FOLUR

Food Systems • Land Use • Restoration



# Enriching lives and lands through Assisted Natural Regeneration

## Financial analysis of enrichment planting of naturally regenerating forests and woodlands with native non-timber products

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### PHOTOS

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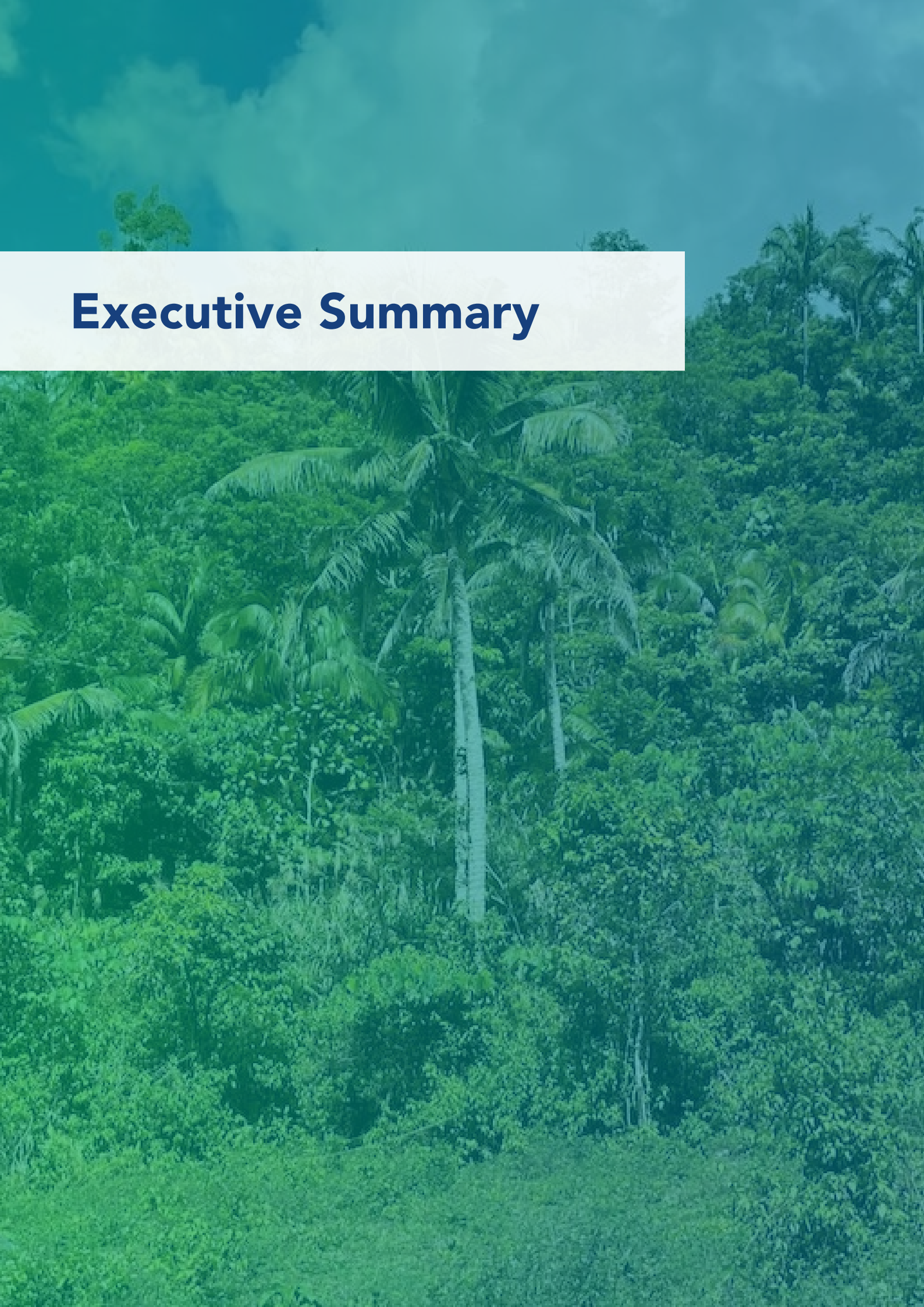
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# Executive Summary



**Assisted natural regeneration (ANR) is a set of practices and interventions designed to enhance and accelerate the recovery of natural and managed ecosystems.** In forest and woodland biomes, the ideal conditions for practicing ANR are found in disturbed forest areas (following logging, fires or other disturbances) and in post-agricultural fallows where native vegetation remnants are retained in or near the site. When practiced using local knowledge and spatial planning, ANR is a highly effective restoration approach for conserving native biodiversity and recovering multiple ecosystem services. Yet, regenerating forests and woodlands that do not hold economic value for farmers, land users, and local communities are frequently recleared, and ANR implementation faces multiple social, economic and policy challenges even under suitable biophysical conditions.

**We explored how ANR with supplemental enrichment planting with native non-timber forest product species (NTFP) can enhance both the economic and ecological values of regenerating forests.** With support from the Global Knowledge Platform of the Food Systems, Land Use and Restoration Impact Program (FOLUR) of the Global Environment Fund (GEF-7), led by the World Bank, we applied financial analysis over 30 years to assess the financial feasibility of growing, harvesting and selling products sourced from 14 NTFP species in the context of naturally regenerating forests and woodlands in five Latin American and African countries (Brazil, Ecuador, Ethiopia, Ghana and Nigeria). The cost-benefit and alternative land-use models are parameterized within the native geographic range and climate conditions of the target species used for enrichment, which occur naturally in forest fragments, fallows or woodland areas in these areas and are widely harvested, used and marketed by local communities.

**We used financial indicators—net present value (NPV), internal rate of return (IRR), and benefit-cost ratio (BCR)—to assess baseline CBA performance and to evaluate how two key parameters—discount rate and productivity—affect profitability and investment risk.** We also evaluate opportunity costs by comparing the net revenue of ANR systems with enrichment to revenue generated from agriculture and forestry land uses within the same location. Further, we compare costs of ANR with NTFP enrichment to costs of ANR without enrichment and costs of minimally assisted natural regeneration with and without revenues from sale of carbon credits on the voluntary carbon market and evaluate the break-even point of carbon pricing for ANR scenarios.

**Twelve of the 14 ANR with enrichment planting systems are financially viable, but profitability varies widely.** Three high-performing species—*Oldeania alpina* (highland bamboo, Ethiopia), *Aniba rosaeodora* (Brazilian rosewood, Brazil) and *Garcinia kola* (bitter kola, Nigeria)—offer exceptional returns, with NPV above USD 70,000 per hectare, BCR from 3–37, IRR from 21–342% and payback times from 3–15 yr. Six species showed strong and consistent performance: *Euterpe oleracea* (açai, Brazil), *Paullinia cupana* (guaraná, Brazil), *Tetrapleura tetraptera* (Prekese, Ghana), *Ilex guayusa* (Guayusa, Ecuador), *Ilex paraguariensis* (yerba mate, Brazil), and *Piper capense* (Timiz Long Pepper, Ethiopia), showing NPVs from USD 1,575–13,443, BCRs from 1.38–5.88, and IRRs from 16% to 82%, and payback within 1–9 years. Models with low initial investment requirements and moderate recurrent costs tend to achieve higher cost-effectiveness and shorter payback times, even when total revenues remain modest.

**Five species demonstrate poor or negative financial performance.** *Parkia biglobosa* (African Locust Bean, Ghana), *Vitellaria paradoxa* (Shea, Ghana), and *Irvingia gabonensis* (bush mango, Nigeria) have positive but low NPVs below the median level of USD 6,266 and long payback periods (10–11 years), indicating weaker financial attractiveness. *Aframomum corrorima* (Ethiopian cardamom, Ethiopia) and *Gnetum africanum* (eru, Nigeria) have negative NPVs and BCRs below 1, indicating that benefits do not cover costs over the 30-year horizon.

**Assisted natural regeneration with enrichment, when properly designed and managed, offers not only ecological benefits but also a resilient investment pathway capable of withstanding diverse economic scenarios.** Eleven of the 14 ANR with enrichment models remain economically viable at elevated discount rates of 15%, and most ANR systems improve economically with increased productivity. Systems enriched with high-value wood products and fast-growing biomass species, such as *Aniba rosaeodora* and *Oldeania alpina*, exhibit strong sensitivity to changes in yield, with profitability increasing rapidly under improved productivity conditions but declining steeply when production falls below expectations. In contrast, models based on production of fruits and leaves—particularly *Euterpe oleracea*, *Garcinia kola*, *Ilex guayusa*, and *Vitellaria paradoxa*—display far greater stability, maintaining positive returns even under conservative yield assumptions. This distinction highlights a structural resilience within NTFP-based systems, where multiple harvest events and local market integration buffer producers against biophysical stresses or price fluctuations.

**Comparison across models reveals a clear trade-off between investment scale and financial resilience**. Low-input ANR systems offer reliable, steady returns with minimal financial risk, whereas high-input, productivity-driven systems deliver superior economic performance only under favorable conditions. These contrasts underscore the importance of aligning restoration design

with both ecological context and investor profile to balance cost efficiency, time horizon, and sensitivity to biophysical and market uncertainties.

**Supplementing assisted natural forest regeneration with enrichment planting of commercial non-timber forest product species shows high economic benefits relative to alternative land uses, and climate benefits on par with other forms of restoration**. For nine of the 14 species, net revenue from ANR with enrichment was higher than the most profitable alternative land use within the same area. For three species, *Aniba rosaeodora*, *Oldeania alpina* and *Garcinia kola*, net revenue from ANR with enrichment is estimated to be more than 10 times higher than that of the most profitable alternative land use at the same site. For six species, *Euterpe oleracea*, *Paullinia cupana*, *Ilex guayusa*, *Tetrapleura tetraptera*, *Irvingia gabonensis*, and *Piper capense*, net revenue from ANR with enrichment (ANR+E) is estimated to be from 1 to 10 times higher than that of the most profitable alternative land use. For three species, *Vitellaria paradoxa*, *Ilex paraguariensis*, and *Parkia biglobosa*, net revenue from ANR+E is lower than that of the most profitable alternative land use. In these cases, including revenue from carbon credit sales by increasing the price per ton of carbon or cost-reduction incentives could further incentivize ANR+E over crop production.

**NTFP sales offer an important alternative income stream for smallholders and community-based forest regeneration and restoration activities, substituting for or complementing income from carbon credits or other economic incentives.** Revenue from the sale of NTFP can replace or reduce the carbon breakeven price. For the three species where net revenue from ANR with enrichment is below that of alternative land uses, sale of NTFPs can lower the price of carbon credits or other economic incentives needed to achieve competitiveness.

**Predicted carbon accumulation from ANR+E systems shows less variation than predicted financial indicators**. The median 30-year carbon accumulation from ANR with enrichment systems is 83.0 tC/ha, which is comparable to accumulation of 79.5 tC/ha from minimally assisted NR, 98.2 tC/ha from ANR without enrichment, 11.3 tC/ha from fuelwood, and 95.3 tC/ha from solidwood plantations. Potential carbon revenue (30-year, discounted) across all 14 sites has a median value of USD 758/ha based on farmer income of USD 6/tC.



**Model results are preliminary, as data on costs and revenues for generating these cost-benefit assessments have not been verified in the context of ANR+E for any of the target species included here**. More definite assessments of feasibility will require a set of well-planned pilot studies with careful accounting of costs and revenues. We did not have the benefit of using data from actual implementation cases on the ground, as these cases do not exist or they are poorly documented in the literature. The study demonstrates a clear need for pilot or demonstration projects to test viability and outcomes in appropriate geographic settings.

**The study highlights several areas where research is needed to improve cost-benefit models of ANR+E and to ensure effective implementation on the ground**. These research questions could be addressed using pilot projects in several countries and geographic contexts. Ideally, research teams would bring together university students and researchers, local civil society organizations and government agencies. Research is needed in three main areas: management practices, economic incentives and mechanisms, and institutional support and governance.

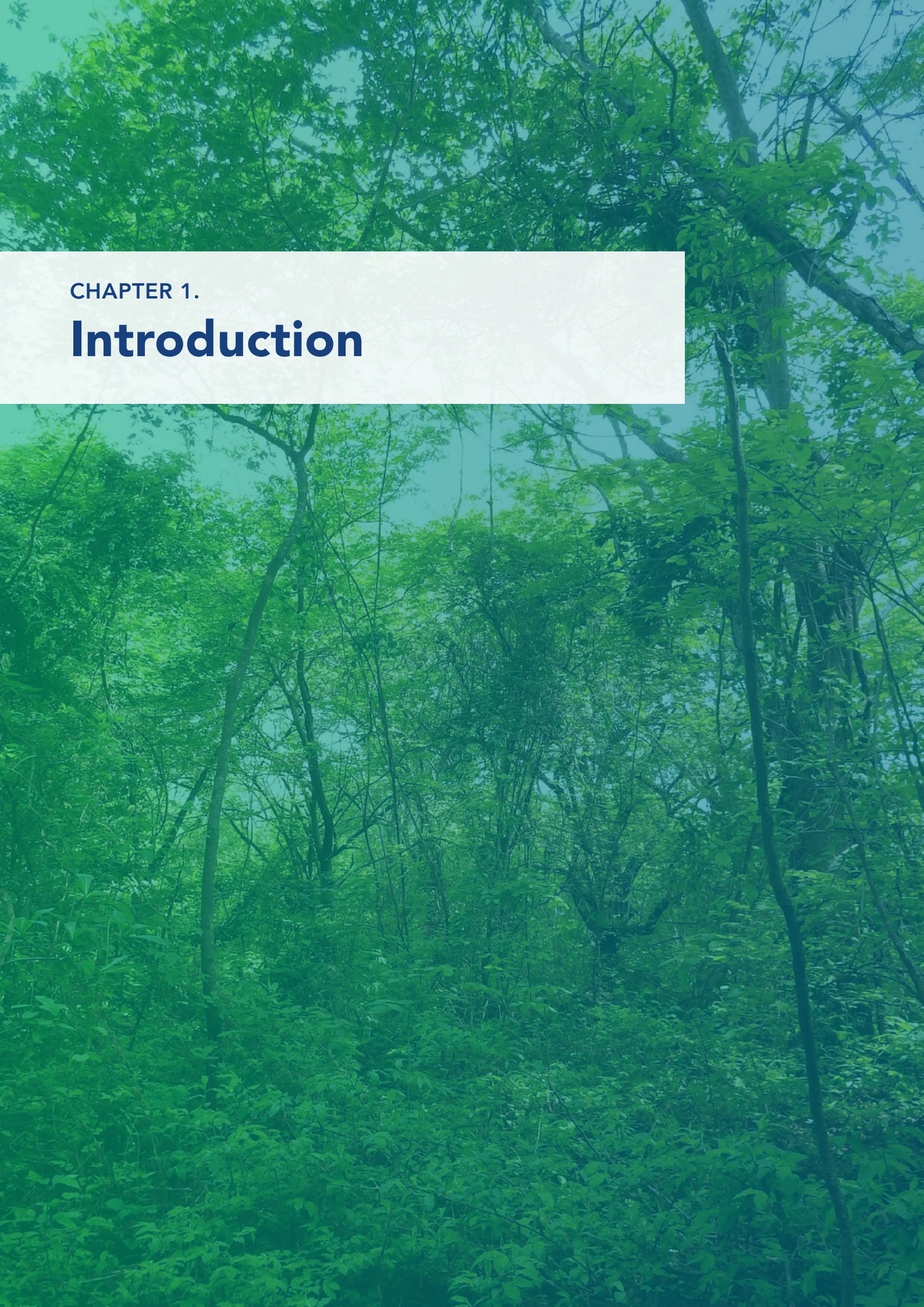
**Spatial planning at the landscape scale with engagement of local communities can help to minimize land-use conflicts and identify areas where protecting forest fallows and regenerating forests (with or without enrichment planting of NTFP) will have positive benefits for smallholders and communities**. Priority areas for ANR are within public or private protected areas, in buffer zones of protected areas, in areas close to forest remnants, in biological corridors and in riparian zones. Lands that are used for implementing ANR should not be restored into forests at the expense of food security for local people.

**On-site technical support and guidance is needed to help local farmers and communities select appropriate sites for ANR and to implement effective and low-cost ANR interventions and schedules for management activities**. Guidance regarding how to plant and care for the NTFP species is also critical. Many species used for NTFP are not fully domesticated, which leads to highly variable rates of harvesting, diminished genetic resources, and overharvesting of wild populations. Technical guidance is also needed regarding how to monitor the ecological and economic outcomes of ANR based on simple measurements of tree size, plant diversity, soil quality and yields of NTFP products. As natural regeneration proceeds, useful species that establish spontaneously can also be monitored for their abundance in the sites, such as firewood, medicinal species, crafts, food, or timber.

**Land and tree tenure arrangements can pose serious challenges to ANR+E.** Rights to use the land or to use the trees are often insecure and can strongly disincentivize land management practices based on natural regeneration. In many countries, naturally growing trees are government property and cannot be legally harvested, even on farmland. In other cases, farmers that allow trees to regenerate on their farms risk losing their property rights. Most government policies that do support NTFP marketing are implemented through local benefit-distribution channels, which follow existing land tenure and resource access rights that exclude large sectors of the population. The informal economies that characterize NTFP use are often based on non-monetized labor, particularly by women, who are not fully recognized within regional institutions and who have insecure land and property rights.

**Cultivation of NTFP in naturally regenerating systems can protect endangered, threatened and vulnerable species and reduce overexploitation of wild populations**. One target species, *Aniba rosaeodora*, is endangered, two species (*Gnetum africanum* and *Irvingia gabonensis*) are near threatened, and two species (*Vitellaria paradoxa* and *Garcinia kola*) are vulnerable. Weak formal regulations and inconsistent customary governance are exacerbated by a policy framework that creates a disenabling environment for sustainable harvesting of NTFPs.

**Shifting the prevailing model of NTFP extraction to one of cultivation through restoration and regeneration brings three types of benefits for smallholders and local communities**. First, it would promote the recovery of local biodiversity and ecosystem services. Second, it would promote sustainable land use alternatives that provide long-term and direct financial benefits for smallholder farmers and communities. Third, it would preserve local knowledge and culture, based on ethnobotanical uses of native species and recovery of forests and woodlands during forest regeneration. By merging socio-bioeconomy with assisted natural regeneration practices, natural ecosystems can be restored as a key nature-based solution to bring economic benefits to local communities.



CHAPTER 1.

# Introduction

## Assisted natural regeneration as a pathway toward regenerative bioeconomy

Large-scale conversion and degradation of forest ecosystems across the global tropics and subtropics have led to biodiversity loss, climate change and land degradation, threatening planetary systems, forest-based livelihoods and human wellbeing (IPBES 2019; UNCCD 2022). Yet, forest cover in many of these areas can return, recovering multiple ecosystem services that support local communities, enhancing climate mitigation and adaptation and creating habitats that support native biodiversity (CBD 2022; Strassburg et al. 2020). Restorative land uses, such as agroforestry, regenerative agriculture, and sustainable forest management can also mitigate biodiversity loss, protect water supplies and store carbon in soils and in vegetation, while ensuring water supplies and food security for local communities (Vieira, Holl, and Peneireiro 2009). In addition to providing material benefits, forest and woodland restoration can enhance social, human and cultural capital through integration of local and traditional knowledge in a locally-based regenerative socio-bioeconomy (Garrett et al. 2024; Krainovic et al. 2025). The urgency of taking restorative actions is evidenced by the declaration of the United Nations Decade on Ecosystem Restoration 2021-2030 (Mills et al. 2020) and Target 2 of the Kunming-Montreal Global Biodiversity Framework, which is to ensure that by 2030, at least 30% of degraded terrestrial, inland water, and coastal and marine ecosystems are under effective restoration (Obura 2023).

Most forest restoration efforts focus on tree planting, but forest ecosystems can also regrow on their own with little or no assistance, under suitable conditions (Chazdon et al. 2025). Early stages of forest regrowth are highly vulnerable to reclearance, however, especially if they do not provide any economic benefits for land users (Bousfield and Edwards 2025; Robinson et al. 2025; de Jong et al. 2025). Thus, a key driver of permanence and additionality of regenerating forest is to enhance its economic value for farmers, land users, and local communities to a level higher than the net revenue earned through prevailing agricultural or forestry land-uses.

Assisted natural regeneration (ANR) is a set of practices and interventions designed to enhance and accelerate the recovery of natural and managed ecosystems (Chazdon et al. 2023). When practiced using local knowledge and spatial planning, assisted natural regeneration is a highly effective restoration approach for conserving native biodiversity (Crouzeilles et al. 2017; Brancalion et al. 2025). Colonization and establishment of local species ensures that regenerating forest ecosystems are adapted to local conditions, maintain essential species interactions, are resilient to disturbances and offer a full range of ecosystem services (Chazdon 2014).

The interventions used in ANR aim to overcome specific obstacles to natural recovery processes, such as active protection, fire mitigation, control of invasive species, control of insect herbivores and fencing to exclude grazing animals (Shono et al. 2020; Oluwajuwon et al. 2024). For these reasons, ANR interventions are site specific and implementation costs vary widely (Shono et al. 2020; Oluwajuwon et al. 2024; Pacheco, Beatty, and Patel 2024; Schimetka et al. 2024). But implementation costs of ANR are substantially lower than for full tree planting, boosting its cost-effectiveness as a restoration approach (Crouzeilles et al. 2020; Pacheco, Beatty, and Patel 2024; Schimetka et al. 2024). ANR practices often rely solely on management of naturally regenerating vegetation, but supplemental enrichment planting can enhance both the economic and ecological values of regenerating forests (Oluwajuwon et al. 2024).

Enrichment planting is commonly used in forest management to supplement existing natural regeneration with seeds or planted seedlings to increase abundance or diversity of ecologically or economically important species (Forbes et al. 2020; dos Santos and Ferreira 2020). Enrichment planting can be implemented during different stages of forest regrowth or in degraded post-logging or post-fire forests (Axelsson et al. 2024). For light-demanding species, enrichment should be implemented early in the forest regeneration process when the canopy is partially open and light availability is relatively high. For shade-tolerant species, planting should be implemented after the canopy has begun to develop; growth and survival may be enhanced through selective pruning or thinning of neighboring trees. Enrichment planting allows for the introduction of shade-tolerant economically valuable or late-successional species without the need to clear existing trees and can improve habitat quality and carbon sequestration (Montagnini et al. 1997; Mangueira. Holl, and Rodrigues 2019). For example, *Ilex paraguariensis*, yerba mate (Appendix 1C), is traditionally planted and harvested in the understory of regenerating or mature stands of Southern Atlantic Forests in Brazil, Paraguay, and Argentina (Lacerda 2022; Lacerda 2023). Integrating yerba mate cultivation with forest regeneration creates a positive synergy where the forest creates a healthier, more resilient crop, and the crop, in turn, supports the conservation and restoration of the forest ecosystem.

Fallow enrichment is a widely adopted practice in shifting cultivation systems to hasten site recovery and diversify species that provide timber and non-timber products (Cairns 2007). In shifting cultivation systems (also known as swidden agriculture), small areas of forest are cleared, burned and planted for subsistence crop production for a few years. When crop production declines, fields are abandoned to fallow and gradually regrow into secondary forests that are later recleared for crop production after soil nutrients are replenished. During this recovery process, fallows become rich sources of non-timber products (NTFP) such as fruits, resins, building materials, and medicinal plants (Padoch 1988). Enrichment can occur at different stages of forest regrowth, depending on the growth requirements of the species.

In the context of forest and landscape restoration, where the aim is to increase forest cover and enhance landscape functions, naturally regenerating forests represent one of several different approaches to forest restoration (Chazdon and Uriarte 2016; Chazdon 2017). Well-managed fallows are effective forms of reforestation that transform crop fields to forests based on applying extensive local knowledge (Wangpakapattanawong et al. 2010). For example, the Akha people in the mountains of northern Thailand developed approaches to facilitate forest regeneration around their village, transforming grass-dominated fallows into forest by preventing fire and promoting tree regeneration from resprouting rootstocks and direct seeding (Durno, Deetes, and Rajchaprasit 2007). Villagers found that natural forest regeneration was more effective than planting trees for restoring forest cover.

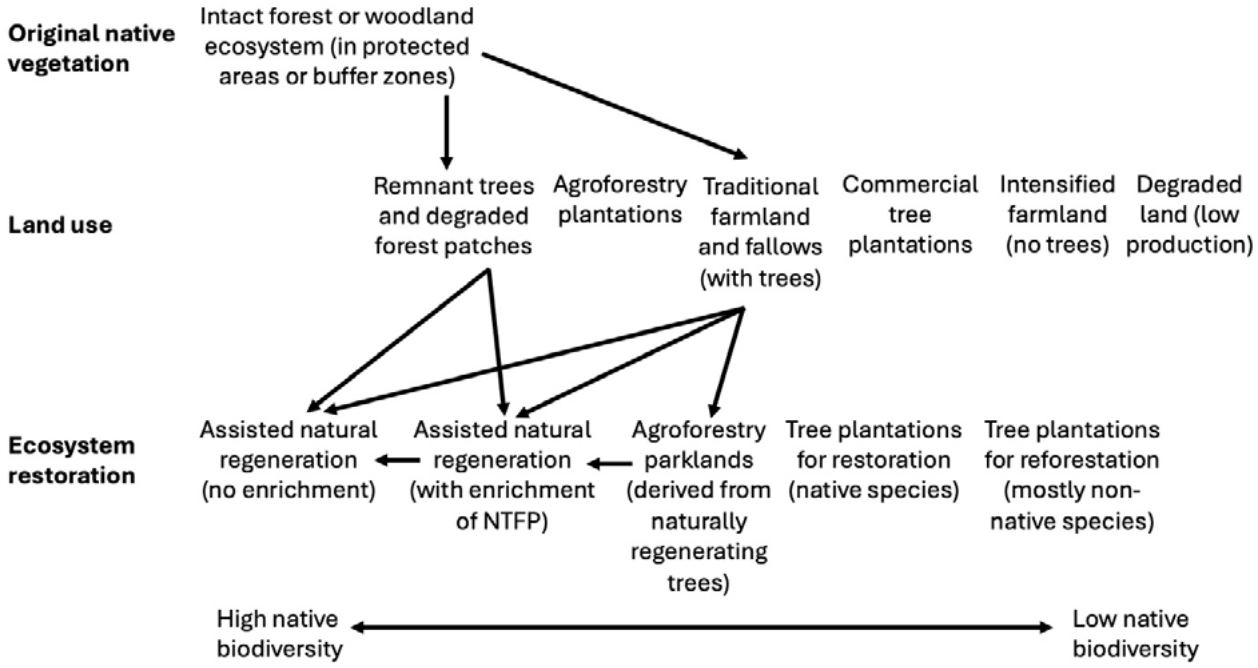


The practice of assisting natural regeneration with supplemental planting or direct seeding of native economically important species is a mixed approach with strong parallels to agroforestry systems and natural forest management (Vieira, Holl, and Peneireiro 2009). As a restoration intervention, ANR can be viewed as combining both active and passive approaches (Chazdon et al. 2024). It is often referred to as "mixed" restoration or "conducting" of natural regeneration (Brancalion et al. 2016). Regenerating forests—with or without enrichment—can be rich sources of both timber and non-timber products and can be managed to enhance forest recovery and ecosystem services while providing sustainable revenue streams (Chazdon and Coe 1999; Guariguata et al. 2010; Fantini et al. 2019; Zambiazi et al. 2021).

## Routes to assisted natural regeneration

Favorable areas for ANR (with or without enrichment) can occur on privately held or public lands under different types of secure land and tree tenure arrangements. The most likely areas where forests and woodlands will undergo natural regeneration are in disturbed forest areas (following logging, fires or other disturbances) and in traditional farmlands and fallows where native trees have been retained within or near the site (Figure 1). Where farming is not mechanized, seeds and rootstocks of native species are often retained in the soil and soil organic carbon levels remain high, enhancing nutrient and water retention. In contrast, plowing, frequent burning and recurrent cycles of shifting cultivation with short fallow periods reduce the rate and diversity of recovery during natural regeneration (Jakovac et al. 2021; Lawrence et al. 2010). Natural regeneration is less likely to happen on intensified farmland, commercial tree plantations or agroforests, as these production areas will generally remain in active land use and have less favorable conditions for establishment of native species. On unproductive degraded lands, restoring tree cover requires intensive and often costly interventions involving tree planting and soil amelioration (Chazdon et al. 2024). Agroforestry parklands are traditional agroforestry practices based on retention of trees on cultivated or recently fallowed land (Boffa 1999). They are prevalent farming systems across semi-arid regions of West Africa and are created using farmer managed natural regeneration techniques (Smale, Tappan, and Reij 2018) based on traditional knowledge. With additional management, agroforestry parklands could transition into assisted natural regeneration with or without enrichment of NTFP.

FIGURE 1. **Likely routes for assisted natural regeneration (ANR), with or without enrichment of non-timber forest products (NTFP)**




*The best conditions for ANR are in disturbed remnant vegetation or in traditional farmland and fallows, where some native trees are retained. Agroforestry plantations, commercial tree plantations, intensified farmland and degraded land have unfavorable conditions for ANR.*

## Objectives and scope

The Food Systems, Land Use and Restoration Impact Program (FOLUR) is a $345 million, seven-year initiative funded by the Global Environment Facility and led by the World Bank. Designed to transform food and land use systems, FOLUR comprises a global knowledge platform and 27 country projects. Country-level initiatives focus on accelerating action in priority landscapes and along value chains for eight major commodities: livestock, cocoa, coffee, maize, palm oil, rice, soy, and wheat. Implemented through the World Bank and partner agencies, FOLUR brings these countries together with a shared objective, i.e., to reduce deforestation and land degradation associated with commodity expansion. The Program integrates policy reform, sustainable agriculture practices, landscape-level planning, and private-sector engagement. It combines global knowledge with country-level action to scale effective models across diverse geographies and to position sustainable land management and nature-positive agriculture as core strategies for climate mitigation, resilience, and inclusive economic growth.

Assisted Natural Regeneration (ANR) aligns directly with the FOLUR Theory of Change by advancing a critical program component, i.e., restoring natural habitats and strengthening integrated landscape management. ANR supports key ToC outputs such as improved soil health, water regulation, biodiversity recovery, carbon sequestration, and wider adoption of sustainable practices, while reinforcing responsible production systems under Component 2 (promoting more sustainable practices and more responsible value chains). It also responds to FOLUR's private sector engagement pillar, as ANR, when successful and organized at scale, creates opportunities to engage companies through cooperatives and structured sourcing arrangements. By reducing degradation, enhancing resilience, and supporting deforestation-free value chains, ANR contributes to FOLUR's core outcomes of sustainable landscapes, restored ecosystems, and long-term global environmental benefits.

By integrating ANR into FOLUR landscapes, the Program can demonstrate nature-positive, low-cost restoration at scale, strengthen community ownership, and attract blended finance for climate and landscape outcomes. The Economics of ANR project (GEF7, FOLUR) aimed to assess the environmental and economic feasibility of implementing ANR by smallholder farmers or communities in appropriate areas and contexts of participating GEF7 FOLUR countries, based on enrichment planting and management of native non-timber products (NTFP) of economic value for regional or global markets.

This pioneering financial analysis of ANR with enrichment of NTFP will help FOLUR countries develop practical, high-impact restoration approaches under GEF-7 and inform how such models can be scaled and integrated into sustainable commodity systems. We focus on cost-benefit analysis (CBA) for small landholdings less than 10 ha in area. Based on a selection of 14 NTFP target species across five countries in Africa and Latin America, we develop cash-flow models over 30 years to assess the financial feasibility of growing, harvesting and selling products sourced from local native species in the context of naturally regenerating forests and woodlands.

The project team involved four researchers working with the ANR Alliance, World Resources Institute and the World Bank FOLUR Team. We collaborated with FOLUR project teams from three countries—Nigeria, Ethiopia and Ghana—to select target species and obtain data from specific regions on the costs and revenues of growing, harvesting, and selling products from these species in local markets. From other sources, we obtained data for five additional NTFP target species (four from Brazil and one from Ecuador) to create a total of 14 case studies, cash-flow models, and alternative land-use models (Table 1, Figure 2).

Robust information regarding the costs and revenues of restoration is challenging to obtain (Schimetka et al. 2024). This is particularly the case for assisted natural regeneration of forests, where the interventions needed are highly site-specific (Pacheco, Beatty, and Patel 2024). Labor costs, for example, are rarely monetized or tracked. Per hectare costs of restoration are generally assessed only for the first three years of implementation, and frameworks for data collection are lacking and poorly standardized (Bodin et al. 2022). We emphasize that the cost and revenue data used in our models are preliminary. In some cases, we adapted data obtained from target species cultivated in plantations or agroforestry systems to apply to the ANR context, adjusting estimates of planting density, labor, and material inputs. We made efforts to confirm cost and revenue data using published peer-reviewed literature sources whenever possible.

Here, we present a financial analysis of assisted natural regeneration of forest and woodlands with supplemental enrichment planting of a single native non-timber forest species as a sustainable revenue stream for local communities and smallholder farmers that enhances local native biodiversity while also accumulating carbon in forest vegetation. The financial analysis consists of three components: (1) a cash-flow analysis over 30 years, including annual implementation costs and NTFP revenues and assessment of financial indicators; (2) a sensitivity analysis to explore effects of discount rates and productivity on financial indicators; and (3) an assessment

of alternative financial models of land-use, including sales of carbon credits from the ANR+E systems.

Although several studies have evaluated economic cost-benefit models for forest restoration based on ecological restoration (Pacheco, Beatty, and Patel 2024), agroforestry systems (Gasparinetti et al. 2022) or timber harvesting in secondary regrowth forests (Zambiazi et al. 2021; Toledo-Aceves et al. 2022), this is the first financial feasibility analysis based on ANR approaches with enrichment of non-timber species. We explore whether enriching naturally regenerating forests and woodlands with these economically and culturally valuable products can be a self-sustaining activity for smallholders or communities with collective or family-based land-use rights. Our study also highlights key enabling factors that can make such arrangements happen successfully and equitably.

Our primary goal was to assess key financial indicators—net present value (NPV), internal rate of return (IRR), and benefit-cost ratio (BCR)— for each scenario of ANR with enrichment. We also compare the net revenue of ANR systems with enrichment to costs of ANR without enrichment (ANR), and natural regeneration with minimal assistance (NR) with and without revenues from sale of carbon credits on the voluntary carbon market. Finally, we compare net revenue of ANR with enrichment with agricultural and forestry land uses in the same location to estimate the opportunity costs, which are the foregone economic benefits of alternative land-use choices where restoration is implemented (Verdone 2015).

The cost-benefit and alternative land-use models are parameterized within the native geographic range and climate conditions of the target species used for enrichment. Only native species are introduced into these systems. The target species all occur naturally in forest fragments or woodland areas in these regions and are widely harvested, used and marketed by local communities.

In Appendix 1(A-N), we provide a case study for each of the 14 target species that describes its suitability for use in ANR systems, the results of total costs, locally parameterized cash-flow and sensitivity models, and key information on ethnobotanical uses, species ecology, cultural and livelihood importance, conservation status, production and harvesting systems, and trade and marketing. We note that the cost-benefit models only monetize revenues from a single planted target species. In practice, however, multiple species can be grown within a site in enrichment scenarios and multiple products can be sustainably harvested from both naturally regenerating and planted species (Souza et al. 2016). For this reason, our models provide minimum estimates of the scope of economic benefits that could be provided by naturally regenerating forests and woodlands with enrichment.



The report targets several groups of users including regional and national landscape and ecosystem restoration programs led by government agencies and civil society organizations, local community organizations, local producer associations and rural development and sustainable land management programs.

## Criteria for selection of target NTFP species

Large numbers of species could be grown and harvested within natural regenerating vegetation without impeding site recovery. Inventories conducted in regenerating and restored tropical and subtropical forests and woodlands in multiple countries show a high abundance and species richness of non-timber forest products (Krainovic et al. 2025; Brancalion 2018; Chazdon and Coe 1999; Souza et al. 2016). But we lack economic and market data for most of them. During this research, we evaluated many species with potential to provide revenue but were unable to obtain the data needed for economic cost-benefit models.

We applied five criteria to select the target species for data collection for cash flow and alternative land-use models.

1. Target species are recognized as economically, ecologically, and culturally significant for local communities in forest ecosystems and regions targeted by FOLUR project
2. Target species' native range includes forest, riparian, or woodland ecosystems within FOLUR project areas
3. Non-timber products of the target species can be sourced from planted individuals growing in secondary regrowth or assisted natural regeneration (including riparian areas)
4. Target species products can be sustainably harvested without removing whole trees/shrubs (fruit/seeds, foliage, bark, resins, vegetative shoots or branches)
5. Data can be obtained from literature or direct sources regarding costs of procuring seedlings, planting, maintenance, and harvesting, market prices, and timescale of production of the target species.

We also conducted literature searches for each of the target species and compiled case studies with ethnobotanical, ecological and agronomic information and relevant material regarding how the species are traditionally and currently managed, harvested, sold and marketed in the selected countries.

The target species vary in terms of their domestication status. Domestication is a process of human selection from a wild state for specific purposes and cultivation, often through selective breeding (Leakey and Newton 1994). The domestication process leads to genetic and physical changes, making products more useful for food, fiber, or ornamentation, and often leads to larger yields, improved taste, or easier harvesting. Four of the target species are fully domesticated: *Ilex paraguariensis* (yerba mate), *Ilex guayusa* (guayusa), *Paullinia cupana* (guaraná), and *Euterpe oleracea* (açai). Four target species are in early stages of domestication and are priority species for domestication (Leakey 2024): *Irvingia gabonensis* (bush mango), *Garcinia kola* (bitter kola), *Vitellaria paradoxa* (shea) and *Parkia biglobosa* (dawadawa). Three target species are not domesticated: *Piper capense* (Timiz pepper), *Tetrapleura tetraptera* (prekese) and *Aniba rosaeodora* (Brazilian rosewood). *Gnetum africanum* (eru), *Aframomum corrorima* (Ethiopian cardamom) and *Oldeania alpina* (highland bamboo) are largely harvested from wild populations in remnant forests or woodland areas and are in early stages of domestication.

Conservation status of the target species also varies widely. One species, *Aniba rosaeodora* (Brazilian rosewood), was classified as Endangered by the IUCN RedList in 2011. Three species are classified as Near Threatened, due to declining wild populations: *Irvingia gabonensis*, *Gnetum africanum*, *Ilex paraguariensis* (yerba mate), whereas *Garcinia kola* and *Vitellaria paradoxa* are classified as Vulnerable. The remaining eight species are unassessed or are classified as "Least Concern." Rising pressure to harvest products from wild populations of these species along with loss of natural habitats increases the urgency of developing methods for cultivation (from seed or vegetative cuttings) to protect and conserve the genetic diversity as well as for supporting sustainable production on farms.

TABLE 1. **Target species used for cost-benefit analysis**

| | Brazil | | | |
|---|---|---|---|---|
| Botanical name | *Aniba rosaeodora* Ducke | *Euterpe oleracea* Mart. | *Ilex paraguariensis* A.St.-Hil. | *Paullinia cupana* var. *sorbilis* (Mart.) Ducke |
| Common name | Brazilian rosewood | Açai | Yerba mate | Guaraná |
| Growth form | Evergreen tree | Palm | Evergreen tree, shrub | Evergreen woody vine |
| Main Product | Essential oil (extracted from wood) | Fruit pulp | Leaf (tea) | Seeds |
| Forest type and region | Upland Amazonian forest | Seasonally flooded swamps and Amazon basin floodplains | Subtropical Atlantic Forest | Amazon basin tropical forests |
| Conservation status (IUCN Red List) | Endangered | Unassessed | Near threatened | Unassessed |
| Domestication status | Not | Fully | Fully | Fully |
| Model location | Maués State Forest, Amazonas State | Altamira, Pará State | Santa Catarina State | Apuí, Amazonas State |
| Natural forest cover in 2020 | 95% | 92% | 23% | 94% |
| Most common land uses in model location | Small-scale farming of guaraná and cassava | Cattle grazing, cocoa plantations, annual crops | Intensive agriculture (soy and corn) and livestock | Cattle grazing |

| | Ecuador | Ethiopia | | |
|---|---|---|---|---|
| Botanical name | *Ilex guayusa* Loes. | *Aframomum corrorima* (A.Braun) P.C.M.Jansen | *Oldeania alpina* (K. Schum.) Stapleton | *Piper capense* L.f. |
| Common name | Guayusa | Ethiopian cardamom | Highland bamboo | Timiz long pepper |
| Growth form | Evergreen tree, shrub | Herbaceous perennial | Grass | Evergreen shrub |
| Main Product | Leaf (tea) | Fruit; spice | Vegetative shoots; Bamboo products | Fruit; spice |
| Forest type and region | Upper Amazon tropical moist forest | Afromontane forest | Afromontane forest | Afromontane forest |
| Conservation status (IUCN Red List) | Least concern | Least concern | Unassessed | Least concern |
| Domestication status | Fully | Semi | Semi | Not |
| Model location | Community chakras northwest of Tena, Napo Province | Yayu Coffee Forest Biosphere Reserve | Dire Inchini (Oromia), Bale Mountains | Kafa Biosphere Reserve |
| Natural forest cover in 2020 | 68% | 53% | 17% | 43% |
| Most common land uses in model location | Cattle grazing | Smallholder coffee agroforestry, livestock grazing | Rain-fed cereal crops | Smallholder farming of grains (teff and legumes) and coffee |

TABLE 1. **Target species used for cost-benefit analysis (cont.)**

| | Ghana | | |
|---|---|---|---|
| Botanical name | *Parkia biglobosa* (Jacq.) R. Br. ex G.Don | *Tetrapleura tetraptera* (Schumach. & Thonn.) Taub. | *Vitellaria paradoxa* C.F.Gaertn. |
| Common name | Dawadawa | Prekese | Shea |
| Growth form | Deciduous tree | Deciduous tree | Deciduous tree |
| Main Product | Fruit pulp, seeds, and medicinal purposes | Fruit, bark (food and medicinal) | Oils for soap and beauty products |
| Forest type and region | Wooded savannas, open woodlands | Moist tropical lowland forest | Wooded savannahs, dry deciduous forests, gallery forests |
| Conservation status (IUCN Red List) | Least concern | Least concern | Vulnerable |
| Domestication status | Early | Not | Semi |
| Model location | Atebubu District, Brong-Ahafo | Suhum-Kraboa-Coaltar District | Nakpalli Village in northern Ghana |
| Natural forest cover in 2020 | 21% | 29% | 2% |
| Most common land uses in model location | Smallholder agriculture of cash and food crops | Smallholder rain-fed agriculture of cash and food crops | Smallholder cultivation of food crops |

| | Nigeria | | |
|---|---|---|---|
| Botanical name | *Garcinia kola* Heckel | *Gnetum africanum* Welw. | *Irvingia gabonensis* (Aubry-Lecomte ex O'Rorke) Baill. |
| Common name | Bitter kola | Eru, afang | Bush mango |
| Growth form | Evergreen tree | Evergreen woody vine | Evergreen tree |
| Main Product | Seeds, chewing sticks | Leafy greens | Fruit, seeds (oil) roots, leaves and bark |
| Forest type and region | Dense evergreen tropical forest | Moist tropical forest | Lowland tropical forest |
| Conservation status (IUCN Red List) | Vulnerable | Near threatened | Near threatened |
| Domestication status | Early | Early | Semi |
| Model location | Near Ondo | Akamkpa LGA | Idanre LGA |
| Natural forest cover in 2020 | 94% | 85% | 84% |
| Most common land uses in model location | Intensive crop cultivation (Cocoa, cassava, oil palm, rubber) | Plantation agriculture (oil palm, rubber, pulpwood) | Plantation agriculture (cocoa, yams, cassava, plantain) |

*Data on natural forest cover in 2020 was obtained for model locations from Global Forest Watch (2025).*

FIGURE 2. **Target species locations for cash-flow and alternative land-use models**




*Nine species are native to Africa (Nigeria, Ethiopia, and Ghana) and five species are native to South America (Ecuador and Brazil). Map created in Google Earth.*

## Opportunities for assisted natural regeneration

There is a huge opportunity globally for forests to recover with low to moderate levels of assistance. ANR interventions have the most successful outcomes in areas where biophysical and landscape conditions support natural regeneration and where local knowledge is applied to best enhance natural regeneration processes that ensure colonization and persistence of local native species. Recent studies provide major insights into the biophysical conditions that support natural regeneration of forests and woodlands in tropical and subtropical regions following deforestation and land use (Chazdon et al. 2025). Moderate-to-high natural forest cover in the surrounding landscape (>40%), intact faunal communities, predominance of non-mechanized farmland and high levels of landscape connectivity strongly enhance the quality of naturally regenerating forests. Low land suitability for agriculture, steep topography and higher soil carbon levels increase the likelihood of natural regeneration.

Across the global tropics, natural regeneration accounted for one- to two-thirds of tree cover gain from 2000–2012 (Fagan et al. 2022). Spatial data on the biophysical conditions in these areas were used to generate models of future natural regeneration potential across the global tropics and indicate that natural regeneration could occur over 215 M ha in tropical forest biomes by 2030, with 98 M ha in Latin America and 25.5 M ha in Africa (Williams et al. 2024). Within Amazonian Brazil alone, an estimated 309,826 $km^2$ exhibit medium to very high natural regeneration potential (Barbosa et al. 2025). Extensive areas of secondary forest regeneration provide opportunities for enrichment planting in Brazilian Atlantic Forest (Crouzeilles et al. 2020) and Amazonia (Smith et al. 2021) as well as in many other countries (Gao et al. 2025). In Africa, the countries with the largest potential for natural regeneration are DRC (7.27 M ha), Madagascar (4.08 M ha), and Côte d'Ivoire (2.16 M ha) (Williams et al. 2024).

Despite this high potential, the biophysical conditions that support natural regeneration are only one factor that influences long-term and effective recovery. Equally important are the socioeconomic conditions that allow local communities to benefit from regenerating forests and that favor natural regeneration over other land uses and harvesting practices (Pandey et al. 2025). Naturally regenerating forests, while providing diverse ecosystem services and supporting local biodiversity, do not provide direct income streams for local communities. In addition to direct costs of protection and interventions to enhance native tree establishment, there are substantial opportunity costs of shifting away from agricultural land use that provided food security and livelihood benefits (Pacheco, Beatty, and Patel 2024).

Land and tree tenure and decision-making power regarding land and tree use are critically important aspects that affect both access to NTFP (Stanley, Voeks, and Short 2012) and the quality and permanence of forest regeneration (McLain et al. 2021; Lazos-Chavero, Meli, and Bonfil 2021; Benzeev et al. 2023; Benzeev et al. 2025). For example, official government recognition of user rights of communities and the formal development of legal regulations for defined management practices led to regeneration of trees on farms and communal areas in Ethiopia (Brown et al. 2011).

When land users lack secure land tenure, they have little motivation to engage in restoration or maintain trees in the long term (Nagendra 2007). In 2020, 82% of land in Africa was publicly owned, and only 9% was privately owned (FAO 2025). In contrast, 58% of land in South America was publicly owned, and 34% was privately owned in 2020. Management rights in publicly owned forests are largely under the control of public administrations (91% in Africa and 89% in South America in 2020) (FAO 2025). Policies regarding land and tree tenure vary widely across the five countries included in this study and are described within each of the case studies.

## Roadmap to the report

Chapter 2 presents the methodology used for the three components of the financial analysis (cash-flow analysis, sensitivity analysis, and alternative land-use scenarios), estimates of costs and revenues, and key assumptions of these analyses. We provide justification for approaches used based on current literature sources.

Chapter 3 presents results for the cash-flow analysis of costs and revenues, sensitivity analysis, and alternative land-use scenarios for 14 target species. We categorize three groups of species: A) robust and high economic potential; B) low or uncertain economic potential; C) species with moderate value where changes in particular variables could make a difference in economic viability. Group C is subject to sensitivity analyses of particular variables to illustrate factors that strongly affect viability. We discuss reasons for the variation in economic feasibility observed across the target species cases and present results of sensitivity analyses of discount rates and productivity of NTFP on financial indicators.



