A comparison of carbon offsets between four reforestation designs in a community context

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ABSTRACT

Research suggests that community-based reforestation can play an important role in climate change mitigation while providing environmental and livelihood benefits. However, there lacks direct comparison between different reforestation design's carbon uptake potential and their relevance to community reforestation. By evaluating the carbon-capture of four reforestation designs in a community context, this study bridges a gap between theory and action consequently facilitating informed project implementation. In a 14 years-old project in Panama, I compare native timber mixtures and monocultures, agroforestry, and natural regeneration with enrichment planting. I use Linear Mixed Models to compare carbon capture and survival rate of five native timber and seven fruit species. Redundancy Analyses were used to examine the importance of design, management, and environmental characteristics in explaining growth and survival. I then integrate community perspectives to interpret results within the local context. In the first decade, mixtures and monocultures of timber (140 tCO_2/ha) stored on average roughly 3x more carbon than agroforestry (40 tCO_2/ha) and enrichment planting (53 tCO_2/ha). *Terminalia amazonia*, showed outstanding carbon storage (209 kg/tree). The project design has the strongest explanatory power (31% of explained variation) followed by management and environmental characteristic (14%, and 2% respectively). The largest threat to the survival and growth was the risk of fire which caused mortality in more than 2/3 of the plots. Some damage was offset by natural regrowth which accounted for 34% of the total carbon, but the participants generally perceived natural regrowth as "dirty". They had a strong preference for agroforestry, particularly coffee (Coffea Sp.), a crop with negligible carbon value, but high economic value. These results highlight challenges, tradeoffs between climate mitigation and community goals and the importance of fire prevention.

Key words – Reforestation, community-based, carbon sequestration, agroforestry, native timber, natural regrowth, tradeoff

RÉSUMÉ

La littérature suggère que le reboisement communautaire peut jouer un rôle important dans l'atténuation des changements climatiques tout en fournissant des avantages environnementaux et de subsistance. Cependant, je n'ai pas trouvé, lors de ma revue de littérature, de comparaison directe entre le potentiel de captation de carbone de différents modèles de reboisement et leur pertinence en contexte communautaire. En évaluant quatre modèles de reboisement dans un contexte communautaire, je comble donc un fossé entre la théorie et l'action, facilitant ainsi potentiellement la mise en œuvre de projets éclairés. Cette étude analyse des efforts de reboisement menés depuis 14 ans au Panama, en comparant des monocultures et des plantation mixtes de d'espèces indigènes, de l'agroforesterie et de la reboisement naturel avec enrichissement. J'utilise des modèles mixtes linéaires pour comparer la captation de carbone et la survie de cinq espèces indigènes et de sept espèces fruitières. Des analyses de redondance ont été utilisées pour examiner l'importance des caractéristiques de design, de l'entretien et de l'environnement pour expliquer la croissance et la survie. J'intègre ensuite les perspectives communautaires pour interpréter mes résultats dans le contexte local. Au cours de la première décennie, les plantations mixtes et les monocultures (140 tCO_2/ha) ont stocké environ 3x plus de carbone que l'agroforesterie (40 tCO_2/ha) et le reboisement naturel (53 tCO_2/ha). *Terminalia amazonia*, avait un stockage de carbone exceptionnel (209 kg/arbre). Le design du projet avait le plus fort pouvoir explicatif (31% de la variation expliquée), suivie par l'entretien et les caractéristiques environnementales (14% et 2% respectivement). La plus grande menace pour la survie et la croissance était le risque d'incendie qui a causé la mortalité dans plus de 2/3 des parcelles. Certains dommages ont été compensés par la repousse naturelle qui représentait 34% du carbone total, mais les participants percevaient généralement celle-ci comme de la mauvaise herbe. Ils avaient une forte préférence pour l'agroforesterie, en particulier le café (Coffea Sp.), une culture dont la valeur en carbone est négligeable, mais la valeur économique est élevée. Mes résultats mettent en évidence les défis, les compromis entre les objectifs de mitigation du changement climatique et les objectifs communautaires et l'importance de la prévention des incendies.

Mots clés – Reforestation communautaire, séquestration de carbone, agroforesterie, espèces natives, repousse naturelle, compromis

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CONTRIBUTION OF AUTHORS

The reforestation project design and monitoring were done as a collaboration between the community of Ipetí Emberá and the Potvin Lab with financing from the Smithsonian Tropical Research Institute and from Dr Potvin's NSERC Discovery grant. Tree Inventories were compiled by local technicians and transcribed to a database. Interviews were done with the help of undergraduate students registered in the Panama Field Study Semester in 2020 and 2021. In 2021 students and I used remote technologies to do the interviews because of the pandemic. Soil and natural regrowth data were collected in 2021 by Brais Marchena, a Panamanian intern, as I could not travel and analyzed by the Smithsonian Tropical Institute Soil laboratory. In 2022, I did the remaining interviews in person and returned preliminary results to the community.

Under the supervision of Catherine Potvin, I developed my research question, cleaned the data, completed all the data analyses, reviewed literature and wrote this manuscript in whole. My committee members and supervisor commented and revised my thesis helping with structure and suggesting edits which I incorporated.

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INTRODUCTION AND LITERATURE REVIEW

Global context of reforestation as a climate mitigation strategy

Reforestation to offset carbon emissions is emerging as an important short-term mitigation strategy against climate change (Bastin et al., 2019; Griscom et al., 2017; IPCC, 2018). If done right, it has the potential to simultaneously conserve biodiversity, benefit livelihoods and mitigate climate change (Cohen-Shacham et al., 2019; Gann et al., 2019; Seddon et al., 2021). To fully exploit this potential however, there is a need for more applied studies testing different reforestation designs (Vincent et al., 2021) and reporting on their successes and failures (Höhl et al., 2020; Mansourian & Vallauri, 2014).

Reforestation is gaining a lot of international attention to fight climate change as it has the largest potential of all land-based methods to capture atmospheric carbon (Griscom et al., 2017). In the last decade, many ambitious international reforestation initiatives have emerged such as the One Trillion Tree Challenge by the World Economic Forum, the United Nation's Trillion Tree Campaign or the Bonn Challenge aiming to reforest 3.5Millon hectares of land by 2030 (U. N. Environment, 2017; Verdone & Seidl, 2017; World Economic Forum, 2021). In 2021, the United Nations embarked in the decade on Ecosystem Restoration with ambitions to "help to end poverty, combat climate change and prevent a mass extinction" (*UN Decade on Restoration*, n.d.). In addition to mitigating climate change, these initiatives aim to conserve biodiversity and enhance local livelihoods (Vincent et al., 2021).

Indigenous People and local communities (IPLC) have the potential to be important protagonists to the success of restoration initiatives as almost 300 million people live on land with restoration potential in the tropics (Erbaugh et al., 2020). IPLC have under their stewardship 40% of the world's forests, over 30% of terrestrial biodiversity hotspots and intact forest, and nearly 20% of the forest carbon (Frechette et al., 2018; Garnett et al., 2018; UNEP-WCMC & ICCA Consortium, 2021). Beyond forest conservation IPLC are stewards of over 30% of land with highest climate mitigation potential (UNEP-WCMC & ICCA Consortium, 2021). This large overlap in area creates an opportunity for reforestation to benefit IPLC in particular if they are engaged in decision making processes (Garnett et al., 2018). Continuous engagement helps tailor projects to the local reality and needs (Gann et al., 2019) which is important to enhance local livelihoods and ensure project perennity (Brancalion & Holl, 2020; Höhl et al., 2020; Vincent et al., 2021).

Carbon financing offers an interesting way for IPLC to harness the momentum of global carbon markets and get paid to conserve or restore forest ecosystems (Boyd, 2009). Carbon financing has been proposed multiple times as a strategy to both reduce emissions and lead to sustainable development (Hultman et al., 2020). Developed in the Kyoto Protocol in 1997, the Clean Development Mechanism (CDM) enables developed countries to offset their emissions by financing emission reduction projects in the developing world with the potential co-benefit of helping developing countries achieve sustainable development (UNFCCC, 1998). In 2007, REDD, then REDD+ (reducing emission from deforestation and forest degradation) was developed as an emission reduction strategy targeted specifically at forested ecosystems (*What Is REDD+? | UNFCCC*, n.d.). More recently the concepts of Natural Climate solutions (using nature to offset carbon) (Griscom et al., 2017) and Nature-based solutions (using nature as a tool for climate mitigation and adaptation) (Cohen-Shacham et al., 2016) have raised in popularity. The Paris agreement also opens the door to using market approaches for countries to achieve emission reductions (article 6) (UNFCCC, 2015).

While the packaging evolves, the idea of carbon financing achieving climate mitigation with the potential for sustainable development as a co-benefit remains important across these global trends brining forth similar hopes and critiques. Some hope to create an economy that values ecosystem services and makes it financially profitable for countries or communities to choose low emission paths (Boyd, 2009). Common critiques include the absence of social and developmental goals in many projects (Hultman et al., 2020) , the narrow framing on carbon coming at the cost of biodiversity conservation (Lindenmayer et al., 2012) and the distraction from emission reduction at the source enabling continued business as usual (Seddon et al., 2021). With those considerations in mind, a lot of research has looked at best practices for carbon financing and a predominant recommendation is the importance of properly engaging and co-designing projects with IPLCs (Duchelle et al., 2018; IUCN, 2020; Seddon et al., 2021). An example of successful ecosystem-based management led by first nations and funded through carbon offsets is the costal first nations – Great bear initiative in British Columbia Canada (Price et al., 2009).

Globally however, implementation of reforestation for climate mitigation is not up to scale (Vincent et al., 2021) and the ambitious expectation to achieve simultaneously multiple goals at an unprecedented scale is proving to be challenging to translate into reality (Höhl et al., 2020). Wortley et al. 2013 report that only 6% of 301 articles on ecological restoration mention community wellbeing as a goal. Meanwhile, a study by Martin et al. 2021 looking at 174 pantropical tree planting organization shows a disproportionate focus on planting trees and a near total lack of monitoring with only 5% of organisations reporting on the survival rate of their saplings. This disconnect between ambitions and practice shows a need for an increased exchange of practical experience such as good practices, lessons learned, successes and failures to better inform project design (Baynes et al., 2015; Brooks et al., 2012; Höhl et al., 2020; Mansourian & Vallauri, 2014; Vincent et al., 2021).

A key necessity of reforestation initiatives is the ability to be sustained in time (Lazos-Chavero et al., 2016). Reforestation for carbon offset is a long-term investment with a horizon of decades which requires long term engagement and care. In the long term, project success can be influenced by the quality of maintenance (Elliott et al., 2019), the duration of payments (Kim et al., 2008; Roopsind et al., 2019) and the prevention of environmental threats such as fires (Barlow et al., 2012; Boeschoten et al., 2021; Lindenmayer et al., 2012). This is further complexified by the fact that different stakeholders may have different, sometimes conflicting, vision of success and that these visions can evolve through time (Baynes et al., 2015; Kohler & Brondizio, 2017; Lazos-Chavero et al., 2016).

Different types of reforestation designs

Depending on the project goals, reforestation can take many forms. A first distinction is between passive and active restoration (Holl & Aide, 2011; van Noordwijk et al., 2020; Vincent et al., 2021). Passive restoration relies on the natural regeneration of forest cover, and it can be a cost-effective solution if the right environmental conditions are present (Höhl et al., 2020; Lewis et al., 2019; Sacco et al., 2021). It can include no intervention at all, or different levels of human intervention such as the enrichment of fallows by planting rows of valuable species (Sacco et al., 2021). In contrast, active reforestation relies on planted trees to restore forest cover and is often seen as a more secure, but costlier alternative (Brancalion et al., 2016). A meta-analysis by Crouzeilles et al., 2017 showed that natural regeneration led to higher biodiversity and improved forest structure in the tropics since most active reforestation planted very few species. However, Shoo et al., 2016 showed that if active restoration included diverse species it led to faster recovery of old growth attributes.

Within active reforestation, many other design decisions are required such as the choice between timber or agroforestry plantations (Fitch et al., 2022; Sharma et al., 2021), mixtures or monocultures (Ewel et al., 2015; Liu et al., 2018), and native or exotic species (Bent et al., 2011; Griess & Knoke, 2011; Mayoral et al., 2017; Sinacore et al., 2022). Due to the wealth of data collected by the timber industry, commercial timber monocultures are the most studied reforestation type with known growth rates and a well-established market (Liu et al., 2018; Messier et al., 2022). There is debate on whether commercial timber monocultures should be included as part of global forest restoration targets as they have low biodiversity (Healey & Gara, 2003; Lewis et al., 2019; Liu et al., 2018) and a systematic lack of permanence since the trees are grown for harvest (Kim et al., 2008). Still, in practice, 45% of the Bonn challenge's reforestation commitments are commercial monocultures (Lewis et al., 2019). This is also the case in Panama where 77% of reforestation in 2008 was done through Teak (*Tectona grandis*) monocultures (Sloan, 2008).

