515335 (0.562)	401071 (0.438)
	Negative	804866 (0.106)	6767686 (0.894)

When including mosaic agriculture and pasture land use into the cropland classification for MapBiomas, the true negative rates slightly increase and the true positive rates decrease. The overall accuracy of the models decreases, but the precision increases to between 39%-42%. Including mosaic agriculture into the MapBiomas data increases the overall amount of "true" cropland present in Brazil. This causes the overall rates (percentages) for true positives and negatives to decrease, lowering model accuracy. However, the actual count of true positives increases, driving increased precision. This indicates that some pixels classified as cropland in Chen et al.'s projected land use may in fact be a mosaic of cropland and pasture.

To determine the "baseline" accuracy of Chen et al.'s LULC data, a confusion matrix analysis was performed using Chen's 2015 "current" land use against MapBiomas' 2015 data for both cropland and cropland + mosaic agriculture.

Table C-8: Chen 2015 vs MapBiomas 2015 (cropland) confusion matrix. Accuracy = 0.896, precision = 0.320

		Predicted (Chen)	
		Positive	Negative
Observed (MapBiomas)	Positive	280795 (0.495)	286585 (0.505)
	Negative	596123 (0.075)	7325455 (0.925)

Table C-9: Chen 2015 vs MapBiomas 2015 (crop + mosaic agriculture) confusion matrix. Accuracy = 0.881, precision = 0.384

		Predicted (Chen)	
		Positive	Negative
Observed (MapBiomas)	Positive	336904 (0.419)	467716 (0.581)
	Negative	540014 (0.070)	7144324 (0.930)

Similar to the projected land use, including mosaic agriculture and pasture into the MapBiomas cropland classification slightly increases the number of true positives and overall precision. Finally, a last series of confusion matrix analysis were performed using projected 2020 Chen et al. data and observed MapBiomas 2020 data, with pasture land use included in the "cropland" classification.

Table C-10: Chen 2020 (SSP1) vs MapBiomas 2020 (crop + pasture) confusion matrix. Accuracy = 0.802, precision = 0.844

		Predicted (Chen)	
		Positive	Negative
Observed (MapBiomas)	Positive	808178 (0.345)	1532114 (0.656)
	Negative	149350 (0.024)	5999316 (0.976)

Table C-11: Chen 2020 (SSP3) vs MapBiomas 2020 (crop + pasture) confusion matrix. Accuracy = 0.805, precision = 0.841

		Predicted (Chen)	
		Positive	Negative
Observed (MapBiomas)	Positive	846796 (0.362)	1493496 (0.638)
	Negative	160102 (0.026)	5988564 (0.974)

Table C-12: Chen 2020 (SSP5) vs MapBiomas 2020 (crop + pasture) confusion matrix. Accuracy = 0.818, precision = 0.801

		Predicted (Chen)	
		Positive	Negative
Observed (MapBiomas)	Positive	1057713 (0.452)	1282579 (0.548)
	Negative	262488 (0.043)	5886178 (0.957)

Including pasture and cropland into the MapBiomas data significantly increases the number of “true positives” across all SSP scenarios and boosts precision above 80%. Overall, this indicates that pixels classified as cropland in Chen et al.’s dataset are likely pasture or a mosaic of pasture and agriculture. This poses limitations to the efficacy of projected cropland abandonment and restoration models. However, despite this misclassification of pasture as cropland, these pixels are still projected to transition away from human-influenced agriculture and toward natural land uses. Conservatively, it is better to include these areas as eligible parcels for restoration (false positives) than exclude misclassified cropland (false negatives). The high true negative counts across all confusion matrices reflect this to be the case, with Chen et al.'s dataset accurately determining areas that are not cropland.

D. Data and code availability

In the interest of transparency and open data practices, all data, analyses, and results generated from this project are outlined in Tables D-1 and D-2 below. The majority of data utilized for this project's analyses are publicly available; sources and links to datasets are provided in Table D-1 when applicable.

A public GitHub account, AgAbandonment-Bren-CI, hosts repositories for the various analyses conducted throughout this project; links and descriptions for these repositories are provided in Table D-2. Due to the size of data utilized for some analyses, raw source data are not pushed to these repositories. Sources to locally download these datasets are provided in Table D-1 as well as each repository's README.md file. This GitHub account will be kept open for future research and reproducibility.

Table D-1. Data used in analyses with links for publicly available sources.