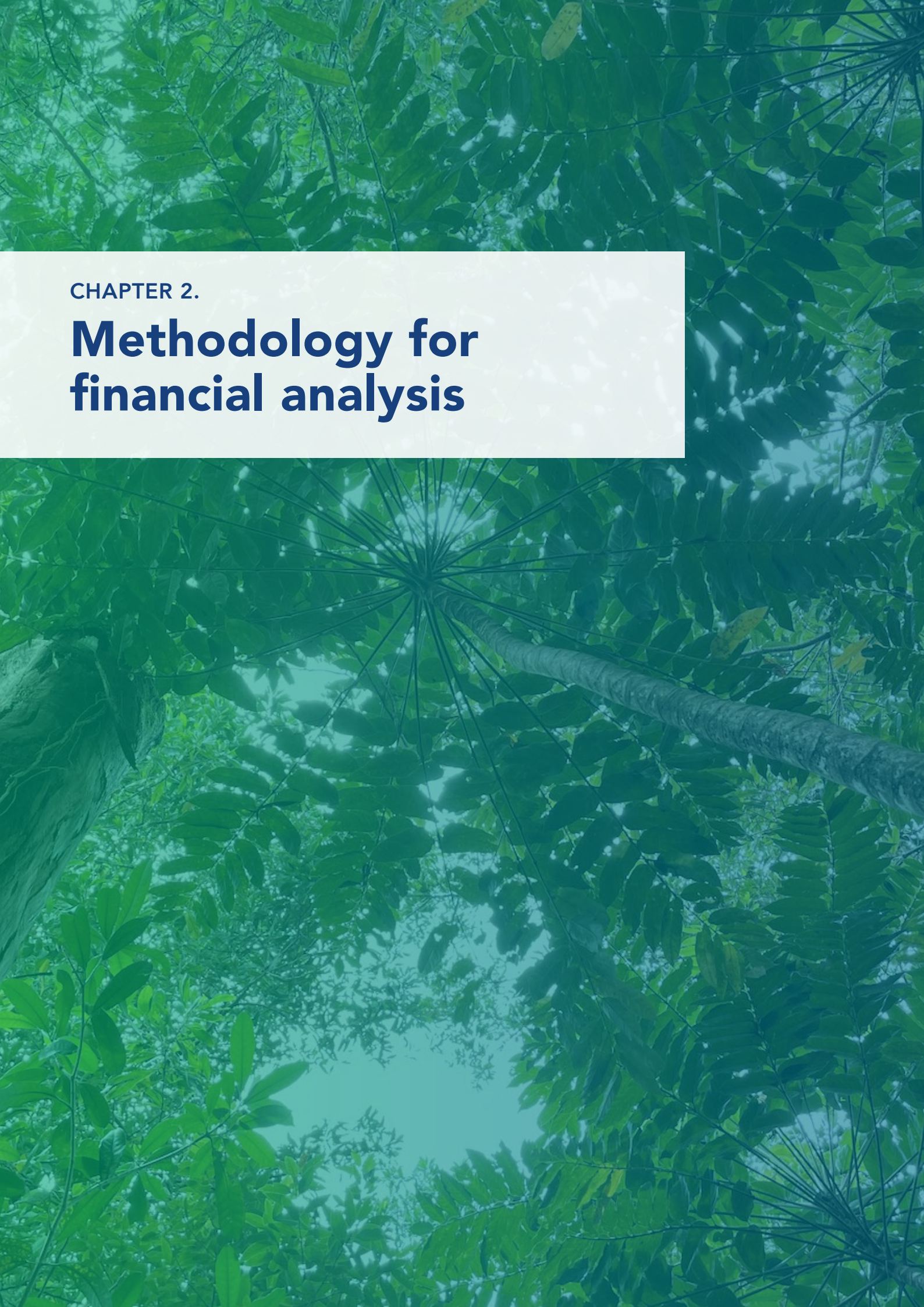
Chapter 3 also includes comparisons of the discounted net revenue and carbon storage of the baseline ANR+E scenario with five alternative land-use scenarios within the same site. We discuss cases where ANR+E exceeds or is similar to net revenue of alternative land uses and compare the carbon benefits and revenues with ANR and NR. We provide results on the break-even point of carbon pricing for both ANR and ANR+E scenarios and discuss assumptions and limitations of the alternative land-use models. We compare input variables, model outputs, model context, assumptions and discussion of limitations of the models and data sources used.

In Chapter 4 we provide conclusions and recommendations. We discuss challenges that we encountered in obtaining data, outline research needs, and the potential for implementing pilot projects. We discuss how to obtain better data on costs and revenues to test the viability and outcomes of ANR systems with enrichment of NTFP and we summarize major barriers and key enabling factors for implementation of ANR systems with enrichment based on the case studies and models presented in the study.

Appendix 1(A-N) contains 14 case studies for each of the target species, including the baseline cash-flow model and the alternative land-use comparisons of discounted net revenue and carbon storage in vegetation biomass.

Appendix 2 contains detailed data on costs of ANR+E for the 14 target species.

Appendix 3 contains a link to the Excel Spreadsheet used to collect data for the target species from Ethiopia, Nigeria, and Ghana.



CHAPTER 2.

# Methodology for financial analysis

We used financial analysis as a tool to determine whether a specific type of land-use change is profitable for a smallholder, investor, or land-user community (Harrison and Herbohn 2016). Here we followed protocols for financial analysis used in earlier studies of ANR with native timber and non-timber products (Maier et al. 2019) and agroforestry in the context of ecosystem restoration (Gasparinetti et al. 2022), using a 30-yr time horizon as recommended by other cost-benefit analyses of forest restoration (Gilroy et al. 2014, Pacheco, Beatty, and Patel 2024). Below we describe the methodology for the three components of the financial analysis (cost-benefit analysis with financial indicators, sensitivity analysis, and alternative land-use scenarios). Finally, we included as revenues the depreciated carbon credits from estimated aboveground biomass that accumulated during ANR with and without enrichment.

# Cost-benefit analysis

The cost–benefit analysis (CBA) evaluates the financial performance of restoration models over a 30-year horizon, integrating detailed information on costs, revenues, and productivity associated with ANR+E systems. The methodology follows standard economic evaluation practices while adapting them to the specific characteristics of restoration projects in tropical forest regions. All values are expressed in U.S. dollars (USD), and the analysis is performed at the per-hectare level for comparability across countries and models. The CBA is organized into four analytical components: (1) Cost estimation; (2) Benefit estimation; (3) Cash flow construction, and (4) Economic performance indicators.

## Cost estimation

Two categories of unit costs form the basis for all cost calculations: (1) Labor costs, measured in USD per day, representing wages for planting, maintenance, weeding, monitoring, and harvesting activities. (2) Machinery costs, measured in USD per hour, accounting for the use of equipment during land preparation and management (although some models rely predominantly on manual labor). These unit costs were supplied directly by national experts familiar with local restoration practices and market conditions.

*Material costs* include expenditures on seedlings, seeds, fertilizers, fencing, tools, and other inputs necessary for establishing and maintaining the restoration system. To account for varying time horizons, annual material expenditures are presented in both nominal terms and discounted values, using the assumed discount rate.

*Service costs* represent the combination of labor and machinery use by year. They capture the operational intensity of restoration phases, with higher effort in early establishment years and steady maintenance needs thereafter. These costs are likewise recorded in nominal and discounted terms. All labor was valued as hired labor, even in cases where activities would typically be performed by family members. For models in which family labor is common, the analysis applied the equivalent market wage rate to these hours to reflect their opportunity cost—the value of alternative uses of household labor time. This approach ensures comparability across countries and models, and it captures the true economic cost of labor inputs, regardless of whether cash payments are made. By incorporating the opportunity cost of family labor, the analysis avoids underestimating the real resource requirements of ANR systems and provides a more accurate representation of long-term management costs.

We categorized total costs into three main activities that occur at different time intervals: implementation (first year), harvest (beginning with year of first production), and management (year 2-30). Implementation costs are equivalent to initial investment costs for ANR+E systems.

## Benefits

The benefit component focuses on monetary benefits (revenues) from non-timber forest products (NTFPs) produced under the restoration model. For each model, experts provided: the key NTFP species; annual average productivity (kg/ha/year); and the farm-gate price (USD/kg). Monetary benefits are calculated by multiplying annual yields by local prices. Monetary benefits related to sale of carbon credits based on carbon sequestration in aboveground biomass were not included in the initial cost-benefit models to provide conservative financial estimates but are included in the alternative land use scenarios (see below).

## Cash Flow Construction

Annual cash flows are computed by subtracting total annual costs from total annual revenues. The model includes: (1) nominal cash flows, reflecting actual yearly balances, and (2) discounted cash flows, which convert all future values into their present-day equivalents. The discounted cash flow series is used to identify the year in which the project reaches its break-even point, when cumulative returns exceed cumulative costs.

A discount rate of 10% per year was applied to all restoration models in this study to ensure comparability across countries. We acknowledge, however, that the appropriate discount rate may vary across countries, reflecting differences in the opportunity cost of capital, macroeconomic conditions, and risk associated with

investments in the sector. Given the diversity of national contexts represented in our ANR cases, the adoption of a single 10% rate serves as a standardized analytical benchmark rather than a country-specific valuation. To address this limitation, we conducted a sensitivity analysis that evaluates changes in project profitability under alternative discount rates from 5 to 15%, allowing us to examine how variations in discounting assumptions affect NPV and the overall financial viability of each restoration model.

### Financial performance indicators

To summarize the financial viability of each restoration model, four standard financial indicators were calculated:

- Net Present Value (NPV): the discounted value of net benefits over 30 years.
- Internal Rate of Return (IRR): the discount rate at which NPV equals zero.
- Benefit–Cost Ratio (BCR): the ratio of discounted benefits to costs.
- Payback Period: the number of years required for cumulative discounted benefits to surpass cumulative discounted costs.

These indicators provide complementary insights into profitability, risk, and investment return, offering a robust basis for comparing restoration models across countries and ecological contexts. For the ANR+E scenarios, which are all based on a 30-year horizon, we did not calculate Land Expectation Value (LEV), which is typically applied when comparing land uses of unequal length (e.g., 10, 15, and 25 years), such as comparing timber plantations with perennial crops systems (Ota et al. 2022; Hovis et al. 2022).

## Sensitivity analysis of cost-benefit models

Sensitivity analyses were conducted to assess the robustness of the financial performance of ANR+E models under different economic conditions. These analyses help identify how two key parameters—discount rate, and productivity—affect profitability and investment risk. By simulating changes in these parameters, we evaluated whether the models maintain financial viability under less favorable assumptions and determined which restoration strategies are most resilient to market uncertainty. Using NPV as an indicator, we assessed how profitability changes under variations in discount rate, costs, and revenues; and identifying the minimum revenue required to maintain NPV ≥ 0 (break-even point).

To address the effect of market uncertainty, the discount rate was varied from 5 to 15%. The productivity sensitivity analysis illustrates the effect of variation in the level of production per hectare or in the price per unit of production from a 50% decrease (lower production or lower price) to a 50% increase in original modeled revenue (higher production or higher price) on the NPV of each ANR model. These simulations do not alter the density of enrichment planting but rather evaluate effects of climate stresses or pest outbreaks on total production (modeled as decreases) or increases in productivity due to improvements in harvesting effectiveness, genetic improvement or increases in market prices (modeled as increases).

## Alternative land use scenarios

Estimated economic and climate values for ANR+E systems are only useful insofar as they can help land users and stakeholders answer pertinent questions for specific places. In one case, a stakeholder may be a proponent or implementer of forest restoration who needs to obtain finance to undertake their work. They need to answer the question: "Is net revenue from the sale of NTFPs positive, after accounting for costs of assisted natural regeneration and target species cultivation?" If the answer to this question is yes, they need not be reliant on their own funding, or on philanthropic funding, or on accessing markets for environmental services such as carbon, to conduct and scale up their ANR activities, although they may still choose to do so. For such a stakeholder who is already committed to reforestation, the cost-benefit analysis of ANR+E would be sufficient.

Alternatively, and more commonly, a smallholder farmer who makes land-use decisions seeks to maximize the net revenue from their land. They are not committed to forest restoration per se, although they would consider it if its benefits outweigh those of alternatives. This stakeholder is interested in the answer to the question: "Does net revenue from the sale of non-timber forest products (NTFPs) exceed net revenue from alternative land uses, accounting for costs of assisted natural regeneration and target species cultivation?" If the answer to this question is yes, even land users who might otherwise be inclined to favor agriculture or timber plantations may instead opt to implement ANR+E.

Some stakeholders may also be interested in the carbon sequestration that accrues from ANR+E compared to alternative land use activities, either as a contribution to the public good of global climate change mitigation, or insofar as greater carbon sequestration allows for greater potential returns from carbon markets. They are interested in the answer to the question: "How does carbon sequestration from ANR+E compare to that of other

forms of natural regeneration, or agriculture or timber plantations?" We addressed these latter two questions, for all 14 target species models by comparing the economic benefits (net revenue) and climate benefits (carbon sequestration) of ANR+E over a 30-year period with five alternative land use scenarios:

1. Minimally assisted natural regeneration without enrichment ("NR"), without and with a supplementary income stream from the sale of carbon credits ("NR+C")
2. Assisted natural regeneration without enrichment ("ANR"), without and with a supplementary income stream from the sale of carbon credits ("ANR+C")
3. Conventional timber production of broadleaf evergreen species (e.g. acacia) for fuelwood ("Fuelwood")
4. Conventional timber production of broadleaf deciduous species (e.g. teak) for solid wood ("Solidwood")
5. Conventional agricultural production ("Ag")

A sixth land use scenario was considered but was not analyzed due to an absence of data: the production of target non-timber species within a monoculture or agroforestry setting to maximize production.

Although a detailed sensitivity analysis of the ratio of financial flows from ANR+E to alternative land uses is beyond the scope of our analysis, we ran a sensitivity analysis for one parameter (discount rate), comparing effects of three discount rates (5, 10 and 15%) on total net revenue over 30 years.

To estimate the net revenue and carbon sequestration of alternative land use scenarios we first identified the precise location at which the ANR+E model would be undertaken. Where survey respondents provided specific latitude-longitudes, these coordinates were used. Where survey respondents provided a mapped location or descriptive location, we converted these to coordinates using Google Maps (Figure 2). Where survey respondents did not provide a location, we obtained locations from literature on cultivation of the target non-timber species. We matched these locations to 1 km x 1 km grid cells in Busch et al. (2024) and extracted corresponding information from that study on net revenues (costs and gross revenues) and carbon accumulation as elaborated below.



## Minimally assisted natural regeneration – cost and revenue

The first alternative land use is termed minimally assisted natural regeneration in this paper and was termed passive natural regeneration in (Busch et al. 2024). The form of natural forest restoration at such sites entailed "minimal human interventions beyond evaluating a site to determine if natural seed sources are adequate to regenerate it and protecting regenerating trees on the site from predation by herbivores (livestock or wildlife) and human encroachment. Implementation costs for [minimally assisted] natural regeneration thus entail primarily site evaluation and protection measures such as fencing and guards."

As stated in Busch et al. (2024), "We generated implementation cost (US$ $ha^{-1}$) surfaces for passive natural regeneration and forest plantations based on 355 observations of reported reforestation costs from 99 source documents spanning 26 low- and middle-income countries (LMICs) in Africa, Asia and the Pacific and Latin America and the Caribbean. We sourced the data from World Bank project documents and the peer-reviewed and grey literature. All source documents were publicly available. We used machine learning to determine the linear regression model that provided the best cost predictions and we used this model and spatial data layers to extrapolate implementation costs in 2020 US$ per hectare across LMICs."

The final linear regression model of implementation costs was based on ten variables out of a total of 70 candidate variables initially considered. These variables included three variables related to restoration method; the inclusion of native species; ln(national GDP per capita); three variables related to biome; two variables related to features of cost data; and year of implementation.

The mean cost of minimally assisted natural regeneration across all 14 sites was $108. Gross revenue for minimally assisted natural regeneration was assumed to be zero, thus net revenue for NR was equal to negative costs.

## Minimally assisted natural regeneration – carbon accumulation

Busch et al. (2024) produced maps of annual carbon accumulation over time in naturally regenerating forests using a modified version of the sigmoidal Chapman–Richards growth function. Specifically, they modelled spatial variation in two parameters of the Chapman–Richards function, the asymptotic limit of aboveground carbon (*A*) and the rate of carbon accumulation (*k*), as a function of 11 principal components derived from 64 spatially explicit environmental covariates to which growth rates are sensitive, such as temperature, rainfall, and seasonality. They then used these statistical relationships to produce 1 km x 1 km global maps of *A* and *k*, which in turn described aboveground carbon stocks as a function of stand age. Changes in residual aboveground carbon from previous land uses were not considered in this model. They obtained the data for their growth functions over the first 30 years of forest regeneration from 256 published datasets of aboveground carbon in naturally regenerating forests, covering 2,309 observations at 410 sites (Cook-Patton et al. 2020). A more recent study that followed a similar approach (Robinson et al. 2025) expanded the coverage of reforestation sites in temperate countries; this would not be expected to greatly change carbon accumulation predictions for the 14 tropical sites in our study. In our study we considered carbon accumulation in aboveground biomass only; not in belowground biomass, soil, or peat.

## Assisted natural regeneration – cost and revenue

We estimated the costs of assisted natural restoration without enrichment (ANR) by including self-reported cost line items only for those activities associated with the restoration of forest ecosystems rather than with the enrichment planting of commercial species. Specifically, we included the following cost line items: ant control, fence installation, fire protection, harrowing, hoeing, labor, limestone application, and maintenance of ANR. We excluded the following cost line items: harvest; fertilizer application, machinery, packing, planting; site preparation, planting hole digging, processing, pruning, replanting, sacks, seedlings, tax, and transport.

We made modifications to reported costs in four cases. For *Ilex paraguariensis* (yerba mate) where no costs associated with ANR were reported we added fencing and weeding costs of USD 1,500 in the first year and USD 250 in subsequent years for both the ANR and ANR+E scenarios. For *Aframomum corrorima* (Ethiopian cardamom) where reported fertilizer costs were very high we reduced this cost by two-thirds in the ANR without enrichment scenario. For *Aniba rosaeodora*, we reduced reported hoeing costs by 60% for the ANR without enrichment scenario. For *Piper capense* where reported ANR costs were below that of NR we increased the ANR cost to twice the cost of NR.

Over 30 yr, the median cost of ANR without enrichment was USD 1,736/ha—sixteen times as high as the median cost of minimally assisted natural regeneration of USD 113/ha, while the average cost of ANR was USD 4,702/ha—five times as much as the average cost of ANR without

enrichment of USD 961 (n = 9 projects) found in a review of ANR project costs (Oluwajuwon et al. 2024). In most cases, published costs of ANR (and restoration in general) are restricted to the first three years of implementation. No data on long-term (30-yr) costs of ANR are available for comparison.

## Assisted natural regeneration – carbon accumulation

Because carbon accumulation curves for assisted natural restoration (ANR) were not modeled in Busch et al. (2024), we inferred these curves by applying a multiplier to accumulation curves for minimally assisted natural restoration in Busch et al. (2024). We selected a multiplier of 1.5 based on Philipson et al. (2020). That is, the levels of carbon accumulation from NR would be achieved 1.5 times faster through ANR (e.g., in 4 years rather than 6 years). Eventual asymptotic carbon density (i.e. value A in a Chapman-Richards equation) is the same for both types of restoration but is achieved more quickly through ANR. As above, we considered carbon accumulation in aboveground biomass only.

## Timber production – cost, revenue, and carbon accumulation

To generate maps of the estimated costs and revenues from timber plantations, Busch et al. (2024) began by modeling which of 15 plantation genera was most likely to be planted at every 1 km cell. That study obtained data on the genus of planted forests at 2.48 million locations across the globe from the Spatial Database of Planted Trees (Harris, Goldman, and Gibbes 2019) and then used machine learning to model the likelihood of each genus of tree crop to be planted in that location using a suite of environmental and socio-economic covariates hypothesized to influence genus selection.

The implementation cost of establishing timber plantations was generated using the same data set and method described above for minimally assisted natural regeneration. However, rather than a one-time cost, as in the case of minimally assisted natural regeneration, costs of establishing plantation forests recurred with every replanting after harvest. Harvest interval was determined using the Faustmann condition that maximizes the net present value of repeated timber harvest.

In contrast to naturally regenerating forest, plantation forests accrued revenue from the sale of wood products that was included in net revenue. In the case of broadleaf deciduous species, this revenue was assumed to come from the sale of solid wood. In the case of broadleaf evergreen species, this revenue was assumed to come from the sale of biomass for bioenergy, including charcoal



production. In both cases, revenue was calculated by multiplying use-specific stumpage price by wood volume (which in turn was calculated by multiplying harvested carbon by a country-specific carbon factor—the ratio between wood volume and carbon content in harvested plantation forests).

Aboveground carbon accumulation in plantation forests undergoing rotational harvest for solid wood or bioenergy was calculated using a similar method to minimally assisted natural regeneration. That is parameters *A* and *k* in a Chapman-Richards growth function were estimated and then extrapolated. The source data on aboveground carbon accumulation in plantation monocultures was from 3,289 observations at 618 sites worldwide (Bukoski et al. 2022). As above, we considered carbon accumulation in aboveground biomass, but not belowground biomass, soil, or peat. We also included carbon accumulation in harvested wood products in the case of solid wood but not bioenergy. We assume that all aboveground carbon accumulation is creditable.

### Agricultural production – net revenue and carbon accumulation

Busch et al. (2024) generated a spatial layer of annual net revenue from agriculture across low- and middle-income countries by combining gridded data on gross crop revenue per hectare and gridded data on livestock density (FAO 2018) with household survey data on production costs (FAO 2020). The agricultural revenue data was based on 33 crops and 9 crop aggregates from IFPRI's SPAM dataset (IFPRI 2019).

Where net revenue from cropland was positive, this value was used as the value of net revenue from agriculture. Where net revenue from cropland was missing or zero, net revenue from pastureland was used instead. Crop value was prioritized because it was based on many more observations and because it was higher than pasture value in nearly all cases. The carbon accumulation from agriculture was assumed to be zero.

## Carbon market revenue

In three scenarios (NR+C; ANR+C; ANR+E+C), we considered the opportunity for obtaining supplemental revenue through the sale of carbon credits. We assumed that natural regeneration projects would be able to access such markets. We assumed a sale price to land users of USD 6 per ton of carbon dioxide, equivalent to a market price of USD 10 per ton and 60% revenue sharing with land users. The 40% reduction in the selling price (USD 10 market price vs. USD 6 to land users) is intended to account for transaction and certification costs.

To calculate net present values from alternative land uses, we applied a 30-year time horizon and a time-discount rate of 10% per year. This differs from the time-discount rate of 5% per year used in Busch et al. (2024). Thus, net present values of revenue are lower in our study than in that study, despite using the same annual revenue values. We applied a breakeven analysis to estimate the carbon price that needs to be exceeded for the ANR+E system to be profitable/outcompete alternative land uses.

## Methodological Limitations

Limitations of the data collection process should be acknowledged. In many cases, the respondents did not possess detailed information on all cost components or productivity parameters. To address this, the questionnaire adopted a top-down approach: country-level experts were first asked to provide an estimate of the total restoration cost, a value they were generally more confident about, and then to disaggregate this total into the main categories of costs—namely, materials, labor, seeds/seedlings, harvesting labor, and machinery.

The authors evaluated the internal consistency of the responses provided by the specialists who completed the questionnaires and conducted targeted adjustments to certain cost and benefit parameters when necessary. These refinements were made to ensure coherence with the authors' own technical experience in restoration, while preserving the substantive information contributed by the experts.

Additionally, since some ANR models incorporate a combination of naturally regenerating vegetation and productive species, an adjustment was applied to the species density. For consistency across all models, we assumed that income-generating species accounted for 30% of the total planting density. This adjustment ensures that the analyzed systems remain within the definition of Assisted Natural Regeneration, rather than being classified as restoration models primarily based on productive plantations. The remaining 70% was therefore considered to represent native species that regenerate naturally or with minimal assistance.

## Questionnaire and Data Collection

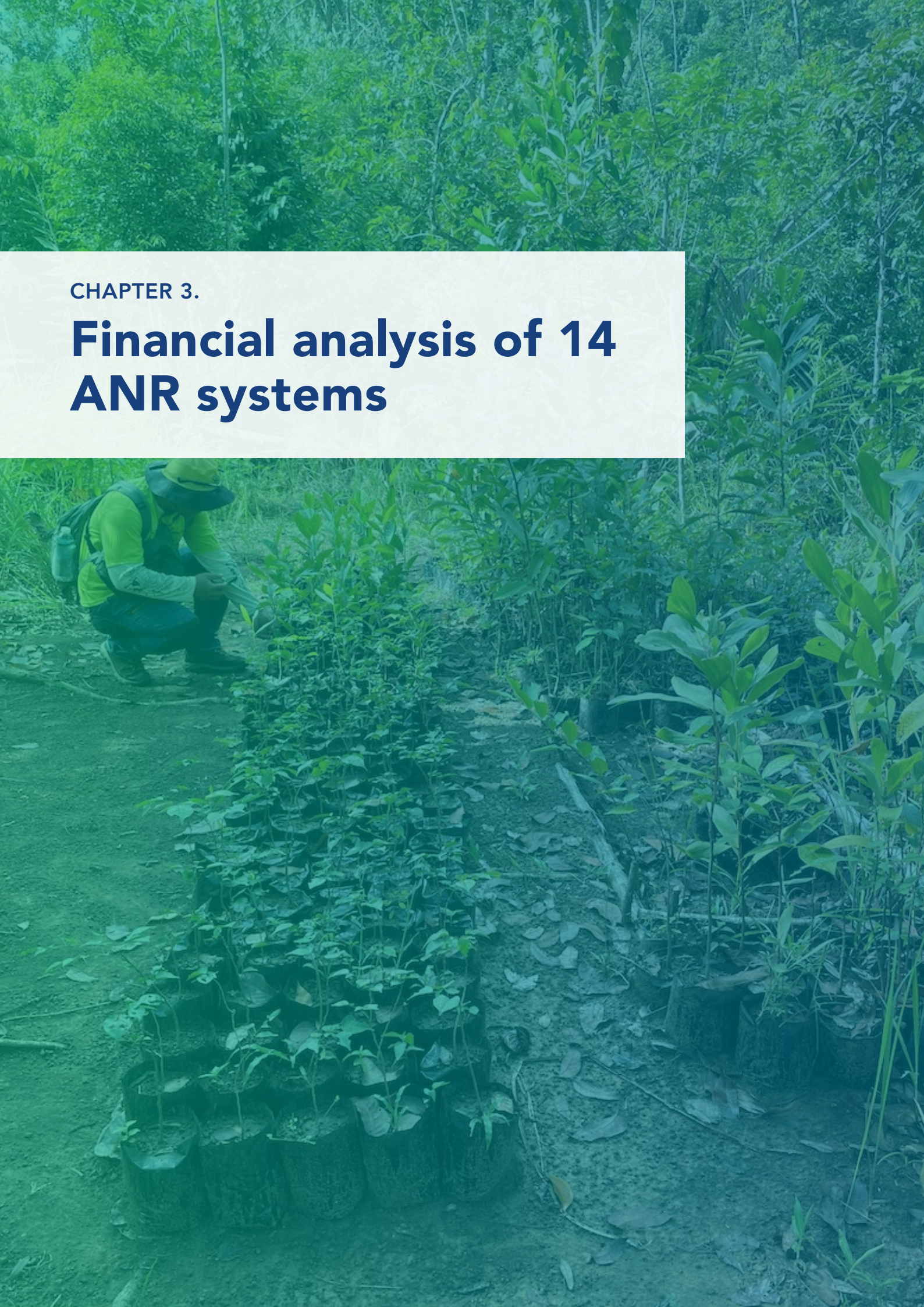
To characterize the Assisted Natural Regeneration (ANR) models used in this study, we designed and applied a structured questionnaire composed of five main sections. The questionnaire aimed to collect information on the biophysical, economic, and management aspects of different ANR systems implemented across multiple countries.



The questionnaires were completed by specialists from each respective country, selected for their expertise and direct involvement with the local ANR models being analyzed. These experts identified the key target species for each model and provided estimates of the costs and benefits associated with their implementation, based on their technical knowledge and field experience.

Below are the sections of the questionnaire. Appendix 3 contains a link to the complete formatted questionnaire as an Excel Workbook.

- **Section I – General Questions:** This section gathered basic contextual information, including the respondent's name, institution, country, currency used in the estimates, and reference year for the monetary values. This information was necessary to ensure data comparability across different national contexts.
- **Section II – Assisted Natural Regeneration Context:** This part focused on the ecological and technical aspects of each ANR system. Respondents were asked to specify the ecosystems where the system could be applied, the altitude range, restoration techniques, target species, and typical project areas. The section also included questions about planting density and whether enrichment planting or mixed systems with income-generating species were used.
- **Section III – Income-Generating Non-Timber Products:** This section collected data on the key productive species associated with each ANR model, including the duration of the harvesting season, time until first harvest, average yields, and farm-gate prices. Respondents were asked to identify the most economically valuable target species and to describe the average production cycle and price structure for non-timber forest products (NTFPs) when applicable.
- **Section IV – Costs of Restoration and Inputs:** The fourth section focused on economic parameters. It included questions on average costs for main input categories such as labor, land, machinery, technical assistance, fencing, and taxes. Respondents were also asked to provide estimates of the total restoration cost per hectare over a 30-year period and to break this cost down into major components: (i) seedlings/seeds, (ii) inputs (including fertilizers, fencing, and pest control), (iii) labor (including harvesting costs), and (iv) machinery. This disaggregation was designed to facilitate comparability among models and to support cost-benefit analysis.
- **Section V – Negative Impacts on ANR:** Finally, this section aimed to capture potential environmental threats to ANR success, such as the estimated percentage loss of regenerating individuals due to fire, flooding, or intensive land use, as well as any other region-specific disturbances.



CHAPTER 3.

# Financial analysis of 14 ANR systems

As countries expand their restoration commitments under national and international frameworks, understanding the financial performance of ANR-based models becomes crucial for informing public policy, investment decisions, and community-based implementation. This chapter compiles and analyzes a diverse set of ANR models implemented across Brazil, Ghana, Ethiopia, Ecuador, and Nigeria, each representing distinct ecological contexts, management approaches, and native species of economic and ecological interest. By examining productivity assumptions, market prices, and financial indicators — including Net Present Value (NPV), Benefit–Cost Ratio (BCR), Internal Rate of Return (IRR), and payback period— the analysis provides a comprehensive assessment of the economic feasibility of ANR with enrichment of non-timber forest products (ANR+E). The results offer insights into how restoration can simultaneously support biodiversity recovery and generate sustainable livelihood opportunities, grounding restoration planning in both ecological and economic evidence.

In this chapter we present a comparative overview of the results of all restoration models, including their key financial indicators and corresponding sensitivity analyses. This comparative assessment provides an integrated understanding of how the models perform relative to one another under standardized assumptions described in Chapter 2. In addition to the comparative analysis, we also present the detailed results for each model individually in Appendix 1(A-N), including full cost structures, benefit profiles, cash flow dynamics, and model-specific sensitivity and break-even analyses.

# Results of cost-benefit models and financial indicators

The financial performance of each Assisted Natural Regeneration (ANR) cost-benefit model was evaluated using four primary financial indicators: Net Present Value (NPV), Internal Rate of Return (IRR), Benefit–Cost Ratio (BCR), and Payback Period. These metrics provide a comprehensive view of financial investment needs, profitability, investment efficiency, and the time required for capital recovery. The indicators reflect not only the magnitude of economic returns but also the timing and consistency of cash flows generated by each restoration system. Together, these indicators allow for direct comparison among models that differ in species composition, management intensity, and temporal structure of revenues. They also provide insights into how each system balances ecological objectives with financial feasibility—highlighting those ANR configurations that deliver robust and sustained returns.

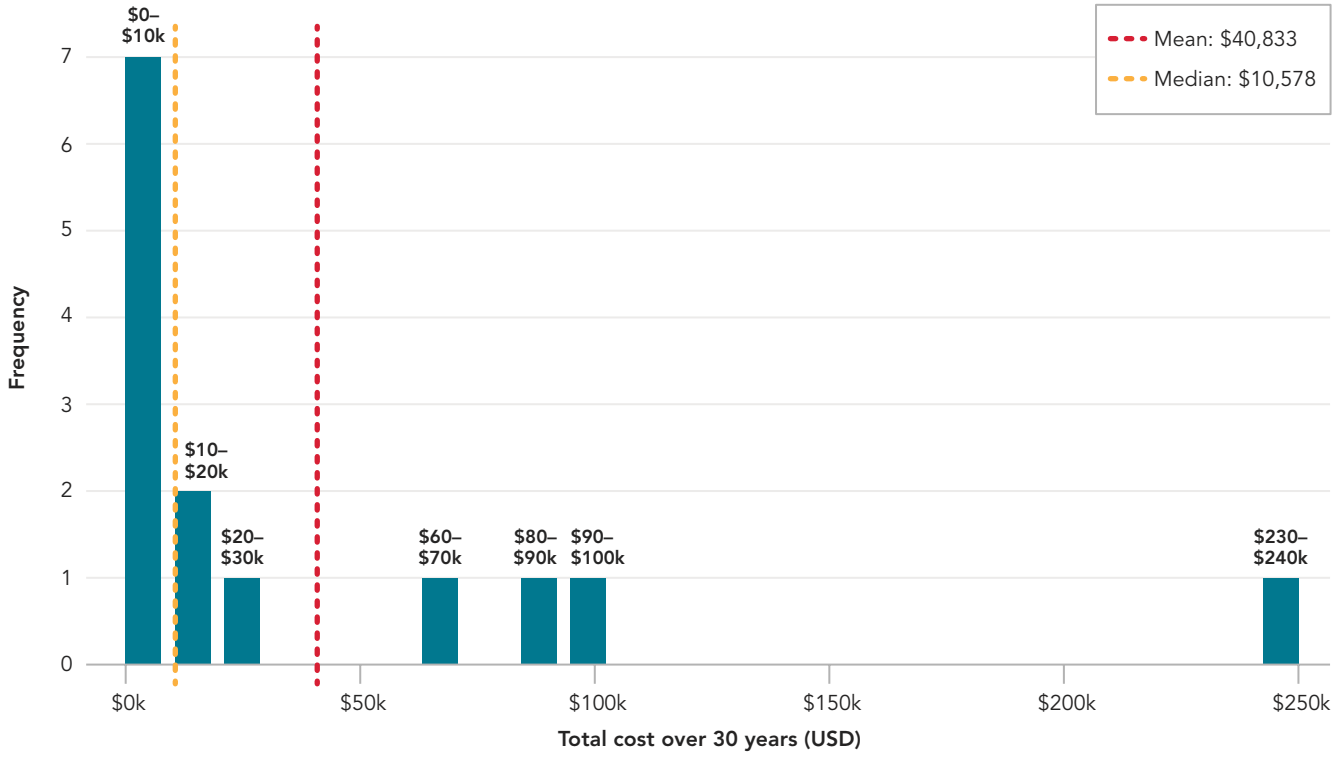
## Costs

The total restoration costs over a 30-year period were below USD 50,000 for 10 of the ANR models (Appendix 2). One model, *Aniba rosaeodora* (Brazilian rosewood) is an outlier in having very high long-term costs (Figure 3). This pattern suggests a high degree of heterogeneity in restoration strategies, labor requirements, and input intensities across countries and ecosystems. The median cost, represented by the yellow dashed line, is USD 10,578, indicating that half of the models can be implemented at relatively modest long-term costs. In contrast, the mean cost, shown by the red dashed line, is much higher at USD 40,833, revealing the influence of a few very high-cost models that expand the upper tail of the distribution. These outliers likely correspond to restoration systems with higher labor intensity, greater use of inputs for enrichment planting, or more expensive local economic conditions.

Figure 4 provides a breakdown of the average undiscounted cost composition over a 30-year horizon for all the ANR models analyzed. The average initial Implementation costs, which include establishment activities like planting and fencing, when applicable, are small over a 30-yr timeframe, 3.7% (USD 1,717) of the overall cost structure. On average, management costs constitute 77.7% (USD 35.652) of the total expenditure. This indicates that the long-term activities required to maintain and protect the restoration areas—such as ant control, fire protection, and weeding—represent the primary financial commitment in these projects. The significant share of management highlights that ANR with enrichment planting requires sustained, and often labor-intensive, investment to ensure ecological success. In contrast, the Harvest costs, associated with gathering non-timber forest products, account for an average of 18.6% (USD 8,532) of the total costs.

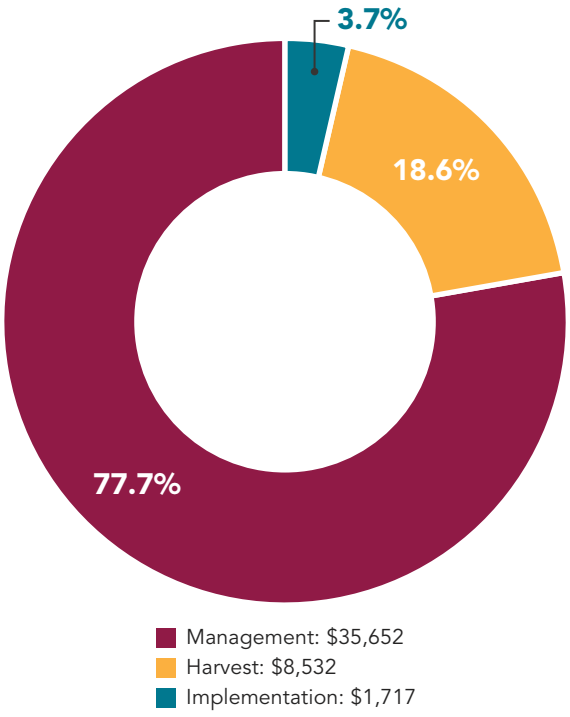


FIGURE 3. **Distribution of total restoration costs (summed over 30 years) across all ANR models**




*See Appendix 2 for detailed cost data for each ANR+E model.*

FIGURE 4. **Average undiscounted cost composition for all ANR+E models across 30 yr**




*Details on cost composition for each of the 14 ANR-+E models are provided in Appendix 2.*

## Benefits

Table 2 shows the average productivity of each NTFP selected, in kilograms per year, and the average expected price for each product. As a disclaimer, it is important to note that the prices used to calculate monetary benefits were based on the stated average farm-gate prices at the time of harvest, without considering value-added processing or market upgrading. These average prices may be influenced by short-term local and global supply - demand dynamics, seasonal fluctuations, and market volatility. For two species, products are based on woody biomass (*Aniba rosaeodora;* Appendix 1A) or culms (*Oldeania alpina;* Appendix 1G), whereas they are based on production of fruits, seeds, and leaves for the remaining species (Table 2).

Eleven models generate relatively modest discounted long-term revenues, below USD 25,000, over 30-yr, while three models (*Garcinia kola, Aniba rosaeodora* and *Oldeania alpina*) exhibit high income potential, creating a long upper tail that drives up the mean. The median revenue is USD 27,425, meaning that half of the models earn less than this amount over the full cycle. In contrast, the mean revenue is substantially higher at USD 200,275, reflecting the presence of a small number of very high-revenue models. These outliers likely correspond to

systems with commercially valuable NTFPs, with potentially more favorable price-yield combinations.

Table 3 summarizes the financial indicators of all ANR+E models using a 10% discount rate, revealing substantial variation across countries, species, and restoration contexts. Overall, most models exhibit positive NPVs, BCRs greater than 1, and IRRs above the discount rate, indicating financial viability. However, a few models show negative returns or very long payback periods, highlighting the importance of species selection, market conditions, and management intensity.

Across the 14 models, the median NPV is approximately USD 6,266 per hectare, reflecting the typical profitability level for the majority of ANR+E systems evaluated. In contrast, the mean NPV is considerably higher at USD 31,200 per hectare, indicating that a small number of highly profitable models exert substantial influence on the average. Overall, the distribution underscores two main insights: (1) Most ANR+E models are financially viable, even under conservative assumptions. (2) Economic performance varies widely, emphasizing the importance of species selection, and market conditions when evaluating the financial attractiveness of ANR strategies.

The median IRR is 35.1%, indicating that for most models the financial return is strong and well above the assumed 10% discount rate. However, the mean IRR is much higher, at 76.4%, driven by a small number of extremely profitable outlier models with IRRs exceeding 100% and even surpassing 400%. This gap between median and mean reflects substantial heterogeneity across models: while the majority offer moderate but solid profitability, a few achieve exceptionally high returns, typically associated with highly valuable NTFPs or favorable productivity-price combinations. Overall, the distribution suggests that ANR+E systems generally deliver attractive economic returns, with potential for very high profitability under the right ecological and market conditions.

The median BCR is 2.95, indicating that for the typical model, every dollar invested generates nearly three dollars in discounted benefits, demonstrating solid financial attractiveness. The mean BCR, however, is much higher at 6.78, pulled upward by a few models with extremely high benefit–cost ratios (above 20 and even close to 40). The large gap between mean and median highlights substantial heterogeneity: while most models deliver moderate but clearly positive returns, a small number of cases achieve exceptionally high cost-efficiency, usually associated with high-value NTFPs or very low management costs. Overall, the distribution confirms that ANR+E models are generally cost-effective investments, with strong potential for exceptionally high returns under the right ecological and market conditions.

TABLE 2. **Summary of species productivity and market prices of target species used for enrichment planting**

| Country | Species | Product | Average Productivity (kg/ha/year) | Price (USD/kg) |
|---|---|---|---|---|
| Brazil | *Aniba rosaeodora* (Rosewood) | Essential oil extracted from wood | 2,713 | 35 |
| | *Euterpe oleracea* (Açaí) | Fruit | 128.00 | 11.54 |
| | *Ilex paraguariensis* (Yerba mate) | Leaf | 5,799 | 0.015 |
| | *Paullinia cupana* (Guaraná) | Seed | 76.80 | 0.35 |
| Ecuador | *Ilex guayusa* (Guayusa) | Leaf | 3,124 | 0.35 |
| Ethiopia | *Aframomum corrorima* (Ethiopian Cardamom) | Seed | 231.00 | 10.00 |
| | *Oldeania alpina* (Highland Bamboo) | Culms | 24,000 | 1.00 |
| | *Piper capense* (Timiz – Long Pepper) | Seed | 64.28 | 5.00 |
| Ghana | *Parkia biglobosa* (African Locust Bean) | Seeds and fruit pods | 480.00 | 1.00 |
| | *Tetrapleura tetraptera* (Prekese) | Fruit | 1,200.00 | 2.00 |
| | *Vitellaria paradoxa* (Shea) | Seed | 1,866.00 | 0.60 |
| Nigeria | *Garcinia kola* (Bitter Kola) | Fruit, seed, twig | 211.60 | 8.48 |
| | *Gnetum africanum* (Afang Vine) | Leaf | 64.68 | 1.35 |
| | *Irvingia gabonensis* (Bush Mango) | Fruit, seed | 165.00 | 5.45 |

TABLE 3. **Financial indicators for each model, considering a discount rate of 10%**

| Country | Species | NPV (USD) | BCR | IRR (%) | Payback (Years) |
|---|---|---|---|---|---|
| Brazil | *Aniba rosaeodora* (Brazilian rosewood) | $152,313.15 | 3.09 | 20.9% | 15 |
| | *Euterpe oleracea* (Açaí) | $13,442.63 | 2.49 | 41.2% | 5 |
| | *Ilex paraguariensis* (Yerba mate) | $1,575.14 | 1.38 | 15.9% | 9 |
| | *Paullinia cupana* (Guarana) | $9,191.05 | 2.67 | 31.3% | 5 |
| Ecuador | *Ilex guayusa* (Guayusa) | $6,265.11 | 4.30 | 82.2% | 4 |
| Ethiopia | *Aframomum corrorima* (Ethiopian cardamom) | -$4,526.37 | 0.80 | -3.8% | - |
| | *Oldeania alpina* (Highland bamboo) | $187,932.62 | 37.12 | 342.0% | 3 |
| | *Piper capense* (Timiz long pepper) | $2,542.25 | 4.95 | - | 1 |
| Ghana | *Parkia biglobosa* (Dawadawa) | $1,362.49 | 4.64 | 31.1% | 10 |
| | *Tetrapleura tetraptera* (Prekese) | $10,814.04 | 5.88 | 47.0% | 6 |
| | *Vitellaria paradoxa* (Shea) | $2,293.37 | 2.07 | 18.8% | 11 |
| Nigeria | *Garcinia kola* (Bitter kola) | $71,144.73 | 24.03 | 59.2% | 7 |
| | *Gnetum africanum* (Eru) | -$23,147.71 | 0.23 | 41.2% | - |
| | *Irvingia gabonensis* (Bush mango) | $5,598.24 | 1.22 | 14.1% | 14 |

The median payback period is 6.0 years, indicating that, for most models, restoration costs are fully recovered through NTFP revenues within the first six years of implementation. The mean payback period is slightly higher at 7.4 years, reflecting the influence of a few models with notably longer payback times—some extending to 14–15 years. The proximity between median and mean suggests that while outliers exist, the overall distribution is not heavily skewed. This implies that these modelled ANR systems generally achieve relatively fast financial recovery, particularly considering the long-term nature of ecological restoration. The presence of a few longer payback cases highlights variability in species productivity, local market conditions, and management intensity. Overall, the ANR models tend to reach financial break-even within the first decade, with most doing so in well under ten years, reinforcing the economic feasibility of integrating NTFP production into restoration strategies.

A few models stand out for their exceptionally strong performance. The *Oldeania alpina* (highland bamboo) model in Ethiopia is the top performer, with an NPV of USD 187,933, an extremely high BCR of 37.12, and an IRR of 342%, reaching payback in just 3 years (Appendix 1G). Similarly, *Aniba rosaeodora* (Brazilian rosewood) in Brazil shows very high returns (NPV USD 152,313), though with a longer payback period (15 years) driven by its high long-term value but substantial early costs (Appendix 1A). Nigeria's *Garcinia kola* (bitter kola) also performs strongly, with a BCR of 24.03, an IRR of 59.2%, and a positive NPV of USD 71,145 (Appendix 1L). Notably, the products of both *Oldeania alpina* and *Aniba rosaeodora* are based on woody biomass production rather than leaves, fruit or seed.



Moderate and consistent performance is observed in models such as *Euterpe oleracea* (açaí; Appendix 1B), *Paullinia cupana* (guarana; Appendix 1D) and *Ilex paraguariensis* (yerba mate; Appendix 1C) in Brazil, which show NPVs around USD 1,575–13,443, BCRs between 1.38 and 2.49, and IRRs from 15.9% to 41.2%, with payback occurring within 5–9 years. Similar mid-range results are observed for *Tetrapleura tetraptera* (Prekese; Appendix 1J) in Ghana and *Ilex guayusa* (Guayusa; Appendix 1E) in Ecuador, both of which show strong BCRs (4.30–5.88) and IRRs around 47–82%, with reasonably short payback periods.

Some models, however, demonstrate poor or negative financial performance. In Nigeria, *Irvingia gabonensis* (bush mango; Appendix 1N) shows a very low NPV (USD 5,598) and a marginal BCR (1.22), with a long payback period (14 years), reflecting low profitability. *Parkia biglobosa* (African Locust Bean; Appendix 1I) and *Vitellaria paradoxa* (Shea; Appendix 1K) deliver positive but modest NPVs and long payback periods (10–11 years), indicating weaker financial attractiveness. *Aframomum corrorima* (Ethiopian cardamom; Appendix 1F) in Ethiopia and *Gnetum africanum* (eru; Appendix 1M) in Nigeria both have negative NPVs and BCRs below 1, indicating that benefits do not cover costs over the 30-year horizon.

In summary, the results show that while most ANR-based NTFP systems are financially viable, their profitability varies widely. High-performing species—such as *Oldeania alpina* (highland bamboo), *Aniba rosaeodora* (Brazilian rosewood), *Garcinia kola* (bitter kola; Appendix 1L), and *Ilex guayusa* (guayusa; Appendix 1E)—offer exceptional returns, whereas others may struggle to recover costs. This result underscores the need for context-specific economic assessment, careful species selection, and supportive market conditions to maximize the financial sustainability of ANR initiatives. Our models do not assess general conditions for enrichment planting across the geographic range of the target species but are based on place-based data collection in areas considered most favorable for implementation.

## Sensitivity Analysis of ANR+E systems

Overall, the results indicate that the profitability of ANR systems is moderately sensitive to variations in discount rate. When the discount rate decreases from 10% to 5%, most models exhibit a substantial increase in Net Present Value (NPV) and Benefit–Cost Ratio (BCR), reflecting the long-term nature of restoration benefits. Conversely, when the discount rate increases to 15%, models with delayed revenue streams—such as wood-product or high-value species like *Aniba rosaeodora* (Appendix 1A)—show a pronounced decline in NPV. Models generating early or frequent returns, such as *Ilex guayusa* (Appendix 1E), *Tetrapleura tetraptera* (Appendix 1J), and *Garcinia kola* (Appendix 1L), remain profitable even under 15% discount rates, highlighting their potential as lower-risk investments for smallholders and local cooperatives.