In addition to commercial monocultures, there is growing interest in alternative reforestation designs such as mixtures with native species and agroforestry (Liu et al., 2018). In fact, the most common reforestation types reported by for-profit and non-profit reforestation organisations in the tropics were agroforestry, mixtures, monocultures and enrichment planting (Martin et al., 2021). Mixtures bring more biodiversity which can increase resilience to climate change and lead to higher carbon uptake if the species are chosen to complement one another (Biodiversity effect) (Liu et al., 2018).

The biodiversity effect is a phenomenon where mixtures perform better than monocultures since they allow the most performant to outcompete others and thrive (selection effect). In addition, the many species will use resources differently, allowing for a fuller use of available resources and may even facilitate resource use of neighbors (complementarity effect) (Loreau et al., 2001). For example, nitrogen fixing plants capture atmospheric carbon and convert it into nitrogen accessible to other plants.

Meanwhile, for community forestry, agroforestry is particularly interesting as it can provide additional streams of income and improve livelihood through the harvesting of fruits (Holmes, Potvin, et al., 2017). An agroforestry design may also be more accessible to community-based reforestation as it can be adapted to respond to local livelihood needs which is vital for project success (Höhl et al., 2020).

Contribution to new knowledge

To inform climate mitigation projects, experiments must directly compare carbon storage and socio-ecological conditions in different reforestation designs. There is notable literature evaluating both active and passive restoration showing that the best solution is often context dependent (Brancalion et al., 2019; R. L. Chazdon et al., 2016; Evans et al., 2018; Philipson et al., 2020; Reid et al., 2018; Shoo et al., 2016). Some studies have compared mixtures vs monocultures, (Ewel et al., 2015; Liu et al., 2018; Mayoral et al., 2017; Tatsumi, 2020) and others agroforestry vs timber or enrichment planting (Badari et al., 2020; Fitch et al., 2022; Soto-Pinto et al., 2009). A recent meta-analysis by Hua et al., 2022 compares mixture and monoculture plantations to actively or passively restored natural forest and old growth. They find that tree biomass is 33% lower in plantations than old growth forest, but comparable to restored natural forests.

In most studies mentioned above however, the comparison criteria tend to focus only on ecological value or wood production without accounting for the social and cultural context of the reforestation. If the goal of research is to inform practice, there is a need for a holistic approach looking at both the climate mitigation potential (Lindenmayer et al., 2012) and the socio-ecological characteristics surrounding a project (Erbaugh et al., 2020). People's motivations and needs, maintenance and engagement can influence project design, and can also directly influence project outcome (Brancalion & Holl, 2020).

Here, I compared the carbon storage potential of four reforestation systems in a fourteen-year-old community-based reforestation project by using participatory action research. The four systems are agroforestry, enrichment planting in fallows, native timber mixtures and monocultures. This study used carbon storage as a proxy for climate change mitigation and analysed how social and environmental conditions influenced project outcome. In learning by doing, action research can integrate both the structured design of a theoretical experiment with the rich complexity of working in a real-world setting (Holmes, Potvin, et al., 2017). It bridges theory and practice by building theory and simultaneously testing its applicability.

This study took place in Ipetí Emberá, an indigenous community in eastern Panama. It has been a hub of collaborative action research for over twenty years, providing a rich history of engagement from community members and researchers. This study built on previous cycles of research, each resulting in iterative learning that informs the subsequent cycle (Holmes, Potvin, et al., 2017). Holmes, Potvin et al., 2017 describe this process in depth and, looking at the first four years of this reforestation initiative, highlight obstacles related to land tenure, payments and governance and the importance of adaptive implementation and strong bridging institutions. More recently, Shinbrot et al., 2022 explore the financial impact of the project's payments on the community by comparing participants and non-participants. They explain that the project "provided financial stability for poorer participants to diversify into other sources of income over time" and that the largest perceived benefit was the economic security of future generations (Shinbrot et al., 2022).

I report on the carbon storage potential of different reforestation designs while also evaluating carbon capture of five native timbers species and seven fruits species with nutritional, cultural and/or economic value. I assessed the importance of the project design, management, and environmental characteristics to explain the differences in carbon storage between plots. I then interpreted findings through the lenses of different stakeholder's interests. This research distinguishes itself in that it not only offers a direct carbon comparison between the four most common reforestation systems, but it shines light on the complexity of translating global ambitions into practice in a community setting. Through this case study, it offers researchers and practitioners insights to optimize project outcomes and highlights the potential of participatory action research in translating theory into action, a critical step in reaching climate goals.

METHODS

The case study

This study took place in Ipetí Emberá, an Indigenous community located 160 km east of Panama City, Panama. The area had an annual precipitation of 2500 mm, an average temperature of 26 ^{o}C and a marked dry season from December to April (Kirby & Potvin, 2007). The soils type was a mix of inceptisol and ultisol (Villarreal et al., 2016) with clay as the dominant soil texture and an average PH of 6,1. While the land was collectively owned (*tierra colectiva*), it was for the most part divided amongst the community members and managed by individual households.

Project Design and Timeline

Enrichment planting

In 2007, after five years of collaborative research and discussion between McGill scientists and community members, three participants engaged in a pilot reforestation project of enrichment planting by clearing rows in fallows to plant valuable timber and fruit species covering a total area of 4.1ha. 3m wide stripes were cleared between 4m of existing 5-10 years old fallows and rows of fruit and timber species were added in the stripes (Hawryshyn & Senikas, 2007). Seedling production and establishment costs were initially covered by Dr Potvin’s research funds, but long-term management was at the discretion of the owners and was not remunerated or monitored.

Plots were only measured in 2020 and 2021, after 12 and 13 years of growth. As this system was experimental, each fallow had very different levels of management and density determined by the plot owner. When they were measured, one participant had 91 planted trees in 0.71ha, the second 552 planted trees in 3.1ha, and the third 208 planted tree in 1.1ha for a total of 851 trees. The first participant kept their plot very clean and cleared most of the natural regrowth including that which was between the rows of planted trees and was not supposed to be cleaned while the second had barely touched their plot and it was hard to tell the rows of enrichment planting from the rows of natural regrowth. The third was somewhere in-between with maintenance provided only to the rows of planted trees. Considering the small sample size and large variation, the enrichment planting’s interest here is to understand how the plots were perceived, cared for, and transformed in a community setting.

Contract with STRI - Timber monocultures & mixtures

In 2008, a full-scale initiative was initiated when the Smithsonian Tropical Research Institute (STRI) agreed to finance the reforestation project through payments for carbon offsets

(Holmes, et al., 2017; Potvin et al., 2007). The community signed a three-year contract (2008-2010) with STRI to offset 3400tCO_2 in 25 years by reforesting 13 ha of the *tierra colectiva* at an average price of 10,20$/ton. During the first year, six participants voluntarily entered the STRI contract and reforested with timber species planted in both mixtures and monocultures for a total of 4679 trees over 3.91 ha (Table 1). They committed to maintain the trees for the 25 subsequent years in exchange for access to the saplings, payments for maintenance, and capacity training.

Table 1. Project design per year

Date	**Reforestation type**	**Number of Participants**	**Number of Plots per participant**	**Total area (ha)**	**Mean initial density/ha (sd)***	
					Planted	NR
2007	Enrichment Planting	3	1	4.91	173 (21)	319 (160)
2008	Timber Mixtures and Monocultures	6	2-3	3.91	1197 (70)	
					Trees	Understory
2009 2010	Agroforestry	7 5	1	9.39	327 (111)	270 (118)

Notes: Enrichment planting density is from 2021 and 2022 when it was first measured. Agroforestry trees include timber, fruit, and shade species while understory species includes coffee, cacao & achiote.

Payments for carbon offsets were input-based, meaning that they were distributed based on the establishment and management of plots rather than on the actual amount of carbon stored (output based) (Skutsch et al., 2011). Since management, such as weeding and watering, is most important in the first years when the trees are young and vulnerable (Boeschoten et al., 2021), participants received 100% of their carbon offset revenue in the first seven years. This method was chosen as it lowers the barrier to entry for participants without experience or access to the material (Holmes, Kirby, et al., 2017; Skutsch et al., 2011). 80% went directly to the participants and 20% went to a community fund that was eventually used to upgrade the communal house.

Timber plantations were always established with mixture and monoculture plots adjacent to one another. The mixture plots contained five native timber species growing together, thereafter referred as target species. The species are *Terminalia Amazonia, Anacardium excelsium, Dalbergia retusa*, *Pachira quinata, and Tabebuia rosea* which are all long lived pioneers that were chosen because they had complementary traits, good carbon sequestration and commercialization potential (Hall & Ashton, 2016) (see Mayoral et al. 2017 for complementary traits). The monoculture plot contained the five native timber species and sometimes a sixth one (*Swietenia macrophylla*) growing separately. Trees were planted with 3m spacing.

The 2008 timber plantations replicated the a portion of the design of STRI's "Agua Salud" research site designed to test the effect of tree diversity on ecosystem functioning (BEF) (Mayoral et al., 2017; STRI, 2022). By planting mixed species and monoculture systems in parallel, the design enabled the estimation of the biodiversity effect on tree growth and CO_2 capture. The Agua Salud project is at a larger scale than the Ipetí project and it is managed by a scientific team. It provides a direct comparison to this applied community-led project.

Addition of agroforestry

For the two following years (2009-2010), eleven new and one returning participant joined the STRI contract and reforested an additional 9.4ha of land with agroforestry. The project shifted to agroforestry in 2009 after participants expressed a desire to gain additional benefits through increased food security and income from the production and sale of fruits (Holmes, Kirby, et al., 2017). These agroforestry systems included the same five timber species as the 2008 plantation but in lower density. In addition, 28 other tree species, mainly fruit trees, were added with the dual objective of providing food and storing carbon (see Table 2).

Between rows of trees, participants planted three commercially valuable understory species for food and sale purposes: *Bixa orellana* (achiote), *Theobroma cacao* (cacao) and *Coffea spp*. (coffee). These crops were chosen as they had a pre-existing market in the community and were thus characterized as “easy to sell” by the participants (Holmes, Kirby, et al., 2017). Each plot was required to have a minimum of 90 timber trees of the five target species and 270 other trees per hectare (Holmes et al., 2017). The addition and choice of understory species was at the discretion of the participants and the harvesting intensity or yield was not measured as part of the project. Since agroforestry plots had a lower density than timber plots (table 1), they also had lower carbon storage targets and thus received smaller payments for carbon offsets.

Carbon storage targets were estimated by Kirby & Potvin, 2007 who quantified carbon stocks in forest, agroforest and pasture in Ipetí. They report that forests with low density of selective logging stored 218 tC/ha or 800 tCO_2/ha in trees and palms > 10cm in diameter at breast height (DBH) while agroforestry of 23years of age stored on average 71tC/ha or about 251 tCO_2/ha. Calculations for the STRI contract targets stipulated that tree would reach 80% of their full carbon storage potential, leaving 20% as a buffer against mortality. If plots exceeded targets, participants could be “liberated” from their contractual responsibilities before the 25 years. The full carbon storage potential of agroforestry was established as 251 tCO_2/ha while timber mixtures and monocultures were predicted to store 55% of the Ipetí’s old growth forest or 440 tCO_2/ha. Tenth year targets were calculated presuming a linear trend of carbon storage of 80.5 tCO_2/ha for agroforestry and 140.8 tCO_2/ha for timber plots. Carbon uptake progressively tappers off as forests get older, but young secondary forests have a relatively linear rate of carbon accumulation (Poorter et al., 2016).

Table 2. List of planted species and their initial quantities

Latin Name	Common Name	Number of Trees Planted
Target Species		
The 5 native timber species common to all reforestation types		
Terminalia amazonia	Amarillo	1114*
Tabebuia rosea	Roble	1060*
Dalbergia retusa	Cocobolo	1013*
Pachira quinata	Pochote	986*
Anacardium excelsum	Cashew	969*
Understory species		
Small fruit species planted under rows of trees in agroforestry and enrichment planting used for sale and consumption		
Coffea spp	Coffee	1532*
Bixa orellana	Achiote	434*
Theobroma cacao	Cacao	304
Other Species		
Tall fruit and timber species providing carbon storage and other benefits planted in agroforestry and enrichment planting.		
Swietenia macrophylla	Mahogany	877*
Annona muricata	Soursop	297*
Persea americana	Avocado	297*
Citrus sinensis	Orange	264*
Inga punctata	Guabo	232*
Mangifera indica	Mango	129*
Anacardium occidentale	Wild cashew	120*
Borojoa panamensis	Borojo	114
Cedrela odorata	Spanish cedar	112
Dialium guianense	Tamarindo/Ironwood	78
Byrsonima crassifolia	Nance	60
Matisia cordata	Sapote	55
Psidium guajava	Guayaba	52
Bactris gasipaes	Pifá	49
Albizia duckeana	Pino Amarillo	46*
Cocos nucifera	Coconut	35
Annona reticulate	Anon	34
Melicoccus bijugatus	Mamón	31
Spondias purpurea	Ciruela	31
Enterolobium cyclocarpum	Corotú	23
Chrysophyllum cainito	Caimito	11
Garcinia intermedia	Lemon drop mangosteen	10
Pouteria sapota	Mamey	10
Averrhoa carambola	carambola	8
Syzygium jambos	Pomarosa	7

Brosimum rubescens	Zapatero	6
Chrysobalanus icaco	Icaco	2
Tabebuia guayacan	Guayacan	2
Unknown		139
Total		**10543**

Note: Species with an asterix (*) have more than 30 surviving individuals at year 10. These are the species included in the species level analyses. Swietenia macrophylla was also planted in timber monocultures.