Dataset	General use	File type	Date created	Download link	Brief description and citation
Future global land cover	Finding areas of projected cropland abandonment both globally (Ch. 2) and in Brazil (Ch. 3) by 2050.	GeoTIFF	March, 2021	Zenodo link	Future land cover (1 km resolution) out to 2100 based on SSP-RCP climate scenarios. Datasets available for either 7 land cover classifications or 20 cover types based on PFT. Chen, G., Li, X. & Liu, X. (2022). Global land projection based on plant functional types with a 1-km resolution under socio-climatic scenarios. *Sci Data 9, 125*. https://doi.org/10.1038/s41597-022-01208-6
Current Brazilian land use and land cover	Determining the accuracy of Chen et al.'s projected land cover for the year 2020 (App. C).	GeoTIFF	August, 2021	MapBiomas Collections	MapBiomas Project - is a multi-institutional initiative to generate annual land use and land cover maps from automatic classification processes applied to satellite imagery. Collection 6 land cover data (30m resolution) for Brazil. The full description of the project can be found at http://mapbiomas.org Souza at. al. (2020) - Reconstructing Three Decades of Land Use and Land Cover Changes in Brazilian Biomes with Landsat Archive and Earth Engine - Remote Sensing, Volume 12, Issue 17, https://doi.org/10.3390/rs12172735
Carbon accumulation potential	Highlighting areas critical to carbon sequestration globally (Ch. 2) and prioritizing Brazilian parcels for restoration based on potential benefits to carbon (Ch. 3).	GeoTIFF	July, 2022	Global Forest Watch	Estimated rate of carbon sequestration (MgC/ha/yr) in above and belowground biomass during the first 30 years of natural regrowth. This global dataset (1 km resolution) was first generated by Cook-Patton et al. in 2020 with values for aboveground carbon storage only. GFW updated this dataset in 2022 to include belowground sequestration rates. Cook-Patton, S. C., Leavitt, S. M., Gibbs, D. et al. (2020). Mapping carbon accumulation potential from global natural forest regrowth. Nature, 585(7826), 545–550. https://doi.org/10.1038/s41586-020-2686-x

Table D-1 (cont.). Data used in analyses with links for publicly available sources.

Future and current biodiversity priority areas	Used for highlighting areas critical to biodiversity globally (Ch. 2) and prioritizing Brazilian parcels for restoration based on associated extinction risk (Ch. 3).	GeoTIFF	2021	SPARC Conservation Priorities	Global spatial dataset at 5km resolution displaying rank-ordered areas of high importance to conserving biodiversity. The rank order of importance was determined by examining current and future ranges of 17,000 vertebrate species and their relative extinction risks. Roehrdanz, P., Hannah, L., Corcoran, D., Corlett, R., Enquist, B., Fajardo, J., Feng, X., Foden, W., Lovett, J., Maitner, B., Marquet, P., Merow, C., & Midgley, G. (2021). Strategic Conservation of Global Vertebrates in Response to Climate Change. *SSRN Electronic Journal: Preprints*. https://doi.org/10.2139/ssrn.3854499
Restoration costs	Assigning restoration costs to abandoned cropland parcels based on restoration method and biome (Ch. 3).	CSV	2017	Data in GitHub repository	Estimated costs for six different restoration methods, depending on environmental condition and Brazilian biome. These data were generated and reported in a Nature Conservancy report from 2017 and manually entered into tabular format for analysis. These data can be found within the GitHub repository for our restoration prioritization analysis. de Miranda Benini, R., & Adeodato, S. (2017). Forest Restoration Economy. *The Nature Conservancy*, 71.
Brazilian boundaries	Cropping and masking raster data to either the country of Brazil or specific biomes/regions within Brazil (Ch. 3).	GPKG	2019	geobr package GitHub IBGE	The geobr package in R was used to read in accurate spatial datasets for various Brazilian boundaries. Biome boundary data was originally sourced from the Instituto Brasileiro de Geografia e Estatística (IBGE) and is at scale 1:250.000. Pereira R, Goncalves C (2023). *geobr: Download Official Spatial Data Sets of Brazil*. R package version 1.7.0999, https://github.com/ipeaGIT/geobr.

				boundary vectors	Instituto Brasileiro de Geografia e Estatística. (n.d.). *Mapas Físicos e Ambientais*. Brasil - Mapas Físicos e Ambientais. Retrieved May 9, 2022, from https://mapasinterativos.ibge.gov.br/sigibge/

Table D-2. Links to GitHub repositories for project analyses.

Analysis	Description	Link to repository
Determining areas of projected cropland abandonment. (Ch. 2 and 3)	Two separate R markdowns determining where projected cropland abandonment will occur globally and within Brazil, respectively. Both analyses utilized future land cover data from Chen et al., 2022. Outputs include rasters for abandonment under six different climate scenarios at 1 km resolution. Brazilian abandonment is utilized as in input for the restoration prioritization analysis.	abandoned-cropland
Prioritizing restoration of abandoned Brazilian cropland. (Ch. 3)	Utilizes rasters of projected abandonment under 6 climate scenarios, as well as data for biodiversity, carbon, and restoration cost, to determine the optimal restoration locations within a specified budget. Outputs include rasters indicating which parcels should be restored (value 1) and which should not (value 0).	restoration-prioritization
Confusion matrices (App. 3)	Compares Chen et al.'s projected land cover against MapBiomas' observed land cover to determine the general accuracy of Brazilian land cover projections used for other analyses in this project.	cropland-projected-observed
Data visualization (Ch. 2 and 3)	Creates an interactive Shiny App where the user can further explore the data and analyses presented in this report.	shiny-app

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