FIGURE 5A. **Integrated discount rate sensitivity analysis for all 14 ANR+E models**

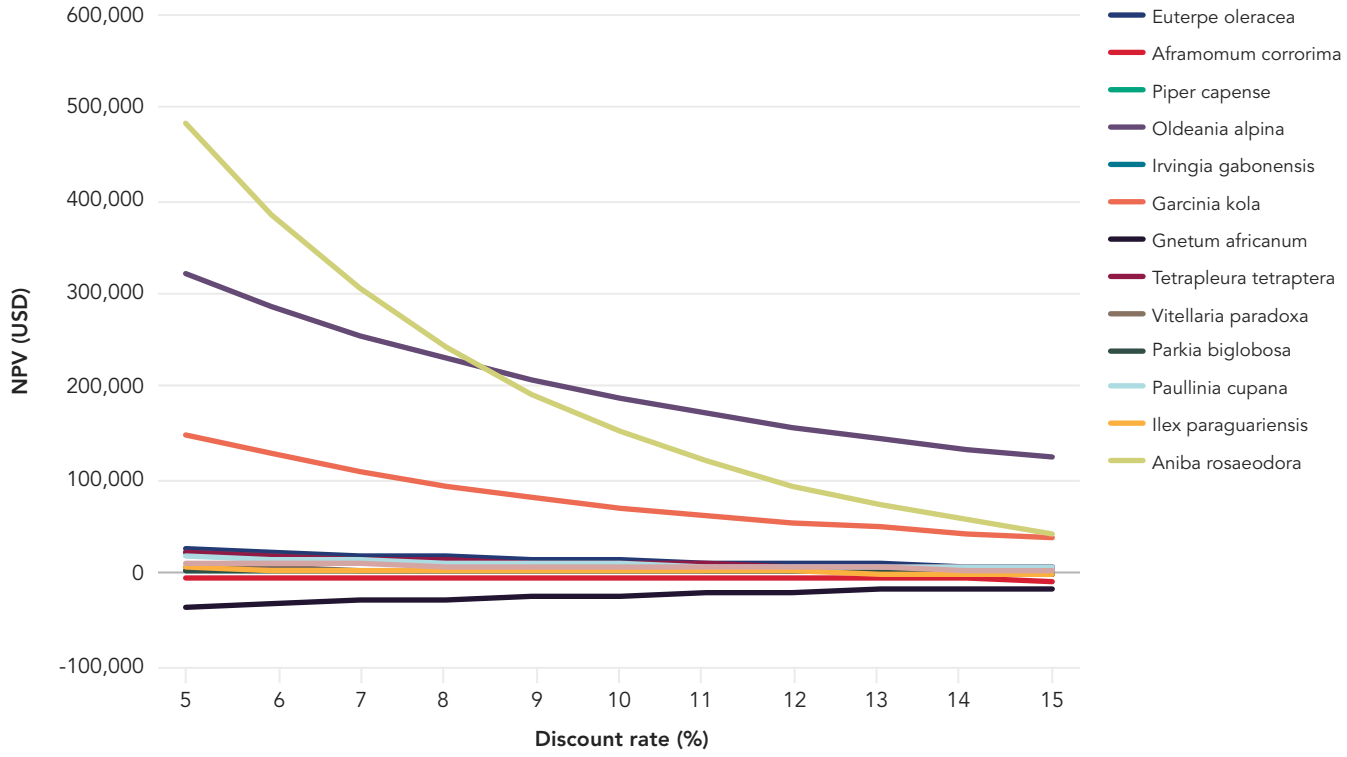



FIGURE 5B. **Detail of integrated discount rate sensitivity analysis for 12 ANR+E models**

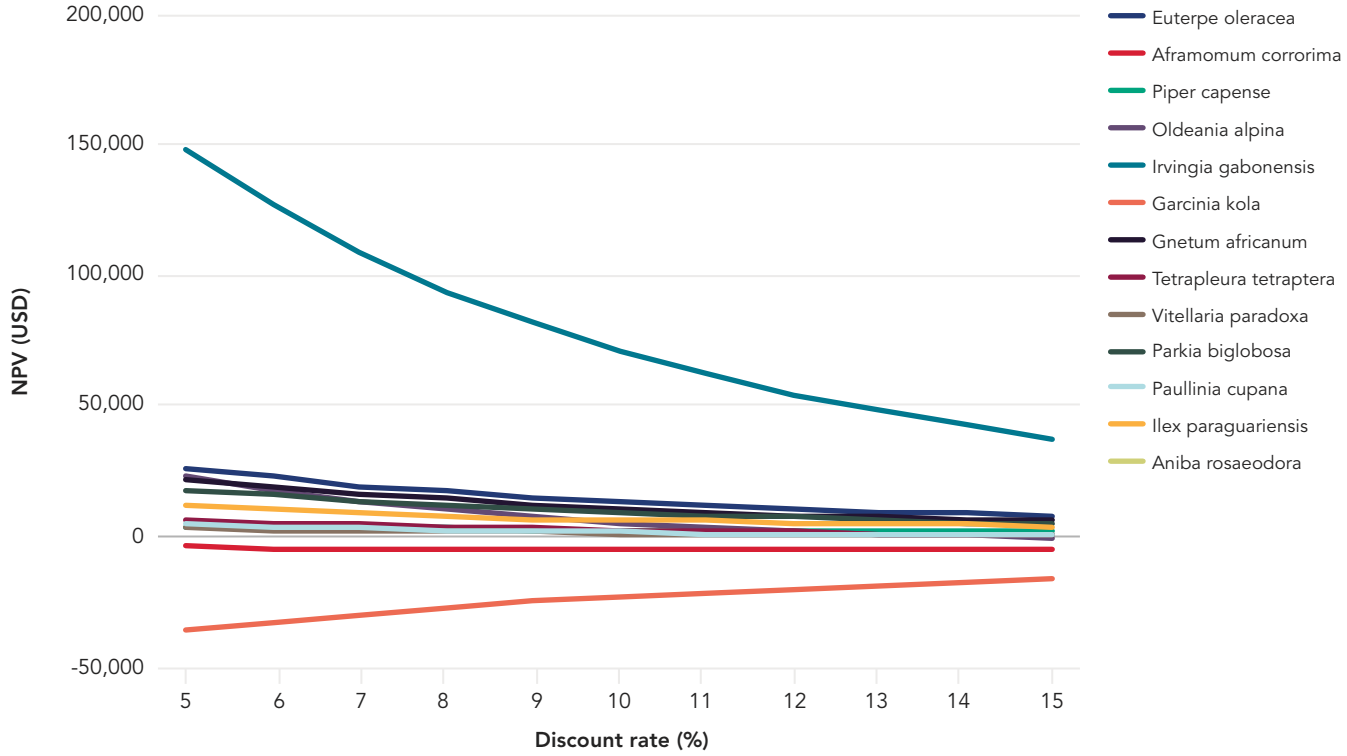
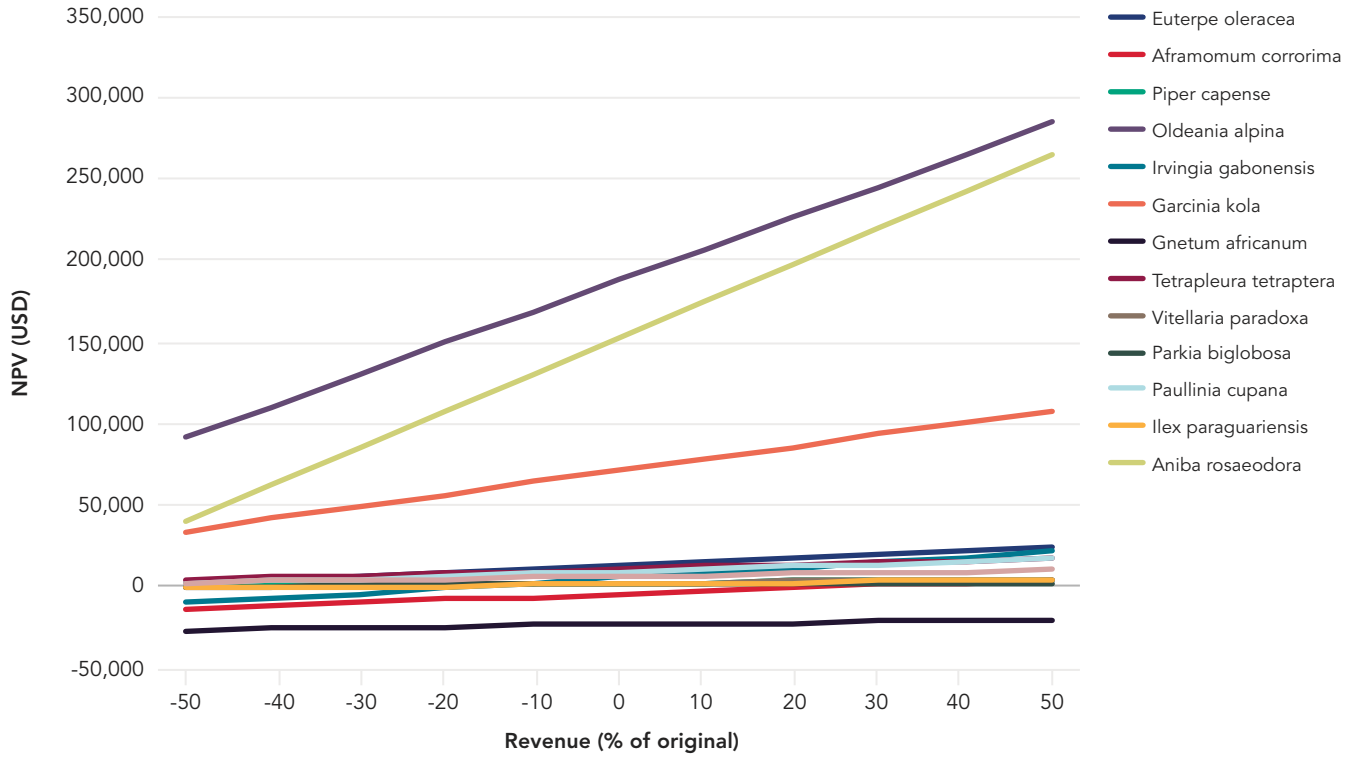


Figure 5 and Table 4 illustrate how the Net Present Value (NPV) of each ANR model responds to changes in the discount rate, revealing the expected downward trends across all species: as discount rates increase, NPVs decline, reflecting the long-term nature of restoration benefits. High-performing species such as *Garcinia kola*, *Tetrapleura tetraptera*, *Ilex paraguariensis* (Appendix 1C), and *Ilex guayusa* maintain positive NPVs even at higher discount rates, indicating strong financial resilience. In contrast, species with weaker baseline performance—such as *Aframomum corrorima* (Appendix 1F) and *Gnetum africanum* (Appendix 1M)—remain in negative territory regardless of discount rate assumptions. Figure 5 highlights considerable heterogeneity across models but overall demonstrates that the majority of ANR systems remain economically viable under a wide range of discount rates, underscoring their robustness to uncertainties in opportunity cost and capital valuation.

The results of the productivity sensitivity analysis highlight differences across species (Figure 6). *Garcinia kola* exhibits exceptionally strong sensitivity, with NPV rising steeply and linearly to more than USD 13 million at full productivity, far surpassing all other models; this indicates that its financial performance is highly dependent on yield and that even moderate productivity can generate very large economic returns. In contrast, *Irvingia gabonensis* (Appendix 1N) and *Gnetum africanum* remain deeply negative across all productivity levels, demonstrating structurally unprofitable economics under the assumed cost and price conditions. Models such as *Tetrapleura tetraptera*, *Ilex paraguariensis*, *Ilex guayusa*, *Oldeania alpina*, and various Brazilian species show modest positive NPVs that scale upward with productivity but remain within relatively narrow ranges, indicating robust but not extreme sensitivity. Overall, the graph demonstrates that while most ANR systems improve economically with increased productivity, only a small subset exhibits transformational gains, whereas two models remain non-viable regardless of yield.

Variations in revenue (either from decrease in productivity or price) exert markedly different effects on the financial outcomes of the restoration models. The x-axis on Figure 6 shows revenue as a percentage of the baseline scenario (0%), while the y-axis displays the corresponding NPV in USD. Each line represents how a species' project viability changes with revenue variations, assuming constant costs and a 10% discount rate. Systems centered on high-value timber and fast-growing biomass species, such as *Aniba rosaeodora* and *Oldeania alpina*, exhibit strong sensitivity to changes in yield, with profitability increasing rapidly under improved productivity conditions but declining steeply when production falls below expectations. In contrast, models based on diversified non-timber forest products—particularly *Euterpe oleracea*, *Garcinia kola*, *Ilex guayusa*, and *Vitellaria paradoxa*—display far greater stability, maintaining positive returns even under conservative yield assumptions. This distinction highlights

FIGURE 6. **Integrated productivity sensitivity analysis for 14 ANR+E models**



a structural resilience within NTFP-dominated systems, where multiple harvest events and local market integration buffer producers against biophysical or price fluctuations. The overall pattern suggests that while productivity enhancement can substantially amplify the financial appeal of certain high-value restoration systems, the broader portfolio of ANR models remains economically robust across a wide range of yield scenarios.

In sum, the sensitivity analyses demonstrate that while the financial performance of models varies under changing assumptions, most of the ANR+E systems remain robust and economically attractive, particularly those integrating early yielding NTFPs with low maintenance requirements. This analysis confirms that assisted natural regeneration, when properly designed and managed, offers not only ecological benefits but also a resilient investment pathway capable of withstanding diverse economic scenarios.

## Comparison of Input Variables and Model Outputs

Across the analyzed ANR models, the relationship between input variables—mainly establishment costs, maintenance intensity, and timing of revenues—and financial performance metrics such as NPV, IRR, BCR, and payback period shows distinct patterns. Models with low initial investment requirements and moderate recurrent costs tend to achieve higher cost-effectiveness and faster payback, even when total revenues remain modest. This pattern is particularly evident in several target species from Ghana and Nigeria, where minimal service expenditures combined with early product yields (beginning between years 5 and 8) contribute to Benefit–Cost Ratios exceeding 4 and IRRs above 30%.

TABLE 4. **Discount rate sensitivity analysis on the model financial indicators**

| Country | Species | NPV 5% (USD) | NPV 10% (USD) | NPV 15% (USD) | BCR 5% | BCR 10% | BCR 15% |
|---|---|---|---|---|---|---|---|
| Brazil | *Aniba rosaeodora* (Rosewood) | $482,759 | $152,313 | $42,630 | 5.05 | 3.09 | 1.84 |
| | *Euterpe oleracea* (Açaí) | $25,860 | $13,443 | $7,581 | 2.86 | 2.49 | 2.14 |
| | *Ilex paraguariensis* (Yerba mate) | $4,668 | $1,575 | $163.66 | 1.81 | 1.38 | 1.05 |
| | *Paullinia cupana* (Guaraná) | $18,245 | $9,191 | $4,865 | 3.51 | 2.67 | 2.05 |
| Ecuador | *Ilex guayusa* (Guayusa) | $11,356 | $6,265 | $3,851 | 4.88 | 4.30 | 3.76 |
| Ethiopia | *Aframomum corrorima* (Ethiopian cardamom) | -$4,113 | -$4,526 | -$4,622 | 0.88 | 0.80 | 0.72 |
| | *Oldeania alpina* (Highland bamboo) | $321,415 | $187,933 | $123,521 | 40.06 | 37.12 | 33.88 |
| | *Piper capense* (Timiz long pepper) | $4,014 | $2,542 | $1,823 | 4.91 | 4.95 | 4.98 |
| Ghana | *Parkia biglobosa* (Dawadawa) | $3,225 | $1,362 | $603 | 6.39 | 4.64 | 3.24 |
| | *Tetrapleura tetraptera* (Prekese) | $21,982 | $10,814 | $5,815 | 7.52 | 5.88 | 4.52 |
| | *Vitellaria paradoxa* (Shea) | $6,387 | $2,293 | $622 | 3.08 | 2.07 | 1.37 |
| Nigeria | *Garcinia kola* (Bitter kola) | $147,995 | $71,145 | $37,586 | 33.60 | 24.03 | 16.68 |
| | *Gnetum africanum* (Afang vine) | -$36,124 | -$23,148 | -$16,866 | 0.23 | 0.23 | 0.22 |
| | *Irvingia gabonensis* (Bush mango) | $22,604 | $5,598 | -$797 | 1.50 | 1.22 | 0.95 |

By contrast, high-yield or high-value timber-oriented models, such as those observed in Ethiopia and Brazil, present significantly larger revenue flows but also higher sensitivity to input intensity. The *Oldeania alpina* model, for instance, combines substantial annual outputs with relatively moderate labor and service costs, resulting in extraordinary financial indicators (NPV of USD 187,933 and IRR of 342%) despite a pronounced dependence on productivity stability.

Meanwhile, Brazilian models such as *Euterpe oleracea, Paullinia cupana*, and *Ilex paraguariensis* (Appendix 1B-D) achieve balanced yet more moderate outcomes, reflecting a proportional relationship between consistent medium-term revenues and stable cash flows, with IRRs ranging from 15.9% to 41.2% and NPVs between USD 1,575 and USD 13,443.

When comparing outputs, models with recurring NTFP production and lower management complexity generally outperform those requiring high upfront or continuous investment. This efficiency is visible in the ratio between discounted revenues and costs, where lean-input models achieve positive NPV trajectories earlier and maintain resilience under discounting. Conversely, capital-intensive systems may exhibit impressive cumulative cash flows but rely on sustained yields and market conditions to offset their initial expenditures. The *Aniba rosaeodora* model exemplifies this pattern, achieving a very high NPV of USD 152,313 but requiring 15 years to reach payback due to substantial early investments and delayed revenue generation (Appendix 1A).

Overall, the comparison reveals a clear trade-off between investment scale and financial resilience. Low-input ANR systems offer reliable, steady returns with minimal financial risk, whereas high-input, productivity-driven systems deliver superior economic performance only under favorable conditions. These contrasts underscore the importance of aligning restoration design with both ecological context and investor profile—balancing cost efficiency, time horizon, and sensitivity to biophysical and market uncertainties.

## Alternative land uses and carbon storage

Here, we address two questions: (1) how does net revenue from assisted natural restoration with enrichment planting of non-timber forest product species (ANR+E) compare to net revenue from alternative potential land uses? (2) how does the climate benefit (carbon sequestration) from ANR+E compare to alternative potential land uses? We compared the economic benefits (net discounted revenue) and climate benefits (carbon sequestration) over 30 years of ANR+E (Figure 7) to alternative land uses including




agriculture (Ag), fuelwood, and solid wood, as well as other forms of regeneration, including minimally assisted natural regeneration (NR), assisted natural regeneration (ANR), NR with sale of carbon credits (NR+C), ANR with sale of carbon credits (ANR+C), and ANR+E with sale of carbon credits (ANR+E+C).

For three species, *Aniba rosaeodora, Oldeania alpina* and *Garcinia kola*, net revenue from ANR+E is estimated to be more than 10-times higher than that of the most profitable alternative land use at the same site (Table 5). For six additional species, *Euterpe oleracea*, *Paullinia cupana*, *Ilex guayusa*, *Tetrapleura tetraptera*, *Irvingia gabonensis*, and *Piper capense*, net revenue from ANR+E is estimated to be somewhat higher (between 1–10x) than that of the most profitable alternative land use. For three species, *Vitellaria paradoxa*, *Ilex paraguariensis*, and *Parkia biglobosa*, net revenue from ANR+E is estimated to be positive but lower than that of the most profitable alternative land use. For *Aframomum corrorima* and *Gnetum africanum*, net revenue from ANR+E is estimated to be negative and is lower than all alternative land uses.

Note that since discount rate affects values for both ANR+E and alternative land uses in the same direction, modifying this parameter has a smaller impact on the ratio of the two financial flows than on each financial flow individually (Table 5).

For the nine species where net revenue from ANR+E exceeds that of alternative land uses, sale of NTFPs represents an alternative to carbon credit sales to achieving competitiveness (Table 6; Figure 8). For the three species where net revenue from ANR+E is below that of alternative land uses, sale of NTFPs can lower the price of carbon credits needed to achieve competitiveness. For the two species where net revenue from ANR+E is negative, production of NTFPs still lowers the price of carbon credits needed to achieve competitiveness for one of the two species.

FIGURE 7. **Economic benefit (30-year discounted net revenue from sale of NTFPs) and climate benefit (30-year undiscounted carbon sequestration) of 14 ANR+E systems**

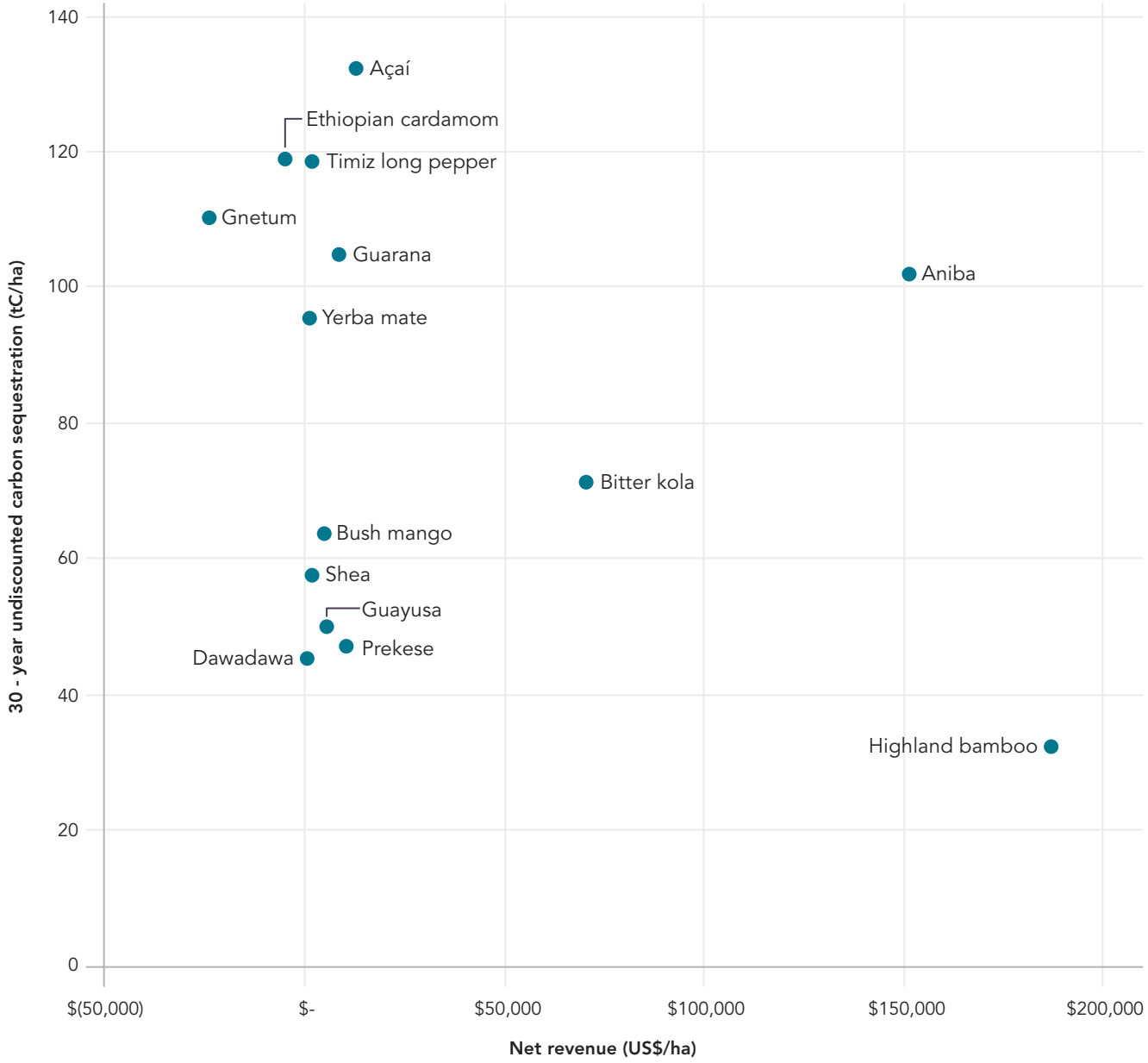


TABLE 5. **Net revenue (discounted USD /ha) from ANR+E and alternative land uses**

| Country | NTFP species | Net revenue ANR+E | Net revenue maximum alternative land use | Ratio of net revenue of ANR+E to maximum alternative land use | | | Potential carbon revenue ($/ha) |
|---|---|---|---|---|---|---|---|
| | | | | 10% discount rate | 5% discount rate | 15% discount rate | |
| Brazil | *Aniba rosaeodora* (Brazilian rosewood) | 152313 | 813 | 187.27 | 142.33 | 149,399.43 | 1064 |
| Ethiopia | *Oldeania alpina* (highland bamboo) | 187933 | 2204 | 85.26 | 54.22 | 123.44 | 199 |
| Nigeria | *Garcinia kola* (bitter kola) | 71145 | 4830 | 14.73 | 19.69 | 10.69 | 524 |
| Brazil | *Euterpe oleracea* (açaí) | 13443 | 3160 | 4.25 | 3.69 | 3.29 | 1325 |
| Brazil | *Paullinia cupana* (guarana) | 9191 | 3937 | 2.33 | 2.93 | 1.70 | 1054 |
| Ecuador | *Ilex guayusa* (guayusa) | 6265 | 2902 | 2.16 | 2.51 | 1.82 | 597 |
| Ghana | *Tetrapleura tetraptera* (prekese) | 10814 | 5013 | 2.16 | 2.82 | 1.59 | 277 |
| Nigeria | *Irvingia gabonensis* (bush mango) | 5598 | 4607 | 1.22 | 3.15 | (0.24) | 568 |
| Ethiopia | *Piper capense* (Timiz long pepper) | 2542 | 2370 | 1.07 | 0.75 | 1.59 | 919 |
| Ghana | *Vitellaria paradoxa* (shea) | 2293 | 4057 | 0.57 | 1.01 | 0.21 | 353 |
| Brazil | *Ilex paraguariensis* (yerba mate) | 1575 | 2915 | 0.54 | 1.03 | 0.08 | 925 |
| Ghana | *Parkia biglobosa* (dawadawa) | 1362 | 6974 | 0.2 | 0.30 | 0.12 | 262 |
| Ethiopia | *Aframomum corrorima* (Ethiopian cardamom) | -4526 | 2733 | -1.66 | (0.67) | (3.36) | 998 |
| Nigeria | *Gnetum africanum* (eru) | -23148 | 3933 | -5.89 | (5.90) | (5.89) | 935 |

*Species are ranked from highest-to-lowest ratio of revenue from ANR+E to revenue from the highest-revenue of alternative land uses based on 10% discount rate.*

TABLE 6. **Breakeven prices. Species are ranked as in Table 5**

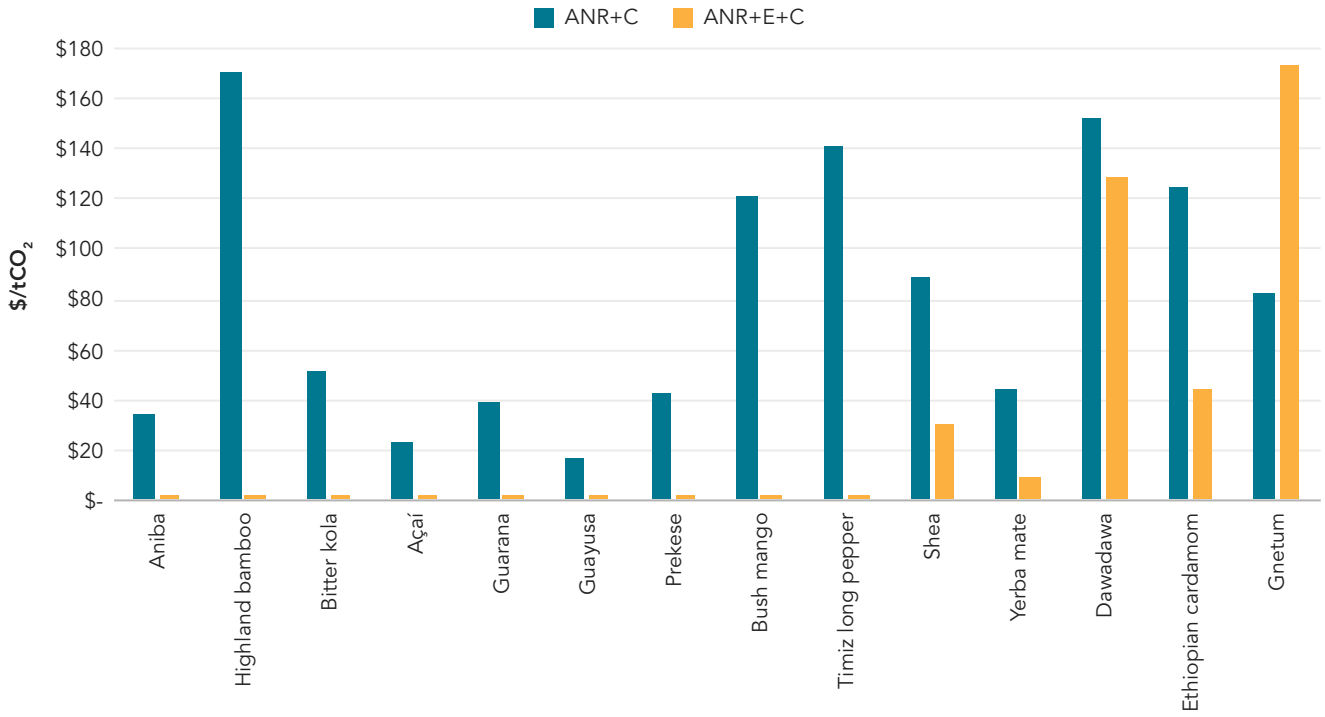
| | What carbon price is needed for ANR+E+C to... | | | | |
|---|---|---|---|---|---|
| | ...have positive net revenue? | ...outcompete agriculture? | ...outcompete fuelwood? | ...outcompete solidwood? | ...outcompete a mixture of ANR and agriculture? |
| *Aniba rosaeodora* | $- | $- | $- | $- | $- |
| *Oldeania alpina* (highland bamboo) | $- | $- | $- | $- | $- |
| *Garcinia kola* (bitter kola) | $- | $- | $- | $- | $- |
| *Euterpe oleracea* (açaí) | $- | $- | $- | $- | $- |
| *Paullinia cupana* (guarana) | $- | $- | $- | $- | $- |
| *Ilex guayusa* (guayusa) | $- | $- | $- | $- | $- |
| *Tetrapleura tetraptera* (prekese) | $- | $- | $- | $- | $- |
| *Irvingia gabonensis* (bush mango) | $- | $- | $- | $- | $- |
| *Piper capense* (Timiz long pepper) | $- | $- | $- | $- | $- |
| *Vitellaria paradoxa* (shea) | $- | $29.97 | $- | $- | $- |
| *Ilex paraguariensis* (yerba mate) | $- | $8.70 | $- | $- | $- |
| *Parkia biglobosa* (dawadawa) | $- | $128.61 | $- | $- | $- |
| *Aframomum corrorima* (Ethiopian cardamom) | $27.20 | $35.10 | $19.79 | $43.63 | $- |
| *Gnetum africanum* | $148.56 | $173.80 | $135.53 | $156.93 | $91.22 |

| | What carbon price is needed for ANR+C to... | | | | |
|---|---|---|---|---|---|
| | ...have positive net revenue? | ...outcompete agriculture? | ...outcompete fuelwood? | ...outcompete solidwood? | ...outcompete a mixture of ANR and agriculture? |
| *Aniba rosaeodora* | $166.48 | $166.49 | $150.29 | $171.07 | $- |
| *Oldeania alpina* (highland bamboo) | $7.88 | $17.05 | $- | $34.52 | $10.23 |
| *Garcinia kola* (bitter kola) | $12.52 | $51.25 | $- | $19.48 | $15.38 |
| *Euterpe oleracea* (açaí) | $8.65 | $22.95 | $- | $18.28 | $- |
| *Paullinia cupana* (guarana) | $16.76 | $39.17 | $1.81 | $26.33 | $- |
| *Ilex guayusa* (guayusa) | $13.55 | $42.70 | $- | $9.85 | $- |
| *Tetrapleura tetraptera* (prekese) | $21.13 | $121.46 | $- | $32.76 | $9.11 |
| *Irvingia gabonensis* (bush mango) | $106.93 | $140.98 | $90.21 | $113.61 | $42.29 |
| *Piper capense* (Timiz long pepper) | $0.91 | $10.12 | $- | $16.39 | $- |
| *Vitellaria paradoxa* (shea) | $23.20 | $88.69 | $- | $34.76 | $4.43 |
| *Ilex paraguariensis* (yerba mate) | $24.93 | $43.85 | $0.02 | $3.33 | $- |
| *Parkia biglobosa* ( dawadawa) | $4.74 | $152.58 | $- | $14.67 | $11.44 |
| *Aframomum corrorima* (Ethiopian cardamom) | $108.84 | $116.74 | $101.43 | $125.26 | $- |
| *Gnetum africanum* | $57.35 | $82.59 | $44.32 | $65.71 | $- |

TABLE 6. **Breakeven prices. Species are ranked as in Table 5 (cont.)**

| | What NTFP species price multiplier is needed for ANR+E to... | | | | |
|---|---|---|---|---|---|
| | ...have positive net revenue? | ...outcompete agriculture? | ...outcompete fuelwood? | ...outcompete solidwood? | ...outcompete a mixture of ANR and agriculture? |
| *Aniba rosaeodora* | 0.32 | 0.32 | 0.31 | 0.33 | 0.19 |
| *Oldeania alpina* (highland bamboo) | 0.03 | 0.03 | 0.02 | 0.04 | 0.03 |
| *Garcinia kola* (bitter kola) | 0.04 | 0.11 | 0.01 | 0.05 | 0.05 |
| *Euterpe oleracea* (açaí) | 0.40 | 0.54 | 0.29 | 0.50 | 0.32 |
| *Paullinia cupana* (guarana) | 0.37 | 0.64 | 0.20 | 0.49 | 0.17 |
| *Ilex guayusa* (guayusa) | 0.23 | 0.59 | - | 0.19 | 0.07 |
| *Tetrapleura tetraptera* (prekese) | 0.17 | 0.55 | 0.03 | 0.21 | 0.12 |
| *Irvingia gabonensis* (bush mango) | 0.82 | 0.97 | 0.75 | 0.85 | 0.54 |
| *Piper capense* (Timiz long pepper) | 0.20 | 0.64 | - | 0.95 | 0.16 |
| *Vitellaria paradoxa* (shea) | 0.48 | 1.40 | 0.08 | 0.64 | 0.22 |
| *Ilex paraguariensis* (yerba mate) | 0.73 | 1.23 | 0.06 | 0.15 | 0.06 |
| *Parkia biglobosa* ( dawadawa) | 0.22 | 4.23 | - | 0.49 | 0.40 |
| *Aframomum corrorima* (Ethiopian cardamom) | 1.25 | 1.33 | 1.18 | 1.40 | 0.24 |
| *Gnetum africanum* | 4.42 | 5.00 | 4.12 | 4.61 | 3.10 |

FIGURE 8. **Breakeven carbon price needed to outcompete most profitable alternative land use**




*The price of carbon or NTFP that must be exceeded for natural regeneration system to financially outcompete alternative land uses in the model location for ANR without enrichment (blue bars) and ANR with enrichment of NTFP (orange bars).*

## Discussion

Here we considered the economic and climate benefits of 14 ANR+E models across five countries in the context of benefits of alternative land uses. Although there is a great deal of uncertainty in the numbers, several conclusions can be drawn.

First, we observed a wide variation in net revenue across ANR+E models. After accounting for costs, net revenue ranges from USD −23,148 for *Gnetum africanum* in Nigeria to USD 187,933 for *Oldeania alpina* (highland bamboo) in Ethiopia, with a median of USD 5,932 per hectare. The ratio of net revenue from ANR+E to net revenue from the maximum alternative land use also varied widely. This ratio spans from −5.89 in the case of *Gnetum africanum* to 187 in the case of *Aniba rosaeodora* in Brazil, with a median of 1.69. The median revenue from the maximum alternative land use is USD 3,547 per hectare.

Predicted carbon accumulation shows less variation. The median non-time-discounted 30-year carbon accumulation from ANR+E is 83.0 tC/ha, which is comparable to accumulation of 79.5 tC/ha from NR, 98.2 tC/ha from ANR, 11.3 tC/ha from fuelwood, and 95.3 tC/ha from solid wood, of which 18.0 tC/ha is in aboveground biomass and the remainder in wood products. Potential carbon revenue (30-year, discounted) across all 14 sites has a median value of USD 758/ha (Table 5).

Second, NTFP sales offer an important alternative income stream for forest restoration projects, substituting for or complementing income from carbon or from other types of economic incentives, such as payments for environmental services. Revenue from the sale of NTFP can replace or reduce the carbon breakeven price (Table 6). The exception is for one crop out of 14 (*Gnetum africanum*) where the cost of producing NTFP is predicted to exceed the revenue gained from its sale.



An important, but often overlooked non-monetary benefit of carbon revenue from ANR+E is an increase of both site permanence and additionality, which are difficult to achieve if natural regeneration has no economic value to smallholders (Brancalion et al. 2024). The carbon prices assumed here are after any necessary deductions to account for the risk of non-permanence.

Our financial models of supplementing assisted natural forest regeneration with enrichment planting of commercial non-timber forest product species show promise. Economic benefits are potentially high relative to alternative land uses, with climate benefits on par with other forms of restoration.

As next steps, researchers should work to confirm the economic estimates by shoring up input data of promising crops and sites. Understanding spatial variation in the factors contributing to revenues and costs can be used to help identify optimal locations for ANR+E projects. For the most promising ANR+E models, forward-thinking reforestation proponents should undertake demonstration projects. In this way the approach can be refined and can be applied effectively to real settings on the ground.

## Caveats and uncertainties

The analysis presented in this chapter has many uncertainties and caveats. First are uncertainties associated with estimating costs and benefits of the core land use: assisted natural regeneration with enrichment planting of target NTFP species. These uncertainties include data responses such as product yields, product prices, and input costs, and parameter assumptions such as exchange rate, discount rate, and carbon density reduction from enrichment planting. Uncertainties in relation to effects of discount rates and production yields were described and examined through sensitivity analyses.

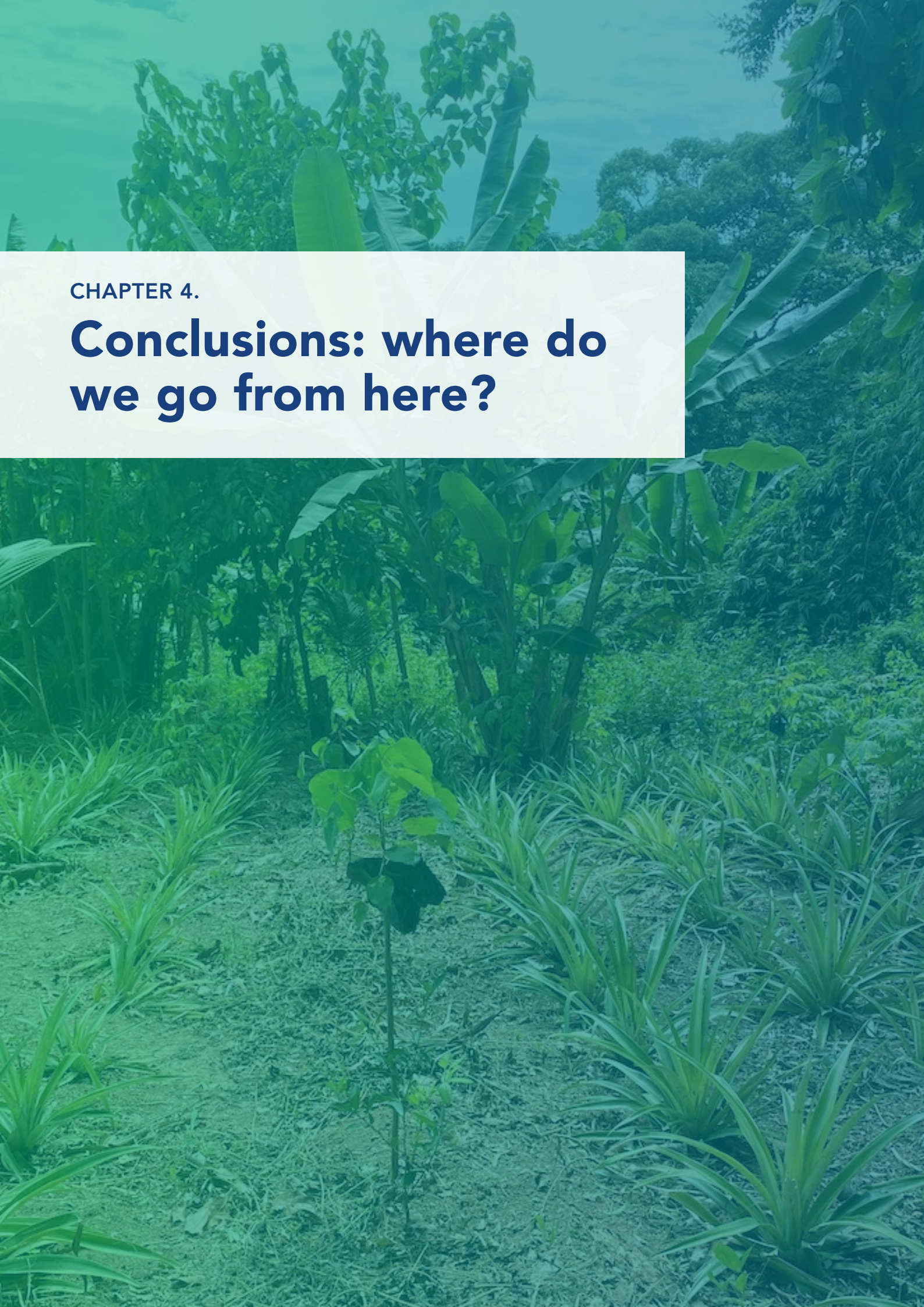
Second are uncertainties associated with estimating costs, benefits, and carbon sequestration associated with the alternative land uses listed above. These uncertainties are described in Busch et al. (2024). Third are those uncertainties and caveats that arise from comparing the core land use to the alternative land uses. These uncertainties are elaborated below.

Locations for ANR+E were compared to alternative land uses at a specific point location. However, the attributes of both ANR+E and the alternative land uses should be expected to vary spatially. A deeper analysis, for example in the context of a scoping exercise preceding a pilot project, would benefit from comparing attribute values (costs, benefits, carbon sequestration) across the full geographic range for which ANR+E is feasible, as well as attribute values of alternative land uses across this range.

Market prices for commercial crops in the ANR+E scenario, and for timber and agricultural products in the alternative land use scenarios, vary over time and space. Carbon prices, exchange rates, and purchasing power fluctuate over time as well. We did not attempt to align in time the market price data across scenarios.

Revenue and cost estimates in the ANR+E scenario were prospective, based on expert surveys, rather than based on actual projects implemented in the target species regions. Meanwhile, the revenue and cost estimates for agriculture and forestry land uses were retrospective, based on production estimates and household surveys of actual profit margins. If prospective estimates are systematically optimistic, or systematically pessimistic, there is potential for bias to arise here as well. Furthermore, actual net revenue from alternative land uses likely does not reflect the maximum potential net revenue in many cases.

We addressed uncertainties in the comparison of net revenue and carbon sequestration values between ANR+E and alternative land uses using a breakeven analysis. We recognize, however, that farmers' land-use decisions are not always based on maximizing net revenue, but they include other behavioral considerations as well, such as risk tolerance, peer effects, incomplete information, and responses to market or climate uncertainties.



CHAPTER 4.

# Conclusions: where do we go from here?

## ANR with enrichment may be highly feasible financially, but real data are needed

In 12 of the 14 cases, the modeled financial benefits for smallholders of ANR with enrichment planting of native NTFP species exceeded the costs, leading to positive net present value and benefit-cost ratios over 30 years. In most cases, the financial viability of these ANR systems proved to be resilient to changes in discount rate and productivity. The financial case for ANR with enrichment is particularly strong for three species: *Oldeania alpina* (highland bamboo; Ethiopia), *Aniba rosaeodora* (Brazilian rosewood; Brazil), and *Garcinia kola* (bitter kola; Nigeria). The estimated net revenue from these products makes ANR significantly more profitable than growing agricultural crops in the same site. An additional three species also show high net revenue when grown as enrichment planting: *Euterpe oleracea* (açai; Brazil), *Paullinia cupana* (guarana; Brazil) and *Tetrapleura tetraptera* (prekese; Ghana), with more than twice the revenue compared to agricultural land use. Three NTFP species showed positive but modest net revenue; with two of these cases showing slightly higher projected revenues than agricultural land use: *Ilex guayusa* (guayusa; Ecuador), *Irvingia gabonensis* (bush mango; Nigeria) and *Piper capense* (Timiz pepper; Ethiopia).

For three NTFP species, net revenues are positive but are lower than those projected for crop production, leading to a significant opportunity cost for ANR with enrichment: *Vitellaria paradoxa* (shea; Ghana), *Ilex paraguariensis* (yerba mate; Brazil) and *Parkia biglobosa* (dawadawa; Ghana). In these cases, including revenue from carbon credit sales by increasing the price per ton of carbon could further incentivize ANR with enrichment over crop production.

Two of the 14 species showed higher costs than benefits for ANR with enrichment: *Aframomum corrorima* (Ethiopian cardamom; Ethiopia) and *Gnetum africanum* (eru; Nigeria). Cost-effective production systems for these species will need to increase prices or reduce the overall costs of planting, management, or harvesting, as models of higher densities did not yield positive net revenues.

Our model results are preliminary, as data on costs and revenues for generating these cost-benefit assessments have not been verified in the context of ANR with enrichment planting for any of the target species included here. More definite assessments of feasibility will require a set of well-planned pilot studies with careful accounting of costs and revenues. We did not have the benefit of using data from actual implementation cases on the ground, as these cases do not exist or they are poorly documented in the literature.

These cost-benefit and carbon storage models assumed that both natural forest regeneration and enrichment planting were initiated in the first year. In most scenarios, however, enrichment planting would take place during the first 2–5 years of natural regeneration, as it is a supplemental activity aligned with other interventions to enhance the natural regeneration process that has already begun in the site. Alternatively, target species could be planted into sites where natural regeneration is well advanced, which may require some pruning or thinning of competing vegetation. Importantly, our results may underestimate the realized total economic value of ANR systems, as they do not include sustainable harvesting of non-timber or timber forest products of spontaneously regenerating native species, which could provide revenues in addition to those provided by the target species planted (Souza et al. 2016).

Using 30-yr CBA models and 10% discount rate, similar to those used in our study, Gasparinetti et al. (2022) evaluated nine restoration models in Brazil, Peru, Cambodia, and Indonesia based on planted agroforestry systems. For these nine models, financial indicators showed a median net present value (NPV) of USD 1,548 per hectare, and a median internal rate of return of 22%. Our results, based on ANR with enrichment of native NTFP species, show substantially higher median NPV (USD 6,266 per hectare) and IRR (35.1%). Following other economic analyses of restoration, our results confirm the importance of cost-benefit analysis using a discounted cash-flow approach (Vergara et al. 2016; Verdone and Seidl 2017; Ding et al. 2017; Pacheco et al. 2024).

## Research Needs

Our study highlights several areas where research is needed to improve financial analysis of ANR with enrichment of NTFP and to enhance effective implementation on the ground. These research questions could be addressed using pilot projects in several countries and geographic contexts. Ideally, research teams would bring together university students and researchers, local civil society organizations and government agencies.

Three research questions focus on management practices.

- What are the conservation status and sustainable use practices for many NTFPs that are largely harvested from wild populations? This information is essential for developing criteria for target species for ANR with enrichment projects and for site selection.

- What is the optimal density and spatial arrangement for production of target NTFP species and how does the density of planting influence economic and ecological outcomes of ANR over time? Are there cases where NTFP species grow better in ANR systems than in monocultures?
- How can costs of production and harvesting be minimized without negatively affecting growth, quality, and yield of target NTFP species and overall forest recovery?

Two research questions focus on economic incentives and mechanisms:

- How do economic incentives, such as Payments for Environmental Services, influence smallholder or community decisions to implement ANR (with or without enrichment)?
- What financial or certification mechanisms can add value to NTFP produced in smallholder ANR systems?

Two research questions focus on institutional support and governance mechanisms:

- What institutional mechanisms can reduce risk for implementers of ANR with enrichment and can ensure stable and adequate market value for harvested products?
- How do local governance and tenure arrangements influence equity and opportunities for women to participate and benefit from ANR with enrichment of NTFP?



## Overcoming challenges for implementation of ANR

Despite the economic feasibility of ANR with enrichment of NTFPs that we have demonstrated here, these systems are not being implemented currently within the broader context of restoration programs. Here we discuss some of the reasons for the slow adoption of ANR and suggest steps to overcome these limitations. Key enabling factors for the successful assisted natural regeneration of forests fall into three main categories: 1) ecological factors that support recovery of biodiversity and ecosystem services; 2) socio-economic factors that lead to direct financial benefits and incentives for local implementers and communities; and 3) governance and institutional factors that empower local communities and create conditions for long-lasting stewardship and engagement with regenerating forests (Chazdon et al. 2017; Mansourian 2020; Alves et al. 2022; Shono et al. 2020). When considering the enrichment of NTFP into these regenerating forests, additional enabling factors apply to ensure sustainable management, enhance silvicultural knowledge and improve equitable access. Another challenge is that combining production and harvesting activities with ANR creates conflicts for land managers and implementers who are not accustomed to managing both types of functions in the same site or property.

### Seeing regenerating forests as a viable land use

Despite the multiple benefits that ANR can bring to smallholders and communities, implementation faces many challenges and barriers. One major challenge is the mindset of farmers and land users, whose mission and livelihood are to produce crops rather than to restore forests. Smallholders produce food for their families as well as for income, and their small land holdings are barely sufficient to meet their needs. Abandoned fields are viewed as fallow lands to be recultivated rather than as young forests or woodlands that are protected and nurtured. The lands that are used for implementing ANR (with or without enrichment) should not be restored into forests at the expense of food supplies for local people (Erbaugh et al. 2020). Spatial planning at the landscape scale with engagement of local communities can help to minimize these land-use conflicts and identify areas where protecting forest fallows and regenerating forests will have positive benefits for all (Duarte et al. 2025). Priority areas for ANR are within public or private protected areas, in buffer zones of protected areas, in areas close to forest remnants, in biological corridors and in riparian zones (Chazdon et al. 2023). As our results suggest here, enrichment planting of valuable NTFP

can provide a pathway for assisted natural regeneration that provides greater net revenues than agriculture or commercial forestry.

## Identifying priority areas for natural regeneration

To leverage the potential for natural regeneration, it is important to identify those areas where natural regeneration is already underway or to predict where it is likely to happen. Efforts to implement ANR will be counterproductive if the conditions are unsuitable. Remote sensing using high-resolution imagery is making this task possible at large spatial scales. Maps of natural regeneration can also be generated using aerial photographs and simple drone technology. Community members can assist with surveys of potential areas for ANR using simple indicators and measurements, such as descriptions of soil quality, remnant vegetation, vegetation height, density of woody seedlings, and ground cover. As part of the selection of areas for ANR it is also important to consider who owns and has rights to use the land, so this information should also be incorporated into site assessments.

## Bringing knowledge and technical expertise to farmers and communities

Another major obstacle for assisted natural regeneration is lack of knowledge and technical expertise. On-site technical support can provide guidance regarding how to select appropriate sites for ANR and how to implement effective and low-cost ANR interventions and schedules for management activities, such as weed control. Guidance regarding how to plant and care for the NTFP species is also critical. Many species used for NTFP are in a state of semi-domestication (Leakey 2024), which leads to highly variable rates of harvesting, diminished genetic resources, and overharvesting of wild populations. Given their incomplete domestication status, technical support for cultivating these species on farms is insufficient. Raising seedlings or vegetative cuttings of NTFP species in nurseries could be another economic activity for farmers or communities. Technical guidance is needed regarding how to monitor the ecological and economic outcomes of ANR based on simple measurements of tree size, plant diversity, and yields of NTFP products. As natural regeneration proceeds, other useful species that establish spontaneously can also be monitored for their abundance in the sites, such as firewood, medicinal species, crafts, food, or timber (Chazdon and Coe 1999; Cotta 2017; Zambiazi et al. 2021).

## Reforming land and tree tenure policies

Land and tree tenure arrangements pose a third set of challenges. Rights to use the land or to use the trees are often insecure and easily revoked or lost. In many countries, naturally growing trees are government property and cannot be legally used, even on farmland (Sears et al. 2021). As described by Chomba et al. (2020) complexities and anomalies in tree and land tenure security in both African and Latin American countries originated during the era of colonial occupations, when forest management policies reflected asymmetrical power imbalances vested in the hands of official forestry agencies. Where trees remain property of the state, there are often perverse incentives to remove them in order to secure access to land without state interference (Binam et al. 2017). In many countries in West Africa, farmers that allow trees to regenerate on their farms risk losing their property rights. In Senegal, for example, the Forestry Code creates barriers to the adoption of natural regeneration on farms, as these trees are state property (Karambiri et al. 2023).