Data collection and transformation

Monitoring carbon capture and survival

To assess survival rate and estimate carbon storage of the plots under the STRI contract, community technicians tagged each tree with a unique numerical identifier. They measured All trees after one and ten years of growth. The 2008 timber plots were also measured after 5 years while the 2009-2010 agroforestry plots were measured after three and seven years. For my analyses, I use the tenth-year measurements for all plots. In enrichment planting systems, since trees were only measured in 2020 and 2021, on the 12^{th} and 13^{th} year, I adjusted the carbon content to a 10-year equivalent presuming linear growth.

For each inventory, community technicians recorded information on the diameter at breast height (DBH), the tree height, the basal diameter, health status, and if the tree was dead, whether a new one had been replanted to replace it. Mortality was coded as a binary variable for each tree: dead or alive. They also noted causes of large-scale death e.g., fire, or project abandonment. Three participants, two with agroforestry plots and one with timber plots, were excluded from analyses as they had abandoned the project to turn their land into pastures or rice fields. Eight participants of which two had timber and six agroforestry plots were impacted by fire including two who saw their full plot burn (one with agroforestry and the other with timber). For each analysis, I indicate whether the fire plots are included.

Carbon dioxide equivalent (CO_{2eq}) was derived from tree biomass which was estimated using allometric equations. Chave et al., 2014 (equation 4) was used to calculate biomass of trees >5cm in diameter.

$$AGBest = 0.0673 \times (WD \times DBH^2 \times H)^{0.976}$$

Where

$$AGBest = Above\ ground\ biomass\ in\ Kg$$
$$WD = wood\ density$$
$$DBH = Diameter\ at\ breast\ height\ (cm)$$
$$H = height\ (m)$$

Equation 1

Wood density values were taken from global wood density database with a geographical selection for tropical central America, using the most precise taxonomic level available (species, genus, family, etc). Biomass-carbon species ratios were drawn from the Thomas et al (2012) wood carbon content database. When more than one value was recorded, I took the average, and if species level data were absent, I used the database's average value of 47,1% for tropical angiosperm species. Carbon was converted to CO_{2eq} using their molecular weight ratio. Lastly, I log transformed the results to give them a normal distribution.

Natural regrowth growing between the rows of planted trees in enrichment planting and over burnt areas in some agroforestry plots also contributed to the total carbon storage. The six participants in agroforestry that had areas burnt in their plots left these to regrow naturally. With the three plots in enrichment planting, there were a total of nine plots with natural regrowth. Brais Marchena randomly positioned a quadrat of 30x30m in enrichment planting plots and plots that regrew after fires and measured ever tree. For the natural regrowth in enrichment planting, since trees were already present for five to ten years before the project start, I considered the proportion of the carbon that had been stored in the tree since the start of the project. To estimate initial DBH measurements, I derived average DBH growth data from the Barro Colorado Island permanent plot (Condit et al., 2012) at the most precise taxonomic level available and subtracted ten years' worth to the current tree measurements. I used Chave et al., 2014 equation 7 (which does not require height measurements) from the R package Biomass (Réjou-Méchain et al., 2017) to estimate initial biomass and took the difference between initial and current values as being the additional carbon stored.

Collecting Explanatory Data

To explain difference in carbon storages and survival rate between plots and between trees, field technicians collected data on environmental, management and design characteristics. At the plot level this study looked at design variables (choice of reforestation type and proximity to village), management variables (cleanliness and occurrence of fire) and environmental variables (soil texture, soil acidity, and proximity to river) (Table 3). There were also differences in carbon storage and probability of survival between individual trees that depended both on the species of the tree and on the environment within which it was growing (ie. The plot level characteristics).

Table 3. Explanatory variables

Measured variables	Type	Description
	Characteristics at the plot level	
Design		
▪ Proximity to the Village	Factor	<2.5 km 2.5-5 km >5 km
▪ Reforestation Design	Factor	Agroforestry Timber Mixture Timber Monoculture Enrichment Planting

Management		
▪ Cleanliness Report on cleanliness from field visits in the first 3 years made by ANCON	Factor	None: always dirty Poor: mostly dirty Good: Mostly clean Excellent: Always clean
▪ Occurrence of fire Proportion of the plot burnt	Factor	None <50% >50%
Environmental		
▪ Soil Texture	Numeric	% Clay and silt
▪ Soil Acidity	Numeric	Average pH value
▪ Proximity to the River	T/F	One side or more of the plot was bordering a river
Characteristics at the tree level		
▪ Species Timber or Fruit Species with >30 surviving individuals	Factor	See Table 2 for list.

I drew the explanatory variables from different sources of data, first are the soil variables which came from soil analyses done in 2021. Depending on the plot size, one to four soil samples of the first 10cm of the mineral layer were collected from random locations on each plot. A plot of one hectare had four sample and a plot half a hectare had two. Each sample had six replicas to reduce random error. The samples were kept a sealed and marked plastic Ziploc for around a week until they were analysed. In a soil laboratory, Smithsonian Tropical Research Institute technicians tested the pH and analysed the soil texture with the Horiba laser diffraction method. I used the plot average values for my analyses. I classified soil texture using the USDA soil classification (*Soil Texture Calculator | NRCS Soils*, n.d.).

I derived the proximity to the river and to the community from maps overlaying planet scope satellite imagery and the GPS coordinate of the participant's plots. I was interested in plots near the two largest rivers that never dry out. The soil quality near the river may be richer in nutrients (Baldwin & Mitchell, 2000), an the proximity to the river can facilitate watering during the dry season or alternatively, a flood may kill young trees. The proximity to the village was calculated by creating buffers of 2.5, and 5km around the community center. This variable was an estimate of the time it took to get to plots, but it did not account for actual roads, paths or slope which could have made some plots more easily accessible than others.

Plot management and cleanliness reports were made from 2008-2015 by the National Association for the Conservation of Nature (ANCON), a local NGO who were tasked with "providing technical assistance and guidance in the proper management of community funds" (from the contract agreement). They acted as a third-party organisation monitoring cleanliness of plots, the compliance with the project and distributing payments to the participants. Before handing out payments, they would visit plots to verify that participants were complying with their plot management responsibilities. They wrote yearly reports on the state of each participant's plot.

Local Perspective

To complement quantitative analyses and contextualize the results to the local context, workshops and interviews were organized with participants, community leaders and field technicians. In 2020, exploratory interviews were carried out with 13 project participants by McGill undergraduate students in the Panama Field Study Semester. The goal was to get a broad idea of what the project was about, from the perspective of the participants, and how it was progressing. These discussions were unstructured and informal, and they aimed to provide general sense of what was important to the participants.

Subsequently, in 2021, semi-structured interviews lasting between 30 minutes to 1 hour were conducted remotely with ten project leaders to understand the community's motivation for engaging in forest restoration. These interviews were led by the 2021 online cohort of PFSS students and focussed on the expected, personal and community benefits of reforestation through carbon offsets. A detailed version of the questions can be found in Appendix I. The interviews were done through virtual means using Zoom and WhatsApp. The students asked questions concerning their motivations for engaging in a reforestation project and their perception of the short, medium, and long terms benefits and the potential risks.

In 2022, interviews were held with three community technicians in person, and a presentation at a local congress was organized to verify and return preliminary results to the community. Both the interview and the congress included a presentation of preliminary results followed by an unstructured discussion about said results. These discussions explored in more depth the preferences in reforestation designs and the contribution of the reforestation project to local livelihoods. The interviews were made in accordance with the McGill research ethics board guidelines under the REB # 21-03-023.

Data Analysis

Assessing Project Objectives

To assess whether the project reached its ten-year carbon objectives, I measured total amount of carbon stored in planted trees and natural regrowth. I included the contribution from all trees and shrubs with DBH >5cm including the understory fruit species planted in agroforestry and enrichment planting, replanted tree, natural regrowth in burnt plots, and the portion of natural regrowth in enrichment planting that occurred after the start of the project.

Measuring the Biodiversity effect

To measure the impact of tree diversity on carbon storage, I calculated the biodiversity effect between suitable timber mixture and monoculture plots using the Loreau et al., 2001 methodology. Of the six participants who planted timber plots, I excluded the one who abandoned the project and two other who had significant burnt areas in their plots. Three participants with six plots remained for analysis, three monocultures and three mixed species, with a total of 2180 surviving trees (52% in a mixed system, 48% in monocultures). Since mixture and monoculture plots had nearly the same initial density, this analysis had the advantage of accounting for both mortality and tree growth. After standardizing results to a one-hectare plot, I measured complementarity and selection effects using the equation below (Loreau et al., 2001):

$$\Delta Y = complementarity\ effect + Selection\ effect = (\ N * \bar{M} * \overline{\Delta RY}) + (N * cov(\Delta RY, M))$$

Where:

$$\Delta \boldsymbol{Y} = deviation\ from\ the\ expected\ mixture\ yield$$

$$= yield\ of\ a\ 1ha\ mixture$$

$$- yield\ of\ the\ five\ species\ in\ \frac{1}{5}ha\ monoculture\ each$$

$\boldsymbol{N} = number\ of\ species\ in\ the\ mixture$ (5)

$$\boldsymbol{M}\ = yield\ of\ species\ in\ a\ 1ha\ monoculture$$

$$\Delta \boldsymbol{RY} = deviation\ from\ expected\ relative\ yield\ of\ species\ in\ the\ mixture$$

$$=\ Rel.Yield.Observed - Rel.Yield.Expected$$

$$The\ expected\ relative\ yield\ of\ a\ species\ in\ a\ mixture$$

$$=\ the\ proportion\ of\ that\ species\ planted\ initially\ (\frac{1}{5})$$

$$The\ observed\ relative\ yield\ of\ a\ species\ in\ a\ mixture$$

$$= \frac{the\ observed\ yield\ of\ that\ species\ in\ a\ 1ha\ mixture}{the\ observed\ yield\ of\ that\ species\ in\ a\ 1ha\ monoculture}$$

Equation 2

In addition to testing the applicability of ecological theory in a community context, measuring the biodiversity effect enabled the comparison of the yield of monocultures and mixtures and the contribution of each target species to that yield.

Species comparison

To compare the carbon uptake and survival of timber and fruit trees species in all four reforestation designs (Timber mixture, monoculture, agroforestry, and enrichment planting) I used (Generalized) Linear Mixed models (G-LMM). Since the density of agroforestry and enrichment planting systems was at most half that of timber systems, their plot level carbon storage, while still relevant overall, were not easily comparable. Thus, I decided to look at tree level carbon storage in this analysis and plot level carbon in the subsequent analysis.

Since I was interested in species performance and its interaction with the reforestation design, I ran analyses on two different response variables: Tenth year carbon storage per tree (CO_{2eq}) and mortality (dead/alive) while accounting for the non-independence of the observations using random effects. For the CO_{2eq} analyses I ran a linear mixed model and for mortality I used a generalized linear mixed model to account for the binary nature of the data. Trees growing in the same plot were not independent from each other since they had the same environmental conditions, design, and management. I assigned species, reforestation type, and their interaction to fixed effect and all other explanatory variables to random effects (Table 3). I also added plot number and density as random variables. I manually removed singular random effects (with a variance of zero) in a sequential manner and re-ran the model until all effects contributed to the variance.

I ran (G)LMM on two different subsets of data: First I compared the five target species across growing systems (equations 3,4), and second, I used only trees in the agroforestry system, and compared all species with over 30 surviving individuals (equations 5,6).

After removing singular random effects, the final models were as follows:

<u>Target Species Analysis:</u>

3) $C0_2 < -lmer(C0_2 \sim Species * System + (1|Plot) + (1|Density),$
$$data = Target\ Species)$$

4) $Mortality < -glmer(Mortality \sim Species * System + (1|Plot) + (1|Density)$
$$+ (1|Distance\_Village), family\ =\ binomial, \quad data = Target\ Species)$$

<u>Agroforestry Analysis</u>

5) $C0_2 < -lmer(C0_2 \sim Species + (1|Plot) + (1|Density) + (1|pH)$
$$+\ (1|Distance\_Village), \quad data = Agroforestry\ Species)$$

6) $Mortality < -glmer(Mortality \sim Species + (1|Plot) + (1|Density) + (1|Fire),$
$$family\ =\ binomial, \quad data = Agroforestry\ Species)$$

Equations 3-6.