## Support for marketing

The marketing of NTFPs, whether they are extracted or cultivated, faces many obstacles, with few national policies that promote sustainable production and marketing. Most government policies that do support NTFP marketing are implemented through local benefit-distribution channels, which in turn are dictated by existing land tenure and resource access rights that exclude large sectors of the population (Delgado, McCall, and López-Binnqüist 2023). The informal economies that characterize NTFP are often based on non-monetized labor by Indigenous or Traditional Peoples and particularly by women who are not fully recognized within regional institutions and who have insecure land and property rights (Clement et al. 2024).

Gross revenues from the sale of NTFP products depend heavily on the quality of products and local market prices. Market prices often fluctuate widely during the year and can be difficult to predict. Some products can be processed and stored for sale when prices are higher, but other products need to be sold as quickly as possible after harvest. Local farmer cooperatives and growers' associations can provide critical assistance to smallholder producers that will maximize their revenues and avoid losses due to marketing failures. For products that are sold in international markets, ecological certification or organic certification of products can also enhance prices and generate new market opportunities, but verification also involves transaction costs for producers and farmers need help to navigate these issues.



## Improving governance, financing and sustainable use policies

Several of the NTFPs examined here are being overexploited and unsustainably managed, threatening the viability of natural populations. For example, *Garcinia kola* (bitter kola) is harvested for bark unsustainably in Eastern Cameroon and is rarely planted or used in assisted natural regeneration (Chimi et al. 2024). Local people lack information on the silviculture of the species. No finances are available for the conservation and sustainable management of NTFPs in the region, and stakeholders in the NTFP sector are not engaged with banking institutions to access capital for business development. Local authorities have little power to regulate resource rights and sustainable use.

Strategies to address these limitations include: sensitization on the threats to *G. kola* populations; building capacity of council forest managers and local people on sustainable harvesting practices and planting techniques; implementing incentives to promote regeneration, plantation on private lands and ownership; value chain development; and enforcement of customary management regulations (Chimi et al. 2024).

In Central Africa, weak formal regulations and inconsistent customary governance are exacerbated by a policy framework that creates a disenabling environment for sustainable use of NTFPs (Ingram et al. 2017). In the case of harvesting *Irvingia gabonensis* (bush mango) in Southern Cameroon, customary tenure arrangements attribute ownership to all individuals or families and access to trees within forests is generally on a first-come, first-served basis. Policy recommendations to remedy this problem include: revising the regulatory framework to better monitor bush mango permits, government promotion and guidance on sustainable harvesting techniques, and collaboration with customary authorities who could help enforce regulations in forest areas (Ingram et al. 2017).

## Quantifying direct benefits for local smallholders and communities

Shifting the prevailing model of NTFP extraction to one of cultivation through restoration and regeneration brings three types of benefits for smallholders and local communities. First, it would promote the recovery of local biodiversity and ecosystem services, including conservation of NTFP that are facing declining populations and habitats in their native geographic ranges (Delgado, McCall, and López-Binnqüist 2023). Second, it would promote sustainable land use, livelihoods, and provide long-term and direct financial benefits for smallholder farmers and communities. Enrichment planting of NTFP at relatively low densities overcomes some of the negative consequences of commercial monocultures or industrialized production systems (Delgado, McCall, and López-Binnqüist 2023), while providing steady and sustainable supplemental income to local land users, communities, or farmers that enhance the value of standing forest.

Third, it would preserve and enhance local knowledge and culture, based on ethnobotanical uses of native species and the recovery of species and multiple benefits of forests and woodlands during forest regeneration (Wangpakapattanawong, Schmidt-Vogt, and Elliott 2009; Reyes-García et al. 2019; Uprety et al. 2012). Aside from the economic benefits, NTFP are culturally important and link the identity, history, and values of people with place, nature, and landscapes (Delgado, McCall, and López-Binnqüist 2023). Harvesting and using NTFPs empowers people to maintain their indigenous and local knowledge of their lands, resources and heritage and reinforces their connection with nature, strengthening their motivation to conserve and protect local species. For example, many of the target species included in this study have been incorporated into indigenous agroforestry systems (Schmidt et al. 2021; Vihotogbé et al. 2007; Parron et al. 2024).

## Integration of ANR within national restoration strategies and forest and landscape restoration programs

Implementation of ANR with enrichment contributes to both ecosystem restoration and to forest and landscape restoration (FLR), involving multiple sectors and stakeholders through actions that regain both ecological and economic functionality and empower local communities (Löfqvist et al. 2023; Elias et al. 2022; Ota et al. 2020). A strength of FLR programs is that different types of restoration practices are practiced across the landscape to balance productive land uses with management approaches that favor conservation

and restoration in other areas (Mansourian and Parrotta 2018). In this framework, areas that are best suited for ANR with enrichment of NTFP can be spatially planned and implemented within a landscape context.

The five countries included in this study have made ambitious restoration commitments based on FLR at the national level and three of the countries (Nigeria, Ecuador and Brazil) have more than 1 million hectares of deforested land with a high potential for natural regeneration (Williams et al. 2024). Development of national strategies for ANR would be a major step toward leveraging this high potential and this process is already underway in Brazil through the National Plan for the Recovery of Native Vegetation. Brazil has the highest global potential for natural regeneration of over 40 million ha (Table 7).

Forest and landscape restoration programs could provide technical support and offer other incentives to land users for their participation, such as risk management strategies, supply of seedlings, or assistance with marketing of products (Delgado, McCall, and López-Binnqüist 2023). The production of NTFP in naturally regenerating forests and woodlands does not generate sufficient income to fully support rural families. Rather, these practices should be viewed as part of a wider spectrum of rural livelihood strategies which recognize their value as household income safety nets, and the importance of the cultural values of NTFPs as reservoirs of traditional knowledge (Turner 2001; Torres et al. 2015). For these reasons, incorporating such practices within the context of a broader FLR project can bring additional sources of revenue and financial incentives, such as payments for environmental services, as well as benefits for tenure security (Pacheco, Beatty, and Patel 2024; Oluwajuwon et al. 2025).

## Towards economically beneficial natural regeneration

This study shows that it is feasible to combine forest regeneration with income-generating production of NTFP. Many other NTFP could be examined as appropriate species for this practice, as we have only begun this exploration here. Although a growing number of studies highlight the potential for sustainable harvesting of naturally regenerating timber and non-timber products from regrowing forests (Krainovic et al. 2025; Toledo-Aceves et al. 2022; Zambiazi et al. 2021; Maier et al. 2019; Melaku, Ewnetu, and Teketay 2014), further assessment of economic and ecological costs and benefits are needed, in addition to studies based on enrichment planting.

With these aspects in mind, we envision a revitalization of the traditional practice of fallow enrichment within 21st century concepts of ecosystem restoration, forest and landscape restoration (Besseau, Graham, and Christophersen 2018) and socio-bioeconomy (Afonso 2022). A socio-bioeconomy is a model of economic development that integrates social equity, community well-being, and environmental preservation by using biological resources sustainably. In contrast to conventional economies, socio-bioeconomy models move beyond a narrow focus on profit, prioritizing instead the fair value generation from biodiversity and ecosystem services, often with the active involvement of traditional and local communities. This approach aims to create inclusive development, support traditional knowledge, and promote nature-based solutions. By merging socio-bioeconomy with assisted natural regeneration practices, natural ecosystems can be restored as a key nature-based solution to bring economic benefits to local communities.

TABLE 7. **Restoration commitments and potential for natural regeneration of forests within the five countries included in this report**

| Country | Bonn Challenge Commitment by 2030 (M ha) | Potential for natural regeneration (M ha) | Available area for forest restoration (M ha) |
|---|---|---|---|
| Nigeria | 4 | 1.15 | 12.71 |
| Ethiopia | 15 | 0.52 | 6.82 |
| Ghana | 2.5 | 0.96 | 7.96 |
| Brazil | 12 | 43.71 | 591.40 |
| Ecuador | 0.3 | 1.99 | 22.49 |

*Based on (Williams et al. 2024). These commitments are part of the global Bonn Challenge, which aims to restore 350 million hectares by 2030 (Saint-Laurent et al. 2020); https://www.bonnchallenge.org/pledges.*

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# Appendices

APPENDIX 1.

# Case studies of 14 target NTFP species

## A. *Aniba rosaeodora* (Brazilian rosewood, pau-rosa)

### Locations for economic models and ANR context

The cost-benefit model for enrichment of assisted natural regeneration with *Aniba rosaeodora* is based in Maués, Amazonas, Brazil. *Aniba rosaeodora* is grown in the Maués municipality of Amazonas, Brazil, in both wild and cultivated settings. The species can grow well in secondary forests and disturbed areas, provided suitable light and soil conditions and is also commercially planted, often in combinations with crops like cassava (Krainovic et al. 2017).

Land tenure arrangements in the municipality of Maués, Amazonas, include a mix of public lands, along with private properties (both titled and informal), and undesignated public lands (Sparovek et al. 2019). Privately owned lands are registered under the nationwide tenure registries such as Cadastro Ambiental Rural (CAR), Land Management System (SIGEF), Terra Legal, or Quilombola territory. Public land includes Indigenous Reserves, Conservation Units, Communitary Territory, Military Land and Rural Settlements. A significant area of Maués is constitutionally recognized as federal land for the exclusive use of indigenous communities, such as the Sateré-Mawé people. Natural forest cover composed 95% of the land area of Maués in 2020 (Global Forest Watch 2025) Large portions of the municipality are designated as conservation units, which are public lands managed for specific purposes, including sustainable use areas such as Pau-Rosa National Forest and Maués State Forest. These public lands with community use rights would be the ideal locations for innovative ANR systems with enrichment of *Aniba rosaeodora*.

### ANR cost-benefit model result

The baseline 30-year economic model for *A. rosaeodora*, shows very high performance, with the second-highest net revenues among the 14 target species (Figure A1). The Net Present Value is USD 152,313 and the Internal Rate of Return is 20.9%. The payback time for net revenue is 15 yr and the benefit-cost ratio is 3.09. Total costs of ANR with enrichment *of A. rosaeodora* are USD 232,580, of which 89.1% are associated with management activities. These are the highest total costs among the models. This model assumes a 10% discount rate and a density of 200 trees/ha in assisted natural regeneration. This density is about a third of the density used in agroforestry plantations to ensure adequate conditions for natural regeneration of native vegetation. NPV is sensitive to increasing discount rate but remains positive at a discount rate of 15% (Figure A2).

### Carbon storage models

Over 30 years, ANR with enrichment of *A. rosaeodora* yielded a total carbon storage of 101.53 MgC/ha. Based on our estimate of land user revenue of USD 6 per ton of carbon, the discounted revenue from carbon credits is USD 1,054/ha over 30 years. This is the second-highest value of revenue generated from carbon storage among all the models. Carbon removal from ANR+E is comparable to that of ANR and somewhat above that of timber plantations for solid wood production.

The climate conditions in Maués support high rates of carbon storage during forest regeneration. Our model assumes that planted individuals offset any reduction in naturally regenerating trees by an equivalent amount of carbon storage, so there is no enhancement of carbon storage as compared to ANR without enrichment. Carbon storage in ANR is 10% higher than the 92.06 MgC/ha removed in minimally assisted natural regeneration.

### Alternative production models

Net revenue from *A. rosaeodora* from ANR with enrichment is estimated to be 187 times higher than that of the most profitable alternative land use, agriculture, at the same site in Brazil (Figure A3). Discounted revenue from carbon storage from ANR with enrichment is comparable to that of ANR without enrichment and is higher than carbon revenue for natural regeneration. Thus, ANR with enrichment of *A. rosaeodora* is a highly favorable land use option for both net revenue and carbon storage in Amazonas State, Brazil and is estimated to provide markedly higher net revenues compared to minimally assisted and fully assisted natural regeneration without enrichment.

FIGURE A1. **30-yr cash flow model for ANR with enrichment of *Aniba rosaeodora***

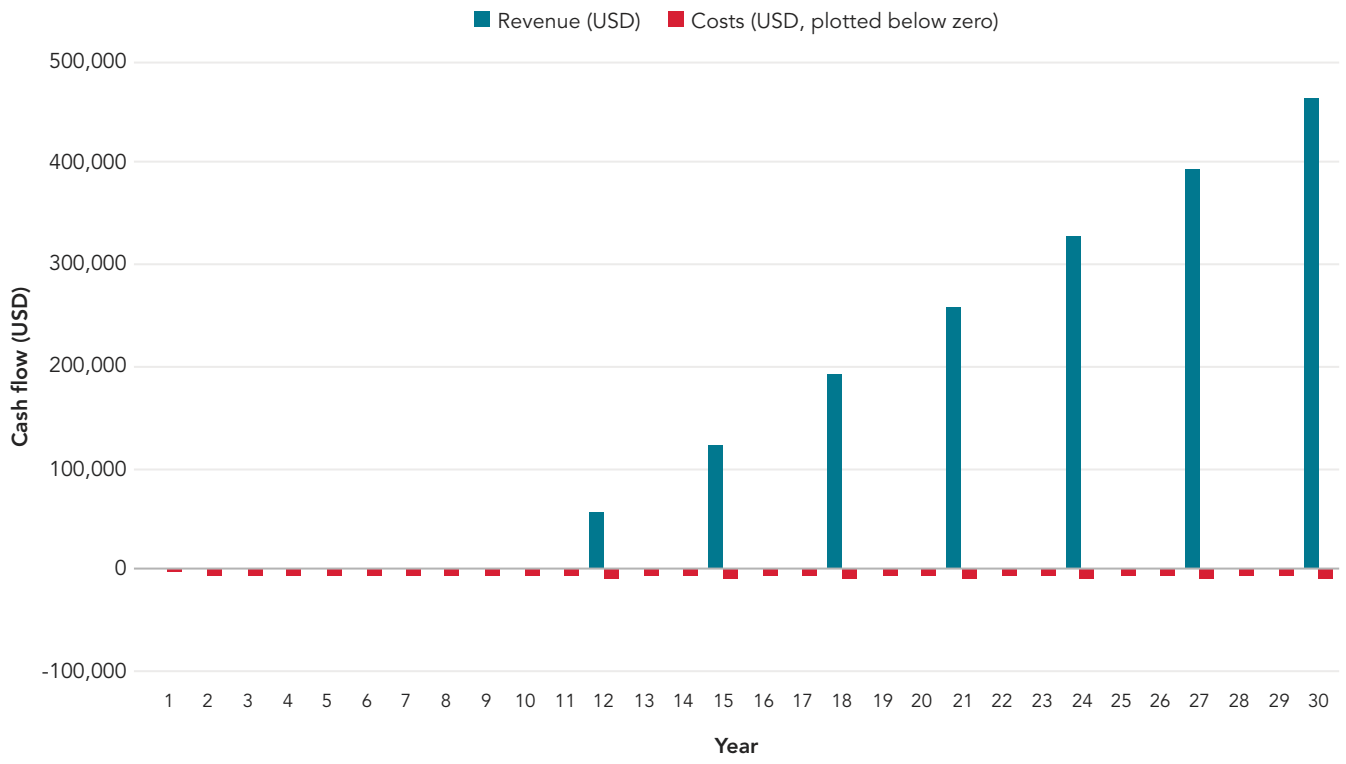



FIGURE A2. **Sensitivity of NPV to discount rate for ANR with enrichment of *Aniba rosaeodora***

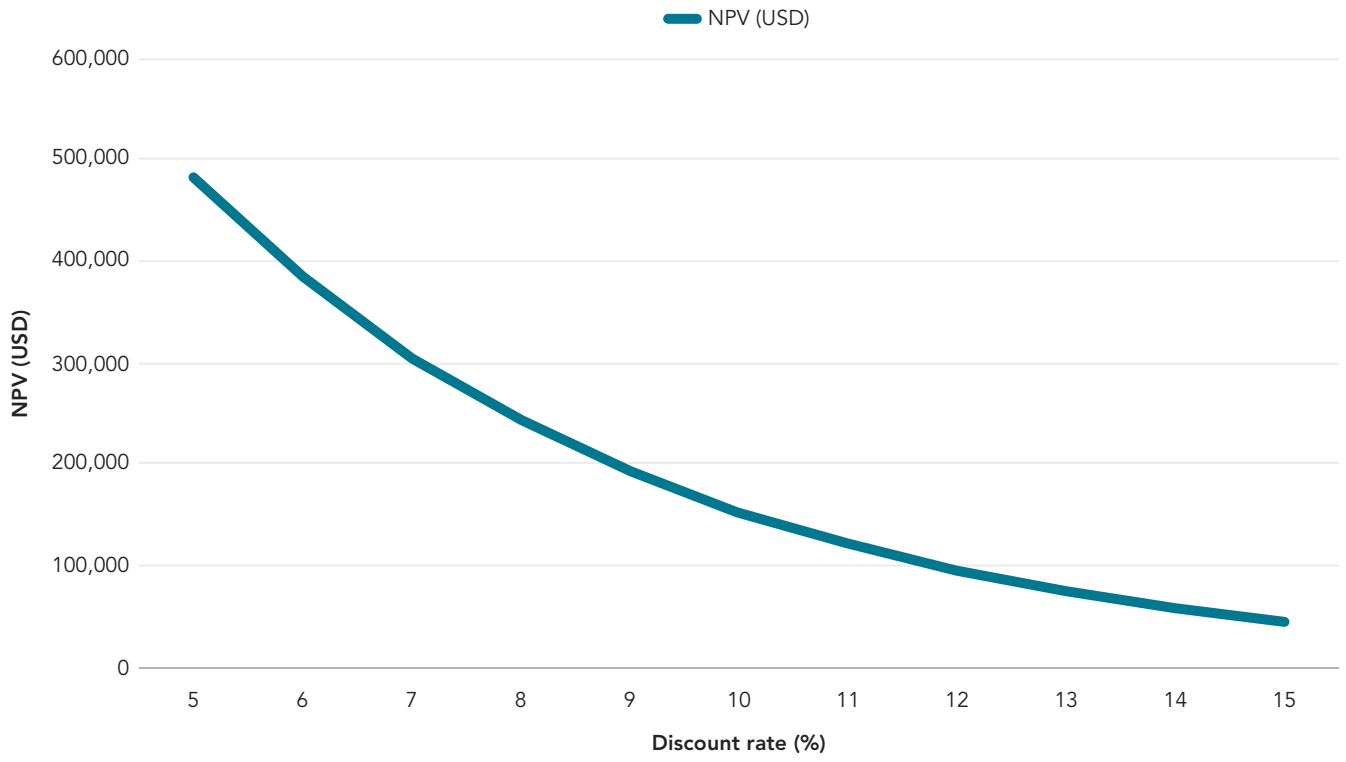
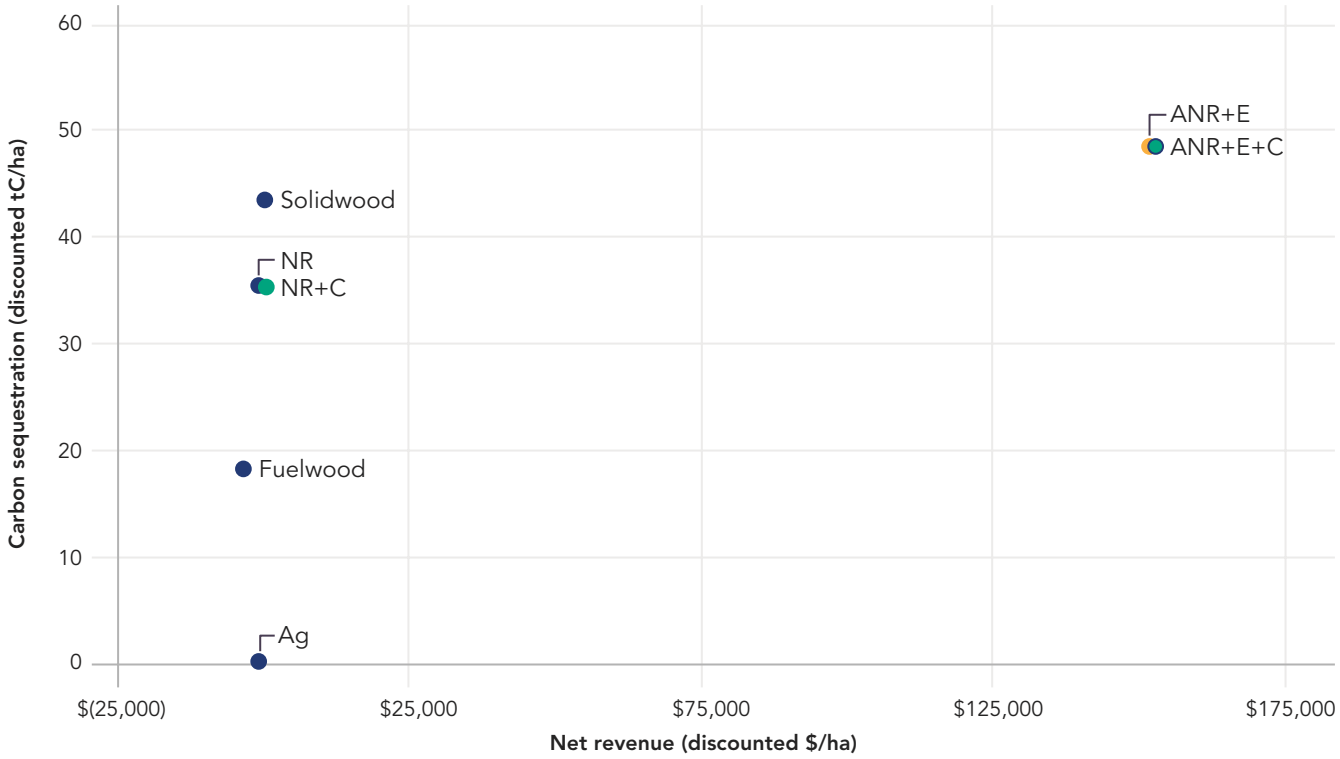


FIGURE A3. **Net discounted revenue and carbon storage for ANR with enrichment of *Aniba rosaeodora* compared to alternative land uses**




*See Chapter 2 for full description of land uses.*

## Species ecology and ethnobotanical information

*Aniba rosaeodora* is an evergreen canopy tree species in the Lauraceae family that grows in tropical moist upland forests in Brazil and across the Amazon Basin in Colombia, Ecuador, Guyana, Peru, Suriname, Venezuela, and French Guiana. In Brazil, it occurs on both banks of the Amazon River, from the state of Amapá to northwest Peru and from the south-central region of the state of Pará extending to the Purus River basin, in the southern state of Amazonas. Trees reach 30 m in height and 2 m in diameter. The purple fruits are dispersed by parrots and toucans.

All parts of the tree are fragrant and contain rosewood oil, which is rich in linalool (Coppen 1995). Rosewood oil is used as a fragrance in perfumes and soaps. The oil is obtained by felling wild *Aniba rosaeodora* trees and steam distilling the chipped wood. Beyond these cosmetic uses, rosewood essential oil is also known for its antibacterial, antifungal, cytotoxic, antioxidant and antimutagenic properties (Amusant et al. 2015). Traditionally, rosewood oil has been used to treat acne, colds, coughs, dermatitis, fevers, frigidity, headaches, infections, nausea, nervous tension and for healthy skin care.

Extraction of rosewood oil began in the 1920s and led to harvesting of over 825,000 trees from natural populations between 1937 and 2002 (Homma 2016). Exploitation of natural populations in the state of Amazonas was intense and predatory through the 1950s, due to its high economic potential. Remaining natural populations are found in remote and difficult to access locations (Junior et al. 2024).

The yield of essential oil ranges between 0.7% and 1.2% (g of oil per g of dried wood as a percentage), with some reports of higher essential oil content (0.9% to 2.6%) in young trees (diameter < 10 cm) than in mature trees (Santana et al. 1997). The discovery of similar quality of rosewood oil in *A. rosaeodora* leaves and branches in the late 1950s kindled interest in sustainable management for essential oil production (Lara, Costa, and Sampaio 2021).

## Cultural and livelihood importance

*Aniba rosaeodora* holds significant cultural and spiritual importance for indigenous peoples, such as the Shipibo-Conibo of the Peruvian Amazon. Traditional Amazonian populations customarily use *Aniba rosaeodora* to treat diseases and in religious rituals (da Trindade et al. 2021). The leaves and wood of *A. rosaeodora* are used in Amazonian folk baths, such as the São João festival in Belém, Pará State, Brazil (van den Berg and da Silva 1986).

## Conservation status

*Aniba rosaeodora* was classified as an endangered species in Brazil in 1992 due to over-exploitation for its essential oil, which requires cutting down entire trees. In 2010, *A. rosaeodora* was included in Annex II of the Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES 2010), to further reduce illegal trade. In Brazil, currently, only planted trees can be exploited, and only with prior authorization from environmental agencies (Lara, Costa, and Sampaio 2021).

Seeds of *A. rosaeodora* are intolerant to drying, therefore, innovative methods are necessary for its conservation (Junior et al. 2024). As wild populations cannot be used for harvesting, sustainable use of A. rosaeodora for rosewood oil requires domestication and development of silvicultural systems. Plantations of *Aniba rosaeodora* (Figure A4) managed for essential oil (including enrichment plantings in assisted natural regeneration) have a high market value, presenting land-use options that conserve the species, protect local forest biodiversity, and create a profitable bioeconomic model for the Amazon region (Junior et al. 2024).

## Production and harvesting

In 2015, Brazil was the only producer of rosewood essential oil worldwide (Amusant et al. 2015). Plantations and sustainable harvesting systems are being developed and tested in both Brazil and French Guiana. Leaves, branches and resprouting stems also produce rosewood oil, suggesting that management by crown pruning can assure sustainable oil production (Krainovic et al. 2018; Figure A5). The canopy management system has also been shown to have good regrowth capacity after successive prunings (Krainovic et al. 2017; Sampaio et al. 2005).

Brazilian rosewood is considered to be shade tolerant, but does require light for growth in height and diameter (Vieira 1972). Experimental plantations in French Guiana showed that trees growing close to the surrounding forest were smaller and produced lower essential oil than trees growing in the middle of the plot due to the availability of light. The study also confirmed that short-rotation cultivation of rosewood trees could be the optimum and most economically attractive system for the production of essential oil (Amusant et al. 2015).

Lara et al. (2025) studied the production chain of *A. rosaeodora* in Brazil. They identified seedling producers, smallholder plantations and processing facilities. Only two private companies hold licenses from environmental agencies to produce rosewood essential oil. Both companies are located in the Central Amazon region and are self-sufficient in biomass production, mainly through the successive pruning of branches and leaves, with only occasional harvesting of entire trees.

Smallholders encountered many biological, technical, economic, and institutional challenges. Stakeholders emphasized the need to create collaborative networks

FIGURE A4. **Young plantation of *A. rosaeodora* in Maués, Amazonas**



*Photo credit:* Hervé Rey (CC).

FIGURE A5. **Canopy pruning in a commercial plantation of *A. rosaeodora* in Maués**



*Photo credit:* Pedro Krainovic (Source: Krainovic et al. 2017).

among smallholders to strengthen the production chain, optimize resources, and expand market opportunities. In addition, they highlighted the need for increased government support, including financial assistance for producers, tax incentives for companies, and price regulation measures.

*A. rosaeodora* can be propagated vegetatively through rooted cuttings, with research showing encouraging results (Monteuuis and Amusant 2020; Botelho, Caetano Quisen, and Barbosa Sampaio 2024).

## Trade and marketing

Due to overexploitation of *A. rosaeodora* natural populations and competition from synthetically produced linalool, from 1980 to 2000 the exported volume of rosewood essential oil fell from over 150 metric tons/year to 46 metric tons/year, while the price per kg increased from USD 12 to USD 40 (May and Barata 2004). This trend continued from 2000 to 2020, with further decline in rosewood essential oil production from 46 to 2 tons/year, increasing the sale price from USD 40/kg to USD 320.00/kg (Lara, Costa, and Sampaio 2021). This price increase has stimulated commercial planting of the species, which is now facing limitations in the availability of seedlings. Few entrepreneurs commercially produce seedlings of the species with regularity, with a total average production of only 20,000 seedlings/year (Lara, Costa, and Sampaio 2021).

Increasing demand for high-quality, natural products is expected to lead to steady future growth in the market for pure rosewood essential oil. The global rosewood essential oil market size was valued at approximately USD 150 million in 2023 (DataIntelo 2025).

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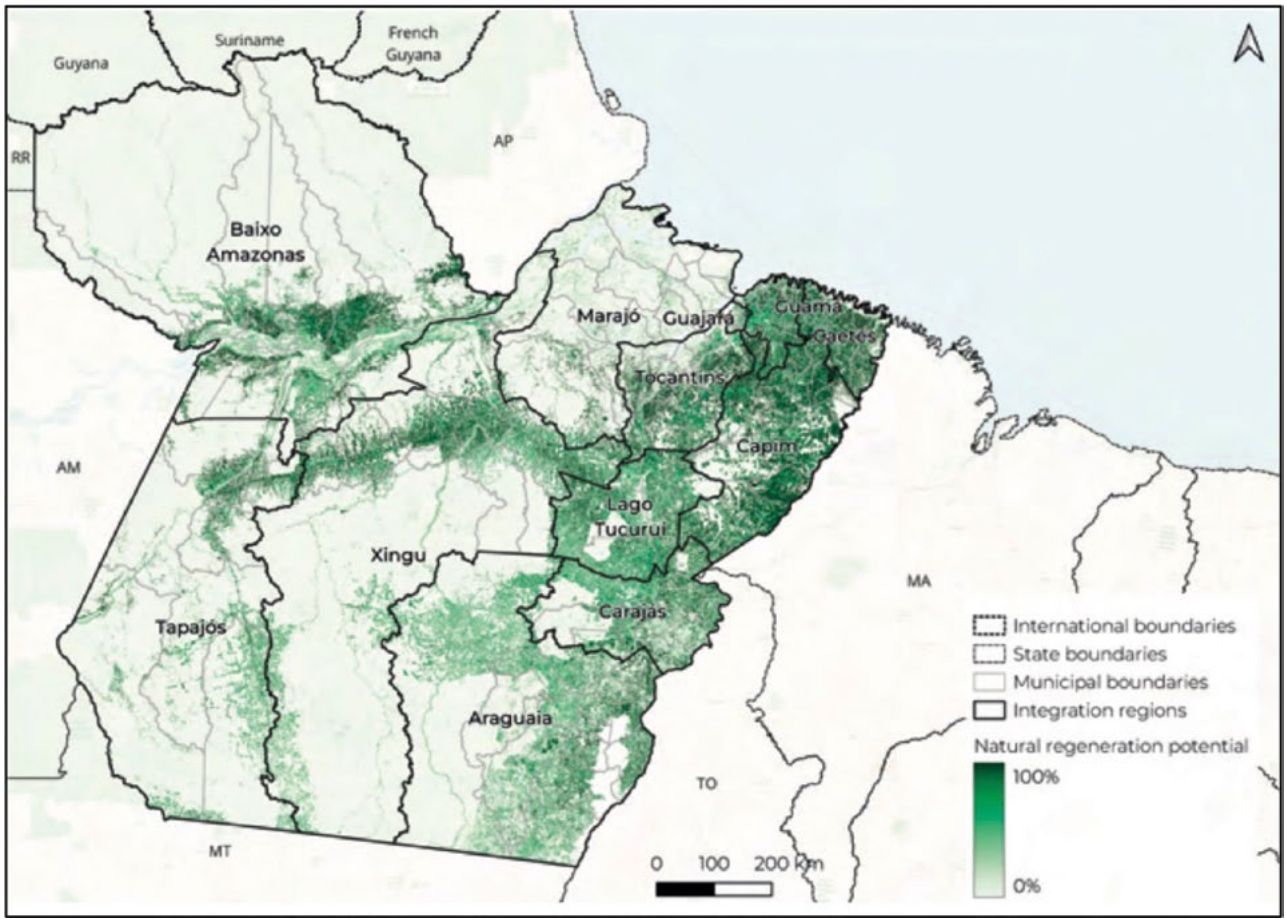
# B. *Euterpe oleracea* (açai, assai)

## Locations for economic models and ANR context

The ANR with enrichment model for *Euterpe oleracea* is located near Altamira, Pará in areas where the species is being grown in plantations and agroforestry systems. In 2020, native forest cover in the Altamira region was 92% (Global Forest Watch, 2025). The area is also the location of several reforestation and forest restoration projects, focused on sustainable production and recovery of degraded forest lands. The state of Pará is prioritizing degraded areas for restoration through its State Plan for the Recovery of Native Vegetation (PRVN-PA), aiming to restore 5.65 million hectares by 2030 (Pará 2023). Approximately 4.45 million hectares in Pará are already undergoing natural regeneration, and natural regeneration potential of deforested areas is high in many areas of the state (Feltran-Barbieri et al. 2023). Pará has a strong bioeconomy potential, with projected growth in socio-biodiversity chains like açaí, cocoa, and Brazil nuts, which can be further enhanced by restoration efforts.

Land and tree tenure in Pará state, Brazil, operates under a complex system involving private, public, and communal land categories, all governed by the national Forest Code and state-level regulations (Sparovek et al. 2019). Landowners are legally required by the Brazilian Forest Code to maintain a significant portion of their property as native vegetation (80% in the Amazon region) known as a "Legal Reserve" (LR). Designated public lands include protected areas, which are managed by government agencies as strictly protected areas or as sustainable use areas, and agrarian reform settlements, which are areas granted with a communal title that can eventually be parceled into individual ownership. Communal and traditional territories include Indigenous Lands, Quilombola Territories, extractive reserves and sustainable development reserves.

FIGURE B1. **Potential for natural regeneration in Pará State, Brazil. Source: Elaborated by IIS based on WRI Brasil**




*Source:* Pará (2023).

Among all of these arrangements, agrarian reform settlements led by the Landless Rural Workers Movement (MST) show particular promise for assisted natural regeneration with enrichment of *E. oleracea* or other native NTFP species, as they encompass 15% of the areas with regrowing secondary forests in the Amazon Biome (Duarte et al. 2025; Guimarães et al. 2025). In many cases, ANR with enrichment of native tree species can be implemented in regenerating forests alongside agroforestry plantings in these settlements.

## ANR cost-benefit models, scenarios and assumptions

Production of *E. oleracea* within ANR systems shows strong profitability and resilience (Figure B2). With a Net Present Value (NPV) of USD 13,443 and an Internal Rate of Return (IRR) of 41.2%, it reaches payback within 5 years and presents a BCR of 2.49. Revenues stabilize after year 5, while costs remain low and constant. Total costs of ANR with enrichment of *E. oleracea* were USD 63,795, of which 70% were related to management. Importantly, its cost structure includes activities related to control of invasive species as part of the ANR intervention, and the high costs in year 1 are associated with seedlings and planting activities. Such performance indicates that açaí-based enrichment systems offer rapid financial recovery and consistent returns over time, reinforcing their potential for sustainable production and income diversification in restored areas. As for the sensitivity analysis, the NPV gradually decreases with higher discount rates, yet remains positive across the range, confirming the model's strong profitability and low sensitivity due to early and recurring revenues (Figure B3). Costs and benefits are modeled based on a density of 120 clumps/ha, which is below the density threshold of 180 clumps/ha associated with loss of tree diversity (Freitas et al. 2025).

## Carbon storage models

Over 30 years, ANR with enrichment of *E. oleracea* is estimated to store 131.85 MgC/ha in aboveground tree biomass. This is the highest carbon storage among all of the models. Our model assumes that planted individuals offset any reduction in naturally regenerating trees by an equivalent amount of carbon storage, so there is no enhancement of carbon storage as compared to ANR without enrichment. The climate conditions in Pará support high rates of carbon storage during forest regeneration. Carbon storage in ANR (with or without enrichment) is 12% higher than for natural regeneration and is also higher than for solidwood or fuelwood plantations.

## Alternative production models

Over 30 years, the net revenue from ANR with enrichment of *E. oleracea* is estimated to be 4.25x higher than that of the most profitable alternative land use, agriculture, at the same site (Figure B4). Carbon credits would provide an additional US$1,325/ha over 30 years.

FIGURE B2. **30-yr cash flow model for ANR with enrichment of *Euterpe oleracea***

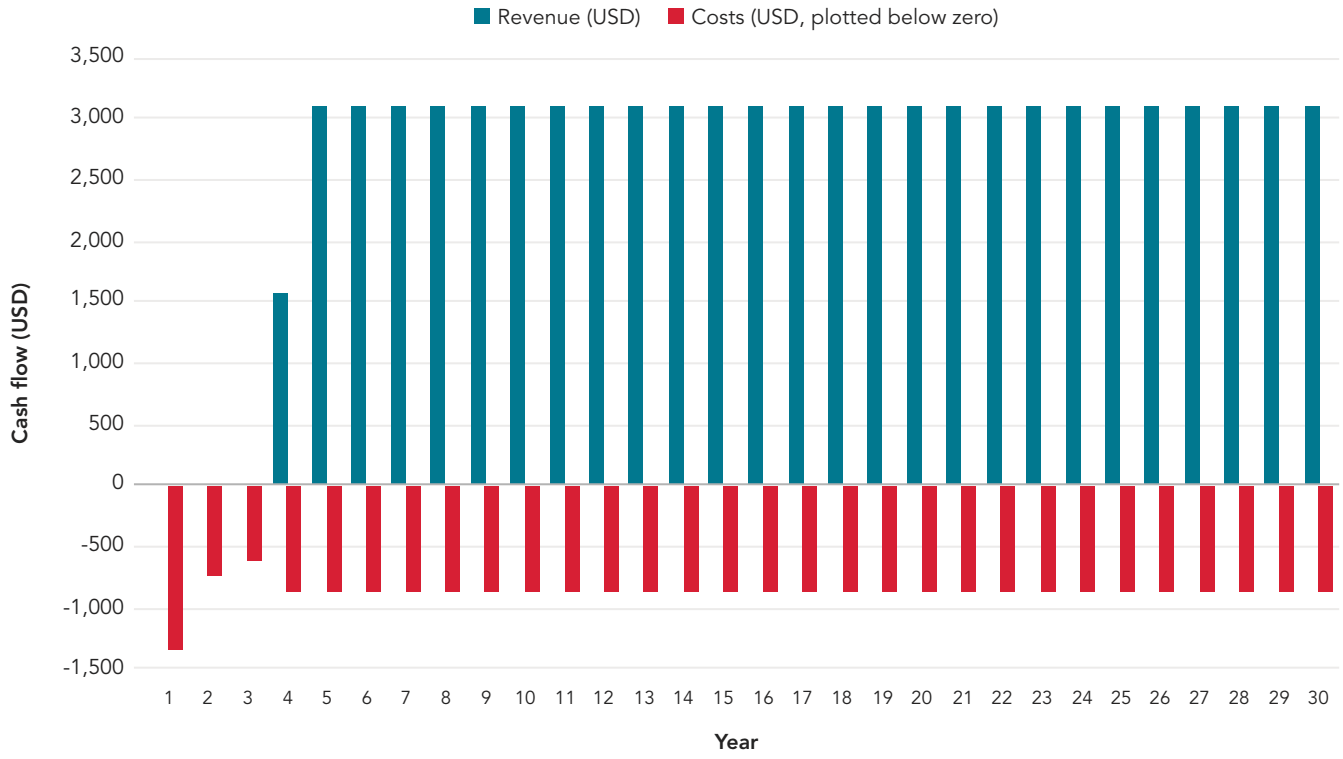


FIGURE B3. **Sensitivity of NPV with discount rate for ANR with enrichment of *Euterpe oleracea***

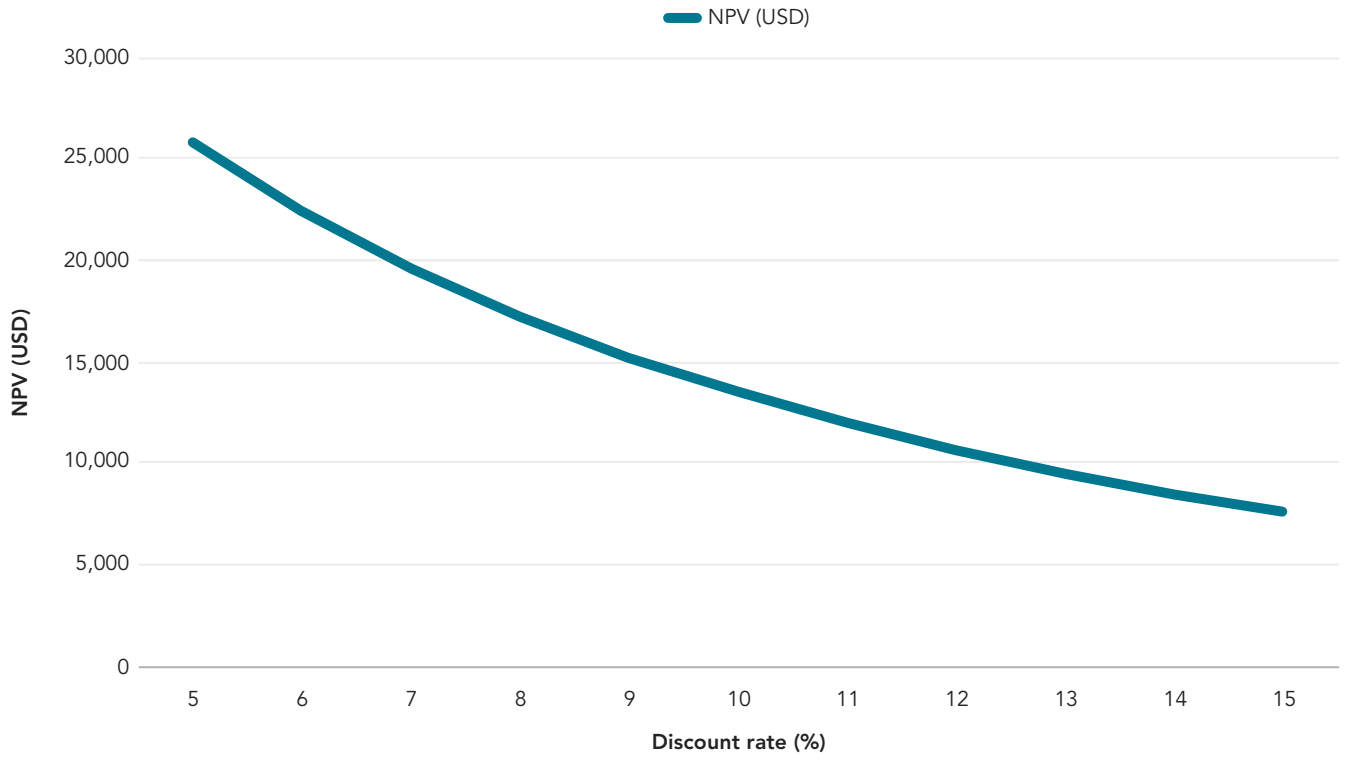
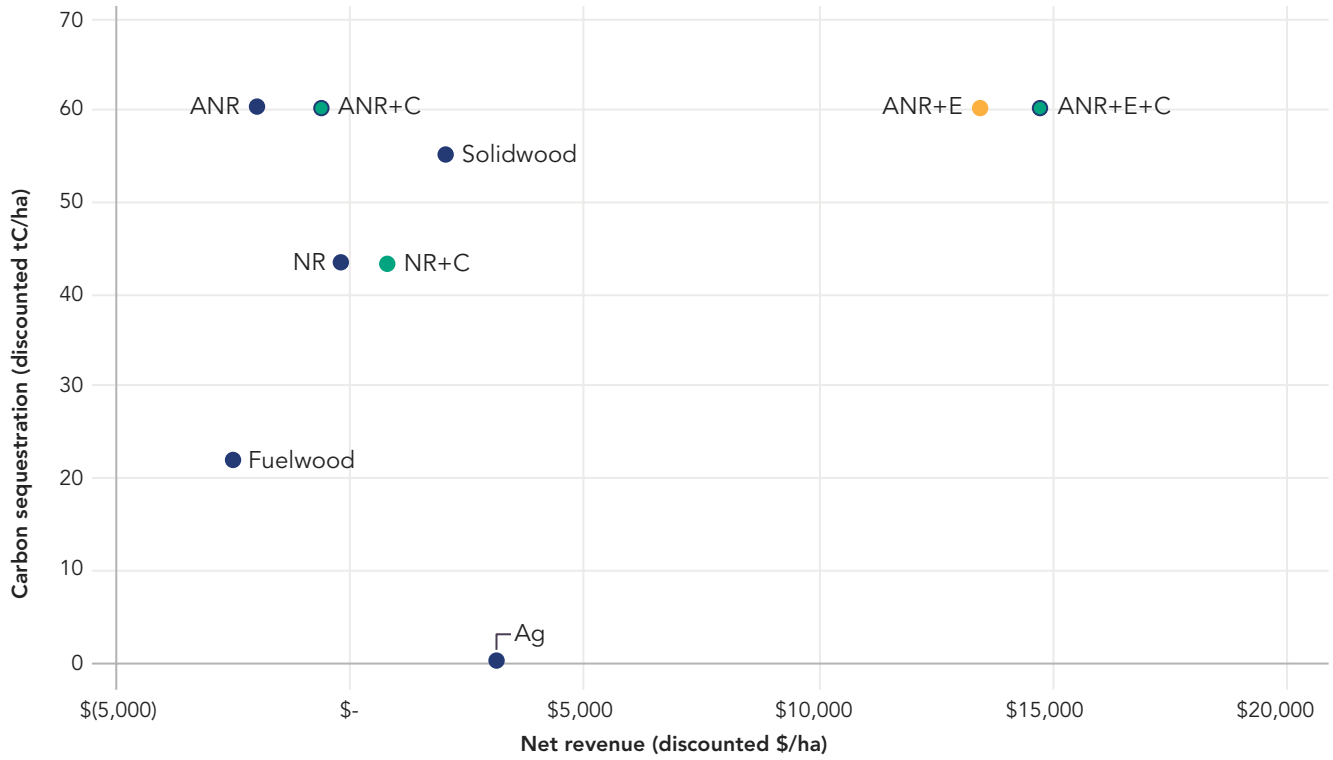



FIGURE B4. **Net discounted revenue and carbon storage for ANR with enrichment of *Euterpe oleracea* compared to alternative land uses**




*Ssee Chapter 2 for full description of land uses.*

## Species ecology and ethnobotanical information

*Euterpe oleracea* is a tall, slender canopy palm (Arecaceae family) native to eastern Amazonia, which mainly grows in seasonally flooded areas (*várzeas*) and forms dense natural stands in Amazonian floodplains. Trees can reach 15–25 m in height, with a crown of pinnate leaves up to 3 m long. The dark purple fruits, approximately 1–2 cm in diameter, have been used as a staple food since the 18th century (Figure B6). Outside of Brazil, *E. oleracea* is also found in neighboring forests of Venezuela, Colombia, Ecuador, Guyana, Suriname and French Guiana (Figure B5). Unlike other closely related palms, *E. oleracea* produces multiple stems (typically 4-9, but as many as 25) that grow from a single basal clump (Cymerys et al. 2012).

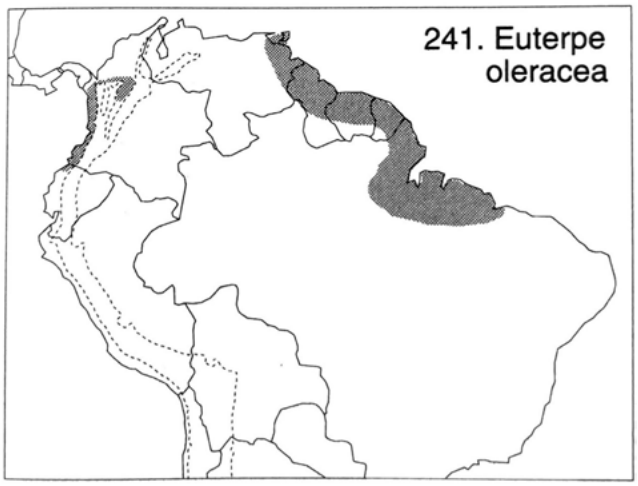
The most prominent use of *E. oleracea* in Brazil is the consumption of its fruit pulp, which is processed into a thick, purple beverage, known as "acai wine" (Da Silveira et al. 2023). The traditional preparation involves soaking and macerating the fruits to separate the pulp from the seeds, resulting in a viscous, nutrient-dense juice that is consumed fresh or frozen (Da Silveira et al. 2023).

*Euterpe oleracea* pulp has an exceptional nutritional profile with high lipid content (30–40% of dry weight), vitamins and minerals. Fruits have a low sugar content compared to other tropical fruits. After removal of pulp, seeds are used for animal feed, organic fertilizer, crafts and jewelry, and as a potential source of bioactive compounds for pharmaceuticals (Pessoa and Teixeira 2012). Processing fruit pulp into freeze-dried açaí (powder) drastically reduces weight and volume for transport, minimizes seasonal waste, and extends the product's shelf life, thereby opening new pathways for applications in foods, supplements, and the international market.

The apical meristem of *E. oleracea* palms is also harvested as palm heart (palmito), a delicacy in Brazilian cuisine (Weinstein and Moegenburg 2004). Harvesting palm heart requires cutting and killing the entire stem, with important implications for sustainable management. The multiple-stemmed habit facilitates sustainable harvesting of both palm heart and fruits from a single clump.

Aside from its dietary importance, *E. oleracea* has diverse medicinal uses, including treatment of fever and inflammatory conditions, relief of gastrointestinal complaints and diarrhea, treatment of skin infections and wounds, traditional remedy for intestinal parasites and as a general tonic to increase energy and improve overall health. These uses are based on the diverse bioactive compounds present such as anthocyanins, polyphenols/antioxidants, fatty acids and sterols (Da Silveira et al. 2023). The use of açaí oil and extract (rich in fatty acids, sterols, and antioxidants) as high-value raw material for cosmetic products (such as moisturizers and anti-aging compounds) and pharmaceuticals expands the value of the fruit's lipid fractions beyond nutrition.

FIGURE B5. **Geographic distribution of *Euterpe oleracea* (shaded areas)**




*Source:* Henderson (1995).

FIGURE B6. **Ripe fruit clusters of *Euterpe oleracea***



*Photo credit:* Dick Culbert (Wikipedia CC).

FIGURE B7. **Harvested fruit of E. oleracea ready for processing**



*Photo credit:* Guapi-Tecnologies (CC).

*Euterpe oleracea* also provides important construction materials for house posts and beams, flooring, walkways and bridges and fencing (Anderson 1988). Leaves are used for roofing thatch, baskets and mats, and stems are carved into utensils, tools, and decorative items. Seeds are used in jewelry and crafts, whereas fibers are extracted for cordage and textile applications (Bovi and Castro 1993).

*Euterpe oleracea* plays important ecological functions in Amazonian floodplain ecosystems. Dense groves provide habitat for numerous bird, mammal, and insect species. Fruits are consumed by birds, fish, and mammals that widely disperse seeds. Leaf litter and fruit residues contribute to nutrient dynamics in floodplain forests and root systems help stabilize riverbanks and prevent erosion (Goulding and Smith 2007). Several landraces have been described for *E. oleracea* that exhibit differences in ripe fruit color, inflorescence morphology, fruit size, and pulp texture (Teixeira et al. 2025).

## Cultural and livelihood importance

*Euterpe oleracea* plays a crucial role in Brazilian culture, economy, and traditional practices. E. oleracea has been an integral part of Amazonian indigenous and traditional communities for centuries, serving as a dietary staple and multipurpose resource.

In municipalities such as Igarapé-Miri (Pará), açaí is deeply embedded in local cultural identity (Santos et al. 2024). The harvesting, processing, and consumption of *E. oleracea* reinforce community cohesion and cultural continuity. Traditional knowledge informs many aspects of utilization and management including identification of productive trees, schedules and techniques for optimal harvesting, methods and equipment for processing fruit pulp, culinary preparations and consumption rituals. This knowledge is transmitted orally and through practice, forming an important component of Amazonian cultural heritage (Teixeira et al. 2025; Brondizio and Siqueira 1997).

In the Amazon region, *E. oleracea* juice is consumed daily as a staple beverage, often accompanying meals with fish, manioc flour (farinha), or tapioca and is prepared in various commercial forms including smoothie bowls, ice cream, and energy drinks (Brondizio 2008). Per capita consumption in urban centers, such as Belém, can exceed 200 liters per year (Rogez, Aguiar, and Nascimento 2004).

Currently, *Euterpe oleracea* has a high economic impact in Amazonia as a source of direct employment (harvesting, processing, transport) and indirect employment in related services, as a source of income and livelihoods for extractive families and smallholders, as a major economic driver in Brazilian states of Pará and Amapá, and as export revenue (IBGE 2021). Pará state is the world's leading producer of *E. oleracea*, responsible for over 90% of Brazil's production (https://www.sambazon.com/blogs/lifestyle/where-does-acai-come-from).

## Conservation status

Recent commercialization and rise of international marketing of *E. oleracea* have led to overharvesting of natural groves for palm heart and fruit, which deplete natural populations and reduce genetic diversity (Weinstein and Moegenburg 2004). The commercial selection for high-production traits may also reduce the genetic

diversity of cultivated populations (Teixeira et al. 2025). A further threat is conversion of diverse floodplain forests to intensified monocultures, which reduces biodiversity and ecosystem services (Freitas et al. 2021). Increments in *E. oleracea* density through management directly reduce the taxonomic, phylogenetic and functional beta diversity of assemblages in the Amazonian Estuary region of Belem in Pará State, Brazil (Freitas et al. 2025).

Although the conservation status of *E. oleracea* has not been formally assessed, measures are being taken to conserve natural populations in protected areas and to develop germplasm collections. Other important conservation measures include on-farm conservation through maintenance of diverse traditional varieties and breeding programs that maintain genetic diversity while improving productivity (de Farias Neto et al. 2003).

Various approaches are being implemented to promote sustainable production of *E. oleracea*, such as following guidelines for sustainable palm heart extraction, organic and fair-trade certification to promote sustainable practices and provide market incentives (Shanley and Medina 2005), integration of *E. oleracea* in agroforestry systems with other species to maintain biodiversity and diverse ecosystem functions (Smith et al. 1995) and strengthening of traditional community-based management systems and local governance of *E. oleracea* resources (Anderson 1992).

## Production and harvesting

Several production systems are being used for *Euterpe oleracea*: 1) traditional extractive harvesting from natural groves in floodplain forests; 2) selective management (including enrichment planting) of natural stands to enhance productivity and increase density; 3) cultivation in monocultures in upland (terra firme) areas; and 4) agroforestry systems with *E. oleracea* planted together with other crops such as cacao, banana, and timber species (Rodrigues et al. 2024). Currently, 87.3% of national production is commercially produced compared to 12.7% that is based on extractive systems (Rocha et al. 2025; (IBGE 2024).

In the floodplains, fruits begin to ripen in July at the start of the dry season, and trees produce fruit through December. Commercial harvesting for domestic consumption and export occurs during this second half of the year (Schauss et al. 2006). Each adult stem produces 4–8 racimes of fruits, each raceme produces 4 kg of fruits. On average, riverine communities produce about 1,160 kg per ha per year to sell in markets in Belem (Almeida et al. 2021a; Cymerys et al. 2012).

When grown from seed, stems begin to produce fruits 3–4 years after planting. The species grows best in partial shade to full sun conditions. Healthy palms produce fruit for many decades. Unmanaged natural stands produce from 300–800 kg of fruit per hectare per year, whereas managed natural stands produce from 1,000–3,000 kg of fruit per hectare per year. Planted systems produce from 3,000–6,000 or more kg of fruit per hectare per year (Homma et al. 2006). Higher productivity in managed and planted systems comes with trade-offs including reduced biodiversity, altered ecosystem functions, and increased labor requirements (Weinstein and Moegenburg 2004).

In traditional riverine communities (ribeirinhos) throughout the Amazon, *E. oleracea* is produced primarily for household consumption with surplus sold in local markets. Seasonal income from sales supplements other extractive activities (Quaresma and da Cunha 2012; Almeida et al. 2021b).

## Trade and marketing

Processing and distribution of *E. oleracea* occurs at different scales, from small-scale, family-run operations that process fruit for local markets to medium-scale processing to supply regional urban markets and large-scale industrial processing for national and international distribution (Rogez 2000). Since the 1990s, market demand of *E. oleracea* has increased within and outside of Brazil. Since the 2000s, *E. oleracea* has gained global recognition as a "superfood," leading to dramatic international market expansion and transformation of traditional production systems (Bussmann and Zambrana 2012). Widespread commercialization created new economic opportunities, but raises concerns about sustainability and the preservation of traditional knowledge (Arantes, do Nascimento, and de Carvalho 2021).

The açaí market experienced exponential growth since the early 2000s. Exports have grown from negligible amounts in the 1990s to tens of thousands of tons of pulp. The United States is the largest importer, followed by Japan and European countries. Domestic Brazilian consumption has also increased significantly (IBGE 2021). The state of Pará accounts for 90% of Brazil's total *E. oleracea* economy. In 2022, Pará state produced 8,158 tonnes (17,985,000 lb) of açaí berries, generating US$26 million in revenue (Jones and Duwe 2024). Among non-timber forest products from extractivism in the Brazilian Amazon, *E. oleracea* has the highest production value, exceeding USD 160.85 million in 2022 (Rocha et al. 2025).

Market integration has influenced traditional use patterns and knowledge transmission in several ways. Younger community members increasingly focus on commercial aspects rather than diverse traditional uses. Traditionally, men harvest fruit while women often manage processing and sales. Commercial preferences for high-yielding, easily processed varieties may reduce genetic diversity of the species. Finally, some traditional uses and management practices are declining as commercial production intensifies (Laval 2012).

The global market value of products derived from *E. oleracea* is substantial, with the overall market US$1.91 billion in 2024. The market is expected to grow, driven by increasing international demand for healthy, natural products (The Business Research Company 2025).

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# C. *Ilex paraguariensis (yerba mate, erva mate, ka'a)*

## Locations for economic models; local land-use and land tenure context

We located our *I. paraguariensis* model in southern Brazil in the Araucaria Forest region of Santa Catarina State. Here, *I. paraguariensis* is being grown in traditional agroforestry systems that have been developed for generations in Indigenous and traditional communities and on small-scale family farms (Nimmo et al. 2018; Lacerda 2023). This region had only 28% tree cover in 2020 (Global Forest Watch, 2025). Several restoration projects have been initiated in the region, such as the seedling planting with the Araucaria Conservation Program and investigations of passive recovery of forest in exotic tree plantations (Bet Stedille et al. 2020). There are several approaches for traditional shade production of *Ilex paraguariensis*, involving thinning of fast-growing early successional vegetation, removing dense bamboo to create space in the understory, or creating gaps in the canopy to provide the ideal growth conditions (Lacerda 2022).

Land tenure in Santa Catarina's Atlantic Forest includes a variety of arrangements, ranging from formal private and public properties to the land rights of Indigenous communities, which can be a source of conflict and are subject to different regulations and policies according to the Native Vegetation Protection Law. Many properties are still under a process of regularization or have unclear boundaries, complicating land use governance and environmental enforcement. State and federal governments, in collaboration with private organizations, are working to formalize tenure, implement conservation measures, and restore degraded areas to address these challenges (Benzeev et al. 2023).

## ANR cost-benefit models, scenarios and assumptions

The cash-flow analysis of ANR with enrichment of *Ilex paraguariensis* shows positive economic indicators with a net present value over 30 years of USD 1,575 and a 132.7% internal rate of return (Figure C1). The benefit-cost ratio is 9.81. Payback time is 3 years, whereas net revenue from *I. paraguariensis* production peaks in year 8. Total costs of ANR with enrichment of *I. paraguariensis* are USD 30,572, with 89% allocated to management activities. This baseline cost-benefit model for *I. paraguariensis* is based on a density of 400 trees/ha and a 10% discount rate. NPV is very sensitive to discount rate but remains positive at 15% (Figure C2).

FIGURE C1. **30-yr cash flow model for ANR with enrichment of *Ilex paraguariensis***

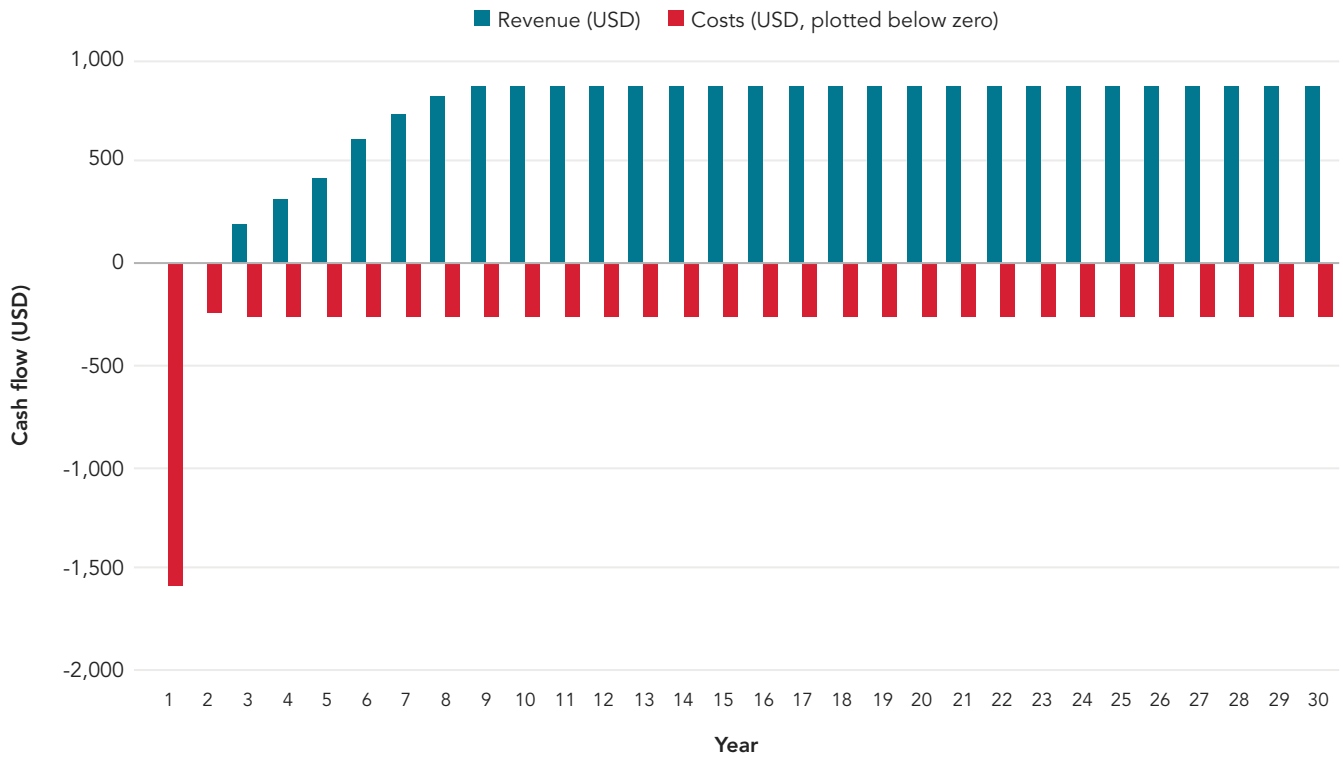
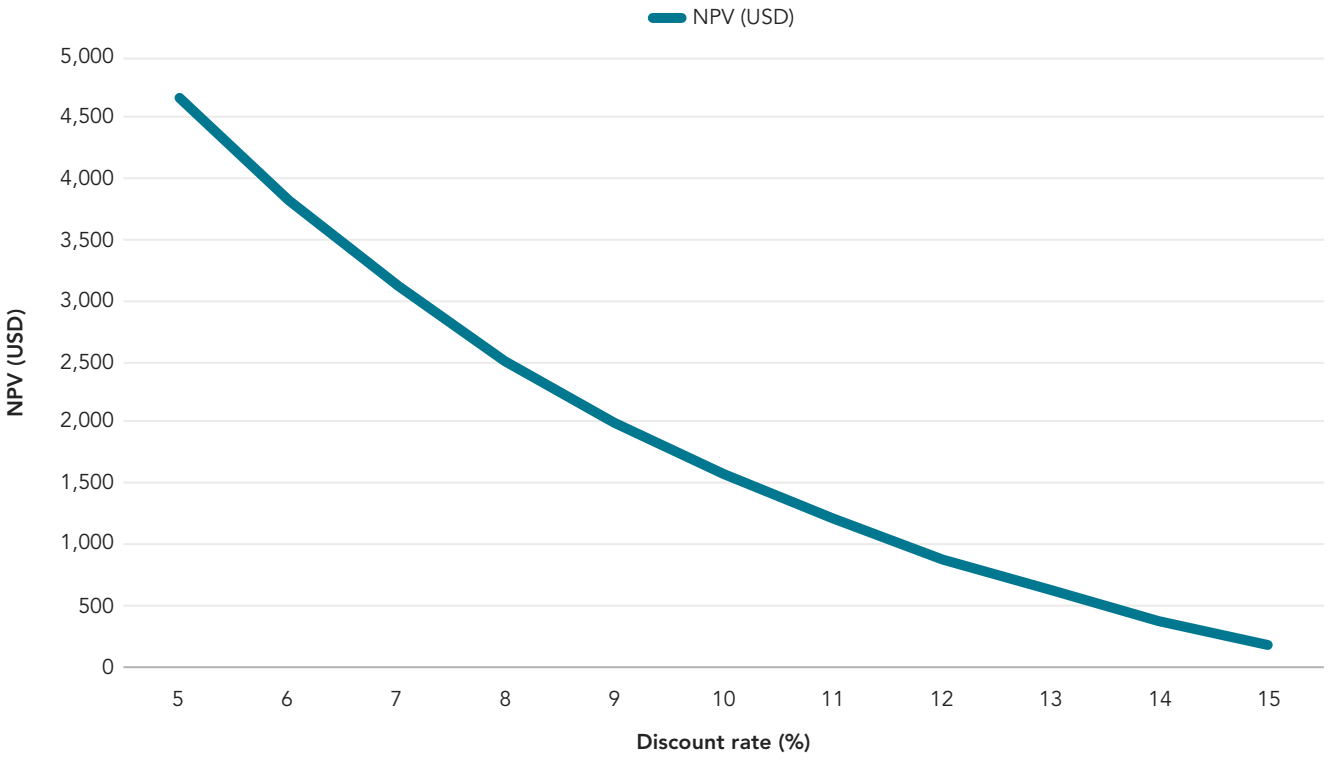


FIGURE C2. **Sensitivity of NPV to discount rate for ANR with enrichment of *Ilex paraguariensis***




## Carbon storage models

Estimated total carbon sequestration in aboveground biomass from ANR with enrichment of *Ilex paraguariensis*, 95.14 MgC/ha, is comparable to that of ANR and is 14% higher than for minimally assisted natural regeneration 83.22 MgC/ha. Furthermore, ANR with and without enrichment store considerably more carbon than timber plantations for solid wood production at the same site.

## Alternative production models

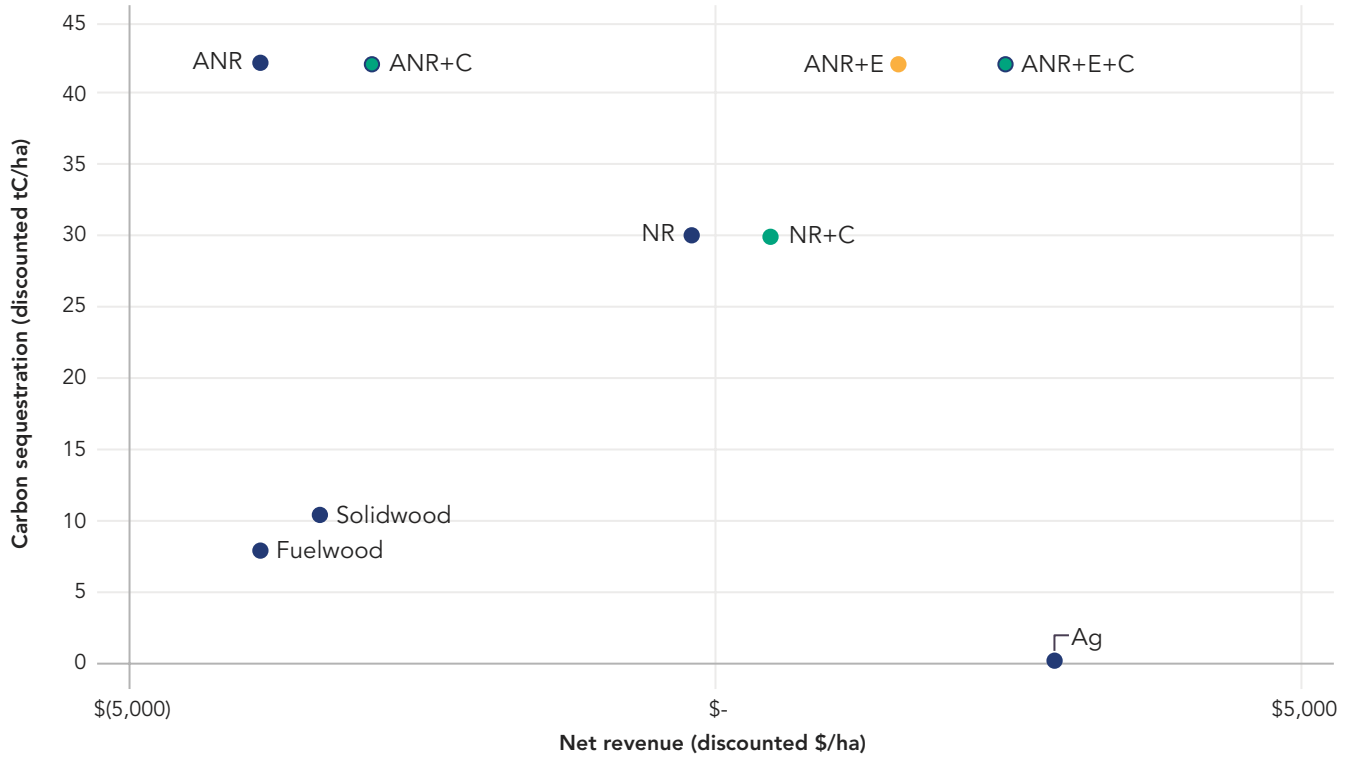
For *I. paraguariensis*, net revenue from ANR with enrichment is estimated to be less profitable (0.54x) than that of the most profitable alternative land use, agriculture, at the same site, but is more profitable than forestry plantations (Figure C3). Including net discounted revenue from carbon adds USD 924.59 over 30 years, making ANR with enrichment nearly comparable to agricultural land use. These results confirm that cultivating *I. paraguariensis* in naturally regenerating forests, even at low densities, is an economically viable land use that is compatible with forest restoration, traditional culture and livelihoods, and is a profitable climate mitigation solution in Santa Catarina State, Brazil.

## Species ecology and ethnobotanical information

*Ilex paraguariensis* is a medium-sized evergreen tree species in the Aquifoliaceae family native to subtropical Atlantic Forest regions of Eastern Paraguay, Northeastern Argentina, and Southern Brazil (Figure C4). It is shade tolerant and prefers cool, humid sites. Trees can reach up to 15 m tall. Flowering naturally occurs between the months of October and December (Alves and Scheer 2024).

In Brazil, *I. paraguariensis* occurs across a broad elevational range, from 160 m in Paraná to 1,800 m in the state of São Paulo and in regions with average annual rainfall from 1,200 to 3,000 mm. Average annual temperatures range from 13.2°C to 21.9°C, with the most common range being from 15°C to 18°C. *Ilex paraguariensis* occurs naturally in soils of low fertility, which typically have low levels of exchangeable cations, high levels of aluminum, and a low pH (Carvalho 2008). The distribution of *I. paraguariensis* closely matches locations of subtropical *Araucaria angustifolia* forest, which cover about 450,000 km$^2$ (Parron et al. 2024).

FIGURE C3. **Net discounted revenue and carbon storage for ANR with enrichment of *Ilex paraguariensis* compared to alternative land uses**




*See Chapter 2 for full description of land uses.*

FIGURE C4. **Trees of *Ilex paraguariensis* in Rio Grande do Sul State in Brazil**



*Photo credit:* Seeds of Change Project (CC license).

FIGURE C5. **Natural growth areas of *Ilex paraguariensis*, highlighting regions with optimal conditions for cultivation in subtropical South America**




*Source:* Souza et al. (2024).

Three types of beverages are prepared from infusions of *I. paraguariensis* leaves: *chimarrão* (green dried leaves infused in hot water), *tererê* (green dried leaves infused in cold water) and *mate* (toasted dried leaves infused in hot water) (Alves and Scheer 2024). These beverages contain caffeine and antioxidants. Leaves of *I. paraguariensis* are often mixed with other medicinal plants to enhance health benefits, addressing conditions like digestive issues, diabetes, and hypertension (Irala et al. 2022; Kujawska 2018).

Dried leaves of *I. paraguariensis* contain about 200 chemical substances, including: minerals, xanthines, flavonoids, anthocyanins and procyanidins, phenolic acids, rutins and saponins. Mate tea is used medicinally to treat fatigue and anxiety, support metabolism and stimulate the nervous system (Lutomski et al. 2020). Beyond beverages, yerba mate is incorporated into various food products, such as ice creams and pastries, and is used in the cosmetic and nutraceutical industries due to its antioxidant and anti-inflammatory properties (Irala et al. 2022; Cândido and Rocha 2025).

The indigenous Guarani and some Tupi communities—whose territory covered present-day Paraguay—first cultivated and consumed yerba mate prior to European colonization of the Americas. After discovery of its commercialization potential by Jesuit missionaries during the 18th century, *I. paraguariensis* became widespread throughout the province and across many Spanish colonial regions. *I. paraguariensis* is widely grown and processed in its native regions of South America, specifically in Paraguay, some parts of northern Argentina (Misiones), Uruguay, and southern Brazil (Rio Grande do Sul, Santa Catarina, Paraná, and Mato Grosso do Sul).

FIGURE C6. **Leaves of *Ilex paraguariensis***



*Photo credit:* H. Zell (Wikipedia).

## Cultural and livelihood importance

*Ilex paraguariensis* is a culturally significant plant in South America, particularly in countries like Paraguay, Brazil, and Argentina. It is traditionally used to prepare stimulating beverages, which are integral to social interactions in these regions. Drinking mate is a common social practice in Paraguay, Uruguay, Argentina, Southern Brazil, and Southern Chile among people of all ages, and is often a communal ritual following customary rules (Wikipedia). Traditionally, the tea is prepared in a hollow gourd and drunk through a wood or metal straw (Figure C7). The plant is also used in folk medicine. It serves as a medium for the intake of other medicinal plants, with 97 species documented in its mixtures, highlighting its role in traditional health practices (Kujawska 2018).

## Conservation status

The conservation status of *I. paraguariensis* is Near Threatened according to the IUCN Red List 3.1. While the species is not currently listed as endangered, ongoing threats of habitat loss and genetic erosion pose significant challenges to its long-term conservation. The socio-economic and cultural importance of *I. paraguariensis* provides a strong incentive for conservation efforts, which must address both ecological and genetic factors to ensure the species' sustainability. In Santa Catarina State, *I. paraguariensis* is included in the list of rare or endangered species (Carvalho 2008). The species is a strong candidate for *in situ* conservation in the Caçador Genetic Reserve in Santa Catarina, as all size classes are represented in this area.

## Production and harvesting

More than 90% of the global production of *I. paraguariensis* occurs in Brazil and Argentina and involves three main types of production systems: (1) monoculture (full sun) plantations; (2) traditional agroforestry (Eibl et al. 2017) and silvopastoral systems (Hanisch et al. 2022); (3) or sustainable harvest from native *Araucaria* forest (Flach 2019; Parron et al. 2024). Currently, Argentina leads the way in terms of area under cultivation for yerba mate, with over 230,000 ha, followed by Brazil, with at least 85,000 ha under cultivation (excluding harvesting from native forests), while Paraguay has about 40,000 (Barreiro 2025).

FIGURE C7. **A selection of gourds used for drinking *I. paraguariensis* tea in Buenos Aires, Argentina**



*Photo credit:* Marshallhenrie (Wikipedia; CC).

In Brazil, around 30 percent of the mate is harvested in native forest areas. Production of *I. paraguariensis* in *Araucaria* forests is a traditional agroforestry system in Southern Brazil with roots in Guarani Indigenous culture (Lacerda 2023). These practices serve to protect forests by creating a multi-use landscape where forest fragments help to maintain ecosystem services and biodiversity corridors, while ensuring the maintenance of cultural and traditional agroecological practices (Reis et al. 2018; Lacerda, Hanisch, and Nimmo 2020).

In Misiones Province of Argentina, *I. paraguariensis* is traditionally grown in monocultures known as *yerbales*, where leaves are harvested multiple times a year. A tree requires around five years to bear harvest, with the maximum production phase requiring seven or eight years. Much of the harvest is done by hand, using small scissors to cut the leaves and twigs one-by-one. This seasonal manual labor is the greatest employer in the mate industry, representing 66% of employees. Regular pruning is required to manage the plants, encourage new growth, and maintain health, especially for controlling the size and shape of the bushes.

Production in monocultures, however, can lead to decreased productivity and soil erosion over time (Eibl et al. 2015). Mate leaves harvested from the shade of native forests are more genetically diverse and more protected from pests. Furthermore, the mate grown in native forests has higher concentrations of caffeine and theobromine (a substance that occurs in chocolate), as well as a softer taste. For these reasons, shaded leaves from native *Araucaria* forests have a higher commercial value.

*Ilex paraguariensis* is naturally shade-tolerant and thrives in subtropical forests, making it suitable for agroforestry systems as well as for enrichment planting in naturally regenerating Araucaria forests. Integrating *I. paraguariensis* with native tree species in agroforestry systems has shown environmental and economic benefits, such as improved soil health and biodiversity. The decrease in total harvest in agroforestry systems of *I. paraguariensis* leaves can be offset by a higher price for organic products, in addition to revenues from timber production and other environmental benefits provided (Eibl et al. 2017). Agroforestry systems can also boost the biodiversity conservation capabilities of forest fragments through increased connectivity (Montagnini, Eibl, and Barth 2011; Eibl et al. 2024).

*In vitro* propagation techniques are being explored to overcome challenges in yerba mate cultivation, such as contamination and oxidation during the initial establishment phase. These methods aim to enhance genetic diversity and improve plant uniformity (Ross, Arriaga, and Pechi 2017).

## Trade and marketing

According to aggregated data from the FAO, 1.7 million metric tons of *I. paraguariensis* were produced across the globe in 2022 with Argentina, Brazil and Paraguay leading the rankings (930, 619 and 105 thousand metric tons respectively) (Alves and Scheer 2024). The global yerba mate market size was valued at US$2.05 billion in 2024 and is anticipated to grow from US$ 2.17 billion in 2025 to US$3.38 billion by 2033 (Bothare 2025).

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# D. *Paullinia cupana (guaraná, guarana)*

## Location for economic models

The economic cost-benefit models for *Paullinia cupana* were based in Apuí, Amazonas State. In 2020, 94% of land cover in Apuí was natural tropical moist forest and 99% was tree cover with over 30% canopy density (Global Forest Watch, 2025). These conditions favor natural regeneration and development of assisted natural regeneration systems. Although there is some production of *P. cupana* in the region, the municipality of Apuí is best known for producing the Amazon's first agroecological coffee since 2012 (Zanon 2021). These features make the Apuí region a good prospect for innovative assisted natural regeneration systems with enrichment of native non-timber species, such as *P. cupana* and *Euterpe oleracea*.

Land tenure arrangements in the municipality of Apuí, Amazonas include a complex mix of official land titles, unallocated public lands, protected areas, and Indigenous territories (Sparovek et al. 2019). Private landowners must comply with Brazil's Forest Code, which mandates the maintenance of 80% of native vegetation in the Amazon biome. The Apuí region includes various protected areas and Indigenous territories. These areas are intended for conservation and sustainable use by traditional communities and indigenous peoples, with specific legal protections, though they often face encroachment and conflict from outside interests (Moutinho and Azevedo-Ramos 2023).

## ANR cost-benefit model

The baseline 30-year economic model for *P. cupana*, shows high feasibility indicators, with the sixth-highest NPV among the 14 target species (Figure D1). The Net Present Value is USD 9,191 and the Internal Rate of Return is 31.3%. The payback time for net revenue is 5 yr and the benefit-cost ratio is 2.67. Total costs of ANR with enrichment *of P. cupana* are USD 28,635, of which 46.7% are associated with harvesting. This model assumes a 10% discount rate and a density of 150 plants/ha in assisted natural regeneration. This density is about a third of the density used in agroforestry plantations to ensure adequate conditions for natural regeneration of native vegetation. NPV is sensitive to increasing discount rate but remains positive at a discount rate of 15% (Figure D2).

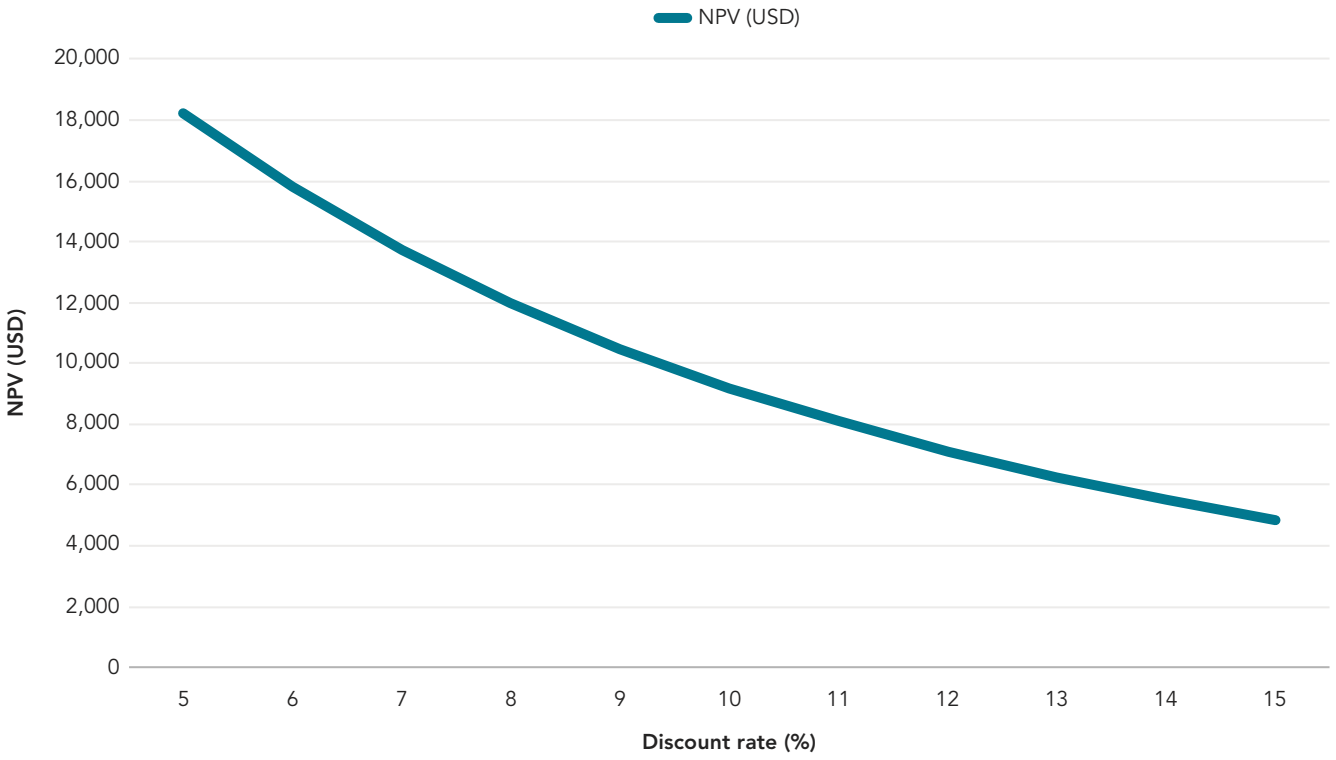
## Carbon storage models

Over 30 years, ANR with enrichment of *P. cupana* yielded a total carbon storage of 104.29 MgC/ha. Discounted revenue from carbon credits is USD 1,054/ha over 30 years. This is the third highest value of revenue generated from carbon storage among all the models. The climate conditions in Apuí, Amazonas support high rates of carbon storage during forest regeneration. Our model assumes that planted individuals offset any reduction in naturally regenerating trees by an equivalent amount of carbon

FIGURE D1. **30 yr cash flow model for ANR with enrichment of *Paullinia cupana***



FIGURE D2. **Sensitivity of NPV to discount rate for ANR with enrichment of *Paullinia cupana***




storage, so there is no enhancement of carbon storage as compared to ANR without enrichment. Carbon storage in ANR is enhanced by 12% over minimally assisted natural regeneration, which yields a total carbon storage of 93.01 MgC/ha.

## Alternative production models

Net revenue from *P. cupana* from ANR with enrichment is estimated to be 2.3x higher than that of the most profitable alternative land use, agriculture, at the same site in Brazil (Figure D3). Discounted revenue from carbon storage from ANR with enrichment is comparable to that of ANR without enrichment and is slightly lower than carbon revenue for solidwood timber plantations at the same site. ANR with enrichment of *P. cupana* is a highly favorable land use option for both net revenue and carbon storage in Amazonas State, Brazil and is estimated to substantially increase net revenues compared to minimally assisted and fully assisted natural regeneration without enrichment.

## Species ecology and ethnobotanical information

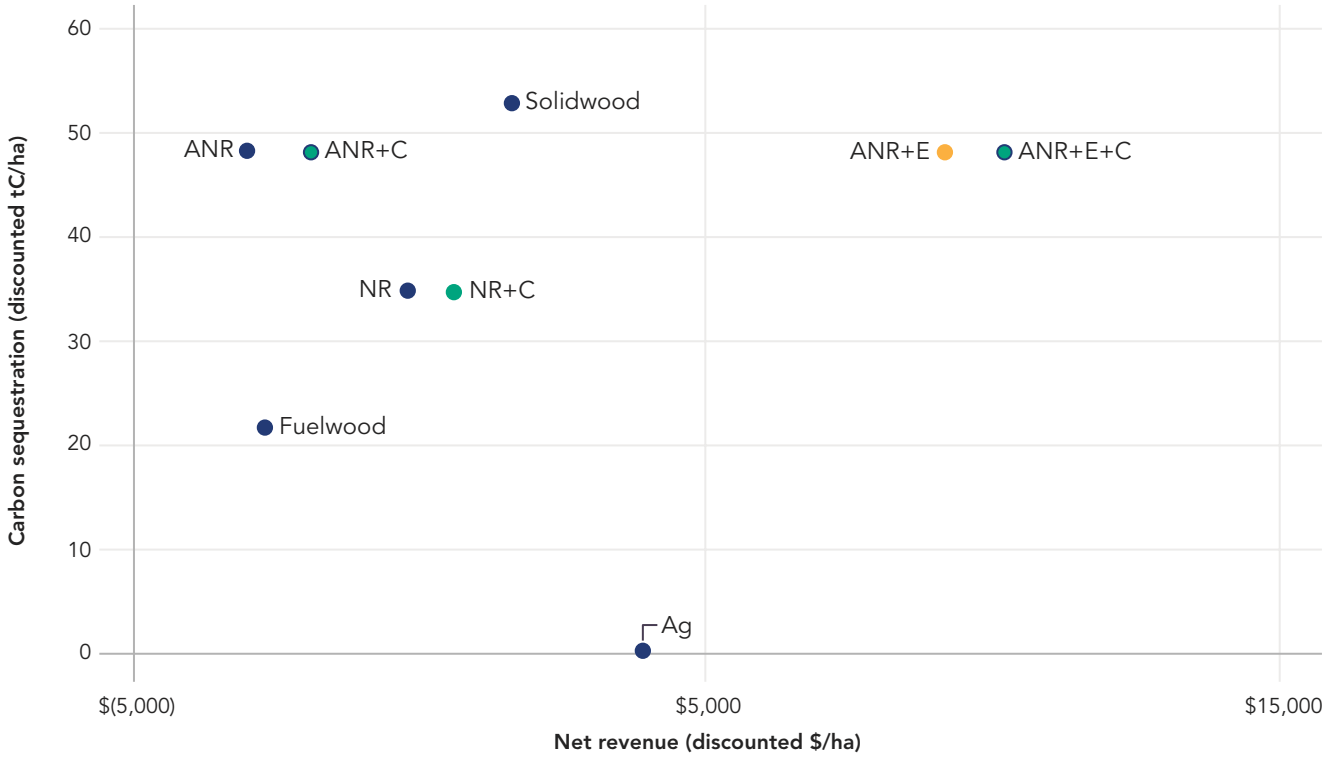
*Paullinia cupana* is an evergreen climbing shrub in the Sapindaceae family, native to the Amazon Basin. It is particularly common in Brazil, but also occurs naturally in Guyana, Venezuela, Ecuador, and Peru. It grows in tropical moist forests at elevations from 0 to 800 m a.s.l. and reaches a maximum height of 13 m. In cultivation, plants are pruned to shrubs about 2 m tall (Lim 2012). In its native range, annual mean temperature is 28–29°C, minimum temperature is above 12°C and mean annual precipitation is approximately 2,000 to 2,200 mm (Lim 2012).

Two subspecies have been described. *P. cupana* var. *cupana* is relatively common in the area between the south of the Atures and Maipures torrents of the Orinoco River and in the region of the upper Negro River and tributaries on the frontiers between Brazil, Colombia and Venezuela, whereas *P. cupana* var. *sorbilis* was likely domesticated in the southern strip of the Amazon River between the gorges of the Purús and Madeira Rivers in Brazil (Lim 2012).

Fruits of *P. cupana* are orange-red capsules that contain black seeds, partially covered by white arils and resembling a human eye (Figure D5). The species is known for stimulant and medicinal properties and has been used for centuries by indigenous communities of the Amazon (Schimpl et al. 2013). When dried or roasted, the seeds can be used to produce commercial products with high caffeine content (2.5 to 6% of dry weight); the caffeine content of guarana seeds is 2 to 5 times higher than that of Arabica coffee beans (Schimpl et al. 2013; Lim 2012).

Guaraná has long been used as a tonic and to treat various disorders (including digestive problems) and became a national soda in Brazil about a century ago (Lim 2012). It is also used as fish-poison and as a dye. Seeds also contain alkaloids, saponins, fats, proteins, oils and resins, which cause the stimulant properties of caffeine (guaranine) to be absorbed very slowly through the intestinal tract and prolongs the stimulant effect for six hours, twice as long as that of an average cup of tea or coffee (Henman 1982).

FIGURE D3. **Net discounted revenue and carbon storage for ANR with enrichment of *Paullinia cupana* compared to alternative land uses**




*See Chapter 2 for full description of land uses.*

FIGURE D4. ***Paullinia cupana* growing in cultivation in Alta Floresta, Brazil**



*Photo credit:* Robin L. Chazdon.

FIGURE D5. **Ripe fruits of *P. cupana* with exposed white aril and black seeds**



*The white aril attracts seed dispersing birds.*

*Photo credit:* Robin L. Chazdon.

Traditionally, the Guarani people shelled, washed and dried harvested *P. cupana* seeds and then pounded them into a fine powder. The powder is kneaded with water into a dough and then shaped into cylinders, which are roasted or smoked. This product is known as guaraná bread, which is grated into powder and combined with sugar and water to produce an invigorating drink (Henman 1982). In other contexts, harvested fruit bunches are fermented for ten days. They are then screened to remove stems and passed through rollers to break up the outer rind of the fruit and dried in the sun.

## Cultural and livelihood importance

Guaraná plays an important role in Tupi, Sateré-Maué and Guaraní cultures. The origin story of the Sateré-Maué tribe is linked to the domestication of *P. cupana*. According to this myth, the domestication of *P. cupana* originated with the killing of a beloved village child by a malevolent god who transformed into a snake and fatally bit the child. But in response, a benevolent god plucked the left eye from the child and planted it in the forest, producing the wild variety. Then, the god plucked the right eye from the child and planted it in the village, producing the domesticated variety (Marques et al. 2019; Garfield 2022).

Cultivation of *P. cupana* is a primary source of income for thousands of smallholder and family farmers in the Amazon basin, particularly around the town of Maués and the states of Amazonas and Bahia. These communities often use sustainable, traditional methods that ensure a high-quality product and help preserve the rainforest ecosystem. Organizations and initiatives, such as the Guaraná Alliance of Maués, aim to improve the quality of life for producers by promoting sustainable practices, securing fair trade, and developing community tourism, which further diversifies income streams for local communities (https://ppa.org.br/en/projeto/alianca-guarana-de-maues-agm/).

FIGURE D6. **Popular guarana soda made using *P. cupana* in Brazil**




*Photo credit:* Adrian Michael (CC).

## Conservation status

No formal assessment of the conservation status of *P. cupana* has been conducted. Aside from habitat loss for wild-grown individuals, the main conservation concern for *P. cupana* is the conservation of genetic resources. The Brazilian Agricultural Research Corporation (Embrapa) is responsible for the conservation of genetic resources of *Paullinia cupana* var. *sorbilis* (Mart.) Ducke in Brazil and has developed cultivars with productive potential and disease resistance. Embrapa recommends vegetative propagation by rooting cuttings to promote large-scale seedling production with short time intervals, which provides homogeneous crops in productivity and quality, precocity, and tolerance to phytopathogens (Nascimento et al. 2023).

## Production and harvesting

For small farmers in the Amazon basin, *P. cupana* is an ideal crop for supplementing incomes. It is a fast-growing perennial crop that can be interplanted with manioc and other subsistence crops, allowing the formation of orchards after manioc harvest (Henman 1982). In Amazonas state *P. cupana* is currently grown by both small and large producers, including large corporations with plantations from 80 to 500 ha. In contrast, around 1,600 family farmers in Maués (state of Amazonas) produce *P. cupana* on farms averaging 3 hectares, and are responsible for 35% of the planted area and 35% of the state's production. The typical *P. cupana* farmer in Amazonas is a landowner, with relatively easy access to agricultural credit for improved production planning and guaranteed minimum prices (Atroch et al. 2012).

Prior to the 1970's, *P. cupana* was produced on a commercial scale only in Maués municipality (Amazonas State). Since the 1980's the Brazilian government has encouraged the cultivation of *P. cupana* in the states of Bahia, Mato Grosso, Pará, Acre, and Rondônia. The most successful case of adaptation was in Bahia state that is currently the largest producer in Brazil and globally (Schimpl et al. 2013).

Almost all commercially grown *P. cupana* is produced in Brazil, with about 70% used by the Brazilian soft drink industry. There is a small export trade, mainly to Japan and the United States. The production is concentrated in the state of Amazonas but *P. cupana* is increasingly being grown in the states of Bahia and Rondônia because of increasing demand.

## Trade and marketing

Guaraná is marketed as sticks and soluble or insoluble powder in capsules and is used industrially to produce sweetened or carbonated soft drinks, syrups, energy drinks, herbal tea and other herbal products. In Brazil, sales of guarana beverages exceed those of cola drinks. In Peru, Guaraná is a Peruvian brand of soft drink containing *P. cupana* fruit (Lim 2012). In 2023, 4,300 tons of P. cupana were produced in Brazil with 60% of the production in Bahia state and 40% in Amazonas state. The global *P. cupana* market size was valued at USD 7.3 billion in 2023 (Research 2024). AMBEV, Brazil's largest beverage company, is a major buyer of *P. cupana* from the Maués region, with purchases of nearly USD 10 million per year (Green 2023).

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# E. *Ilex guayusa (Guayusa, waysa, waisi, wayus, wais)*

## Locations for economic models and ANR context

We selected community chakras in rural areas NW of Tena in Napo, Ecuador as our location for the economic cost-benefit model (Franco et al. 2018). The region had 68% of natural forest cover in 2020 (Global Forest Watch 2025). In the ANR scenario, the density of *I. guayusa* plants is 550 trees/ha, 30% of the planting density in most chakra agroforestry systems in the region (1,650–5,000 plants/ha) (Aguinda 2016; Krause and Ness 2017; Franco et al. 2018). Our model is based on organic production, using no chemical fertilizers or pesticides. In contrast to chakras, the only revenues from the modelled ANR system derive from harvest and local sale of *I. guayusa* leaves, as it is managed as a regenerating second-growth forest. *Ilex guayusa* is deeply embedded in indigenous Amazonian cultures, serving important ceremonial, social, and medicinal functions that must be respected and preserved during commercialization efforts. Enrichment planting of naturally regenerating forests with *I. guayusa* can be a beneficial approach for smallholders and Indigenous Communities who are interested in restoring forests while receiving some economic benefits through commercial production.

In Tena, Napo Province, indigenous communities primarily hold land under communal tenure, a system where land is owned collectively by community members. This arrangement is legally recognized and protected by the Ecuadorian Constitution, which designates communal lands as inalienable, indivisible, and indefeasible.

## ANR cost-benefit models, scenarios and assumptions

The baseline cost-benefit model for *I. guayusa* is based on a density of 550 trees/ha and a 10% discount rate (Figure E2). Total costs of ANR with enrichment are USD 5,404/ha, of which 77% are related to management. Fencing and fire protection are not needed in this region. The cash-flow analysis shows a net present value over 30 years of USD 6,265 and a 82.2% internal rate of return. The benefit-cost ratio is 4.30 and payback time is 4 years. NPV remains positive at a discount rate of 15% (Figure E3).

Data for cost and benefits of production of *I. guayusa* was provided by Asociación Kallari, an association of Kichwa farmers and artisans in Ecuador's Napo province that produces and sells organic agricultural products and crafts. The association commercializes products like cacao, chocolate, guayusa, and vanilla, with a focus on both local and international markets.

FIGURE E1. **Planting of *I. guayusa* in a former pasture**



*Source:* Aguinda (2016).