The target species analysis of $C0_2$ controlled only for plot and density as random variables while the mortality analysis also accounted for the distance from the village. In the agroforestry analysis, the $C0_2$ model controlled for plot, density, pH and distance from the village while the mortality model controlled for plot, density, and fire.

The target species analysis provided information to complement the biodiversity effect analysis and had a sample size of 2472 surviving trees for carbon analyses and 3836 for mortality analyses (equation 3 &4). The agroforestry analysis provided information on seven additional fruit species and had a sample size of 591 for carbon analyses and 1678 for mortality (equation 5 & 6). In these analyses I excluded the two plots that were completely destroyed by fire as I was interested in the tree species' influence on mortality not that of fire. To compare the different level of the factor variables I ran post-hoc tests with the emmeans package in R and ggemmeans to visualize the models.

Comparing the importance of design, management, and environmental characteristics.

To study the importance of plot level characteristics on mortality and carbon storage, I ran three Redundancy Analysis (RDA) in R, one for each group of explanatory variables: environmental, design and management (Table 3). Each was followed by a post-hoc ANOVA to test the significance of the whole model, of each axis and of each variable. The response matrix was standardized to one hectare and was composed of three columns: Total plot CO_2, plot mortality and final density. For this analysis, I kept all burnt plots since fire is an event that impacts mortality at the plot level. The data included 26 agroforestry and timber plots which were composed of 8469 trees. I included all planted trees but not the three understory species planted between the rows of trees. Understory species had high mortality but contributed minimally to the carbon budget and thus were excluded. I excluded enrichment planting from this analysis as I did not have data on mortality. I note that 26 plots is a relatively small sample size which should be kept in mind when interpreting results, but still believe the results can point to interesting conclusions.

To understand how much of the variance was explained by each explanatory matrix I used the VarPart function in R. I created three explanatory matrices, one for environmental, design and management variables that I inputted into a varpart function. This partitioned the explanatory power of each model and their combined effects using adjusted R-squared.

RESULTS

Assessing Project Objectives

Over ten years, the plots under the STRI contract stored 686 $\mathrm{tCO_2}$ and the pilot project 261 $\mathrm{tCO_2}$ out of the expected 1359 $\mathrm{tCO_2}$. Timber mixture and monoculture plots that did not burn down and were not abandoned, were perfectly in line to reach their carbon storage objectives with an average 140 tCO_2/ha (SD=32). Remaining agroforestry plots on the other hand, were 37% below the expected value with an average of 48 tCO_2/ha (sd= 26) (figure 1). Enrichment planting stored an average of 53 tCO_2/ha (sd=12) (figure 1). Two participants lost their plot due to fire while three abandoned the project to convert their plot to pasture or rice culture. leaving 12 remaining participants in the STRI contract and three additional from the pilot project in enrichment planting. Fire, mainly caused by loss of control during slash-and-burn agriculture, also affected the plots of two third of the remaining participants to a lesser extent. On average, remaining plots are underperforming by 23% and the overall target is underperforming by 46% (figure 1).

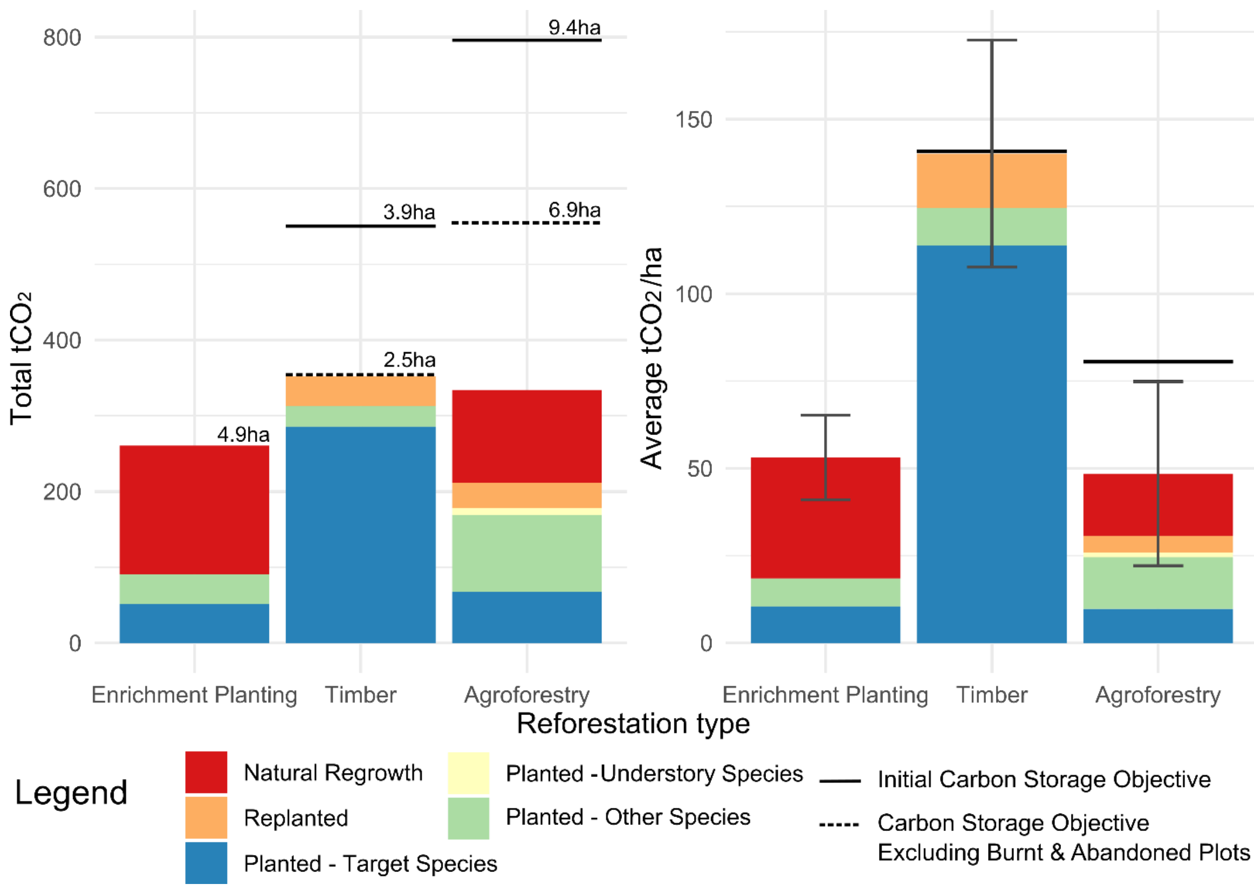

Figure 1. Tenth year carbon storage (tCO_2) per growing system as compared to the ten-year target (black bar). The full black bar represents the objective as per the contract agreement while the pointed line represents the carbon objective of the unburnt and not abandoned plots. Each system's carbon is split between the contribution of natural regrowth, replanted trees, and planted target, other, and understory species.

Planted trees accounted for 61% of the total carbon, while natural regrowth accounted for 31%. The remaining 8% was due to active replanting efforts to offset tree death by some participants. Of the trees planted initially, 49% were the target species and they accounted for 70% of the planted carbon. Other tree species accounted for 29% of the planted trees and 29% of the planted carbon. The three understory species planted for food purposes, *Coffea spp, B. orellana* and *T. cacao,* represented 22% of trees planted but only 1% of total planted carbon (Figure 1). In the agroforestry plots they represented 45% of the trees planted and only 3.4% of the carbon. In comparison, natural regrowth in the agroforestry plots which was led by the natural regeneration of burnt plots accounted for 37% of the total carbon.

Measuring the Biodiversity effect

I found that the non-burnt mixtures stored 175tCO_2/ha while the non-burnt monocultures stored 121tCO_2/ha. Mixed systems performed better than monocultures for an additional 54 tCO_2/ha. *T. amazonia* and *D. retusa* sequestered the most carbon in monocultures (163tCO_2/ha and 165 tCO_2/ha respectively). In mixtures, *D. retusa* stayed nearly constant while *T. amazonia* doubled its carbon storage as compared to monocultures (figure 2). It also sequestered double the carbon of any other species in mixtures. *A. excelsum* also overperformed in mixtures compared to monocultures, nearly doubling its carbon storage. It performed better than *D.* retusa in mixtures, but it remained far below *T.amazonia*. *T. rosea* had the lowest carbon storage in both systems.

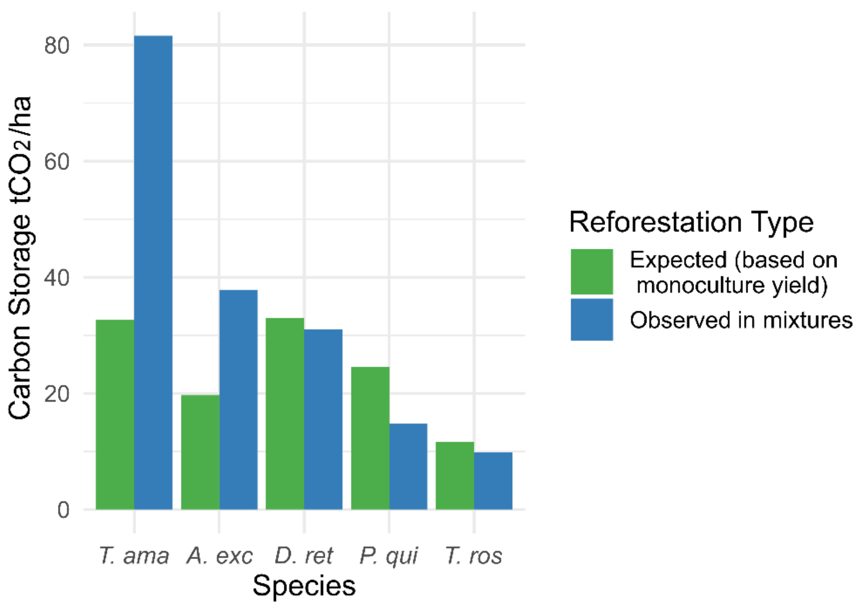

Figure 2. Mixture carbon storage per target species for a system planted with equal proportion of each species. The expected value is taken from dividing the one-hectare monoculture yield by five (the number of species). The observed values are the carbon sequestered in mixtures. The

sum of the five species gives you the carbon for a 1ha mixture. The species are *Terminalia amazonia, Anacardium excelsum, Dalbergia retusa, Pachira quinata, Tabebuia rosea.*

Complementarity effects explained 80.2% of the difference between systems while selection effects were responsible for 19.8%. Two species experienced overyielding in mixtures: *T. Amazonia* and *A. excelsum* (Figure 2). This overperformance in mixtures suggests that intraspecific competition was limiting growth in the monocultures and was more important than inter specific competition.