FIGURE E2. **30-yr cash flow model for ANR with enrichment of *Ilex guayusa***

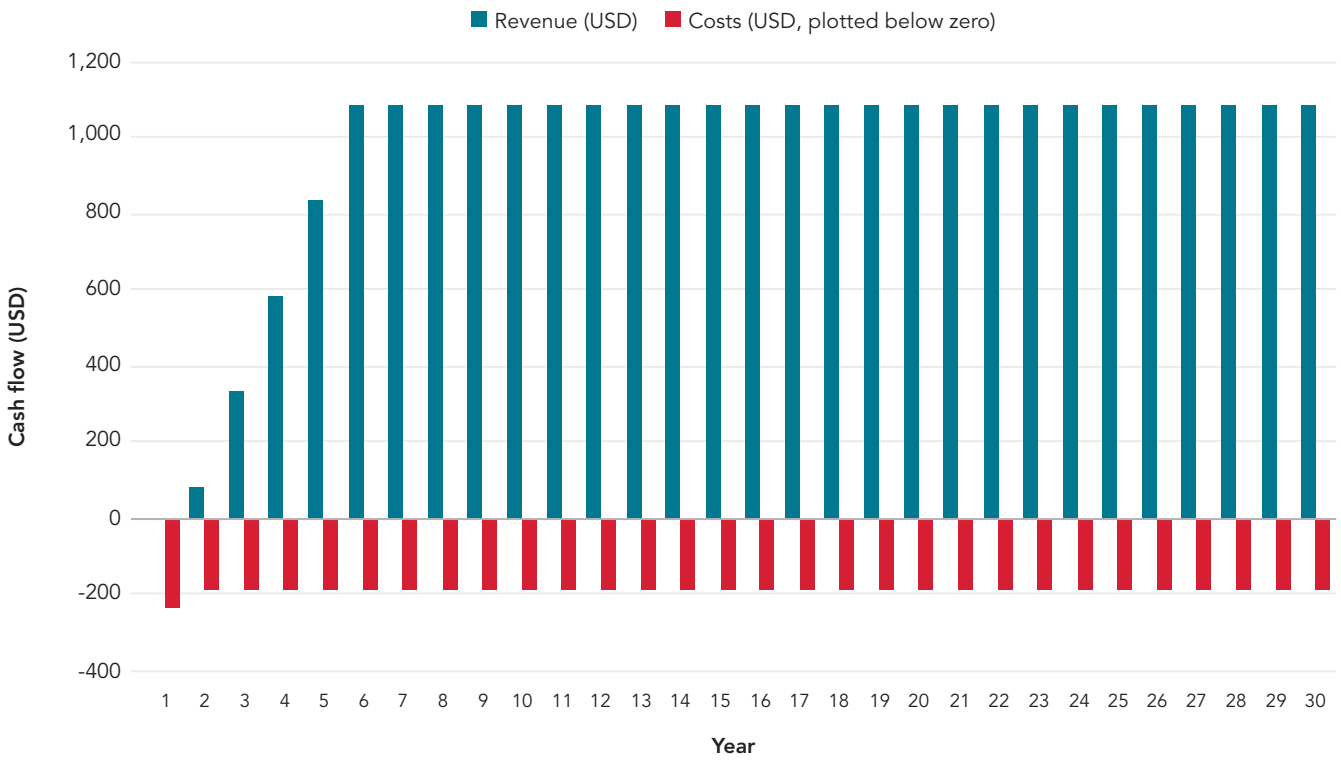
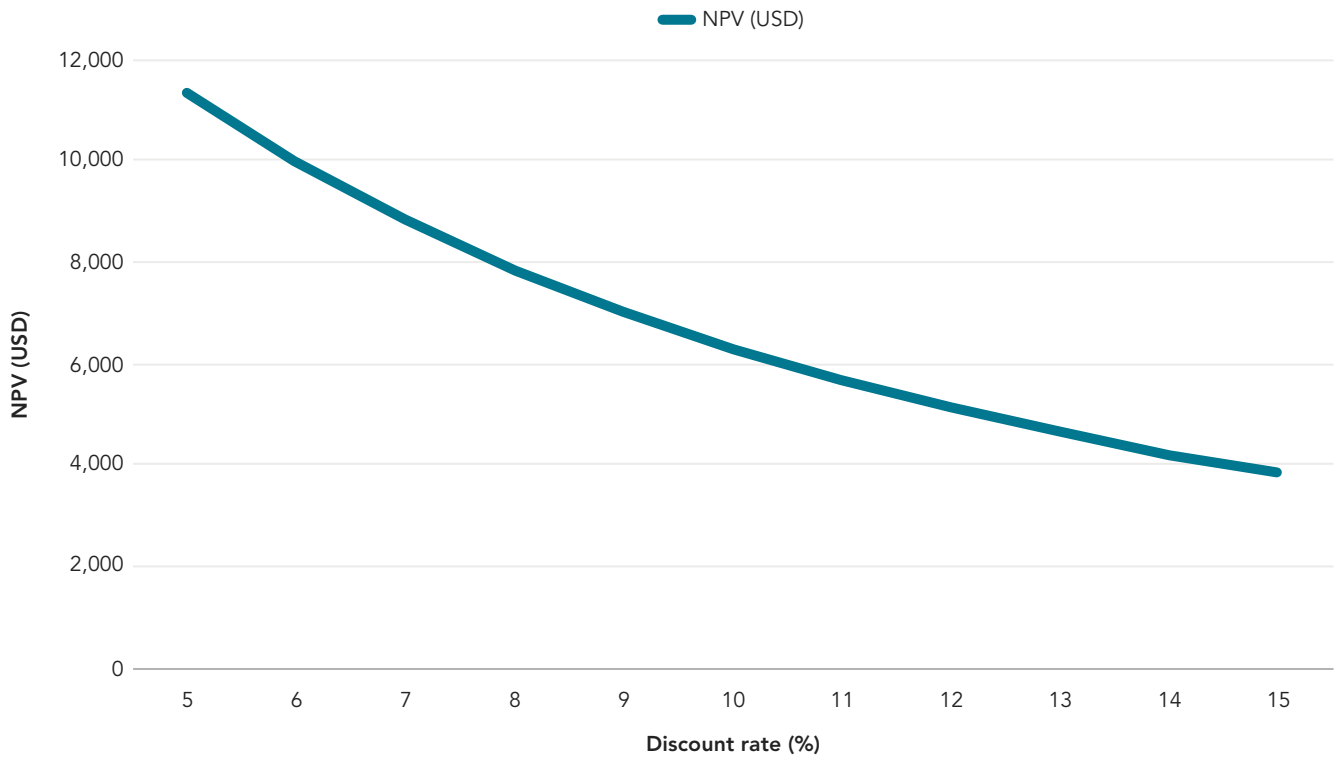



FIGURE E3. **Sensitivity of NPV with discount rate for ANR with enrichment of *Ilex guayusa***



## Alternative production models

Enrichment of ANR with *I. guayusa* is 2.2x as profitable as agricultural land uses (Figure E4). The additional net revenue from carbon credits, USD 597 further increases benefits of ANR+E. After agriculture, the next most profitable land use is minimally assisted natural regeneration with carbon credits. These results confirm that cultivation of *I. guayusa* in naturally regenerating forests, even at low densities, is an economically viable land use that is compatible with forest restoration and climate mitigation solutions in the Tena/Napo region of Ecuador.

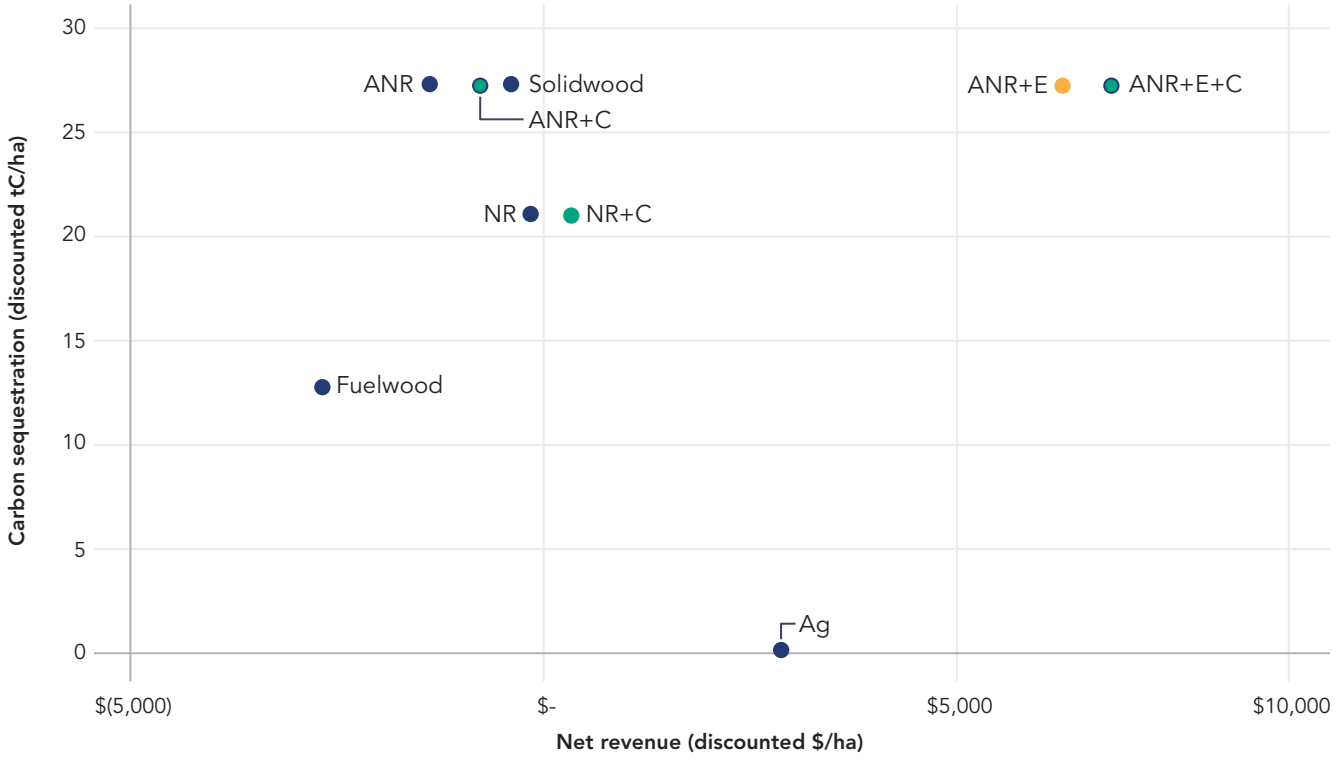
## Species ecology and ethnobotanical information

*Ilex guayusa* is an evergreen tree in the Aquifoliaceae family native to the upper Amazon basin of Colombia, Ecuador and Peru (Figure E5). The species grows in tropical rain forest areas across a broad elevational range, from 200 to 2,600 m. a.s.l. Unmanaged adults can reach 25 m in height, but typically reach an average of 10 m height in domesticated plantings. Trees are dioecious (separate male and female plants) and, despite production of seeds, are only known to reproduce asexually by cuttings extracted from the base of the plant (Dueñas et al. 2016). Trees are long-lived and can remain productive for over 100 years (Aguinda 2016). This species is closely related to *Ilex paraguariensis*, yerba mate, which occurs in Atlantic Forest regions of Argentina, Paraguay, and southern Brazil.

Based on archaeological and historical records, *I. guayusa* has been used and traded as a medicinal plant in the greater Andes-Amazon region since at least 500 C.E. The widest use involves preparing leaves to make an infusion for drinking. In the Ecuadorian Amazon region, *I. guayusa* is widely used in folk medicine, cultural and religious rituals, and in household and commercial beverages. Leaves contain caffeine, theobromine, phenolic compounds and flavonoids, which are antioxidants (Radice, Cossio, and Scalvenzi 2017). Traditional preparation involves harvesting mature leaves, which are then dried and brewed as an infusion. The brewing process varies among communities but typically involves steeping dried leaves in hot water for extended periods to extract the active compounds.

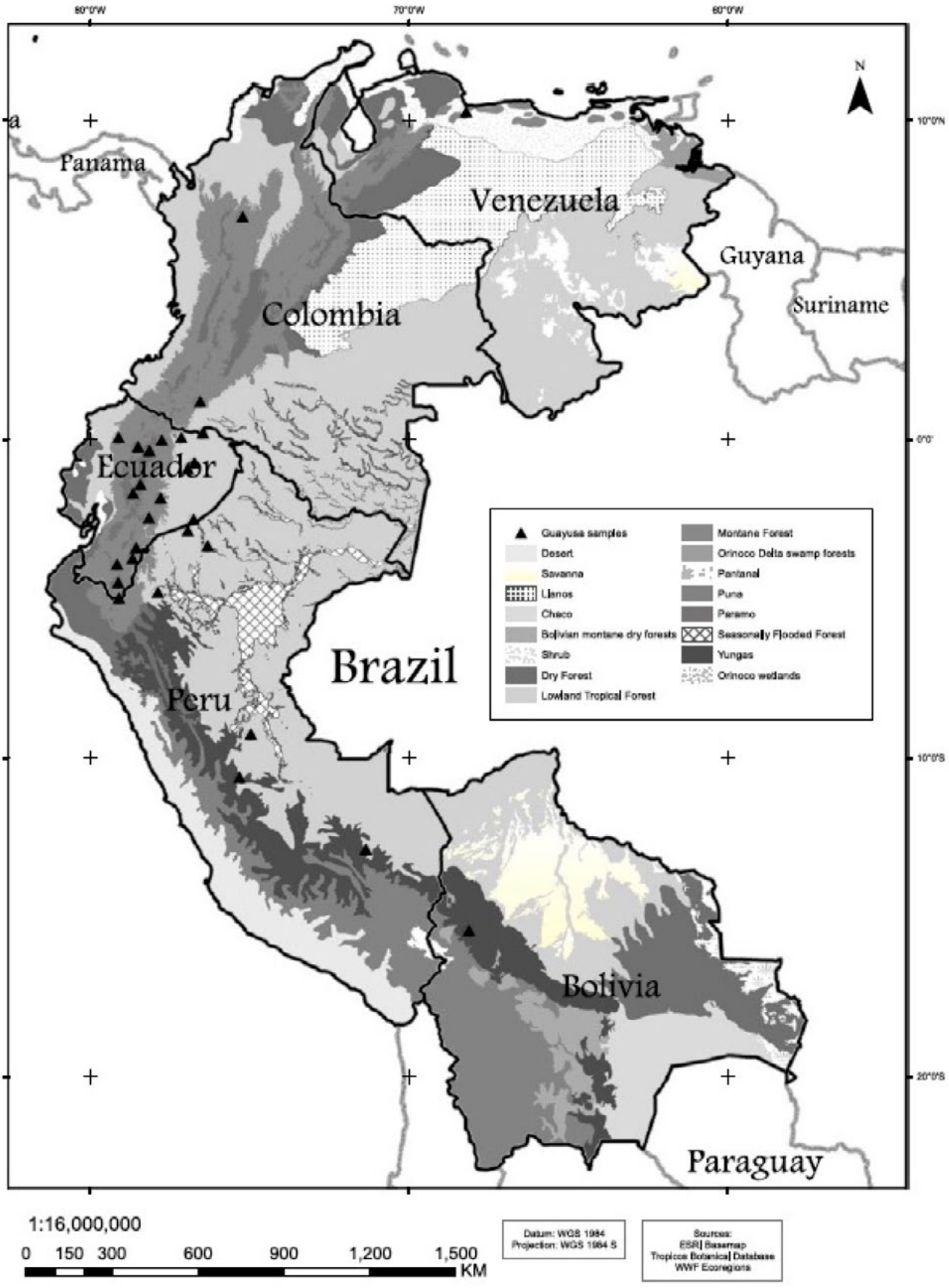
Across the upper Amazon, *I. guayusa* is used to treat diabetes, venereal diseases, improve digestion and appetite, strengthen the body, treat pain, increase fertility, and daily purging. Tea is used as a stimulant, stomach tonic, diuretic, flu remedy and to help people to dream. Some rituals involve use of *I. guayusa* together with ayahuasca (*Banisteriopsis caapi)* in a psychedelic brew.

FIGURE E4. **Net discounted revenue and carbon storage for ANR with enrichment of *Ilex guayusa* compared to alternative land uses**




*See Chapter 2 for full description of land uses.*

FIGURE E5. **Map of likely distribution of *Ilex guayusa***




*Source:* Dueñas et al. 2016.

FIGURE E6. **A cultivated tree of *Ilex guayusa***



*Photo credit:* Wikipedia; Creative Commons Attribution-Share Alike 3.0 Unported license.

FIGURE E7. **View of *Ilex guayusa* from above**



*Photo credit:* Anna Premo (Wikipedia).

## Cultural and livelihood importance

Local indigenous people in the upper Amazonian region have planted *I. guayusa* trees for subsistence consumption in their chakras (agroforestry gardens) for centuries (Krause and Ness 2017). Chakras are highly diverse, with often more than 50 species grown together, including medicinal plants, timber species, fruit trees and annual crops.

*Ilex guayusa* plays a central role in indigenous ceremonies and daily rituals. In the "cosmovisión" concept of the Amazonian ethnic groups, *I. guayusa* provides many benefits, from improving human health to cleansing the stomach daily as a ritual purification. Tea prepared from *I. guayusa* leaves has "magical" properties and is also given to hunting dogs to drink before a hunting expedition to improve their abilities and skills (Radice et al. 2017).

The plant is considered sacred among the Kichwa people of Amazonian Ecuador and is an integral component of their legends and myths. Kichwa communities drink *I. guayusa* tea in the early morning in community rituals to help avoid insect and snakebites and to improve hunting and fishing success. (Radice et al. 2017; Krause and Ness 2017). During these community rituals, some Kichwa adults weave fishing nets and traps and shoulder bags, play music, and tell stories. Communities brew the leaves for morning beverages consumed during pre-dawn gatherings, where community members share dreams, discuss daily activities, and maintain social bonds (Radice et al. 2017). These ceremonial uses are deeply embedded in indigenous cosmology and social organization.

*I. guayusa* has gained international attention in recent decades as a potential commercial crop and functional food ingredient, increasing scientific interest in its chemical composition, cultivation, and market potential. The transition from traditional household use to commercial production created new opportunities and challenges for indigenous communities, while raising important questions about cultural preservation, sustainable development, and benefit-sharing.

## Conservation status

Although *I. guayusa* is not a threatened species, research has revealed limited genetic diversity within cultivated populations, likely due to the predominance of vegetative propagation. This finding has important implications for disease resistance and pest management, adaptation to climate change, and long-term sustainability of production systems (Dueñas et al. 2016).

Strategies to ensure genetic diversity in cultivated populations include: maintenance of traditional cultivation systems, *in-situ* conservation of diverse populations, *ex-situ* conservation through germplasm banks, and community-based conservation programs (Dueñas et al. 2016; Carvalho et al. 2021). Several varieties of *I. guayusa* have been identified in the Ecuadorian Amazon region (Aguinda 2016).

## Production and harvesting

In Ecuador, *I. guayusa* is widely cultivated in home gardens and agroforestry plots, known as chakras from 150 to 1,500 m a.s.l. in areas with 2,000–4,000 mm of annual rainfall and mean temperatures from 20–26°C (Aguinda 2016). The preferred spacing is 4 m x 4 m (625 plants/ha), allowing other species to grow in the agroforestry system. Young plants are sensitive to direct sun and grow best under 50–70% shade. Once plants have reached approximately 2–3 years and about 1 m in height, they can tolerate more direct sun exposure, increasing growth rates and leaf yield (Krause and Ness 2017). Leaves can be harvested one year after planting at intervals of 2–3 months (Aguinda 2016). Regular pruning of trees is an important management practice to stimulate the production of basal shoots, reduce leaf damage from pests, and to increase the number of leaves on lateral branches (Aguinda 2016).

Commercial production of *I. guayusa* represents an additional commodity for farmers to hedge against market price fluctuations and can guarantee more steady incomes. Among Kichwa producers, 80% are women (Franco et al. 2018). Growing *I. guayusa* in diverse polycultures, such as chakras, provides more secure food and financial security and helps to conserve local biodiversity (Franco et al. 2018). Other species grown in chakras include cacao, coffee, native timber trees, medicinal plants, and fruit trees (Aguinda 2016, Franco et al. 2018).

Recent research has led to improved cultivation protocols for commercial production. Carvalho et al. (2021) developed tissue culture protocols enabling rapid multiplication of planting material, production of disease-free plants, maintenance of genetic uniformity and year-round propagation capability.

## Trade and marketing

Leaves of *I. guayusa* are traditionally marketed in packages tied with string in the form of a necklace, after drying at ambient temperatures (Noriega et al. 2025; Figure E8). The global market for *I. guayusa* has experienced significant growth in recent years, driven by increasing consumer interest in natural energy drinks and functional foods. The current commercial *I. guayusa* agroforestry system operates on a pre-determined price (currently US$0.35/kg), which is contractually set between growers and the company (Krause and Ness 2017).

Production of *I. guayusa* is economically profitable and exceeds the revenues of other traditional cultivated species (Aguinda 2016). One hectare of cultivation in an agroforestry system, for example, after 4–5 years of establishment can provide revenues between US$ 7,000–8,000 per year (Aguinda 2016).

Krause and Ness (2017) analyzed the *I. guayusa* value chain, identifying key stakeholders and opportunities for adding value. Most commercial production is USDA certified organic, requiring that producers adhere to a specific set of production standards. *Ilex guayusa* products are also certified by Fair Trade USA, which requires grower associations to be established in each community where social premiums are distributed back to the groups based on the quantity sold (Krause and Ness 2017). Principal importers of *I. guayusa* are USA, Canada, and Europe (Aguinda 2016).

In 2024, the *I. guayusa* market was valued at USD 9.63 million, with projections to reach USD 12.05 million by 2029 and a projected annual growth rate of 4.6% from 2024–2029 (Forecast 2025). Ecuador is the world's largest producer, covering about 98% of the market (Noriega et al. 2025). In the provinces of Napo, Pastaza, and Orellana, 72 tons per year were produced in 2022, under the model of 625 plants per hectare, generating more than USD 3 million in *I. guayusa* leaf exports (Noriega et al. 2025). These activities are boosting the development of indigenous communities through sustainable agroforestry systems, complying with organic production and Fair Trade standards that promote conservation and restoration of the Amazonian forests in Ecuador (Franco et al. 2018).

FIGURE E8. **Dried leaves of *Ilex guayusa* for sale**



*Photo Credit:* Anna Premo. Wikimedia.

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# F. *Aframomum corrorima* (Ethiopian cardamom, *Korarima*)

## Location for economic models

The Yayu Coffee Forest Biosphere Reserve (YCFBR) is a prime location where enrichment of natural regeneration could be combined with economic activity based on cultivation of *A. corrorima* and other NTFPs and protection of remaining wild populations. YCFBR is located in Illulabor province, Oromia State, 560 km west of Addis Ababa. In 2020, 20% of the area was in natural forest cover (Global Forest Watch 2025). Yayu lies in the Eastern Afromontane Biodiversity Hotspot with altitudes range of 1,200 to 2,000 m a.s.l. The YCFBR was registered by UNESCO in 2010. An important feature of YCFBR is its richness of non-timber forest products such as the production of high-quality, specialty coffee varieties (Yohannes et al. 2024). In the outer transition and buffer zones, economic activities are allowed (Gole et al. 2008). Ninety-five percent of the landholdings are less than 1.0 ha in area. Direct drivers of deforestation in the area are agricultural expansion, coffee plantation development, high demand of timber and non-timber forest product and illegal timber harvesting. In this region, spice is the second-highest source of household income followed by forest honey and firewood. Non-timber forest products collected from this area are marketed at village and local markets and can play a significant role in the socioeconomic wellbeing of the local communities (Yohannes et al. 2024).

In the Yayu Coffee Forest Biosphere Reserve, land is state-owned according to the Ethiopian constitution. Communities and individuals have the right to use the land for agriculture and other purposes, but they do not own the land itself. Tree tenure arrangements are a complex mix of formal usufruct rights, traditional systems, and informal management (Groth et al. 2023).

## ANR cost-benefit models, scenarios and assumptions

Despite ecological relevance, the Ethiopian cardamom system displays negative financial performance under current assumptions (Figure F1). With an NPV of –4,526 USD, and BCR below 1 (0.80), it fails to recover investment within the 30-year horizon. Total costs are USD 65,471, of which 85% are management costs. The model's cost structure includes Assisted Natural Regeneration (ANR) activities such as control of invasive species and fencing, both of which increase early-stage expenditures while providing limited impact on short-term revenue generation. High establishment and maintenance costs, including fencing and fertilization, outweigh moderate revenues, suggesting the need for improved market access or cost-sharing mechanisms to make this system viable. The model's NPV remains negative across all discount rates, highlighting structural financial infeasibility and high sensitivity to discount rate changes (Figure F2). As enrichment of ANR, density of *A. corrorima* is set at 1,500 plants/ha, about 30% of the density in full plantings, with an average annual production of 231 Kg/ha.

FIGURE F1. **30-yr cash-flow model of ANR with enrichment of *Aframomum corrorima***

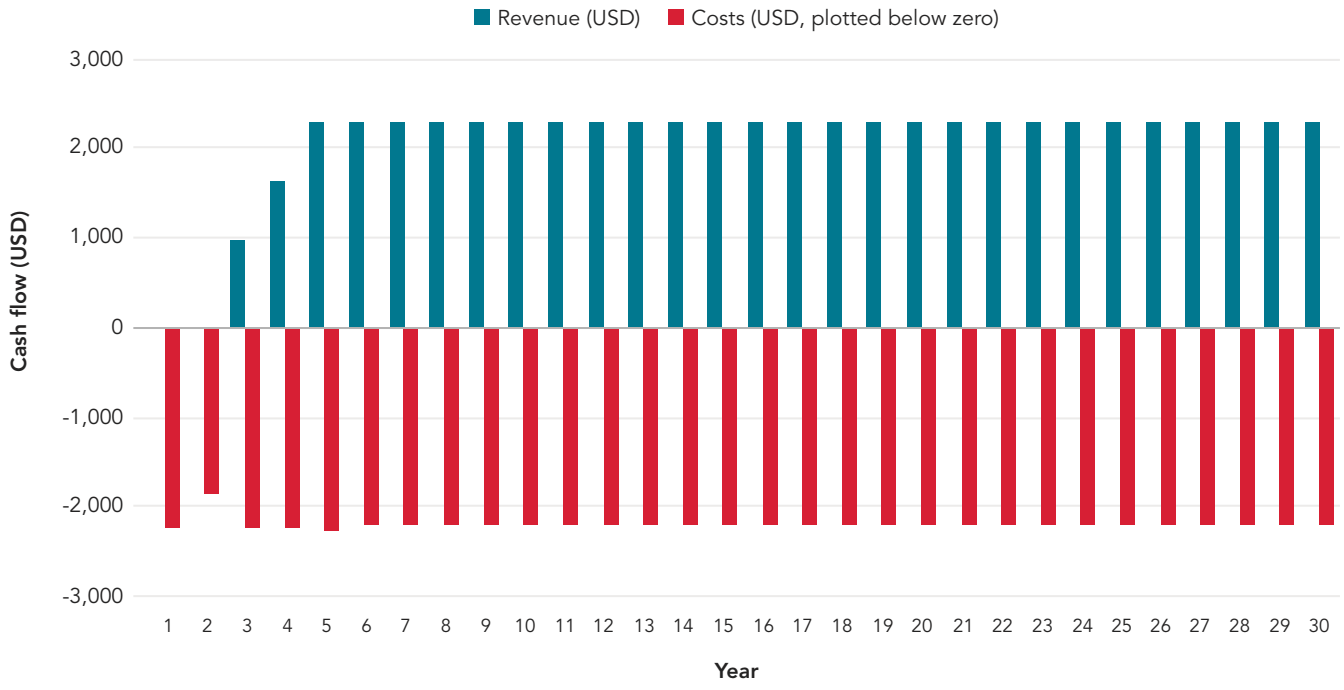
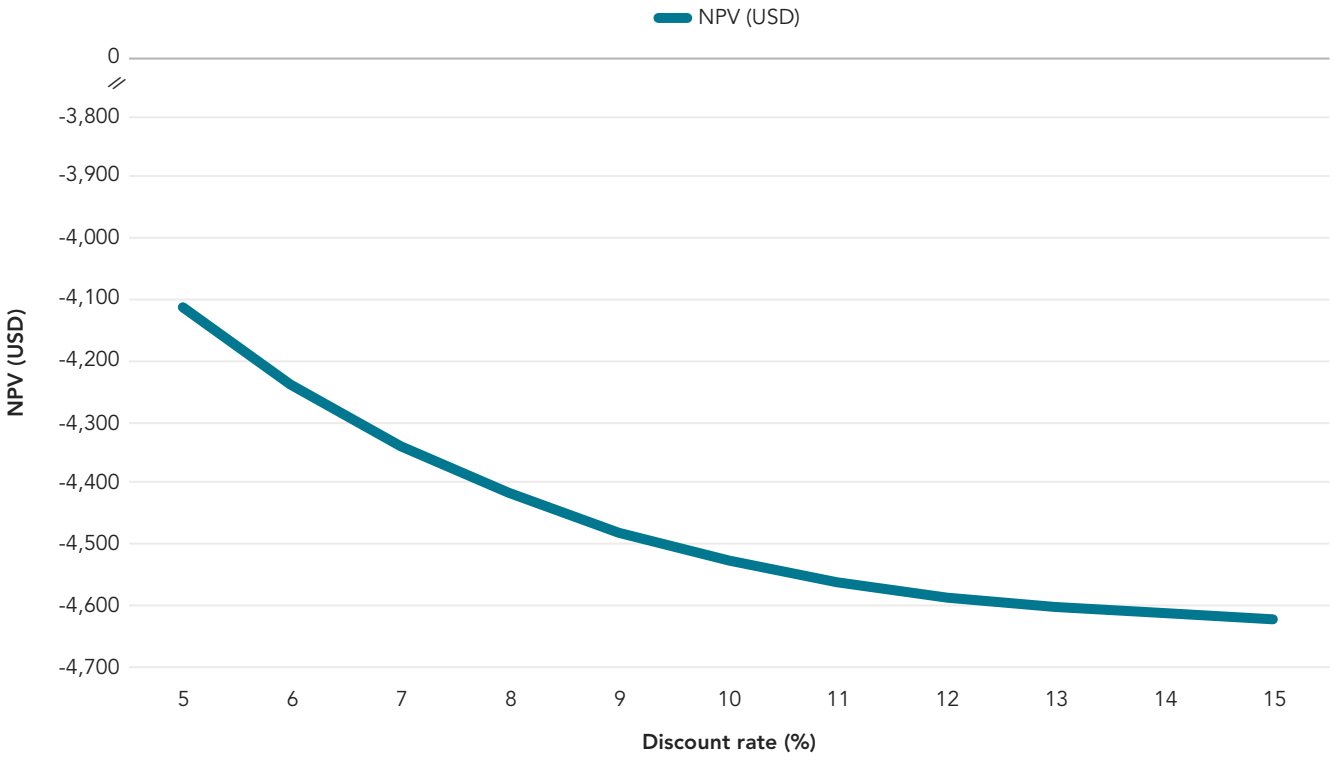


FIGURE F2. **Sensitivity of NPV to discount rate for ANR with enrichment of *Aframomum corrorima***




## Carbon storage models

When compared at the same site, carbon sequestration from ANR with enrichment of *A. corrorima* (118.7 Mg C/ha) is comparable to that of ANR without enrichment and timber plantations for solid wood production, but is 24% higher than minimally assisted natural regeneration.

## Alternative production models

Solidwood and agricultural production were more profitable than ANR with enrichment at this site (Figure F3). Sale of carbon credits added $998 to the net revenue of ANR with enrichment but were not sufficient to offset the negative cash flow of this system.

## Species ecology and ethnobotanical information

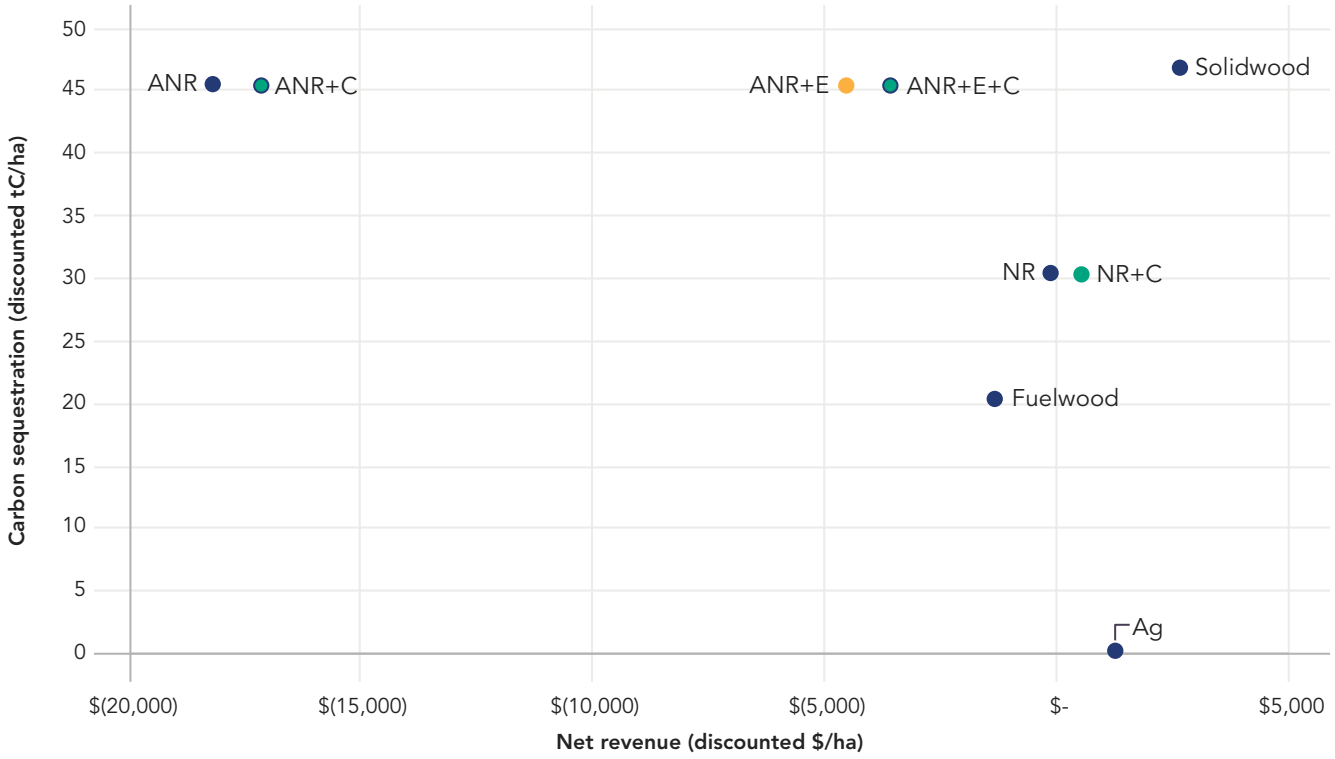
*Aframomum corrorima* is a tropical, shade-loving herbaceous perennial in the ginger family (Zingiberaceae). Plants reach 1–2 m in height and have strong fibrous subterranean rhizomes. The species is native to Tanzania, southwestern Sudan, western Uganda and Ethiopia. In Ethiopia, the species is known as *korarima*, and mainly grows in southern, south-western and western regions, particularly in montane moist evergreen forests at altitudes ranging from 1,500 to 2,300 m a.s.l. (Woldu 2004).

*Aframomum corrorima* is an aromatic food flavoring spice and medicinal plant widely used in traditional medicine by the people of southern Ethiopia. The seed is the most commonly used part, but leaves and rhizomes are also used (Eyob et al. 2008). Seeds contain different types of essential oils and are traditionally used as tonic, carminative and purgative drug (Eyob et al. 2008). Its dried fruits are used to prepare stews and sauces for daily dishes (e.g. *wot;* stews or sauces traditionally eaten with *injera*—a sourdough-risen flatbread) (Worku 2015). It is also used for flavoring liquors, processed foods and in confectionery, cosmetics and pharmaceuticals (Woldu 2004). Korarima is also important for soil conservation as the rhizomes and leaves spread on the ground, covering and protecting the soil from erosion in hilly areas (Eyob et al. 2008).

## Cultural and livelihood importance

*Aframomum corrorima*, red pepper, ginger, turmeric, black cumin and cardamom are the six most important spices produced by smallholders in Ethiopia (Asfaw 2020). In Kaffa zone of southwestern Ethiopia, spice production contributes a mean income of 1,611.14 ETB with a minimum of 0 ETB and a maximum of 25,000 ETB, which is 3.24% of households' annual income (Afeto et al. 2023). *A. corrorina* is a source of income for growers and collectors as its seeds reach high prices in local and export markets. Fruit pods are collected from wild plants close to the places where the informants live. Occasionally plants are cultivated in home gardens (Eyob et al. 2008).

FIGURE F3. **Net discounted revenue and carbon storage for ANR with enrichment of *Aframomum corrorima* compared to alternative land uses**




*See Chapter 2 for full description of land uses.*

FIGURE F4. **Ripe fruit pods of *Aframomum corrorima* (top left); Growing *A. corrorima* on farms (right); Seed pods ready for grinding (bottom left)**



*Source:* Yohannes et al. 2024.

The high value of seed as spice, brings economic returns from sales that are much higher than most of other food cereal crops in the growing regions (EARO 2000). The cash value obtained from sale of *Aframomum corrorina* is the most common use category for key informants in Debub Omo and Kaffa followed by spice, medicine and soil conservation (Eyob et al. 2008).

Landholdings used for *A. corrorima* production are small. In Kaffa biosphere reserve, the average lands allocated for production were less than 0.1 hectare (Afeto et al. 2023), whereas in the same region Mulatu and Gadisa (Mulatu and Gadisa 2020) found that average land size covered by *A. corrorina* per household was 0.25 hectares with maximum of 1.05 ha. Over 47% of the households sampled cultivated *A. corrorima* for generating cash income, whereas 17.5% cultivated for home consumption and 35.1% for both market sale and home consumption. Income from market sales covers 96.2% of households' average income from spice marketing (Afeto et al. 2023).

## Conservation status

Production of *Aframomum corrorima* is declining in Gamo Gofa, Debub Omo and Kaffa zones due to the deforestation of natural forests of the area destruction of the plant's natural habitat (Zakir 2018). Habitat destruction for expansion of arable and grazing land, new settlements and forest fires have led to low supply and high demand in local and export markets (Eyob, Tsegaye, and Appelgren 2009). The growing pace of uncontrolled and/or unsystematized agricultural development poses an alarming threat to genetically diverse native populations (Woldu 2004).

## Production and harvesting

In Ethiopia, *A. corrorima* can be produced on farms and by forest harvesting. Cultivation occurs where its initial domestication is assumed to take place as shown by the co-occurrence of both wild and cultivated genotypes. Cultivation is most common in forested areas of the southern and southwestern parts of the country where suitable shade trees and favorable warm-humid climate with humus-rich soils occur (Yohannes et al. 2024).

*Aframomum corrorima* can be propagated either by seed or by vegetative propagation of rhizomes; the latter is by far the most common method, as it yields earlier and ensures a true-to-type propagation than the former (Chombe and Bekele 2018). Gamo Gofa, Debub Omo and Kaffa are the three major *A. corrorima* growing regions of southern Ethiopia (Eyob et al. 2008). In all three study regions, most of the medicines are collected from wild plants close to the places where the informants live. Occasionally the medicines were collected from cultivated plants at the home gardens.

*Aframomum corrorima* yield is highest under filtered shade with 55–63 % light intensity and in the lower strata of natural forests. In the wild, plants start bearing fruit two years after emergence, whereas in domestication fruit maturity may take three to five years for a plant to produce a usable harvest. In Yayu Biosphere Coffee Reserve Forests, harvesting mainly occurs between October and February. Forest harvesters (who are primarily men) walk for up to three hours to access the wild fruits, often combining trips with other tasks such as hanging beehives in the forest (Yohannes et al. 2024). The Kaffa Biosphere Reserve has a high potential for *A. corrorima* production, with an average productivity of 400 kg per hectare (Mulatu and Gadisa 2020).

Production and marketing of *A. corrorima* in the Kaffa region face serious challenges due to plant disease, animal and pest damage, low yield due to climate change, low productivity of existing varieties, poor extension support, lack of improved production practices, lack of well-designed output marketing center, and traditional harvesting and post-harvest handling techniques (Mulatu and Gadisa 2020).

## Trade and marketing

*Aframomum corrorima* is one of the most highly priced spices in Ethiopia, where it is considered as a potential substitute for Indian cardamom. The economic returns obtained from yields were much higher than food cereals grown in the major *A. corrorima* growing zones (Yohannes et al. 2024). In the early 1970s, over 118 tons of *A. corrorima*—worth over USD 1,180,000—was exported from Ethiopia to Europe (Woldu 2004). In early 1978, *A. corrorima* pods sold for USD 9/kg in the export market, mainly as a substitute for cardamom. But due to short of supply in the year 2001, the export market price reached as high as USD 23.5/kg (Eyob et al. 2008).

About 60.9% of the households sampled in the Kaffa Biosphere Reserve provide spice products to markets, with wide variation among different districts (kebeles). In the sample kebeles, 91%, 60%, 56% and 38% of Yama, Modiyo, Tega and Wareta households, respectively, participate in the selling of spice products (Afeto et al. 2023).

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# G. *Oldeania alpina* (Highland Bamboo)

## Locations for economic models

We selected a location in Oromia in the Bale Mountains for our economic model. This area is well suited for ANR as forest cover at elevations below 2600 m is actually increasing through natural regeneration (Tiye et al. 2025). These areas are prime areas for enrichment planting of *Oldeania alpina* that are also contributing to reforestation in the region. In 2020, natural forest cover in the district was only 17% (Global Forest Watch 2025). The area is an important region for conservation of the vulnerable Bale Monkey (*Chlorocebus djamdjamensis*), endemic to Southern Ethiopia, whose declining populations depend on *Oldeania alpina* as a food source (Mekonnen et al. 2022).

Throughout Ethiopia, all land is technically owned by the state. Communities and individuals primarily hold rights to use the land and its resources, but they cannot own, sell or mortgage the land itself. In areas such as the Bale Mountains National Park, conflicts have arisen between park management and local communities over land use and resource access, with ongoing discussions about relocation and compensation strategies (Yimer 2023).

## ANR cost-benefit models, scenarios and assumptions

The *Oldeania alpina* (highland bamboo) model in Ethiopia is the top performer of the 14 non-timber species evaluated in this study, with an NPV of USD 187,933, an extremely high BCR of 37.12, and an IRR of 342%, reaching payback in only 3 years (Figure G2). In the ANR enrichment scenario, *Oldeania alpina* is planted at a density of 3,150 culms/ha, about 30% of the density used in agroforestry systems. Once they reach maturity, culms will be thinned every year to maintain these low densities and to permit natural regeneration of other native tree species. Farmers can also use bamboo for fencing around ANR plots, providing a source of revenue each year after culms reach their mature size for harvest. Total cost of ANR with enrichment of *O. alpina* is low (USD 15,616), of which 62% is management cost and 33% is harvesting cost. NPV declines with increasing discount rate but remains positive and the top performer among the target species at a discount rate of 15% (Figure G3).

## Carbon storage models

Carbon sequestration from ANR+E (32 MgC/ha) is considerably below that of ANR without enrichment (51.1 Mg C/ha) and timber plantations for solid wood production (114.6 Mg C/ha), at the same site.

## Alternative production models

For highland bamboo, net revenue from ANR with enrichment is estimated to be 85x higher than that of the most profitable alternative land use, solid wood, at the same site in Ethiopia (Figure G4). Carbon revenues for ANR with enrichment provide an additional USD 199/ha.

FIGURE G1. **The bale monkey and its main food source, highland bamboo (left); Traditional home made from highland bamboo at Arbegona, Sidama Region, southern Ethiopia (right)**





*Photo credits:* Nik Borrow (left); Addisu Mekonnen (right).

FIGURE G2. **30-yr cash-flow model for ANR with enrichment of *Oldeania alpina***

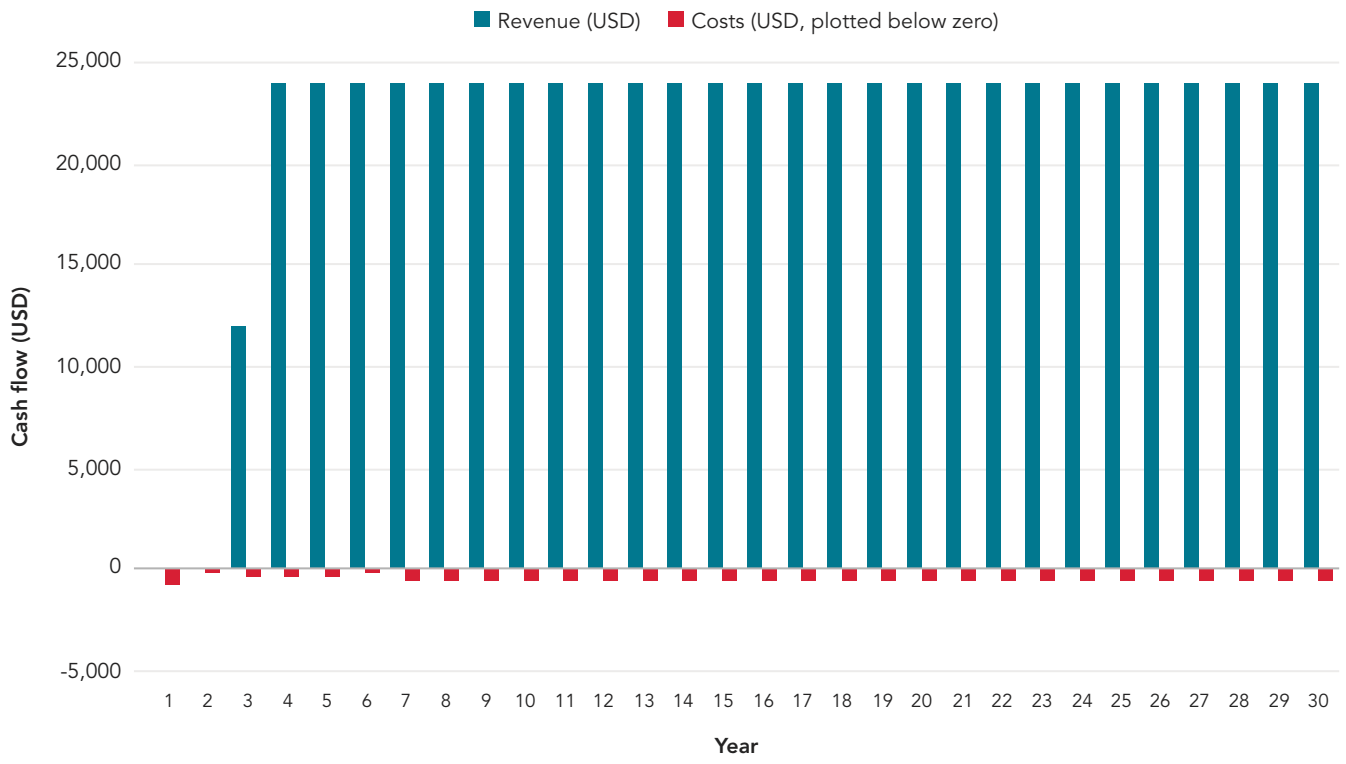



FIGURE G3. **NPV sensitivity to discount rate for ANR with enrichment of *Oldeania alpina***

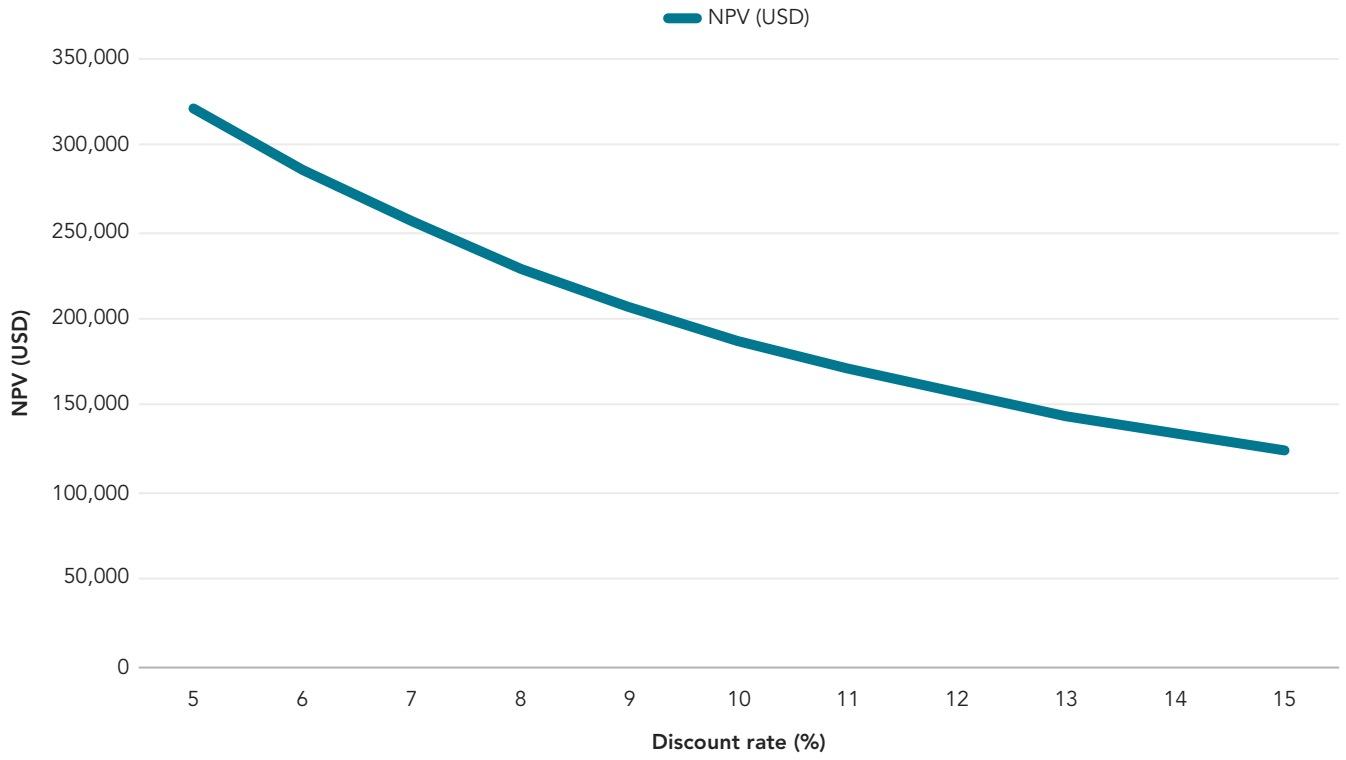


FIGURE G4. **Net discounted revenue and carbon storage for ANR with enrichment of *Oldeania alpina* compared to alternative land uses**




*See Chapter 2 for full description of land uses.*

## Species ecology and ethnobotanical information

*Oldeania alpina* is a perennial bamboo species in the family Poaceae. It is one of the two bamboo species native to Ethiopia, where it grows in dense stands on mountains and volcanoes surrounding the East African Rift Valley between 2,100 meters and 3,100 meters elevation and mean annual temperatures from 11.5 to 19.3 °C. *O. alpina* thrives in areas with annual rainfall from 873 to 1,962 mm (Yebeyen et al. 2022). In Ethiopia, *O. alpina* grows across ~330,000 ha in the south, south-west, central and north-western highlands within an altitudinal range of 2,300–4,000 m above sea level (Embaye 2000; Kidane et al. 2023). *Oldeania alpina* is found mainly in the Amhara, Oromia, and Southern regions. Across Ethiopia, 19.7% of the land area (9,880,265 ha) is suitable for growing highland bamboo (Alemayehu and Hido 2023).

*Oldeania alpina* has high ecological and economic value across highland regions of Ethiopia. It serves as a windbreak and grows quickly, helping to protect soils and prevent erosion (Mamude and Befikadu 2022). It plays a significant role in carbon sequestration, with estimated total system carbon storage over 442 Mg C/ha, making it a vital component in climate change mitigation strategies (Yebeyen et al. 2022).