Comparing Target Species

The target species analysis at the individual tree-level unveiled significant effects of species ($p<0.001$), reforestation type ($p<0.05$) and their interaction ($p<0.001$) on carbon storage (Figure 3A). All species were significantly different from each other with *T. amazonia* storing the most carbon per tree ($p<0.001$) at an average value of 209kg $CO_2/tree$ after ten years. The

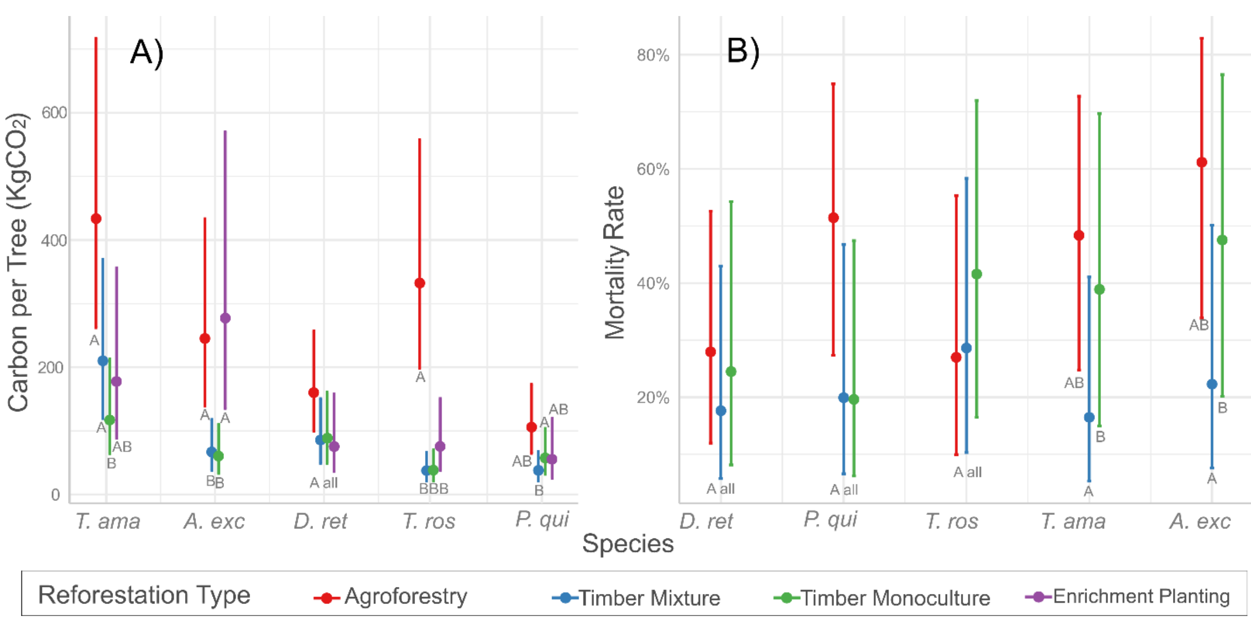

Figure 3. (A) Carbon and (B) mortality ratio per tree across reforestation types and species. Compact Letter Display: Bars within the same species that do not share a letter are significantly different from each other at a p-value ≤ 0.05. The species are *Terminalia amazonia, Anacardium excelsum, Dalbergia retusa, Pachira quinata, Tabebuia rosea.*

subsequent species were *A. excelsum* (129kg), *D. retusa* (98kg), *T. rosea* (78kg) and *P. quinata* (60kg) with a $p<0.05$ level of significance between each (Table 4). For the reforestation types, agroforestry stored more carbon per tree than mixtures and monocultures ($p<0.05$). In figure 3A, this same relationship was observable and significant in the interaction between reforestation types, *A. excelsum* ($p<0.05$) and *T. rosea* ($p<0.001$). Other notable interactions are the improved performance of *T. amazonia* in mixtures ($p<0.01$) and agroforestry ($p<0.05$) as compared to monocultures. An opposite trend can be observed with *P. quinata* which stored significantly more carbon in monocultures than in mixtures ($p<0.05$).

Table 4. Average CO_2 per tree per target species and reforestation type.

Species	**Reforestation Type**	Agroforestry kg/tree (C.I)	Timber Mixture kg/tree (C.I)	Timber Monoculture kg/tree (C.I)	Enrichment Planting kg/tree (C.I)
	Average CO_2 (kg/tree)	227 (147-350)	70 (40-123)	67 (38-120)	109 (56-213)
T.amazonia	209 (146-298)	434 (262-717)	210 (119-370)	117 (64-213)	178 (89-356)
A.excelsum	129 (89-185)	245 (139-433)	67 (38-118)	60 (33-111)	277 (135-570)
D.retusa	98 (68-140)	160 (100-257)	86 (49-151)	89 (49-161)	75 (36-158)
T.rosea	78 (54-111)	332 (198-558)	38 (21-66)	38 (21-70)	76 (38-151)
P.quinata	60 (42-86)	106 (65-173)	38 (21-67)	57 (32-104)	55 (26-120)

Note: the 95% Confidence interval is represented in parenthesis.

Likewise, the target species analysis on mortality found all the fixed effects to be significant ($p<0.001$) (Figure 3B). *D. retusa* had the lowest death rate at 23% mortality followed by *P. quinata* (29%), *T. rosea* (32%), *T. amazonia* (33%) and *A. excelsum* (43%) (Table 5). *D. retusa* has significantly lower mortality than both *T. amazonia* ($p<0.05$) and *A. excelsum* ($p<0.001$) while *P. quinata* was significantly different to *A. excelsum* ($p<0.01$). For the systems, mixtures had significantly lower mortality than monocultures ($p<0.001$) with 21% mortality as compared to 34% in monocultures. Figure 3B, shows that this same relationship is observable and significant ($p<0.001$) in the interaction between systems, *T. amazonia* and *A. excelsum*. Agroforestry had the highest average mortality (43%) but was not significantly different from other systems.

Table 5. Average mortality rate per target species and reforestation type

Species	**Reforestation Type** — Average Mortality rate	Timber Mixture (C.I)	Timber Monoculture (C.I)	Agroforestry (C.I)
		20.7% (7-47)	33.5% (13-64)	42.6% (22-66)
D.retusa	23.1% (10-44)	17.6% (6-43)	24.5% (8-54)	27.9% (12-53)
P.quinata	28.6% (13-51)	19.9% (7-47)	19.6% (6-47)	51.4% (27-75)
T.rosea	32.1% (15-55)	28.6% (10-58)	41.6% (16-72)	27% (10-55)
T.amazonia	32.9% (16-56)	16.5% (5-41)	38.9% (15-70)	48.4% (25-73)
A.excelsum	42.6% (22-66)	22.3% (8-50)	47.5% (20-77)	61.2% (34-83)

Note: the 95% Confidence interval is represented in parenthesis.

Comparing Agroforestry Species

Five of the other agroforestry species stored comparable amounts of carbon to the target species including three fruit species (Figure 4A). Pino Amarillo, which is most likely *Albizia duckeana*, was planted as a non-edible shade tree and stored the most carbon. With an average of 773kg per tree, it was significantly above all other species including *T. amazonia* ($p<0.01$) (Table 6). The Latin species identity remains uncertain because it was misidentified as a sapling, and no-one was not able to see it's fruiting body (see pictures in appendix IV). The fruit tree with most carbon was *I. punctata* (Guaba) with an average 218kg per tree which was comparable (ie. not significantly different) to *T. amazonia* (329kg), *T. rosea* (243kg) and *D. retusa* (136kg). Finally, *A. occidentale* (Cashew: fruit tree) with 111kg, *S. macrophylla* (Caoba: shade tree) with 87kg, and *M. indica* (Mango: fruit tree) with 78kg were comparable to *D. retusa* and *P. quinata* (87kg). Two fruit species stored significantly less carbon than the target species and those were *C. sinensis* (Orange) with 29kg and *A. muricata* (Soursop) with 24kg. The target species

Anacardium excelsum was not included in this analysis as most agroforestry participants chose to plant *Anacardium occidentale* instead leading to a very small sample size of *A. excelsum*.

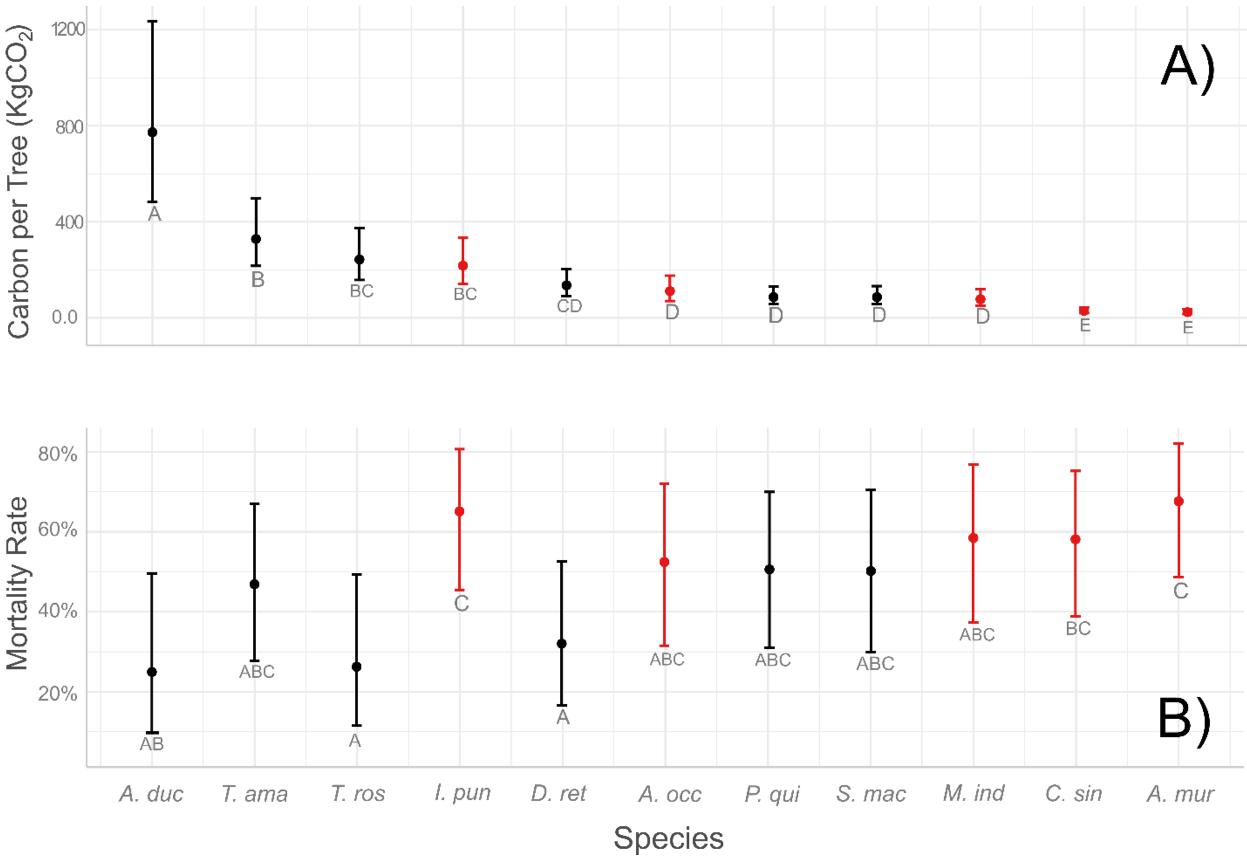

Figure 4. (A) Carbon and (B) mortality ratio per tree across agroforestry species. Fruit species are in red. Compact Letter Display: Entries that do not share a letter are significantly different from each other at a p-value ≤ 0.05. The species are *Albizia duckeana*, *Terminalia amazonia*, *Tabebuia rosea*, *Inga punctata*, *Dalbergia retusa*, *Anacardium occidentale*, *Pachira quinata*, *Swietenia macrophylla*, *Mangifera indica*, *Citrus sienensis*, and *Annona muricata*.

Mortality was largely similar across species with only a few with significant differences (Table 6). The three species with the least mortality were *A. duckeana* (25%), *T. rosea* (26%) and *D. retusa* (32%), all non-fruit trees. The three with the highest mortality were *M. indica* (59%), *I. punctata* (65%) and *A. muricata* (69%), all fruit trees. *T. rosea* and *D. retusa* had significantly lower mortality than the three species with highest mortality and *A. duckeana* was significantly different ($p<0.05$) only from *I. punctata* and *A. muricata*. The remaining species were comparable amongst themselves.

Table 6. Average carbon and mortality of fruit, timber, and shade species in agroforestry

Species	CO_2 kg/tree (C.I)	Mortality (C.I)
A. Duckeana	773 (484-1235)	25% (10-50)
T. amazonia	329 (216-499)	46.9% (28-67)
T. rosea	243 (158-374)	26.2% (12-49)
I. punctata	218 (142-333)	65.1% (45-81)
D. retusa	136 (91-202)	32% (17-53)
A. occidentale	111 (70-176)	53.8% (33-73)
P. quinata	87 (58-131)	50.6% (31-70)
S. macrophylla	87 (57-132)	50.2% (30-70)
M. indica	78 (50-120)	58.5% (37-77)
C. sinensis	29 (20-43)	58.1% (39-75)
A. muricata	24 (16-35)	67.6% (49-82)

Note: Fruit species are in bold. (C.I) represents the 95% confidence interval

Breakdown of the influence of design, management, and environmental characteristics

The three Redundancy Analyses (RDA) assessed the explanatory power of the design, management and environmental matrix and the significance of their variables. They identified which plot level characteristics were significant and demonstrated how they influenced plot mortality, final density, and carbon sequestration (Table 7).

In the design RDA, the x-axis, the most important one, was strongly explained by the reforestation type while the y-axis was explained by the distance from the village (Figure 6-A). The first RDA axis was the only significant axis ($p<0.001$) and it explained 97.7% of the variation. This axis separated agroforestry on one side with a loading factor of -0.598 and mixtures on the other with a loading factor of 0.574. Monoculture were closer to the middle with a value of 0,163. Distances below 2.5km or above 5km from the village were slightly positive (0.13 & 0.009) while distances between 2.5-5km were slightly negative (-0.06). The dependent

Table 7. A) Loading factor for the RDA explanatory of design, management, and environmental explanatory characteristics on the x-axis. B) Centroid (mean scores) for RDA response variables of mortality, carbon, and final density on the x-axis.

A) Explanatory Matrices	Description	Loading factor of the RDA's 1st axis (x)
Design RDA		
▪ Proximity to the Village	<2.5 km	0.130
	2.5-5 km	-0.060
	>5 km	0.009
▪ Reforestation Design	Agroforestry	-0.598
	Timber Mixture	0.574
	Timber Monoculture	0.163
Management RDA		
▪ Cleanliness Report on cleanliness from field visits in the first 3 years made by ANCON	None: always dirty	-0.708
	Poor: mostly dirty	-0.686
	Good: Mostly clean	0.259
	Excellent: Always clean	0.227
▪ Occurrence of fire Proportion of the plot burnt	None	0.618
	<50%	0.107
	>50%	-0.771
Environmental RDA		
▪ Soil Texture	% Clay	-0.344
	% Silt	0.654
▪ Soil Acidity	Average pH value	0.009
▪ Proximity to the River	One side or more of the plot was bordering a river	0.169

B) Centroid of the response matrix on the RDAs' 1st axis	Design	Management	Environmental
Mortality	-1.249	-1.157	-1.075
Carbon	1.306	1.069	1.283
Final density	1.415	1.002	1.198

variable of mortality clearly increased in agroforestry plots while carbon stocks and density were correlated with mixture plots (Figure 6-A). Both reforestation type and distance had significant explanatory power ($p<0.001$ and $p<0.05$ respectively).

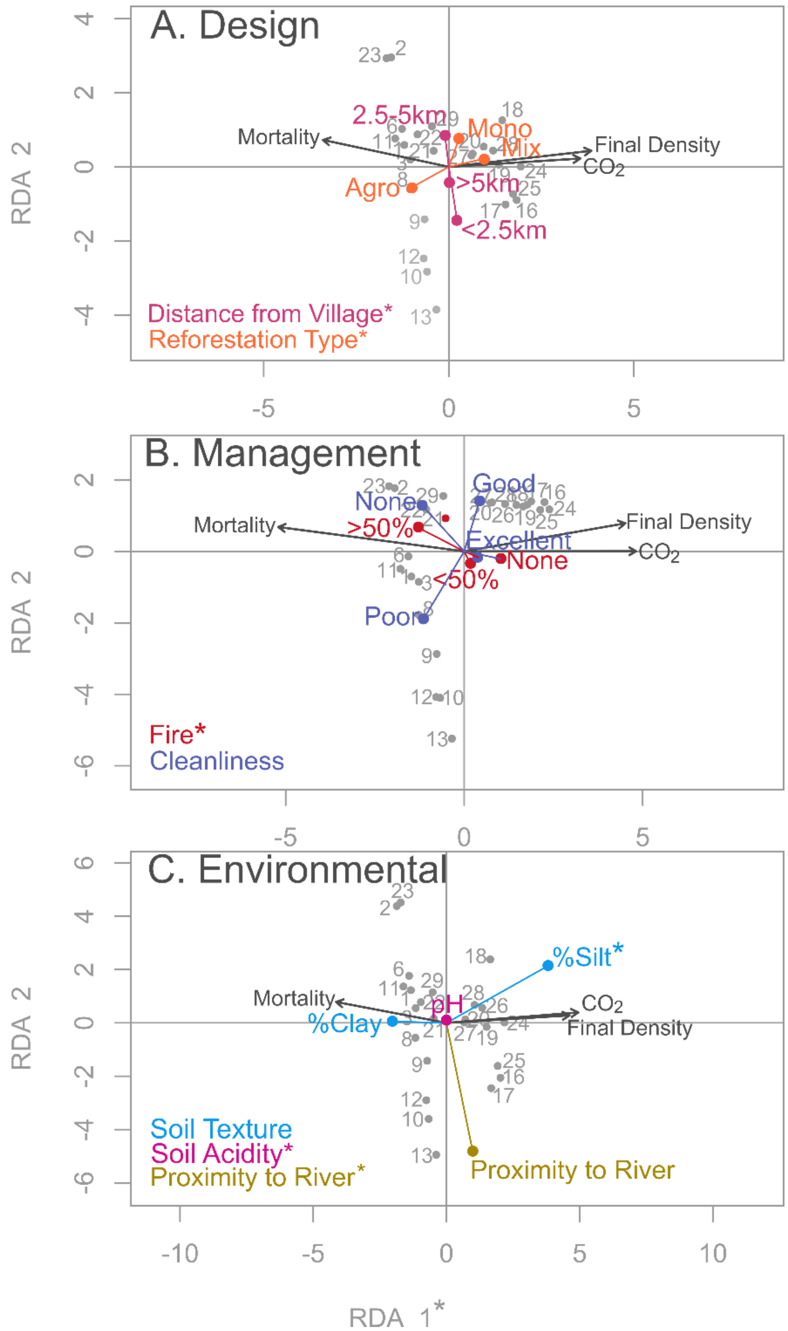

Figure 5. Redundancy Analysis (type 2 with weighed average) of design, management and environmental characteristics on mortality, final density, and Carbon sequestration per plot. The angle between variables is representative of their correlation. A star signifies statistical significance ($p<0.05$).

In the management RDA, the x-axis was characterised equally by fire and cleanliness (Figure 6-C). The absence of fire (0.618) was inversely correlated with a majority of fires (-0.771), absence of cleanliness (-0.708) and poor cleanliness (-0.686). The first RDA axis was the only significant axis ($p<0.05$) and it explained 98.3% of the variation. Plots with a burnt area of less than 50% had a slightly positive loading factor (0.11) and so did plots with good (0.26) and excellent (0.23) cleanliness. In this space, there was higher mortality in largely burnt plots and those with poor or no maintenance. Inversely, carbon stock and density were associated with good or excellent maintenance and smaller or no fires. While cleanliness had a large influence on the RDA space, its explanatory power was not significant. Fire was both important and significant ($p<0.05$).

In the environmental RDA, the x-axis was explained most strongly by soil texture parameters followed by proximity to the river (Figure 6-B). The first RDA axis was the only significant axis ($p<0.01$) and it explained 98.1% of the variation. On this axis, silt and clay content were inversely correlated with loading factors of 0.654 and -0.344 respectively. Distance from the river had a loading factor of 0.169 and soil pH of 0.009. The dependent variables of carbon stock and final density were correlated with increased silt content, while mortality was negatively correlated to this explanatory variable. Mortality was also positively correlated with increased clay content, but its explanatory power was not significant. Silt content ($p<0.01$), distance from the river ($p<0.05$) and pH ($p<0.01$) were all significant explanatory variables.

When looking at the position of the plots in figure 5. One will notice similar patterns between RDAs. In the top left corner, we always find plot 2 and 23, these are plots that were completely burnt. Moreover, there is a general tendency of having higher number plots to the right and lower values to the left. This is because plots 1-13 are agroforestry plots and the higher numbers are timber plots.

Partitioning of Variance

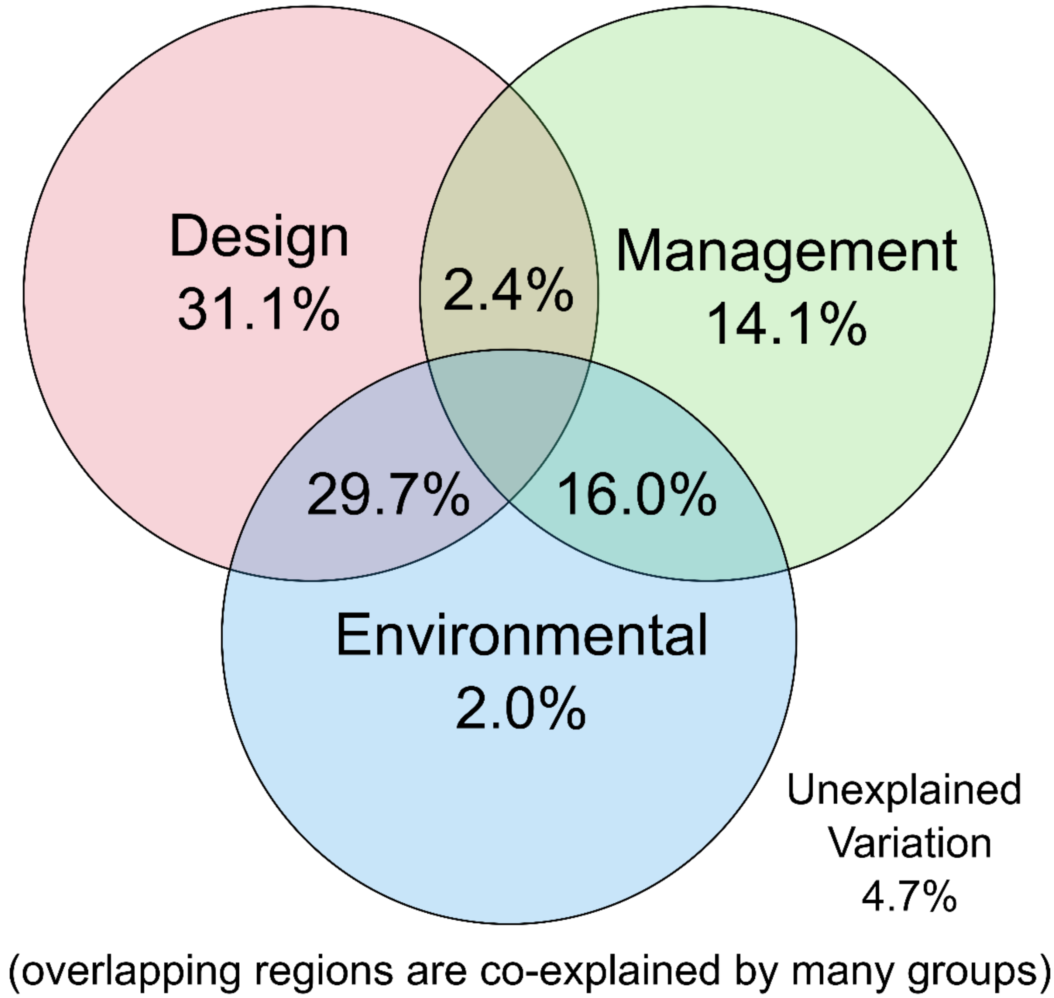

Figure 6. Venn diagram partitioning the explanatory power of design, management, and environmental characteristics.

At the plot level, the RDA characteristics related to the project design, management and environmental conditions cumulatively explained 95.3% of the total variation in the three dependent variables plot's mortality, final density, and carbon sequestration (figure 5). Design characteristics were significant at a $p<0.001$ and exclusively explained 31.1% of the variation.

management characteristics were significant at a $p<0.05$ and exclusively explained 14.1% of the variation while environmental characteristics exclusively explained 2% of the variation ($p<0.01$).

The joint-effect between environmental and design conditions was responsible for an additional 29.7% while management and design explained an additional 2.4%. management in conjunction with environmental characteristics had an explanatory power of 16%. Join-effects represent the overlap between the explanatory power of the different groups, and it occurred because the groups were not perfectly independent (P. Legendre & L. Legendre, 2012).

Community Perceptions

Project Goal

The main motivation for engaging in reforestation projects mentioned by all community leaders was to restore the forest or recuperate the forest that had been lost. Motivations mentioned by > 50% of respondents (n=9) were grouped into 4 main categories: environmental, socio-economic, cultural and governance. Along with restoring the forest, the second most important environmental goal was to have more biodiversity with diverse trees that attract animals and create an environment for medicinal plants to grow (6/9). In socio-economic goals, were an improved quality of life and increased revenue (8/9) followed by capacity building and empowerment in the community (6/9). For cultural goals, the community leaders wished to see youth get engaged in reforestation (7/9). This aligned with discussion with participants who saw their reforestation plots as a legacy for their children and grandchildren. Lastly, in governance, they wanted to lead by example, inspiring neighboring communities to also restore forests (6/9).

Preferences

Participants were driven by the desire for increased forest cover, but still wanted their plots to be productive. One community technician mentioned that he preferred agroforestry plots because trees did not need to be cut down to provide livelihood benefits. He argued that these forests would be more permanent than timber plots. A similar perspective was echoed through the participants where many were interested in more agroforestry, in particular planting coffee crops or increasing their coffee production.

I observed a ridge between the valuation of trees in the reforestation plots or in old growth forests in comparison to secondary natural regrowth. Community leaders viewed favorably the enrichment planting plots that were clean and cleared of most of their natural regrowth while they considered the plot with no maintenance as “dirty”. Many participants considered their reforestation plots as a legacy for their children, but when asked if fallows were also a legacy, a local technician explained that they did not have “useful” species like in the reforestation plot. While some species found in fallows had artisanal or medicinal uses, they were very abundant and thus there was little use to cultivate them. The choice of species was important.

Concerns

Participants at the local congress called importance to the need for continued engagement and income generating opportunities throughout the duration of the project. One participant explained that he had created a nursery from the seeds of his timber trees, but that he has no market to which he could sell the saplings. Moreover, there was confusion about the remaining decade in the contract and a wish for renewed financing. Specifically, the concept of payment for carbon and the idea that they had already been paid for their trees’ carbon through maintenance activities in the first 7 years was unclear.