Over 200 different uses of *O. alpina* have been documented in districts of Ethiopia including fences, house construction, furniture, baskets, hand tools for processing crops, bamboo knife, sieves, beehives, flooring material, handicrafts, animal shelters, and grain storage structures. Various landraces of *O. alpina* are cultivated across Ethiopia, each with distinct morphological traits and traditional uses. These landraces are preferred for different products based on their properties, such as strength and workability, which are crucial for local bamboo processors (Kidane et al. 2023). The shoots of *Oldeania alpina* are seasonally harvested for food, providing an additional source of nutrition and income (Kedir 2024).

FIGURE G5. **Native range of *Oldeania alpina* (Highland bamboo) in Africa (left); Stand of *Oldeania alpina* (right)**





*Source:* Wikipedia (left).
*Photo credit:* Odie Weber.

## Cultural and livelihood importance

Highland bamboo is a primary means of livelihood for many families in Ethiopia (Wakweya 2023) and is a crucial source of income for households in Ethiopia, particularly in the Masha district. It is used extensively for house construction and fencing, with bamboo structures lasting between 15 to 30 years for houses and 2 to 10 years for fences (Kedir 2024). Bamboo accounts for a significant portion of income in some areas, such as 28.1% in Yina (Kedir 2024). Mekonnen et al. (2014) found that household's cash income contribution of bamboo was 3.9% in Tikur Enchini, 3.4% in Masha, 5.7% at Asosa/Bambasi, 7% in Chencha, 18% in Hagerselam and 38% in Banja and Bahir Dar Zuria. Highland bamboo contributed 19% of household income in Dawuro zone, southwestern Ethiopia (Obsa, Kassa, and Tajebu 2015) and 17.2% in Beles River Basin, northwestern Ethiopia (Abebe, Minale, and Teketay 2022).

## Conservation status

The conservation status of *Oldeania alpina* is not listed as a specific category by the IUCN for Ethiopia, but the species is considered to be of significant conservation value and faces high pressure and various threats to its sustainability within the country. The main threats are unsustainable harvesting, poor management practices, land-use changes (especially expansion of agriculture and *Eucalyptus globulus*), damage by pests/diseases and climate change (Embaye 2000). The Bale monkey (*Chlorocebus djamdjamensis*), an arboreal, forest-dwelling, threatened primate restricted to a small range in the southern Ethiopian Highlands, relies mostly on *Oldeania alpina* as its food sources and prefers bamboo forest habitat. As most of the Bale monkey's range lies outside protected areas and most of its historical bamboo forest habitat is degraded or destroyed, the conservation of Bale monkeys and highland bamboo is therefore highly inter-dependent (Mekonnen et al. 2022).

## Production and harvesting

Most farmers prefer to plant highland bamboo at the lower side of their farm and riverside, which are considered marginal lands not suitable for crop production. Naturally grown bamboo stands owned by churches are also found as mixed forests with tree species like *Juniperus procera* and *Hagenia abyssinica* (Kidane et al. 2023).

*Oldeania alpina* is also grown in traditional agroforestry systems, where it is integrated with other crops and livestock to optimize land use and enhance biodiversity

(Worku and Bantihun 2017). In agroforestry systems, high rhizome density can cause competition for nutrients with other crops, but management practices such as fencing, thinning, and terracing can be used to control rhizome proliferation and maintain bamboo stands (Mamude and Befikadu 2022). Bamboo can be harvested within 4 years after planting and provides consistent yields every year (Ben-Zhi et al. 2005).

## Trade and marketing

Bamboo's current utilization, marketing, and trade remain underdeveloped in Ethiopia, with a minimal contribution to the economy (Lin et al. 2019). For instance, in Assosa and Injibara, the use of bamboo is mostly limited to the construction of traditional products (e.g., huts, beehives, fencing, furniture, and other household utensils), with minimal market and demand for handmade bamboo products (Alemayehu and Hido 2023). Ethiopia is a weak player in the global bamboo trade. Ethiopia exports bamboo products worth USD 0.23 million, accounting for about 0.02% of the global exports, mostly as bamboo poles (EEFCC 2020). For both of the Ethiopian native bamboo species, annual economic contribution to Ethiopia's gross domestic product (GDP) in 2020 was estimated to be around Ethiopian Birr (ETB) 56,250,000 and engages over 750,000 farmers in the sector (EEFCC 2020).

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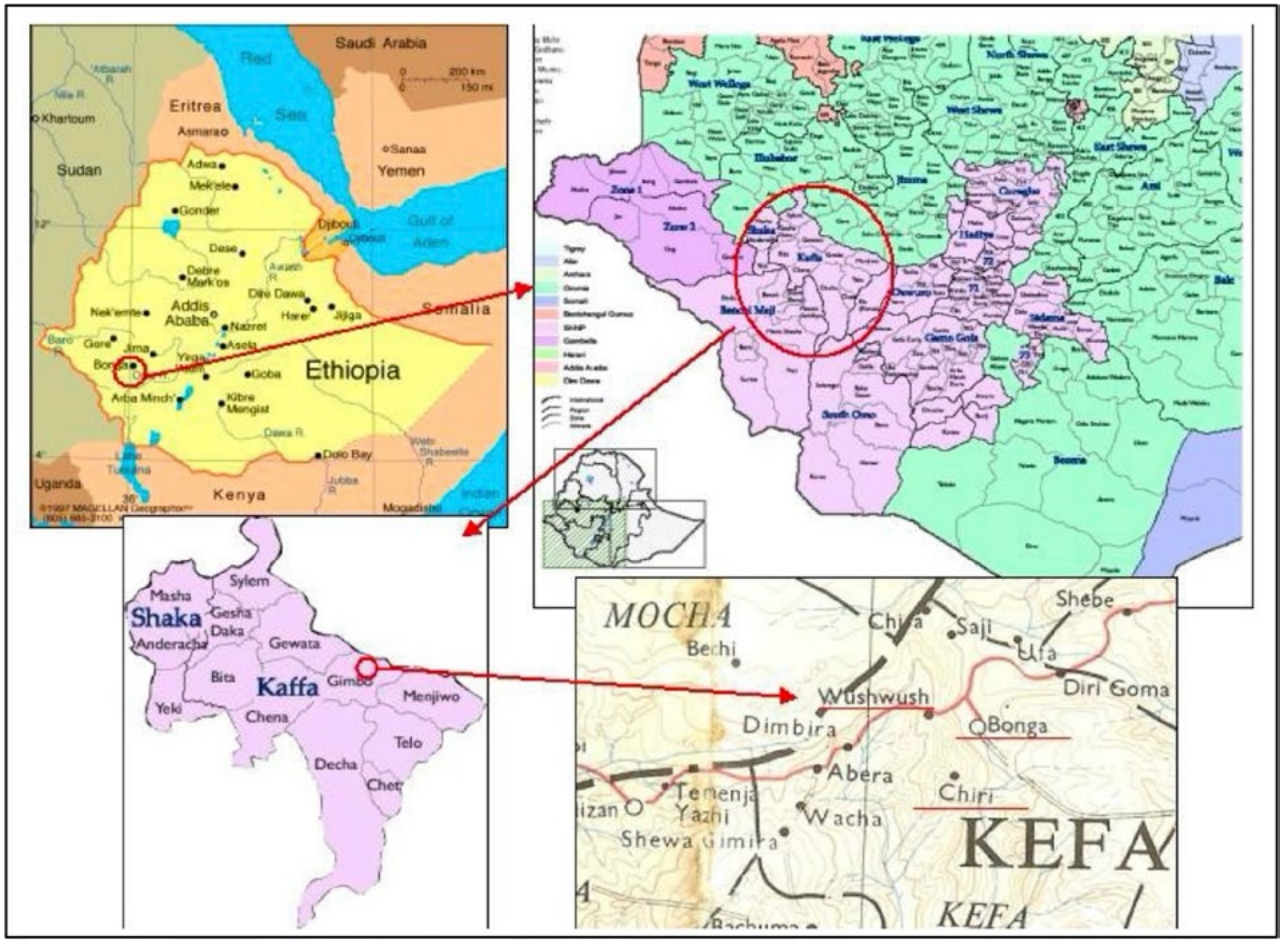
# H. *Piper capense* (Timiz, long pepper)

## Locations for economic models

The ideal location for producing *Piper capense* in naturally regenerating forest is in Bonga's coffee forest in the southwestern plateau of Ethiopia (Kaffa zone) (Fig. H1). In 2020, natural forest cover in the area was 43% (Global Forest Watch 2025). The original forest area covers 161,424 ha and lies within 7°00–7°25N latitude and 35°55–36°37E longitude, stretching across five woredas: Gimbo, Menjiwo, Tello, Decha, Chena. The altitude of the area is from 1000 to 3350 m. Annual rain fall ranges is from 1710 to 1900 mm in Bonga Station, in one long rainy season, starting from March to October. Over 85% of the total annual rainfall, with mean monthly values from 125 to 250 mm, falls during the 8-month long rainy season. The average temperature is 19.4°C (Avril 2008). Farming is a common activity of many rural communities, and almost all sampled households (about 97%) were engaged in agricultural activities, such as production of cereals, coffee, pulses, enset (*Ensete ventricosum* (Welw.) Sheeseman) and others (Melaku, Ewnetu, and Teketay 2014).

The growth requirements and ecological distribution of *Piper capense* make this species highly suitable as a native species within assisted natural regeneration of forest ecosystems in Southwestern Ethiopia. This species, which is widespread in mature Bonga coffee forests and in disturbed forest habitats, can be cultivated on small farms through cuttings (Hailu and Zakir 2021) or transplanted seedlings at low cost and minimal maintenance. Plants become productive within 1–3 years, with peak production after 3–4 years. Plants live for 8–10 years and would then be replanted (Avril 2008). Ideally, enrichment of *Piper capense* seedlings would be implemented in regenerating forests that have attained 50–60% canopy closure. Indigenous tree species frequently used as shade trees, such as *Millettia ferruginea* and *Albizia gummifera*, support growth of *Piper capense* by providing the necessary canopy cover (Furo, Manaye, and Negasa 2020).

FIGURE H1. **Location of potential ANR sites for enrichment with *Piper capense***




*Source:* Avril 2008.

In the Kafa Biosphere Reserve, community land and tree tenure arrangements are based on Ethiopia's state ownership of land, which grants usufruct rights to communities. Communities can gain secure use rights through participatory forest management (PFM) and by developing communal forests, which allows them to manage, use, and benefit from forest products. Communities are permitted to sustainably harvest and sell non-timber forest products (NTFPs) from their managed forests, which provide an important source of income (Mekonnen and Bluffstone 2014).

## ANR cost-benefit models, scenarios and assumptions

The cost-benefit model for *Piper capense* shows quick payback and strong profitability despite its simplicity. With a benefit-cost ratio of 4.95, NPV of USD 2,542, and a payback period of 1 year, it performs remarkably well due to very low costs and early revenue generation (Figure H2). Total costs of ANR with enrichment are USD 3,590, of which 84% are for management costs and 15% for harvesting costs. Assisted Natural Regeneration (ANR) activities focused on the control of invasive species, which helps maintain suitable conditions for natural regrowth without adding significant financial burden. Timiz long pepper is a promising NTFP species for low-input restoration strategies, providing fast financial returns and incentives for adoption by smallholders. Despite a small revenue base, the NPV remains positive and only moderately affected by discount rate increases, indicating quick payback and low exposure to capital costs (Figure H3).

## Carbon storage models

Over 30 years, ANR with and without enrichment of *P. capense* accumulate 118.1 Mg C/ha in vegetation biomass, which is 31% higher than for minimally assisted natural regeneration (90.3 MgC/ha). Carbon sequestration from ANR is similar to that of timber plantations for solid wood production.

## Alternative production models

For *Piper capense*, net revenue from ANR+E is estimated to be slightly higher (1.1x) than that of the most profitable alternative land use, solidwood plantation, at the same site in Ethiopia (Figure H4). Carbon credits increase revenue of ANR by $919/ha.

FIGURE H2. **Top: 30-yr cash-flow model for ANR with enrichment of *Piper capense***

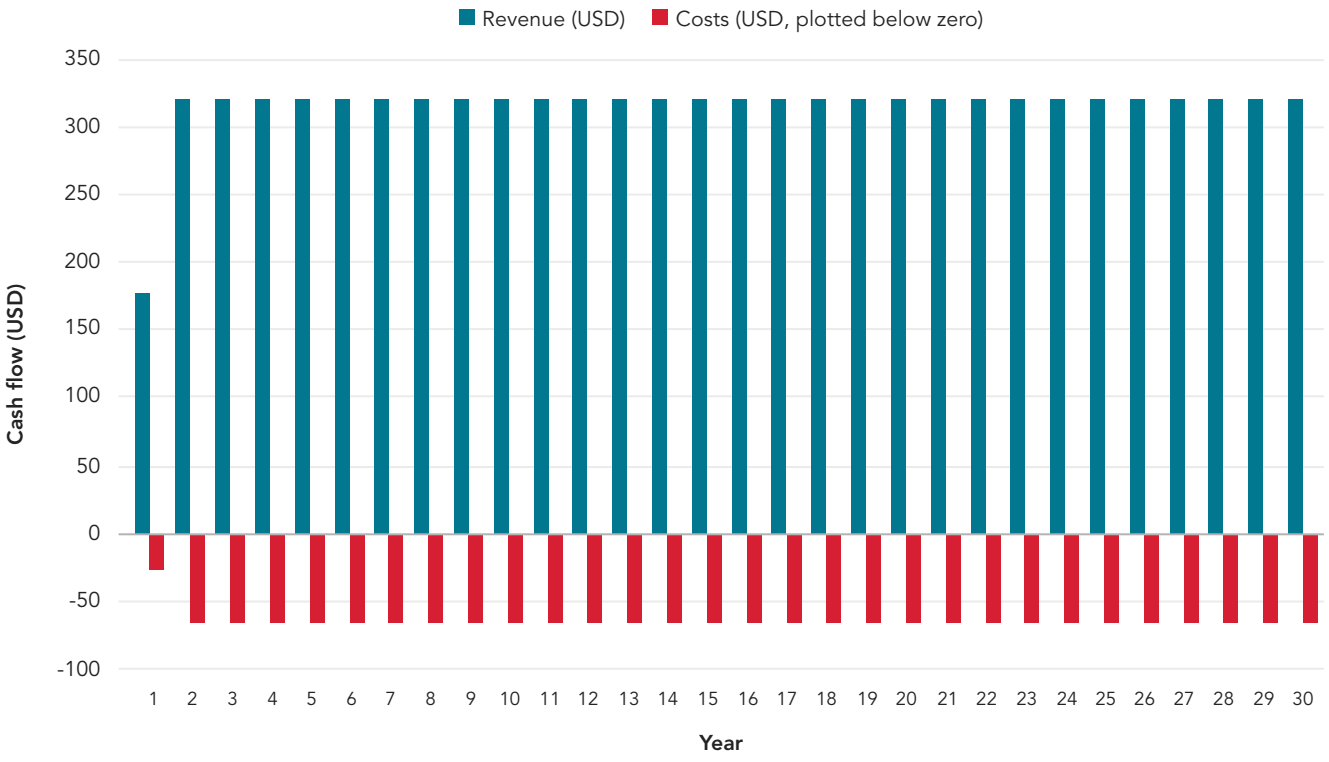


FIGURE H3. **Sensitivity analysis for NPV to discount rate for ANR with enrichment of *Piper capense***

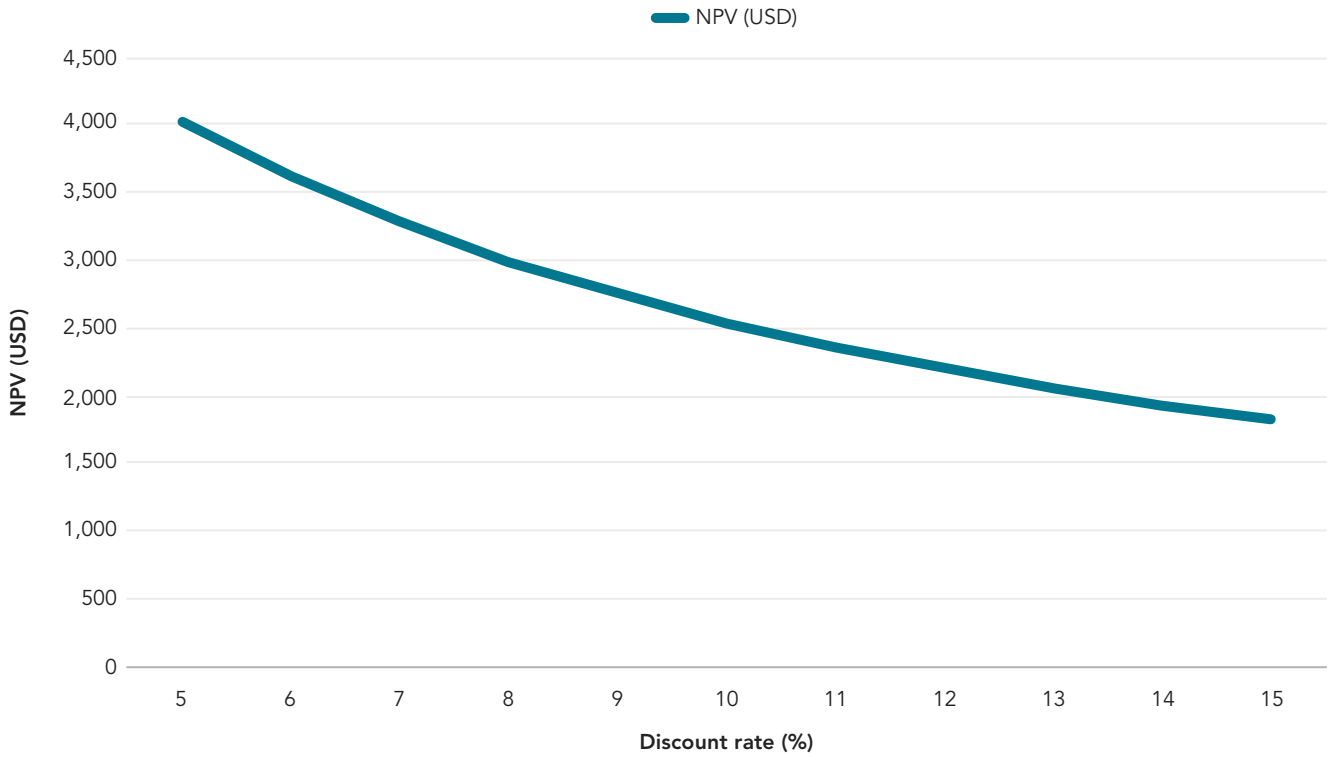
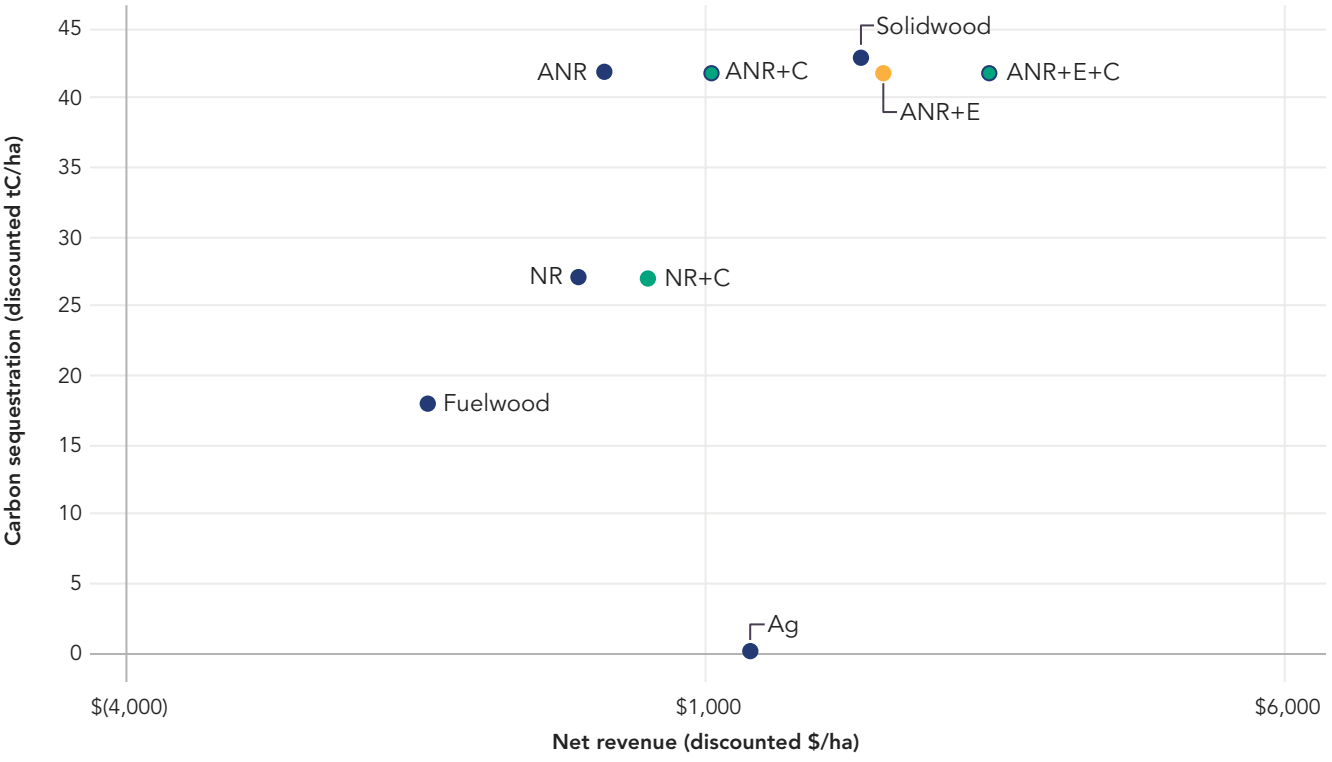



FIGURE H4. **Net discounted revenue and carbon storage for ANR with enrichment of *Piper capense* compared to alternative land uses**




*See Chapter 2 for full description of land uses.*

## Species ecology and ethnobotanical information

*Piper capense*—known locally as Timiz, long pepper, or *turfo*—is a shade-tolerant shrub species in the Piperaceae family endemic to African forests (Figure H5). Within Africa, *Piper capense* ranges from Sierra Leone to Ethiopia and Sudan, south to Angola, Kenya, Tanzania and South Africa (Fern 2014). It is a close relative of *Piper nigrum*, black pepper. It grows in the forest understory, reaching heights from 1–2m tall. Its base is semi-woody with many branches (Shehasen 2024). It occurs naturally in wild and semi-wild environments within moist Afromontane forests of southern and southwestern Ethiopia at elevations from 1,300–2,400 m a.s.l. (Avril 2008; Enkossa, Nemomissa, and Lemessa 2022).

*Piper capense* commonly occurs in the Bonga's coffee forest of the South West of Ethiopia (Kaffa zone). It grows under similar ecological conditions as wild coffee but can also be found at higher elevations. Regions in Oromia with comparable climatic conditions also support its growth (Shehasen 2024). In the Kaffa zone, Gimbo and Detcha are the two main woredas that produce *Piper capense* fruits (Avril 2008). Here, as a natural forest crop, *Piper capense* thrives under 50-63% shade (Avril 2008) and is naturally abundant in the Bonga coffee forest, with over 3,000 plants per ha (Nune 2008).

FIGURE H5. ***Piper capense* (Timiz pepper) growing in the forest understory**



*Photo credit:* Alexey Yakovlev.

FIGURE H6. **Dried fruits of *Piper capense* for sale at a local market**



*Source:* Avril (2008).

*Piper capense* is harvested traditionally for human consumption as a spice and for oils used in beverages and medical applications. All parts of the plant including flowers, leaves, bark, and roots are gathered for their medical and culinary benefits (Shehasen 2024; Figure H6). It is also popular in the Islamic regions of North Africa where it has been introduced by Arab traders (Avril 2008). In addition to its use to enhance flavors, the oils are used in beverages and medical applications. In Ethiopia, *Piper capense* is commonly used in cooking traditional meat stews—together with other spices—and to flavor coffee, tea and butter (Avril 2008). It can be used to cure both human and animal diseases like pins and needles in the legs, breathing problems and digestive problems. Extracts and compounds isolated from *Piper capense* have anticancer, antibacterial, antimalarial, hypoglycemic, anti-epileptic, and antidepressant properties (Kamsu and Ndebia 2024). A review by Kamsu and Ndebia (2024) revealed 31 traditional uses of *Piper capense*, most of which have been scientifically confirmed. The piperine produced by *Piper capense* increases serotonin, assisting with mood regulation and digestive disorders. Antibacterial and anti-inflammatory properties support respiratory health, detoxification, and kidney function, while also serving as an aphrodisiac (Shehasen 2024).

## Cultural and livelihood importance

*Piper capense* is linked to Ethiopian culture in several ways: it is gathered in a unique ecosystem, transformed in traditional ways, and is used in many national dishes and is a key component of traditional health practices (Avril 2008, Shehasen 2024). In southwest Ethiopia, *Piper capense* is largely harvested from wild-grown plants with distinctive recognized varieties (Avril 2008). Plants are also managed along forest borders and in home gardens, which are close to farms and easier to protect (Agize and Zouwen 2016). Most farmers that gather or cultivate *Piper capense* have very small holdings or difficult access to land (Avril 2008). For these smallholders and their families, *Piper capense* provides from 10–60% of household income. Although production of *Piper capense* is small in comparison with *Aframomum corrorima* (Ethiopian cardamom), there is substantial local and regional trade. Women generally harvest wild *Piper capense* in the forest, which can provide income for purchasing clothes and household necessities. Children also harvest wild fruits to buy school supplies. Men generally harvest the managed and cultivated plants, using

this income to pay governmental taxes, eudir (contribution to help neighbors) and farm costs. When *Piper capense* is cultivated, it is produced without fertilization nor irrigation and on very small areas (Avril 2008).

In the Bonga Forest area, almost all of the households sampled harvested at least one type of non-timber forest product (Melaku, Ewnetu, and Teketay 2014). The mean cash income contribution of these products to annual household income in the 2009/2010 production year was 47% of total income. Among NTFPs, forest coffee (*Coffea arabica*) contributed most to household incomes at 64%, followed by honey (24%) and spices (12%). The major spices harvested were *Aframomum corrorima* and *Piper capense* (Melaku, Ewnetu, and Teketay 2014).

## Conservation status

Deforestation due to agricultural expansion and environmental degradation pose critical threats to the remaining moist Afromontane forests in southwestern Ethiopia (Enkossa, Nemomissa, and Lemessa 2022; Shehasen 2024). Although development of coffee shade agroecosystems tends to slow down total deforestation compared to annual-crop production systems, intensive coffee management leads to degradation of forest biodiversity by simplifying the forest structure and clearing understorey herbs and shrubs (Enkossa, Nemomissa, and Lemessa 2022). Currently, *Piper capense* populations are not threatened, but there is concern regarding erosion of genetic diversity. Germplasm banks for *Piper capense* and other non-timber forest products are currently under development in the region and will play a pivotal role in conserving the genetic resources necessary for sustainable agricultural production (Shehasen 2024).

## Production and harvesting

In the Sheka, Kaffa and Bench Maji forests in Ethiopia, farmers harvest and produce several non-timber forest products including forest wild and semi-wild coffee, forest honey, wild forest spices and bamboo. *Piper capense* is often grown under the forest canopy, which provide necessary shade and support. This practice is prevalent in the Sheka, Kaffa, and Bench Maji zones, where farmers use trees like *Millettia ferruginea* and *Albidia gumminifera* as shade trees (Furo, Manaye, and Negasa 2020). Growing *Piper capense* under tree shade provides ideal microclimate for growth and production of spice crops by damping the diurnal ambient air temperature oscillations (Furo et al. 2020). Domestication and production on farms will likely increase as market demand increases and the value chain becomes more formalized (Avril 2008, Shehasen 2024).

Harvested fruits are dried in the sun or smoked over a wood fire; the latter process is faster and less dependent upon weather conditions, but wholesalers prefer the sun-dried product (Avril 2008). Once dried, they can be stored for months. Farmers can gather from 2–4 kg of fresh fruit per shrub, on average. Costs of production are low, as seedlings can be transplanted directly and require minimal maintenance. Still, gathering from wild plants is advantageous, as it can be combined with harvesting other non-timber products (firewood, honey) and it allows more crops to be grown on the farm (Avril 2008). On the other hand, production on farms allows larger yields and reduces competition with baboons, who readily consume the fruits. Finally, cultivated plants are close to home and require less time to harvest. These reasons support the practice of planting and managing *Piper capense* in naturally regenerating forests with moderate levels of shade that are located close to farms and villages.

*Piper capense* should be planted during the rainy season with mulching or occasional water during the dry season. Growth is optimal at altitudes between 500–1,500 m a.s.l., annual rainfall between 1,200–7,000 mm and temperatures of 20–35°C in soils rich in organic matter (Shehasen 2024).

## Trade and marketing

Trade in *Piper capense* is often combined with trade in *Afromomum corrorima* (Ethiopian cardamom), but prices of *Piper capense* are much lower and it generally has a lower market demand (Agize and Zouwen 2016). Prices of *Piper capense* fluctuate during the year. Wholesalers in the Bonga area and Addis Ababa sell the dried fruits in the market in 50 kg bags. The *Piper capense* production sector is small, with no processing factories, no cooperatives and little research and support by the government. But production offers high potential due to the strong links to culture and unique biodiversity of the region. Farmers trek long distances to urban centers like Addis Ababa for distribution (Avril 2008).

While *Piper capense* holds significant cultural and medicinal value, its international trade and market value remain underdeveloped compared to other spices. Market pricing remains low due to insufficient processing knowledge and quality issues, suggesting an urgent need for improvements across the value chain to enhance marketability (Shehasen 2024). Lack of awareness regarding processing methods and quality control is hindering the marketability of *Piper capense*; these aspects are crucial for enhancing its appeal in international markets (Shehasen, 2024).

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# I. *Parkia biglobosa* (African locust bean, *Dawadawa, Néré, Iru*)

## Locations for economic models

The models were based on locations in Atebubu District in northern Ghana across five towns: Asante, Mampong, Atebubu, Yeji, and Kwame Danso. (Latitude: 7°45'N; Longitude 0°5'W). The area is a transition zone between Guinea Savanna to the north and deciduous forest to the south. The vegetation is a mixture of trees, shrubs and tall grasses with a sparse distribution of trees. In 2002 natural forest cover in the region was 21% (Global Forest Watch 2025). The zone has a bimodal rainfall with major and minor growing seasons. Mean annual rainfall is 1,300 mm (Nyadanu et al. 2017). Enrichment planting of *P. biglobosa* in naturally regenerating fallows will boost species populations and ensure a sustainable supply of this important cultural and economic resource. Our model is based on a planting density of 50 trees/ha.

A unique user-right tenure arrangement exists for *Parkia biglobosa*. In the Atebubu District and surrounding areas in northern Ghana, the tenure system for *Parkia biglobosa* is complex and primarily based on customary and communal landholding systems, where the traditional landowner (often a "dawadawa chief") typically retains the rights to the tree's products, not the farmer cultivating the land (Amoako et al. 2015). For example, in the Dagomba and Gonja areas, where traditional controls for tree tenure were enforced, the abundance of *Parkia biglobosa* was high and fallow fields maintained higher abundance of *Parkia biglobosa* than farmlands (Amoako et al. 2015). Protecting and restoring *P. biglobosa* in savanna landscapes of northern Ghana's savannah landscape will require continued access and benefits of the tree to women in the region (Lelea et al. 2022).

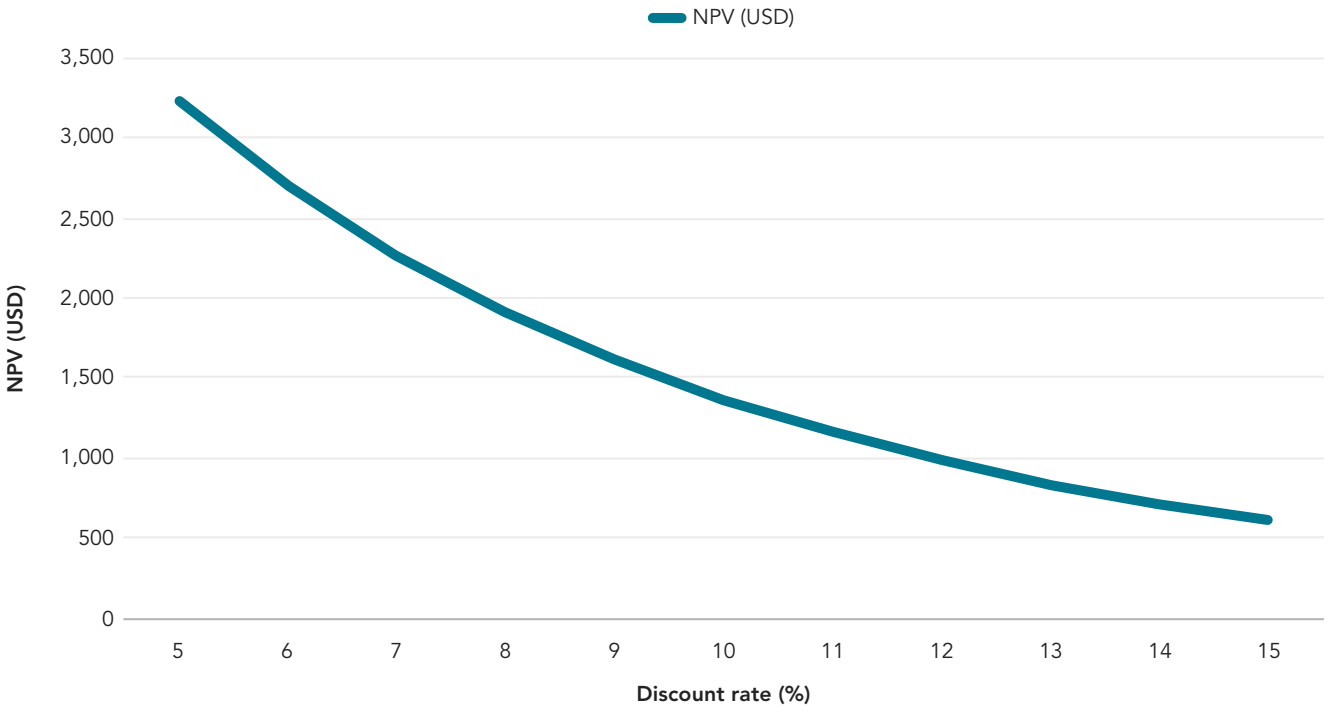
## ANR cost-benefit models, scenarios and assumptions

This savanna enrichment model integrates *Parkia biglobosa* supplemental planting with native species regeneration and fire protection. Despite low establishment costs, it achieves a modest NPV of USD 1,361, IRR of 31%, payback in 10 years, and a BCR of 4.64 (Figure I1). Revenue starts around year 8, growing steadily to ensure consistent net gains thereafter. The implementation of this system also includes fencing and fire protection, which are critical for safeguarding regenerating individuals against grazing pressure and recurrent burning, both common in semi-arid savanna landscapes. Total costs are very low (USD 1,159) of which 55% are for management and 40% are for harvesting. The combination of moderate inputs and strong market value for locust bean products makes this model both financially sound and ecologically aligned with community-based restoration in semi-arid ecosystems. The model exhibits a stable but modest decline in NPV in the sensitivity analysis, suggesting consistent returns and good resilience under varying discount rates, typical of diversified NTFP systems (Figure I2).

FIGURE I1. **30-yr cash-flow model for savanna woodland enrichment of ANR with *Parkia biglobosa***



FIGURE I2. **Sensitivity of NPV to discount rate for savanna woodland enrichment of ANR with *Parkia biglobosa***




## Carbon storage models

Timber plantations for solid wood production have the highest carbon storage at this site (67.4 MgC/ha). Carbon sequestration from ANR+E (44.8 MgC/ha) is 8% below that of ANR without enrichment (48.5 MgC/ha) and 29% higher than for minimally assisted natural regeneration (29.3 MgC/ha).

## Alternative production models

For *Parkia globosa*, African locust bean, net revenue from ANR+E is estimated to be lower (0.2x) than that of the most profitable alternative land use, agriculture, at the same site in Ghana (Figure I3). The additional revenue from carbon credits, USD 262, is not sufficient to compensate for reduced revenue. ANR with enrichment is estimated to provide higher revenue than solidwood or fuelwood plantations at this location.

## Species ecology and ethnobotanical information

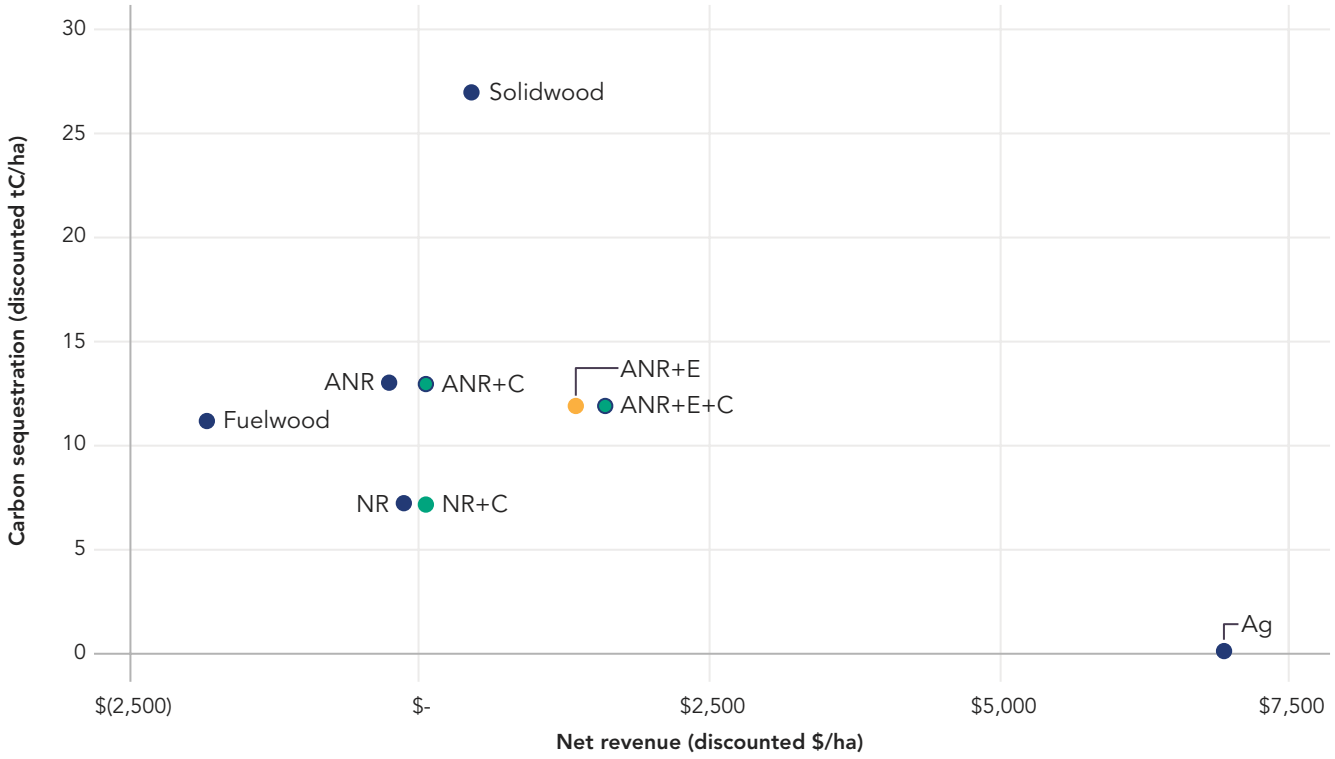
*Parkia biglobosa* is a deciduous, multipurpose tree of the Fabaceae family, which grows to 7–20 m in height across savannah woodlands of the Sudanian region of Africa (Lelea et al. 2022). In gallery forests across Benin Republic, Burkina Faso, Côte d'Ivoire, Cameroon, Nigeria, and Mali, trees can reach heights of up to 30 m (Omotayo, Ajibade, and Oyawoye 2024).

*P. biglobosa* is widely distributed across 19 countries within a belt between 5°N and 15°N, from the Atlantic coast in Senegal to southern Sudan and northern Uganda. The belt is widest in West Africa (maximum 800 km) and narrows to the east (Figure I4). Along with *Vitellaria paradoxa*, *P. biglobosa* is among the most common trees in agroforestry parklands across the region (Boffa 1999).

*Parkia biglobosa* is protected and planted in agricultural fields and fallows in savanna regions (Figure I5). It tolerates a wide variety of climatological conditions, within areas experiencing a dry season of 5–7 months/year, from 800 to 1,500 mm of annual rainfall (Boffa 1999). It can grow in regions with an annual rainfall of 500–800 mm in the Sahel, but also occurs in regions with much higher rainfall. The species prefers regions with a mean annual temperature of 26–28°C, but can tolerate lower temperatures and occurs up to 1,500 m a.s.l. altitude. Although it prefers deep soils with good drainage and fertility, *P. biglobosa* can also be found on shallow lateritic soils, stony slopes and rocky hills (Sina and Traoré 2002).

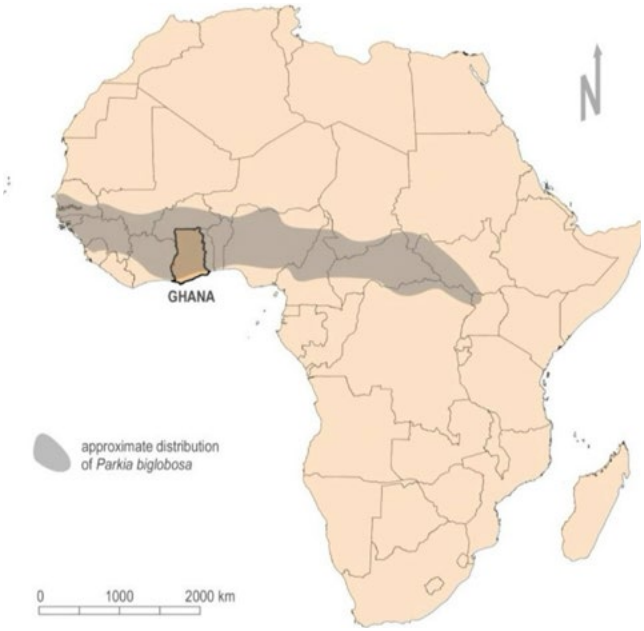
*Parkia biglobosa* is used for food, medicine, and income generation, especially in the northern regions of Ghana. The use of the fermented beans of African locust bean dates back many centuries and was already described in the 14th Century (Sina and Traoré 2002). The indehiscent pods of the tree, commonly referred to as locust beans, are initially pink and turn dark brown when fully mature (Figure I6). They are 30-40 cm long and can contain up to 30 seeds. Seeds are embedded in a sweet, powdery yellow pulp.

FIGURE I3. **Net discounted revenue and carbon storage for ANR with enrichment of *Parkia biglobosa* compared to alternative land uses**




*See Chapter 2 for full description of land uses.*

FIGURE I4. **The distribution of *Parkia biglobosa* in Africa**




*Source:* (Amaoko 2012).

FIGURE I5. ***Parkia biglobosa* in savanna woodland Burkina Faso**



*Photo source:* Wikipedia.

The strong-smelling fermented seeds are rich in protein and fat and are boiled and fermented to make the popular food condiment (Dawadawa in Ghana, Sumbala in Burkina Faso, and Iru in Nigeria), a key product in local markets (Nyadanu et al. 2017; Figure I7). The umami-rich condiment is used to flavor food or make tea (Lelea et al. 2022). The yellow powder from inside the pods can be boiled to make a sweet, refreshing drink or can be consumed directly as a high-energy snack. It is especially vital for low-income households as a source of protein and vitamin B. Young leaves and pods can be cooked and eaten as vegetables (Teklehaimanot 2004).

FIGURE I6. **Round inflorescences and elongated pods of *Parkia biglobosa* in Burkina Faso**



*Photo credit:* Ji-Elle Wikimedia.

FIGURE I7. **Dawadawa, The Hausa name for the fermented paste made from the seeds of the *Parkia biglobosa***



*Photo credit:* Achiri Bitamsimli, Wikimedia Commons.

The leaves of *P. biglobosa* are sometimes eaten as a vegetable, usually after boiling and then mixed with other foods such as cereal flour. Young flower buds are added to mixed salads (Sina & Traoré 2002). Roots and empty seed pods are boiled into a liquid used to seal floors and walls. Bark and root decoctions are rich in tannins, and are used to treat conditions like diarrhea, wounds, and skin infections. The plant is used in traditional treatments for malaria, diabetes and diarrhoea. (Sina and Traoré 2002; Lelea et al. 2022). The bark is burnt and mixed with earthworm casts and used to smooth away scars. Bark is also soaked and the water is rubbed on the skin for 'bone pain'. Fruit pulp, pods, and leaves serve as fodder for livestock. Wood is used for tools and construction, while ash from the wood is used in soap and dye making. The pod husks can be used to create a black dye for pottery (Sina & Traoré 2002).

As a leguminous tree, *P. biglobosa* contributes to soil fertility by fixing nitrogen, which benefits surrounding crops in agroforestry systems. Trees also reduce wind erosion and provide shade under their spreading crowns (Teklehaimanot 2004).

Trees may start flowering at 7 years, while still relatively small (Sina & Traoré 2002). Fruit pods measure about 15-45 cm long and 2 cm wide and are arranged in slightly bent, long hanging clusters (Figure x). Flowering and fruiting occur in the dry season (Hall et al. 1997; Sina & Traoré 2002). Bats are the principal pollinators (Pettersson and Knudsen 2001). Throughout West Africa, *P. biglobosa* pods are favored foods of chimpanzees, baboons, and other primates, who are important seed dispersal agents (Hopkins 1983). Antelopes, cattle, sheep, and goats also feed on the pods and disperse seeds.

## Cultural and livelihood importance

The production and consumption of *P. biglobosa* hold cultural significance in Ghana, often being associated with traditional ceremonies and local identity (Omotayo, Ajibade, and Oyawoye 2024). Dawadawa and other products are mainly sold in local and regional markets across West Africa, contributing significantly to household livelihoods. Women are primarily responsible for harvesting, processing, and marketing of dawadawa, making it a critical source of income for women in northern Ghana. In the Nadowli District of northern Ghana, a district with high levels of poverty, the most lucrative indigenous rural enterprise was dawadawa processing, with a benefit-cost ratio of 1.4 (Abankwah and Abebe 2011). Women have accumulated folk knowledge about *P. biglobosa* over many years and can distinguish individual genotypes by the taste and color of their pulp (Nyadanu et al. 2017).

Mature pods of *P. biglobosa* are collected for domestic use during a time when other foods are scarce, leading to the importance of this species as a food and nutrition security plant for local people and one of the priority wild edible fruit trees in Sub-Saharan Africa (Ouédraogo 1995; Houndonougbo et al. 2020). During food scarcity periods, young green whole pods are roasted and eaten by both

adults and children (Nyadanu et al. 2017). In the Pendjari Biosphere Reserve in Benin, *P. biglobosa* can contribute up to 53% to family net income during its fruiting period (Vodouhê et al. 2011).

## Conservation status

Although its IUCN conservation status is of least concern, there are serious threats to the sustainability of populations of *P. biglobosa* across much of its geographic range. *P. biglobosa* remains undomesticated and exposed to constant anthropogenic pressures in its natural habitats. Populations are dominated by ageing individuals and regeneration rates are low, leading to fragmentation and reduced populations across traditional agroforestry systems in West Africa. Little is known about the conservation status of P. *biglobosa* in central and eastern Africa (Houndonougbo et al. 2020).

High demand and over-exploitation have led to poor natural regeneration of *P. biglobosa* stands. Young trees are becoming scarce in northern Ghana (Lelea et al. 2022) and Nigeria (Odebiyi et al. 2009). Regeneration failure is caused by overharvesting of seeds, which are not allowed to germinate, and destruction of seedlings by browsing animals (Teklehaimanot 2004). In addition, shorter fallow periods, climate change, and weak institutional arrangements contribute to the species' decline. Depending on the country and context, tree tenure issues can disincentivize regeneration, as the benefits may not go to the land cultivator. In southern Burkina Faso, *P. biglobosa* trees are owned by heirs of the original settlers, and even though people may own the land they cultivate, they are required to share the fruits of *P. biglobosa* with the owners of the trees. For people who do not own the land, tree planting may be seen as an act of appropriation and is not allowed (Ouedraogo 2002; Raebild, Hansen, and Kambou 2012). In northern Ghana, *P. biglobosa* trees belong to the owner of the land and not to those who are farming the land (Lelea et al. 2022).

## Production and harvesting

In the central region of Ghana, products of *P. biglobosa* are harvested from wild populations, and there is little interest in cultivation (Nyadanu et al. 2017). In fact, there are some cultural constraints on tree planting due to a local myth that those who grow it will die by the time the tree reaches reproductive maturity. But the species is in an early stage of domestication by several criteria (Nyadanu et al. 2017).

*P. biglobosa* is propagated mainly by seeds, which are orthodox. To break seed dormancy, small farmers usually soak seeds in water overnight. Seedlings reach 20–25 cm tall after 20 weeks in the nursery, and are then planted out into the field. Direct sowing is possible, but the success rate varies depending on soil moisture and the degree of insect and rodent damage, as these pests are attracted by the strong smell of germinating seeds. Vegetative propagation of *P. biglobosa* is also possible. Grafting, cuttings taken from seedlings, and marcotting of 11–25 years old trees showed good results in Burkina Faso and Nigeria (Sina and Traoré 2002).

Coppicing is another common system for production, as *Parkia biglobosa* trees readily coppice after cutting. Copicing promotes use of *P. biglobosa* as a fodder source. Mature trees cut back to 50 cm above the ground, produce new shoots after one week. The tree's coppicing ability can continually produce biomass with a cutting interval of 16–24 weeks without compromising nutritional value (Hall et al. 1997).

The annual production of fruits varies between 25–130 kg/tree, depending on year and site. Average annual production of seeds is 900 kg/ha, of pulp 2.2 t/ha and of husks 1.9 t/ha. The production of trees planted in agricultural fields is on average higher than that of trees growing in fallows. Fruits are normally collected in April and May. Harvesting is either done from the ground using long-staked cutters, or by climbing the trees.