DISCUSSION

Trade-offs

Reforestation projects for climate mitigation in community contexts embed carbon sequestration objectives within existing social economic and cultural priorities that can either align or contrast, but need to be accounted for to insure the sustainability of the project (Bayrak & Marafa, 2016). In the present case study, while the contract agreement was centered on the offset of carbon emissions, the community leaders looked at the project as an opportunity to create sustainable forest-based livelihoods. Namely, they spoke of cultural revitalization, diversifying income sources, food security, youth education and providing a legacy to future generations. Even with such distinct objectives, the collaboration was possible because both saw reforestation as a path to achieve their respective goals. Divergence in interests arose when looking into the trade-offs of different reforestation types.

Land-use and livelihoods

Our results show that timber systems have the highest climate mitigation potential as they have the highest carbon content per area. However, these systems do very little for the provision of food security and have a very long waiting period for returns on investments (Holmes, Kirby, et al., 2017). In this case study, the community asked to shift the project to agroforestry after the first year as it brought more short-term benefits, additional income, and food security from the fruit production. Moreover, it was an entry door for poorer farmers who did not have the flexibility of waiting 25 years for returns on investments or the space to forego food production on their land (Holmes, Kirby, et al., 2017). Indeed, the yearly median income of participants who engaged in agroforestry was 887$, which was below the median income of the community (1224$) and more than 4.5 times below that of timber participants (4043$) (Holmes, Kirby, et al., 2017). This highlights a need for reforestation projects to offer continuous livelihood benefits and for it to be economically sustainable through time (Lazos-Chavero et al., 2016).

Reforestation projects to offset carbon are often evaluated based on three principles, leakage, additionality, and permanence (Roopsind et al., 2019). Leakage occurs when a project's positive effect is negated by the displacement of the emitting activity to another area (Bayrak & Marafa, 2016). Permanence refers to the displacement of activities through time whereby the gains are lost once payments end. Additionality refers to the causal link where gains can directly be associated to the project and would not have happened otherwise (Roopsind et al., 2019). In Ipetí, agricultural and pastoral expansion into the forest are the main driver for deforestation (Potvin et al., 2007). While returns from timber are higher than those from cattle, the community had, at the start of the project, a strong preference for cattle raising as it was les risky and had a good insurance value (Coomes et al., 2008). This project lowered the reforestation entry leading a few participants to engage in this land use change. In this case, the direct affiliation with the project ensures additionality.

As for leakage and permanence, agroforestry could offer better prevention as it replaces an economically productive activity (agriculture or cattle ranching) with another activity that still provides subsistence and economic revenues in the short term but with additional carbon and ecosystem benefits (Holmes, Kirby, et al., 2017; Pagiola et al., 2016). A "lack of alternative sources of resources and income" can be a pressure factor leading to leakage (Atmadja & Verchot, 2012) which is a risk for enrichment planting and timber plots that are "not productive" from the moments the payments for maintenance end (at year 7) until the end of the contract (year 25). Moreover, the permanence of timber plots may change after the end of the contract where participants are free to harvest the timber. Long term carbon storage would need to look at the harvest intensity and the lifecycle of the wood products. This topic would require further investigation.

The project might also have led to a positive spillover effect (positive leakage) by encouraging more people to engage in reforestation (Lima et al., 2019). Off the body of knowledge and experience build from this reforestation project, interest grew in the community of Ipetí and the neighboring Emberá community of Piriatí to reforest further. In 2020, both communities entered a new reforestation for carbon offset partnership with McGill University, and so far, more than 25 participants have joined. This demonstrates the potential of participatory action research to empower local communities and to act as a catalyst for change (Mateo-Vega et al., 2017).

Agroforestry

In terms of sustainability and relevance to a community context, agroforestry did provide continuous livelihood benefits (Holmes, Kirby, et al., 2017), however, they underperformed relative to their carbon objective by 37% (Figure 1). While this study's findings of 48 tCO_2/ha are comparable with other traditional coffee- polyculture systems found in Mexico that stored between 39 and 46 tCO_2/ha , (Soto-Pinto et al., 2009) they are mismatched with the project's targets. These targets were based of the yields of traditional agroforestry systems in Ipetí reported by Kirby & Potvin, 2007 of 251 tCO_2/ha after 24years. The reference system for agroforestry had an average density of 470 trees per hectare with a total of 62 species and an average age of 23 years. 70% of the trees were edible and 12% only were understory species (such as coffee). In contrast, after ten years, this project had an on average 142 timber and fruit trees with 180 understory fruit species. Coffee was the most abundant representing 43% of all species planted.

This can be explained by people replacing dead trees with coffee, which is an income producing crop (Fitch et al., 2022). This shift in species composition towards smaller understory species and low-density systems was not accounted for in the project design and led to a mismatch in the carbon storage targets. This underlines the importance of understanding the project motivations (Höhl et al., 2020) and of having quality representative data on which to build projections (Potvin et al., 2007). Moreover, it shows a need for follow-up and accompaniment to ensure that goals are met (Martinelli et al., 2019).

A solution could be to continue the intercropping system with coffee but increase the density of shade trees. This has shown to be beneficial for carbon and ecosystem (Badari et al., 2020; Fitch et al., 2022) but as the forest cover increases above 50% shade trees will significantly reduce the yield of the coffee harvests as they will compete for nutrients, water and light (Blaser et al., 2018). In a study comparing coffee, timber monocultures and agroforestry, Fitch et al., 2022 report that enriching timber plots with coffee crops can provide additional livelihood benefits without compromising the carbon of the plantation. However such a practice reduced yields compared to pure coffee plots (Fitch et al., 2022). Similarly, a study by Badari et al., 2020 comparing mixed timber plots with agroforestry suggested that dense agroforests (625 shade tree/ha) could act as transient land uses providing livelihood benefits from coffee in the beginning and shifting to native forest recovery and coffee abandonment in the later years. In terms of carbon uptake, Badari et al., 2020's agroforestry system was halfway between the timber and agroforestry plots reported here.

If coffee crops are not profitable in dense forests, an alternative could be to promote traditional agroforestry systems with more carbon rich fruit trees such as those described by Kirby & Potvin, 2007. While intensively managed agroforestry systems' carbon storage potential is closer to that of conventional agriculture, planting large perennial fruit trees increase the carbon uptake (Montagnini & Nair, 2004). This case study identifies three carbon rich fruit tree with good carbon storage potential, *Inga punctata* (ice cream bean or guaba) (Soto-Pinto et al., 2009), *Anacardium occidentale* (cashew or marañon) (Biah et al., 2019) and *M. indica* (mango) (Sharma et al., 2021). It is to note however that other studies have found that Inga does not grow well on nutrient poor soils (Breugel et al., 2011; Hall & Ashton, 2016) and that anacardium occidentale has many problems with pests (Freire et al., 2002; Lhano et al., 2019). *Persea americana* (avocado or aguacate) had good carbon storage potential and were easy to sell, it had such high mortality rates that the sample size was too small to include in carbon analyses. Any widespread promotion of this species should proceed with caution. Other large fruit trees namely *Pouteria sapota* (Mamey), *Bactris gasipaes* (Pifa) and *Matisia Cordata* (Sapote) were planted but in too small sample sizes for me to significantly evaluate their potential. Interestingly, those are all species found in traditional agroforestry home gardens (Kirby & Potvin, 2007) and species that were mentioned as having good carbon potential in the interviews with participants. These all bring household consumption benefits, and most can be sold (Holmes, Kirby, et al., 2017).

However, many participants showed interest in this coffee specifically as it had a well-established market (Voora et al., 2019) and thus provided the most straightforward alternative source of resources and income (Atmadja & Verchot, 2012). In that regard, a third alternative to optimize the productive ability of the agroforestry system is to keep the lower density, but plant over larger areas. A few participants were limited in space, but when taking the sum of all the participant's land, the areas allocated to reforestation represented less than 2% of their total land holding (Holmes, Potvin, et al., 2017). The trade-off here is that larger areas have a higher maintenance cost. Since this project's payment for offsets was based on the cost of maintenance, it would require a higher price per ton of carbon.

In summary, I identify three strategies to increase the carbon capture of agroforestry systems that would need to be investigated further: 1. increase the density of shade trees (Blaser et al., 2018) 2. plant more carbon rich fruit trees (Segura & Andrade, 2012) or 3. plant over larger areas. For options optimizing coffee production, a study of local yields and financial benefits should be a priority. Recognizing trade-offs between systems and within systems is important to make informed decisions (Martin et al., 2021).

Natural Regrowth

Worthy of mention is the important carbon contribution of natural regrowth which was observed both in enrichment planting (EP) and in plots that suffered from fire. Enrichment planting adds social and economic value to fallows with timber and fruit trees (R. L. Chazdon & Guariguata, 2016; Paquette et al., 2009) while protecting the natural regrowth which contributes to the ecological diversity (R. Chazdon, 2017) and the carbon budget (R. L. Chazdon et al., 2016). In this case study, natural regrowth in EP systems was composed of 30 different species and contributed to 60% of the carbon even if it represented only 42% of the trees present. Moreover, in agroforestry plots, natural regrowth provided an unexpected but welcomed buffer to mitigate the impacts of fire. It accounted for nearly a third of all carbon stored (figure 1). Compared to timber systems EP stored only 40% as much carbon, but since it "combine[d] both "artificial" planting and "natural" management of the existing forest" it had lower implementation costs (Paquette et al., 2009) making it a cost-effective mechanism (Lewis et al., 2019).

From a cultural standpoint however, natural regrowth was not perceived as valuable within the community. Many of the species abundant in natural regrowth are fast growing pioneers such as species of the genus *Cecropia* (Guarumo). These were seen as competitors to the desirable timber and fruit species and were often cut down. People were looking for productive land-use through reforestation (Martin et al., 2021) and natural regrowth was often perceived as “messy” or unused (Zahawi et al., 2014). This perception may be influenced by local policies offering land titles to settlers who “improve” “unproductive” land (being either primary forest or regrowth) by cutting down the trees (Holmes, Potvin, et al., 2017; Zahawi et al., 2014).

Between the participants that had fires on their plots, the degree of management intervention post-fire varied. In plots with high intervention, total carbon from regrowth was reduced compared to those with little intervention. In fact, intensively-managed systems can hamper natural regrowth (Badari et al., 2020). For instance, one participant reported that they actively removed any undesired growth to prevent them from shading understory fruit species. In contrast, two other participants had not managed their plantations since the fire burned their plots early in the project. When measuring carbon, the low management plots had the most carbon of all the agroforestry plots and were the only two on track to reach their carbon storage objectives.

Ecologically, old fallows may be considered young secondary forests (Paquette et al., 2009), but historically they are unutilized land waiting to be returned to agriculture, pasture or left to regrow as forests (Potvin et al., 2007). They are poor in density of timber and fruit species useful to the community (Tschakert et al., 2007). Active reforestation plots are seen as more valuable. This again is a trade-off between management efforts and perceived value. However, if a plot burns, natural regeneration is a cost-effective way to recover some of the lost carbon and can complement active reforestation efforts (R. L. Chazdon et al., 2016).

Figure 7. A plot without natural regrowth above and a plot with natural regrowth below. Both were burnt around the same time.

Lessons

Through the process of a 14-year reforestation project, and in the prospect of a subsequent iteration to this research cycle, I identify four key takeaways and lessons that can serve to inform design and implementation. (1) First, I underline the importance of making the project objectives of all stakeholders explicit from the start (Gann et al., 2019) in order to have clear goals and be able to measure their progress (Evans et al., 2018). (2) Once the goals are clear, the trade-offs of different designs can be evaluated to develop a menu of options (Holmes, Kirby, et al., 2017; Vincent et al., 2021) that, in the context of reforestation for carbon offset, have provisions to achieve carbon capture goals. (3) With project implementation comes a need for capacitation to empower local actors and bring everyone to a level playing field (Brooks et al., 2012; Lazos-Chavero et al., 2016). (4) Lastly but not least, is the critical importance of mitigating risks of fire for the entire duration of the project (Barlow et al., 2012; Boeschoten et al., 2021; Lindenmayer et al., 2012).

Clarify stakeholder goals

Reforestation in a community context can be understood as a complex social-ecological system (SES) where social and ecological components interact with each other and influence project outcomes (Ostrom, 2009). Using the framework of Ostrom 2009, we can analyse how the governance system (in this case the carbon offset contract) and the different users (participants) shape the resource system (the reforestation plots) to optimize for different resource units (carbon offsets, provision of food and/or income). These lenses highlight the complexity of SES where different participants (users) may have a variety of reasons for participating in a reforestation project and may wish to optimize for different resource units (Lazos-Chavero et al., 2016).

Moreover, the buyer, may favor different outcomes than the participants (Höhl et al., 2020). For example, while most agroforests are not reaching their carbon targets, many participants consider their plot successful because they are now harvesting fruits. A project's expected benefits can be related to carbon, but also to the social, economical, environmental, and cultural outcomes (Kohler & Brondizio, 2017). Clarifying project goals at the start of the project can help inform the project design (Vincent et al., 2021), the choice of indicator and the evaluation metrics to monitor project success through time (Dumitru et al., 2021; Mansourian & Vallauri, 2014).

Adapted design

As shown in this case study, each reforestation systems brings a set of strength and trade-offs and a project's success will depend on the alignment of the benefits with the vision and motivations of both the buyers and the participants (Le et al., 2012). For carbon offset, a menu of reforestation options could be offered (Holmes, Kirby, et al., 2017), with provisions to ensure acceptable carbon storage potential. This could be accompanied with a requirement to maintain a certain density of trees in agroforestry systems (Badari et al., 2020) and assistance (Le et al., 2012) such as providing seedlings to replace mortality so that not all dead trees get replaced by coffee. Offering multiple options gives the opportunity for participants to best align the project with their personal goals (Holmes, Kirby, et al., 2017) which increases the likelihood that they will stay committed to the project in the long term (Gann et al., 2019).

Capacitation

Community-led projects bring a social dimension to reforestation which, in addition to a adapted design, requires investment in capacity building for maintenance (Cerbu et al., 2013). Not all participants started on a level playing field in terms of know-how and access to appropriate tools to clean, water and protect their plots against pests or fires. Some of the older participants had worked in the field their whole life and had a strong network of labour exchange while others struggled to uphold both their family obligations with their contract obligations and would often subcontract the work (Holmes, Potvin, et al., 2017). This showed in the results where management accounted for 14% of the variation in plot performance and where mortality varied from 15%-70% between participants (excluding fully burnt plots). In comparison, Mayoral et al. (2017)'s study that was using the same target trees species as us, had a mortality rate of at most 15%. This highlights the importance of providing access to needed tools, training, and accompaniment especially when the trees are young (Martinelli et al., 2019).

Controlling Fire

Fire has been reported as a reforestation project inhibitor across the literature and is particularly prevalent in community-based projects (Barlow et al., 2012; Boeschoten et al., 2021; Elliott et al., 2019). This research further emphasises the need for efficient fire control as two third of the plots suffered damage from fire. Preventative mechanisms included fires breaks and watering during the dry season, however, in many occurrences either the fire break was not made, or fire jumped over it. In the case of the two total burns, the fire came from the neighboring community and jumped across the Pan-American highway (a two-way paved street). This greatly underwhelmed the project's benefit socially, economically, and ecologically (Barlow et al., 2012).

This study's findings on the potential of *T.amazonia* and *D.retusa* to capture carbon are aligned with results from the Agua Salud project. They report 172.7tCO_2/ha for the *T.amazonia* monoculture and 112.93 ttCO_2/ha for the five species mixture while I report 163tCO_2/ha and 175tCO_2/ha respectively (Mayoral et al., 2017). Where results differ is in the mortality rate; while they report average rates below 6% for all species, the average mortality in Ipetí are of 21% for mixtures and 34% for monocultures. This highlights the social characteristics that become increasingly important in community contexts in particular the need to bring fires under control.

Fire exists outside the boundaries of the project which requires larger scale coordination with neighbours and local authorities and even neighbouring communities. Fire is closely intertwined with agriculture as slash-and burn has been deeply rooted in the culture for thousands of years (Fischer & Vasseur, 2002). In this case study, all fires were caused by agricultural burns going out of control. To reduce landscape level risks, community-led initiatives can work with local authorities to implement mechanisms for liability and retribution as well as implement structured communication with neighbors (Elliott et al., 2019; Pasicolan et al., 1997). Pasicolan et al., 1997 highlight the role of community collaboration in creating voluntary vigilantes while Elliott et al., 2019 analyze the creation of organized fire patrols that were included in the project budget.

Assigning responsibility is not always straightforward (Barlow et al., 2012): one can look at the compliance of participants with their fire-break duties, or turn to neighbors who did not warn before burning. A participant expressed concern about fire destroying their plot and asked whether the contract forsaw the replacement of seedlings by the buyer. During interviews with leaders, some suggested that the neighbor who burnt trees should be responsible for replacing them. Moreover, project funding only covered maintenance costs for the first seven years, while the reforestation contract requires the participants to prevent fires for the whole 25 years. This disconnect between short term funding strategies and long-term needs is well documented (Höhl et al., 2020; Holl & Brancalion, 2020; Mansourian & Vallauri, 2014). Fire pressure could be alleviated by securing steady long-term financing (Engel et al., 2008; Lazos-Chavero et al., 2016).

CONCLUSION

In conclusion this study clearly demonstrates the importance of design and environmental characteristics in planning reforestation projects and that of management in their implementation (figure 5). Along with the project design came the trade-offs between the different growing systems. Timber plots optimized carbon storage, especially in mixtures where there was a 45% increase in carbon storage because of the biodiversity effect (175tCO_2/ha vs 121 tCO_2/ha) (figure 2). Agroforestry and enrichment planting stored only ~50tCO_2/ha each due to low density planting, but one provided food security and the other richer biodiversity at a lower implementation cost. As for social characteristics, preventing fires has been and will be paramount to the long-term viability of the project. While fire has been the project's main threat, natural regrowth from enrichment planting and post-fire regrowth partially buffered the loss and proved to be an important carbon sink accounting for 31% of the project's total carbon (figure 1).

This research's findings point towards an adaptive reforestation design that is aligned with the desires of the community and the carbon buyer (Lazos-Chavero et al., 2016). I shine light on many variables that impact project success such as species composition (Mayoral et al., 2017; Soto-Pinto et al., 2009), preventing fire (Barlow et al., 2012; Elliott et al., 2019), and the reforestation system's design (Badari et al., 2020). Moreover, I identify promising timber and fruit species for carbon offset in the neotropics. The process of doing participatory action research proved an effective catalyst to initiate more reforestation action (Lima et al., 2019). As a consequence of this project, local interest in reforestation grew and, in 2020, the community of Ipetí Emberá along with the neighboring Emberá community of Piriatí entered in a new reforestation contract to offset carbon emission. As we need to scale up reforestation across the globe (Cohen-Shacham et al., 2019), this thesis demonstrates how indigenous people and local communities can be empowered to lead their own initiatives and need to be included as important actors in reforestation (Garnett et al., 2018).

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APPENDICES

APPENDIX I - Community Leader Interview Questionnaire

Context: From 2008-2010 the community of Ipetí engaged in a first reforestation project to offset carbon emissions. Now in 2020, the local congress signed a three partied agreement with

McGill university and a local women's association AMARIE, to initiate a new reforestation project. This project will be implemented both in Ipetí, and the neighboring community of Piriatí.

Goal: The goal of these interviews was to understand what the expected benefits were of engaging in such reforestation projects. The results served to 1. Inform research on the first reforestation project (this thesis) and 2. Set the ground for the creation of a comprehensive evaluation framework for the 2020 project.

Methodology: In groups of two, undergraduate students from BIOL553 interviewed leaders of the Alto Bayano Congress using zoom and a list of seven open-ended questions designed beforehand by myself. I attended all interviews to listen and take notes. I also aided with translation when necessary, asked additional questions when relevant, and answered the participant's questions that the students could not answer.

Questionnaire:

Q1. What is your role in this project? Ie. Please describe what you do, what you are responsible for and who do you work with.

Q2. How do you understand the outcomes/deliverables/results of this project? What are the goals of the project?

Q3. What do you hope to gain from this project personally? And your family? Ex. Professional experience, a legacy for my children, a source of income, feeling like I'm helping the earth etc.

Q4. More generally, what are the benefits you want to see resulting from this project? Probing more at the community level?

Q5. Drawing form the answers of Q.2-4; What are the expected deliverables/accomplishments of the project at the short/medium and long term? Ie.1/5/25 years? (These should be in the form of actions)

Q6. How can we **measure progress** through time? What could be indicators of success/failure? Who and how should these indicators be measured? note: you can group points together if they have the same indicator.

Q7. What are potential challenges/threats/risks that could hinder the success of the project? What other opportunities do you think could happen?

APPENDIX II - Research ethics certificates and approvals

Research Ethics Board Office
James Administration Bldg.
845 Sherbrooke Street West. Rm 325
Montreal, QC H3A 0G4
Website: www.mcgill.ca/research/research/compliance/human/

Research Ethics Board 1
Certificate of Ethical Acceptability of Research Involving Humans
REB File #: 21-03-023
Project Title: Forest conservation, restoration and livelihoods in eastern Panama
Principal Investigator: Prof. Catherine Potvin
Department: Biology
Other Researchers:
Katia Forgues, Master's student, Biology Department, McGill University
Paola Fajardo, Doctoral student, Biology Department, McGill University
Camilo Alejo Monroy, Doctoral student, Biology Department, McGill University
Lucie Viciano, Climate Officer, McGill Office for Sustainability, McGill University

Funding: NSERC, CRC

Approval Period: 11 May 2021 to 10 May 2022
The REB-1 reviewed and approved this project by delegated review in accordance with the requirements of the McGill University Policy on the Ethical Conduct of Research Involving Human Participants and the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans. Deanna Collin, Senior Ethics Review Administrator

RENEWAL
McGill University
Research Ethics Board Office
www.mcgill.ca/research/research/compliance/human

REB File Number: 21-03-023

Project Title: Forest conservation, restoration and livelihoods in eastern Panama

Principal Investigator: Professor Catherine Potvin
Department: Biology
Approval Date: May 4, 2022
The REB-1 reviewed and approved the Continuing Review application for the above project. The renewal of ethics approval is **valid until May 10, 2023**.

APPENDIX III - Consent Document for Participants

McGill University, Canada

Consent Document for Participants

REB file # 21-03-023

Researchers:

RQ3: Two local field-assistants: Yarelis Ruíz (Ipetí) and Eduardo Garabato (Piriatí); Katia Forgues, Master's student, McGill University katia.forgues@mail.mcgill.ca; Undergraduate students from the Panama Field Study Semester to be identified in the coming months/year.

Principal Investigator: Catherine Potvin Catherine.potvin@mcgill.ca

The following information describes the research project in which you have been invited to participate.

We aim to better understand socio-ecological conditions that favour tropical forest conservation and restoration. We seek to document how changing livelihoods affect land uses and what incentives could encourage forest protection by local Indigenous communities, using two case studies in eastern Panama. The research takes place specifically in the Emberá communities of the *Tierras colectivas del Alto Bayano* in the Province of Panama and the *Tierras colectivas del Rio Balsa* in the province of Darien.

RQ3: Identify the core elements of an evaluation framework that could be used to assess the success of the community-based carbon offset project developed in collaboration with McGill in the Bayano.

Participant recruitment

Participants will be selected by the traditional authorities and/or will voluntarily participate in the research activities.

No discomfort or risk is expected to occur to you as a result of the research.

Project procedures

The data collected during the interviews will be used by me and my research team to answer the research questions. Data will be collected largely by audio tape recorder, with the researcher making additional notes as required. Once the data have been obtained, they will be transcribed from tape to paper for the purposes of analysis. Data will be stored in a computer and in hard copy in secure storage at all times and destroyed after 7 years.

A summary of the project findings will be made available to you prior to finalizing the draft report.

The researchers and principal investigator will have access to identifiable data. Confidentiality will be preserved. No names will be used in the final report.

Results could be used in a companion project if approved by the traditional authorities and community.

Participant involvement

The time limit of this interview will be at the discretion of your time availability.

Participant's rights

You have the right to:

- decline to participate;
- decline to answer any particular question;
- withdraw from the study at any point;
- ask any questions about the study at any time during participation;
- provide information on the understanding that your name will not be used unless you give permission to the researcher;
- be given access to a summary of the project findings when the project is concluded;
- request that the audio tape be turned off at any time during the interview;
- request that your answers not be used in any subsequent study.

Project contacts

You are welcome to contact me and my supervisors at any time to ask questions regarding the project. The researcher and supervisors can be contacted at the above address. If you have questions about your rights or wellbeing as a participant in this study, please contact the McGill Ethics Office: lynda.mcneil@mcgill.ca

APPENDIX IV – “Pino Amarillo” pictures for ID

APPENDIX V - TCPS CORE Certificate

PANEL ON RESEARCH ETHICS
Navigating the ethics of human research

TCPS 2: CORE 2022

Certificate of Completion

This document certifies that

Katia Forgues

successfully completed the Course on Research Ethics based on the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2: CORE 2022)

Certificate # 0000489113 **6 May, 2022**

PANEL ON RESEARCH ETHICS
Navigating the ethics of human research

TCPS 2: CORE

Certificate of Completion

This document certifies that

Katia Forgues

has completed the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans Course on Research Ethics (TCPS 2: CORE)

Date of Issue: **16 January, 2019**