Thinning of older trees is practiced in Burkina Faso, Benin, Mali and Nigeria to promote fruit production and reduce the effect of shade on associated agricultural crops. In Burkina Faso, a decline in millet and sorghum yields occurred when cultivated under *P. biglobosa* trees. In some regions of Burkina Faso, regular weeding, and establishment of fire breaks, are customary in plantations of African locust bean.

Recognition of *P. biglobosa* as a desirable species for rehabilitating arid savanna lands has stimulated interest in propagating seedlings in nurseries (Shao 2002). Research to develop vegetative propagation methods will also allow multiplication of superior trees and on-farm domestication of the trees (Teklehaimanot 2004).

## Trade and marketing

The products of *P. biglobosa* are more important in local and regional markets than in international trade. Local trade is important in West Africa, especially in the Sahel region, where the dried or fermented seeds are often transported far from the sites of production, often across country borders (Sina and Traoré 2002). Based on a nationwide survey in Nigeria, sale of *P. biglobosa* products contribute an estimated 14.5% to household revenues (Teklehaimanot 1997).

In Burkina Faso, fruits of *P. biglobosa* are highly commercialized, with over 50% of respondents in a nationwide survey participating in trade (Teklehaimanot 1997). In general, women are fully responsible for the sale of fermented seeds, but both men and women sell the dried seeds. The yearly revenue earned from the sale of *P. biglobosa* products in Burkina Faso constitutes 28.8% of household income (Teklehaimanot 2004).

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# J. *Tetrapleura tetraptera* (*Prekese, uhio, Aridan,* Aidan fruit)

## Locations for economic models and ANR context

The economic model for *T. tetraptera* is based in moist-semi deciduous forest vegetation in the Suhum-Kraboa-Coaltara district (Latitude 6°2'3.84'N; Longitude: 0°27'8.64'W) in southeastern Ghana. The district operates under a dual system that combines customary ownership with state/public land ownership. The district is home to two ethnic groups (Akan and Ga-dangme) and has an annual rainfall of 1,270–1,651 mm and a mean annual temperature of 24–29°C (Kemigisha et al. 2018). Communities living in this district are characterized by high poverty levels, with most households depending on subsistence farming. The literacy levels range from 35–80%. The most common crops in the district are oil-palm and cocoa (Kemigisha et al. 2018). The area had 29% of natural forest cover in 2020 (Global Forest Watch 2025).

In the Central African Republic, *Tetrapleura tetraptera* is used in conjunction with Farmer Managed Natural Regeneration (FMNR) agroforestry systems to combat land degradation and improve rural livelihoods (Kpolita et al. 2022). In this context, farmers prune unwanted stems and branches from the selected stumps to direct the plant's energy toward the most vigorous shoots. The trees are then protected from livestock, fire, and other potential threats. These uses indicate that *T. tetraptera* would also provide similar benefits from supplemental enrichment planting in assisted natural regeneration systems in Ghana and other areas. Our cost-benefit model is based on a density of 100 trees/ha.

## ANR cost-benefit models, scenarios and assumptions

This woodland restoration model combining enrichment and maintenance of natural regeneration demonstrates excellent profitability, with an NPV of USD 10,814, IRR of 47%, payback in 6 years, and a BCR of 5.88 (Figure J1). Total costs are USD 6,151, of which 81% are management costs. Revenues start in year 5 and rapidly surpass costs, reflecting the economic potential of *Tetrapleura tetraptera* in assisted natural regeneration and fire-management regimes. Its implementation also incorporates ANR activities such as control of invasive species, fencing, fire protection, and ant control, which are essential for reducing regeneration pressure and ensuring seedling survival in savanna environments characterized by grazing and recurrent fire. The NPV shows strong returns in the sensitivity analysis, even under high discount rates, evidencing the robustness of this short-to-medium-term income model with efficient cost-benefit performance (Figure J2).

FIGURE J1. **Top: 30-yr cash flow model for enrichment of ANR with *Tetrapleura tetraptera (prekese)***

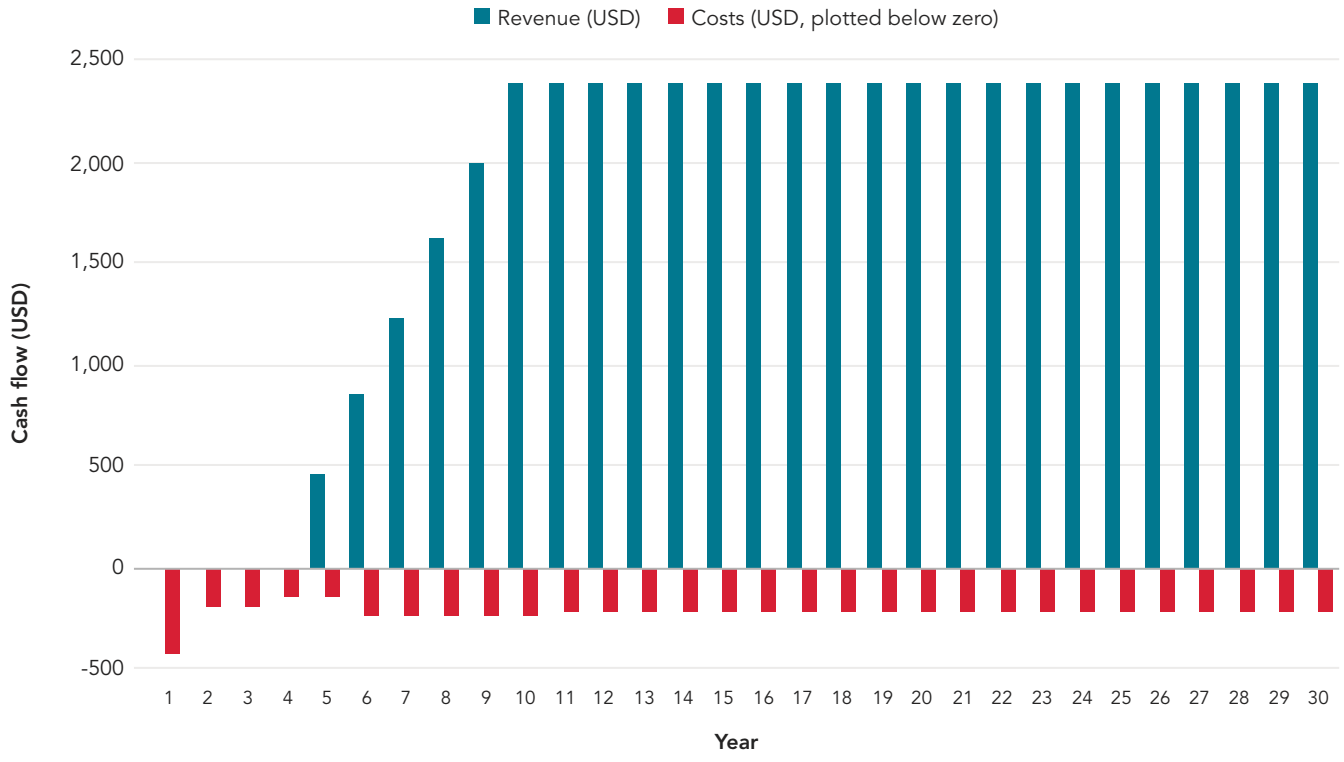
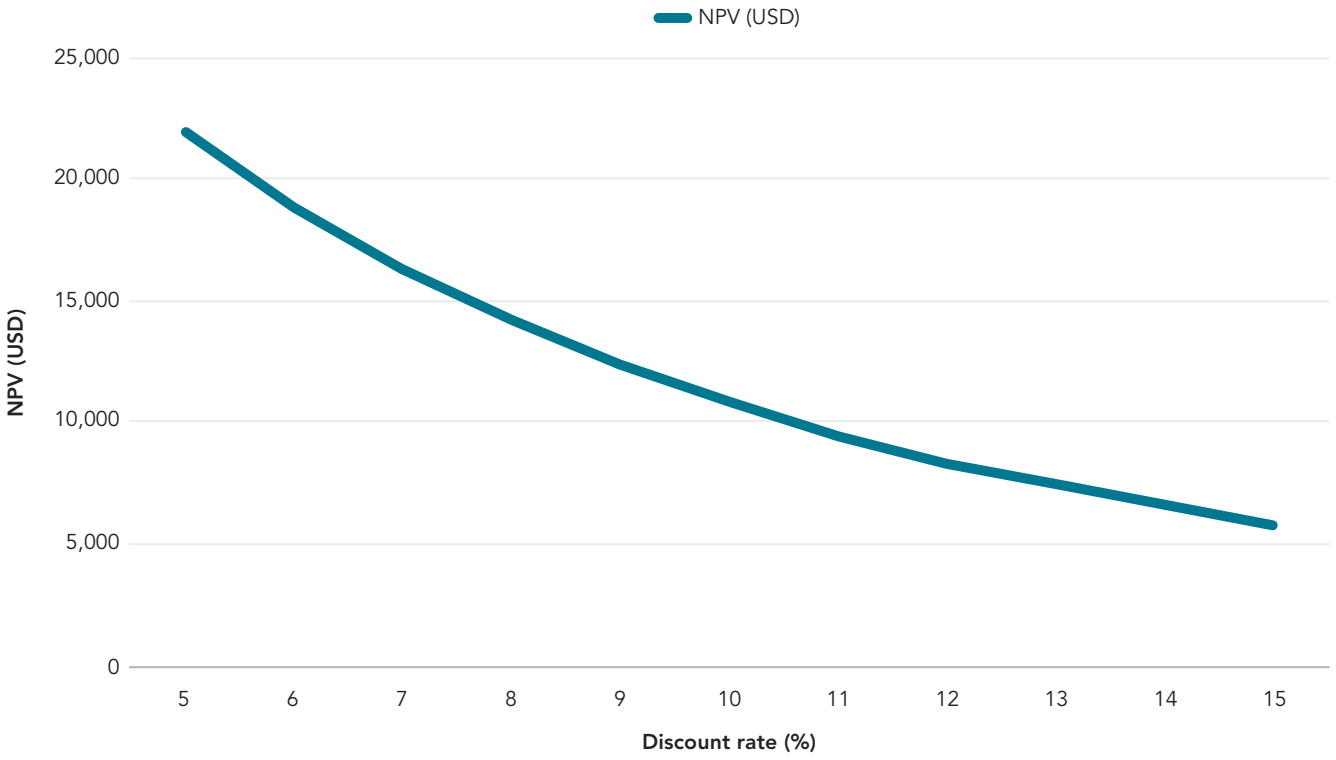


FIGURE J2. **Sensitivity of NPV to discount rate for enrichment of ANR with *Tetrapleura tetraptera***




## Carbon storage models

At this location, the highest carbon sequestration after 30 years is in timber plantations for solid wood production (70.5 MgC/ha). When compared at the same site, carbon sequestration from ANR with enrichment of *T. tetraptera* (46.6 Mg C/ha) is 8% lower than that of ANR without enrichment (50.4 Mg C/ha) but is 63% higher than minimally assisted natural regeneration.

## Alternative production models

For *T. tetraptera*, net revenue from ANR+E is estimated to be 2.2x higher than that of the most profitable alternative land use, agriculture, at the same site in Ghana (Figure J3). Additional revenue from carbon credits is USD 277/ha.

## Species ecology and ethnobotanical information

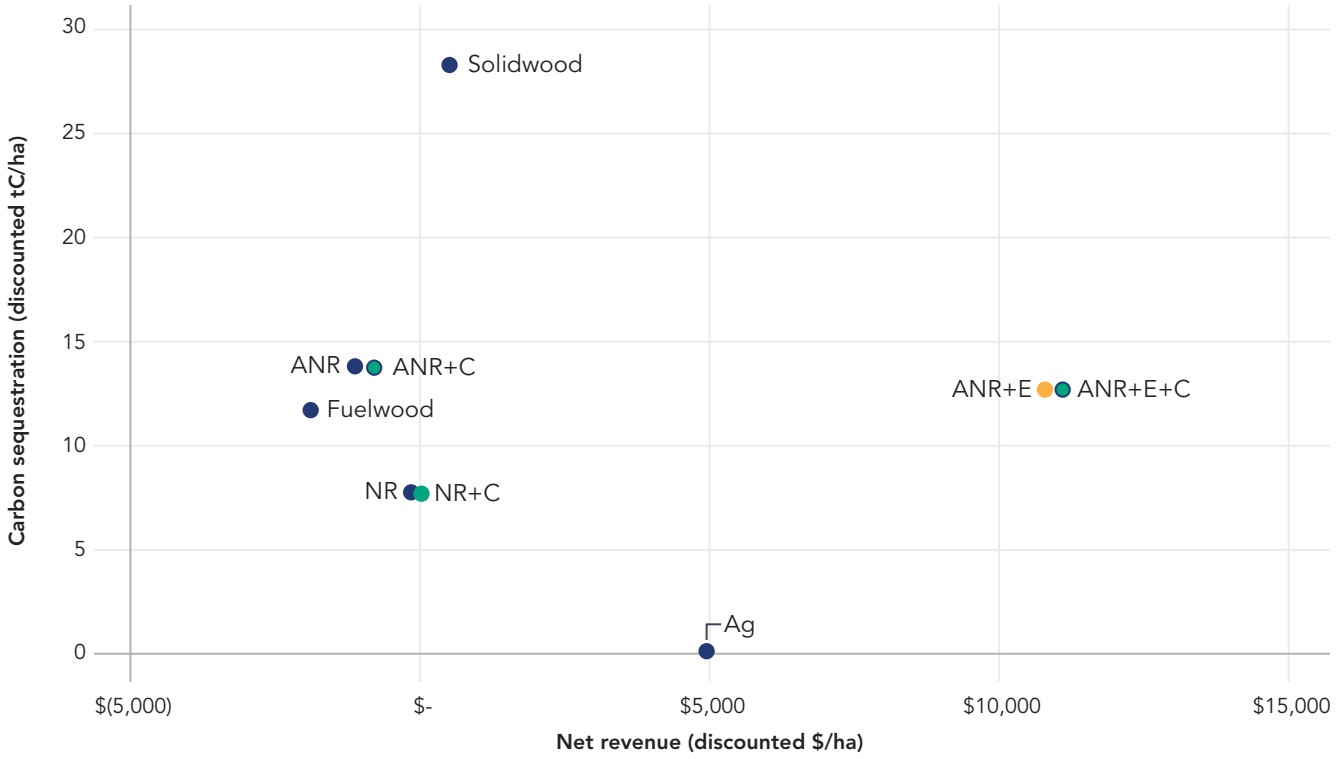
*Tetrapleura tetraptera* is a deciduous tree in the family Fabaceae native to 22 countries in Western and Central Africa (Figure J4). Trees can grow up to 25 m tall with a diameter at breast height of up to 3.0 m (Kemigisha et al. 2018). *T. tetraptera* grows in forests on the fringe of the West and Central African rainforest zone, where it is particularly common in secondary forest (Figure J5). It is found throughout the high forest zone, in riverine forest, in the southern savannah-woodland and in the forest outliers in the African plains (Fern 2014).

In Ghana, *T. tetraptera* is widely distributed across the transition zone and wet evergreen zone (Okyere-Agyapong, Amissah, and Bosu 2019). In Nigeria, the species is predominantly found in Southern forest regions including Akwa Ibom State, Cross River State, Rivers State and Abia State (Akpan and William 2016). Flowering begins towards the end of February and is over in early April. The indehiscent pods ripen from September to December. When the pods fall, their smell attracts small animals, who probably disperse the seeds (Orwa et al. 2009). Elephants are also common seed dispersal agents (Steentoft 1988).

Across its range, *T. tetraptera* is considered a multipurpose tree with high importance for food and medicine. The sweet smell or fragrance of the fruit is highly valued; it is used to flavor dishes. Fruit and stem bark are used for medicinal purposes (Adesina, Iwalewa, and Johnny 2016). It is mostly used to prepare palm nut soup and other types of soups called light soup because of its aroma. It is also used in perfumes, pomades, alcoholic beverages and biscuits as a flavoring agent (Adusei et al. 2019).

The fruit of *T. tetraptera* is a shiny dark brown pod with four wing-like ridges, two hard and woody ridges and two rather soft ridges; the latter two have an edible pulp (Figure J6). The seeds, which rattle in the pods, are small, black, hard, flat, about 8 mm long, are embedded in the body of the pod, which does not split open. The kernel contains oil (Orwa et al. 2009).

FIGURE J3. **Net discounted revenue and carbon storage for ANR with enrichment of *Tetrapleura tetraptera* compared to alternative land uses**




*See Chapter 2 for full description of land uses.*

FIGURE J4. **Distribution map of *Tetrapleura tetraptera***



*Source:* (WFO 2025).

FIGURE J5. ***Tetrapleura tetraptera* tree in Cameroon**



*Photo credit:* Joeymo; https://creativecommons.org/licenses/by-nc/4.0/.

*T. tetraptera* has many medicinal and nutritional properties (Adesina et al. 2016). Medicinal attributes are due to presence of bioactive compounds such as alkaloids, flavonoids, saponins, tannins, phenols and glycosides (Okwu 2003). Fruit of *T. tetraptera* is reported to have anti-arthritis, anti-inflammatory and anti-diabetic properties (Ojewole and Adesina 1983). It is also used in managing schistosomiasis, a chronic parasitic disease caused by blood flukes (Kemigisha et al. 2018).

In Ghana, fruits of *T. tetraptera* are used to produce beverages or supplement existing drinks to enhance their nutritional and medicinal value. It is often used to improve the aromatic quality of beer. Some local producers of the traditional gin 'akpeteshie' which is distilled from palm wine, flavor the gin with prekese (Adadi, Barakova, and Krivoshapkina 2019).

A study *T. tetraptera* in Ghana, Nigeria and Uganda documented local uses for medicine, food, timber, and cultural rituals (Kemigisha et al. 2018). Most households in the three countries used *T. tetraptera* fruits for medicine with 82.5 % of the respondents in Ghana, 60.3% in Nigeria and 68.5 % in Uganda. Fruits of *T. tetraptera* were used to treat a total of 20 diseases, with respondents reporting 14 diseases in Ghana, 15 in Uganda and 12 in Nigeria. Food was the second use reported in the two west-African countries with 72.0 % of the respondents in Ghana and 33.5% in Nigeria (Kemigisha et al. 2018).

*Tetrapleura tetraptera* is among the best-known spices from Nigerian forests that is mostly used in local dishes to enhance aroma and flavor to food and beverages (Akpan and William 2016). Medicinally, it is used to cure fever and as an enema for constipation. The species also produces valuable timber, and its demand outweighs its supply, suggesting an important role for domestication and establishment in plantations or agroforestry systems.

FIGURE J6. **Ripening fruits and foliage of *Tetrapleura tetraptera* in Cameroon**



*Photo credit:* Joeymo; https://creativecommons.org/licenses/by-nc/4.0/.

## Cultural and livelihood importance

Although much of the use of T. tetraptera is within the household, indigenous people and traditional communities across West Africa, have commercialized and marketed various parts of the plant, such as the pods, to generate income (Tchapda et al. 2022). Cultural uses of *T. tetraptera* were reported in Uganda and Nigeria (Kemigisha et al. 2018). These include: protection against evil spirits, thieves and witches and restoration of lost love relationships. Fruit, seeds, and stem bark are all used for cultural purposes. Planting T. *tetraptera* trees in the compound was also reported as a cultural practice in Uganda (Kemigisha et al. 2018).

Fruits are the only part of the tree that are commercially sold in retail shops, local markets or along roadsides. Kemigsha et al. (2018) found that households who reported selling T. tetraptera fruits made up 16%, 15% and 6% of the respondents in Ghana, Nigeria and Uganda respectively. Average fruit sale per trader per market-day was estimated by traders to range from 0.6 to 151.0 kg in Ghana; mean prices of fruits in Ghana and Nigeriawere 2.6 ± 2.1 (USD/kg) and 0.4 ± 0.5 (USD/kg) respectively (Kemigisha et al. 2018).

## Conservation status

*Tetrapleura tetraptera* was most recently assessed for *The IUCN Red List of Threatened Species* in 2018, and was listed as Least Concern. But populations of *T. tetraptera* are declining in many regions due to deforestation, poor seed germination and overexploitation (Akpan and William 2016; Fredrick, Chima, and Noah).

## Production and harvesting

*T. tetraptera* produces orthodox seeds with hard, impermeable seed coats whose dormancy hinders germination and limits successful regeneration for sustainable production (Olaniyi, Olajuyigbe, and Adegeye 2022). To break dormancy of seeds, it is necessary to treat seeds with sulphuric acid or to mechanically scarify them. Vegetative propagation techniques can also be used to produce seedlings. Stem cuttings taken from seedlings of *T. tetraptera* were amenable to vegetative propagation with or without growth regulator application (Olaniyi, Olajuyigbe,

and Adegeye 2022). Vegetative propagation offers several advantages such as fixing desired traits in species, mass propagation of superior trees, reduced gestation period and the ability to combine multiple genetic traits (Leakey and Van Damme 2014).

In Ghana, the Centre for Biodiversity Utilisation and Development at the Kwame Nkrumah University of Science and Technology in Kumasi has been involved in the domestication *T. tetraptera* and offering assistance to farmers (Aduasah, Asibey, and Amoako-Atta 2002). Efforts to domesticate *T. tetraptera* are challenged by pest infestation, reducing tree growth and fruit production (Mohammed et al. 2025). Tree mortality was significantly less (17.8%) in mixed plantation than monoculture (43.5%), however, suggesting that an integrated pest management strategy combining eco-friendly pest control methods and mixed plantations could mitigate tree mortality caused by the insect pest, a longhorned beetle from the Cerambycidae family (Mohammed et al. 2025). Growing *T. tetraptera* at low densities in mixed species assisted natural regeneration plots could also be an effective management strategy.

Studies on germination and seedling growth show that *T. tetraptera* has some degree of shade tolerance. Germination of *T. tetraptera* seeds was not significantly influenced by light intensity, but seedling growth and leaf production were significantly affected by light intensity. The result showed that 50% and 75% light intensities are the most suitable for the early seedling growth (Fredrick, Chima, and Noah 2020). Seedlings grown on loamy sand soil generally performed better than other soil types in height, stem diameter, and number of leaves (Akpan and William 2016).

The average yield of a mature *T. tetraptera* tree is between five to ten fertiliser bags full per season, where each bag weighs about ten kilograms. Yield tends to increase with age and branching pattern of the tree (Aduasah, Asibey, and Amoako-Atta 2002).

*T. tetraptera* has potential to improve livelihoods of communities in Sub-Saharan Africa, but achieving this potential requires domestication. As *T. tetraptera* trees fruit early (about two years and a half after planting), they could be planted in agroforestry systems (Addo-Danso et al. 2012). Domestication of *T. tetraptera* has already been attempted in some countries, and farmers in Ghana already manage *T. tetraptera* through natural regeneration on their farms (Blay 1997; Kemigisha et al. 2018). Including T. *tetraptera* as an agroforestry tree in farms and planting it as shade tree in coffee, tea and cocoa plantations may improve livelihoods while also enhancing sustainability of land management (Kemigisha et al. 2018). For these same reasons, *T. tetraptera* is a promising species for enrichment planting in ANR systems in Ghana and other countries within its geographic range.

## Trade and marketing

In Cameroon, the fruits of *Tetrapleura tetraptera* are primarily marketed through local and regional market systems. The marketing chain involves several actors and channels, from small-scale rural harvesters to wholesalers and online marketplaces that serve both domestic and international markets (Tchapda et al. 2022). Major constraints on commercialization are low market value of fruits and the lack of a uniform measurement unit for sales (Aduasah, Asibey, and Amoako-Atta 2002).

Fruits are picked when they turn brownish-black or drop down due to gravity. They are usually not sufficiently dry prior to harvesting or gathering. Therefore, further drying is essential to reduce moisture content in fruits to extend their shelf life. Before sale, 3 or 4 dried fruits are fastened together using thread (Adadi, Barakova, and Krivoshapkina 2019).

FIGURE J7. **Fruits of *Tetrapleura tetraptera* for sale in a market in Ghana**



*Photo credit:* Felix Nartey (Wikipedia).

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# K. *Vitellaria paradoxa* (Shea nut, *nkuto*, Karité)

## Locations for economic models and ANR context

The location of our economic and alternative land-use models is Nakpalli Village in the north-eastern part of Ghana with a natural density of 50–70 *V. paradoxa* trees/ha (Jepsen, Stopponi, and Jørgensen 2024). Nakpalli is in the Sudanian Savanna ecoregion. Farming seasons are defined by a single rainy season between July and September. The average annual rainfall is 1,000 mm (Jepsen et al. 2024). Farmers in Nakpalli typically manage agroforestry parkland systems by seasonal crop rotation with sequential cultivation and fallow periods. Natural forest cover in this savanna woodland region is low, only 2% (Global Forest Watch, 2025). Shea trees are by far the most dominant tree species in local agroforestry systems. Farmers fallow their land for an average period of 2.8 years and cultivate the lands for 3 years on average (Jepsen et al. 2024). The main crops cultivated are yam (*Dioscorea rotundata* (Poir.) J. Miège), maize (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench), cassava (*Manihot esculenta* Crantz) and millet (*Pennisetum glaucum* (L.) R. Br). The parklands and surrounding areas in Northern Ghana are dominated by tree species of anthropogenic interest, such as shea (*Vitellaria paradoxa* Gaertn.; Figure K1), locust bean (*Parkia biglobosa* (Jacq.) R.Br. ex G. Don), cashew (*Anacardium occidentale* L.), mango (*Mangifera indica* L.), neem (*Azadirachta indica* A. Juss) and teak (*Tectona grandis* L.f.).

In addition to their natural regeneration in agroforestry parklands, shea trees also grow in uncultivated bushlands (Cronkleton et al. 2021; Lovett and Haq 2000; Poudyal 2011). Bushlands are characterized by mixed, self-established remnant vegetation with minimal human disturbance. This is the context for assisted natural regeneration with enrichment using remnant or newly established *Vitellaria paradoxa* trees. Shea trees successfully regenerate in burned crop fields and fallows, enhancing its importance for assisting natural regeneration of forests in the region (Lohbeck et al. 2020). The main factors that negatively affect natural regeneration are grazing and limited seed dispersal if adults are not close by (Lohbeck et al. 2020). Hence, fencing and enrichment planting are of vital importance to regenerate natural populations in areas with low densities of adult trees.

FIGURE K1. ***Vitellaria paradoxa* trees and farming near Chiana, Kassena Nankana District - Ghana**



*Photo credit:* Axel Fassio/CIFOR.

In this area of Ghana, management and land-use decisions by farmers follow a customary land tenure system, where land is allocated to people who ask for it by the village chief for cultivation (Ubink, Hoekema, and Assies 2009). Formal land registration or land titling for smallholder farmers are not practiced in the village. Customary rights do not guarantee legal ownership of the land. Access to shea trees varied among shea collectors in Nakpalli (Stopponi et al. 2025). Collecting shea nuts in fields and fallows was restricted to household family units, with rights of access for all women within the same household. But some shea collectors, mainly marginalized groups such as widows or divorced women, were relegated to gathering nuts in bushlands (Ubink, Hoekema, and Assies 2009).

## ANR cost-benefit models, scenarios and assumptions

The baseline 30-year economic model for *Vitellaria paradoxa*, shows positive but modest feasibility indicators (Figure K2). The Net Present Value is USD 2,293 and the Internal Rate of Return is 18.8%. The payback time for net revenue is 11 yr and the benefit-cost ratio is 2.07. This model assumes a 10% discount rate and a density of 80 trees/ha in assisted natural regeneration, within the range of density in natural populations. This density is about a third of the density used in agroforestry plantations to ensure adequate conditions for natural regeneration of other native vegetation. Total costs over 30 years are USD 5,539, of which 58% is management costs, 30% is harvesting costs and 12% is implementation costs. NPV remains positive at a discount rate of 15% (Figure K3).

## Carbon storage models

Over 30 years, ANR with enrichment of *V. paradoxa* yielded a total carbon storage of 57.14 MgC/ha, which is 5% lower than for ANR without enrichment (60.15 Mg C/ha). The discounted revenue from carbon credits is USD 353 over 30 years. Carbon storage in ANR is nearly double that of minimally assisted natural regeneration, which yields a total carbon storage of 38.29 MgC/ha.

## Alternative production models

For shea, net revenue from ANR+E is estimated to be 0.57x that of the most profitable alternative land use, agriculture, at the same site in Ghana (Figure K4). This means that implementing ANR with enrichment of *V. paradoxa* carries a substantial opportunity cost. An increase in the carbon price from USD 6 to 30/ton of carbon would make the net revenues of ANR with enrichment on par with those of agricultural land use in the same site. Meanwhile, carbon sequestration from ANR+E is comparable to that of ANR and below that of timber plantations for solid wood production, at the same site.

FIGURE K2. **Cash-flow over 30 years for ANR with enrichment of *Vitellaria paradoxa***

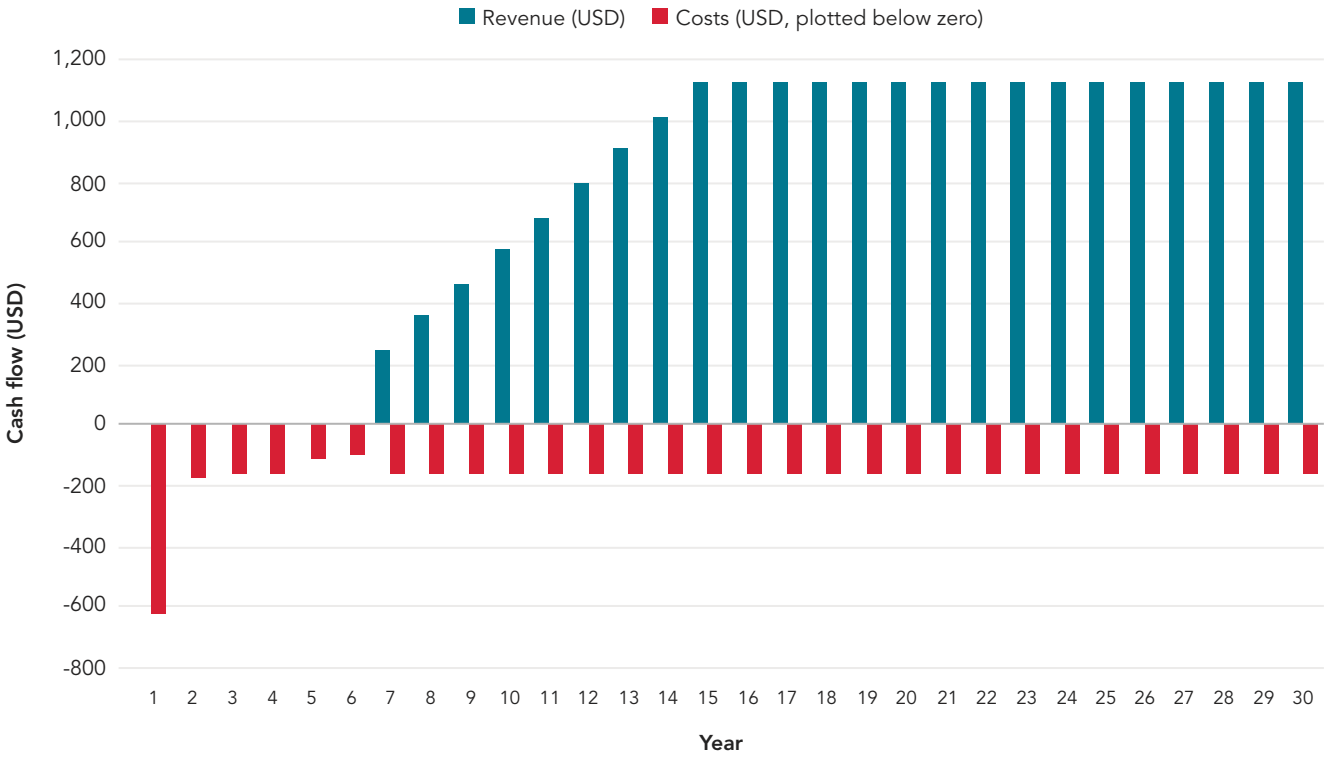


FIGURE K3. **Sensitivity of NPV to variation in discount rate for ANR with enrichment of *Vitellaria paradoxa***

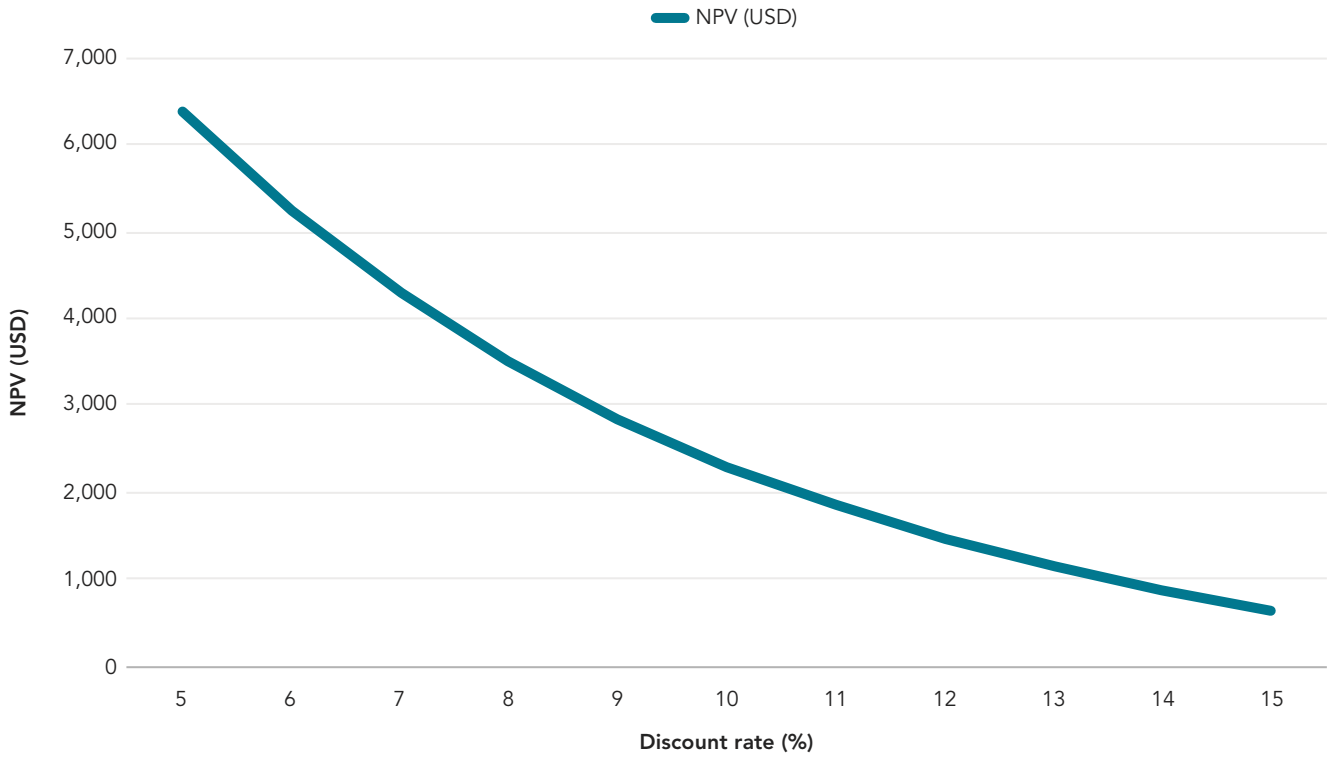
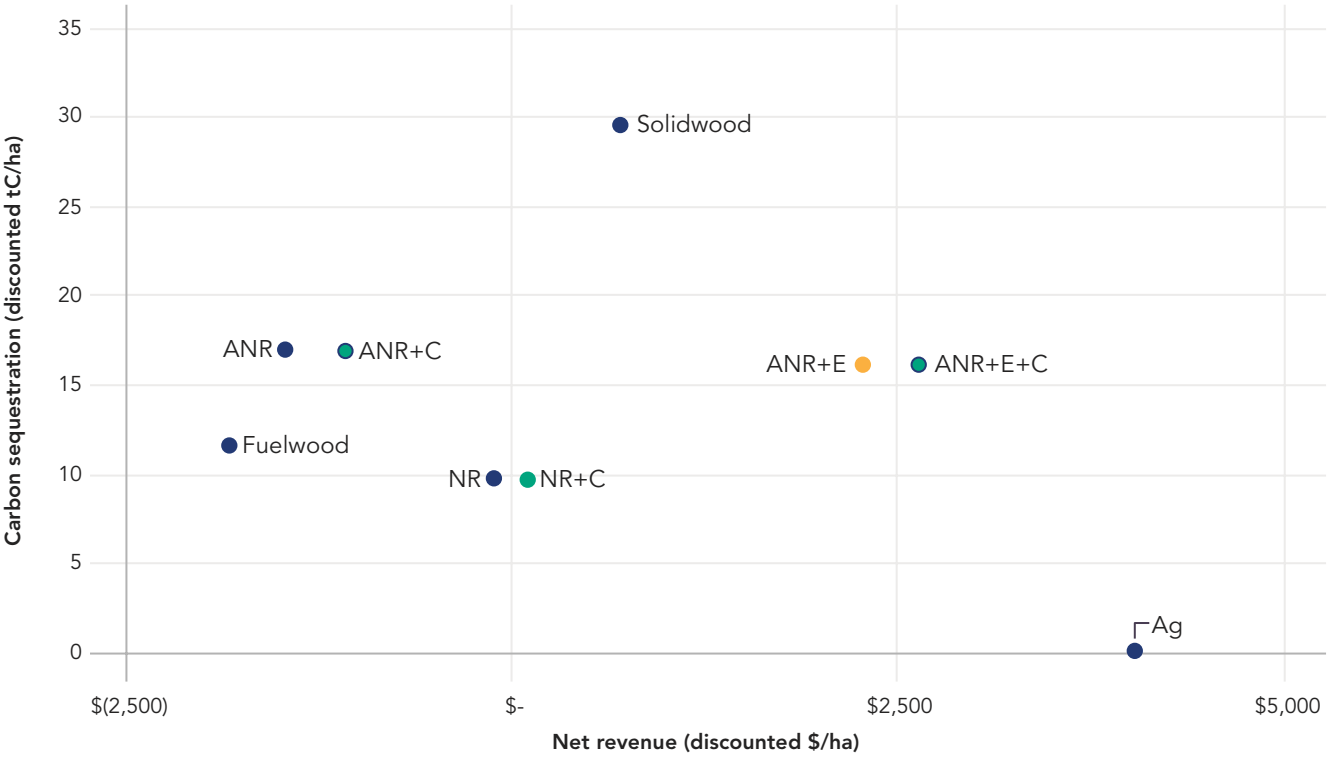



FIGURE K4. **Net discounted revenue and carbon storage for ANR with enrichment of *Vitellaria paradoxa* compared to alternative land uses**




*See Chapter 2 for full description of land uses.*

## Species ecology and ethnobotanical information

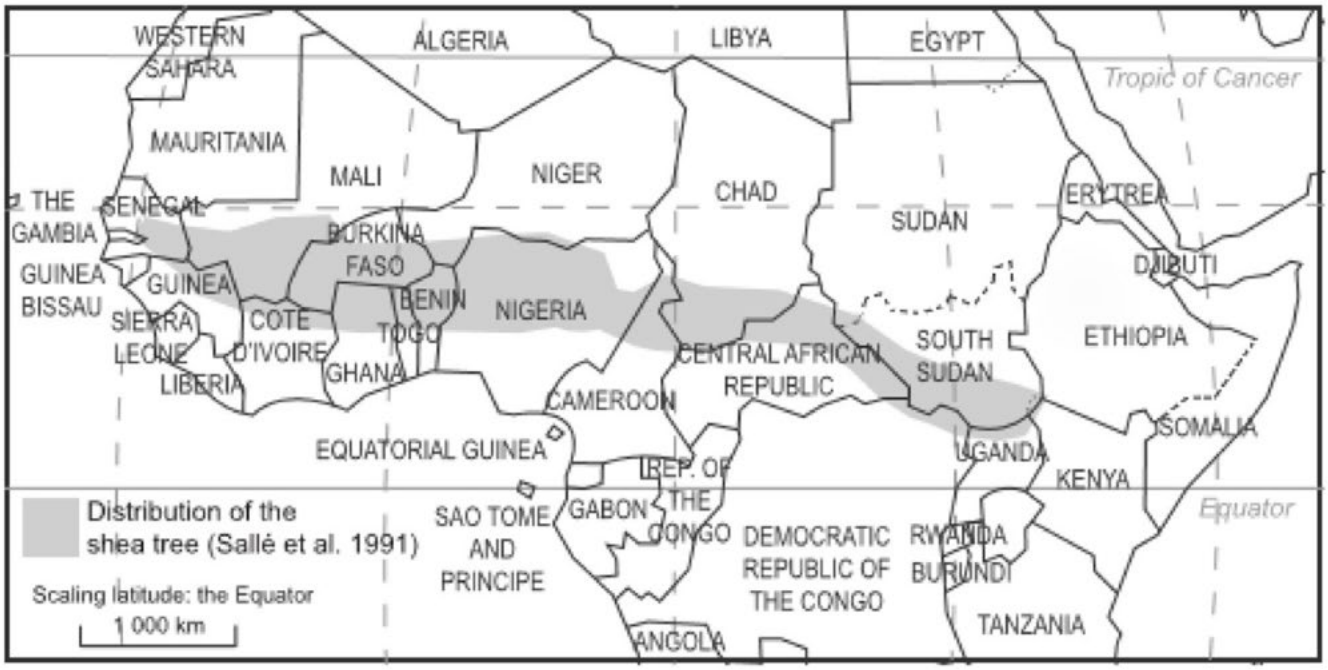
The Shea nut tree, *Vitellaria paradoxa* (formerly *Butyrospermum parkii*) is a semi-domesticated, slow-growing deciduous fruit tree in the Sapotaceae family. It is indigenous to Africa and a major component of the woody vegetation in the semi-arid Sudan and Guinean zones (Lovett and Haq 2000; Masters 2002). Shea trees occur in 19 countries across the African continent, from Senegal to Ethiopia, extending over more than 5,000 km of habitat area (Wikipedia; Figure K5). Natural stands and managed shea agroforestry parklands cover 300–350 million ha of Sahel-Sudanian-Savanna Africa (Lovett 2018). Shea tree ecosystems cover 50 million ha, including agroforestry cropped areas, set aside land, shrubland forest, and improved parklands (GSA 2020). Trees reach up to 25 m in height with a wide crown and a trunk diameter of up to 2 m. *Vitellaria paradoxa* trees are found in areas with temperatures ranging from 24 to 40°C and annual rainfall of between 500–1,400 mm (Ky-Dembele et al. 2021).

All parts of the tree, including the flower, fruit pulp, nuts, bark, root, and leaves, are used in rituals or traditional medicines to treat various diseases and injuries while the wood and charcoal are used for building, mortar and cooking (Choungo Nguekeng et al. 2021; Maanikuu and Peker 2017). But the fruits of *Vitellaria paradoxa* are the most importance resource. Shea fruits are flat and round and resemble large plums. Each fruit contains from 2–4 shiny brown seeds, called shea nuts (Figure K6). Fruits take from 4–6 months to ripen. On average, a tree can produce 15–20 kg of fresh fruit per tree. The oil-rich and edible seeds are embedded in a thin, tart, nutritious pulp. Shea butter is produced by removing the shells of the nuts and boiling the inner kernels (Figure K6), which are then dried, roasted, and ground into a paste. Water is then added causing the shea oil to separate and rise to the surface. Traditional production is often performed by women and is completely manual. Due to the importance of this species, *V. paradoxa* has been included on the priority list of African forest genetic resources by the UN Food and Agriculture Organization (Lovett and Haq 2000).

In the Western Hemisphere, shea butter is most commonly used as an emollient in cosmetics and is less commonly used in food. At least 50% of collected shea kernels in West Africa are used to make butter and oil for local consumption, whereas only 10% of all shea exports are destined for the international personal care sector (Lovett 2018). Throughout Africa, shea nuts are used extensively for food and for medicinal purposes. They are a major dietary source of fat. In Ghana and Nigeria, shea butter is a major ingredient for making African black soap.

The edible protein-rich caterpillars of the moth *Cirina butyrospermi* feed solely on *Vitellaria paradoxa* leaves are widely collected and eaten raw, dried or fried. Fruit pulp is high in vitamin C, whereas kernels are rich in fat (17.4–59.1 g/100 g dry weight). Fat from the kernels also have antioxidant and anti-inflammatory activities (Honfo et al. 2013). *Vitellaria paradoxa* is also an important source of honey (Ky-Dembele et al. 2021).

FIGURE K5. **The distribution of *Vitellaria paradoxa* across Africa**




*Source:* Global Shea Alliance.

FIGURE K6. **Fruits (left) and boiled kernels (right) of *Vitellaria paradoxa***



*Photo credits:* Marco Schmidt (Wikimedia Commons).

In the Sudanian ecological zone of Northeast Ghana (Navrongo) and South-Central Burkina Faso (Nobéré), *Vitellaria paradoxa* is the most common tree in agroforestry parklands, composing 38% of all trees and 12% of regenerating stems (Lohbeck et al. 2020). The species has cryptogeal germination, allowing shoots to remain below ground for months and avoid damage from fires. Trees are also tolerant of frequent droughts, which are characteristic of the region, due to their deep roots (Boateng 1978).

## Cultural and livelihood importance

Shea butter is an important dietary component across regions of Africa that are home to 200–300 million people, providing 7–10 kg of dietary fat per person in many communities (Lovett 2018). Despite its large contribution to West African economies, over half of the total shea harvest—around 350,000 tons per year—is consumed domestically (Ky-Dembele et al. 2021).

In the Sahel Region, shea fruits mature between May and August, during a period of food scarcity; the sweet fruit pulp is usually consumed as food and shea butter serves as cooking oil to complement household food needs (Tanzile, Fielmua, and Domapielle 2023). In the Bole District in Ghana, shea contributed between 8 and 25 percent of women's income (Ingram et al. 2016). Processing of shea nuts and butter function as forms of natural insurance against low farm yield and other income shortfalls (Choungo Nguekeng et al. 2021). In Burkina Faso, collecting and processing sheanuts and kernels contributed to as much as 12 percent of total household income of the poorest households and 7 percent of total household income of the well-off households (Pouliot 2012).

Women are largely responsible for collection of fruits from trees and processing kernels into shea butter (Jepsen et al. 2024). Shea butter is referred to as 'women's gold' due to the livelihood benefits that women farmer derive from shea production and processing across the value chain (Pouliot 2012). A study in Wa Municipality in northern Ghana found

FIGURE K7. ***Vitellaria paradoxa* tree**



*Photo credits:* Marco Schmidt (Wikimedia Commons).

that 93.7% of the women participated in the shea value chain as a main source of their livelihood (Adams, Abudulai, and Bashiru 2016). Despite its crucial importance for poor people's livelihoods and for the generation of income for women, the time-consuming activities of harvesting and processing generate low returns per unit of labor. The Global Shea Alliance estimates that 16 million women living in rural communities collect fresh shea fruits for processing.

FIGURE K8. **Shea butter production process near Chiana, Kassena Nankana District - Ghana**



*Photo credit:* Axel Fassio/CIFOR.

## Conservation status

The current conservation status of *Vitellaria paradoxa* is Vulnerable (IUCN 2.3). Shea parklands across Sahel-Savannah eco-zones are significantly threatened by invasive land use change and expansion of intensive mechanized agriculture (Lovett 2018). Intensified agricultural practices, shortened fallow periods and frequent burning have led to aging tree populations and reduced seedling recruitment (Jepsen et al. 2024). Climate change, increasing demographic pressure, disappearance of fallows, and uncontrolled tree harvesting for fuelwood and charcoal have all led to decline of natural populations and limit the natural regeneration of *Vitellaria paradoxa* (Ky-Dembele et al. 2021). Rapidly declining tree densities cause soil erosion and reduce water infiltration and rainfall, which negatively affect agricultural productivity. Land tenure security and tree usufruct arrangements discourage protection and planting of shea and other native trees (Poudyal 2011). Although the majority of people interviewed from Nakpalli Village in the north-eastern part of Ghana wanted more shea trees on their lands, only 10% had planted or transplanted trees. In large part, this reluctance to plant stems from the cultural belief that shea trees are "gifts from God" and should not be planted by humans (Stopponi et al. 2025).

Genetic studies highlight that *V. paradoxa* maintains high genetic diversity across varying land uses, suggesting resilience to farmer selection and anthropogenic pressures (Abdulai, Krutovsky, and Finkeldey 2017). In addition to traditional land-use practices, restoration practices that enhance natural regeneration and enrichment planting of *V. paradoxa* where recruitment levels are low play a critical role in sustaining this culturally, ecologically and economically important species in the semi-arid Sudan and Guinean zones of Africa (Mbawine and Dzekoto 2023).

## Production and harvesting

Trees start to bear fruit at 10-15 yr old with full production reached at 20-30 yr. Fruits are produced for up to 200 years (Wikipedia). A mature tree can bear on average 15–30 kg fruits per year (3-6 kg of kernel) and up to 50 kg during very good harvest years. (Nikiema and Umali 2007). Fruits of *V. paradoxa* are largely collected from wild-grown trees rather than from cultivated trees. A study on the anthropic selection of shea trees in Northern Ghana shows that farmers describe shea trees as "wild", since they rarely plant them, meaning that most trees stem from natural regeneration (Lovett and Haq 2000). Human selection over millennia indicates that the shea tree is a semi-domesticated species and two subspecies are recognized (Hall, Aebischer, and Tomlinson 1996). According to local farmers in northern Ghana, shea trees are selected due to their yields but other properties of the trees, such as health, size, growth, age, competition with crops and spacing allowing for mechanical soil preparation, are also important (Lovett and Haq 2000). Farmers in Southwest Burkina Faso identified 25 shea ethnovarieties based on primary fruit and nut variants (Karambiri et al. 2017).

Shea trees regenerate naturally in farmlands, fallow lands and other woodlands (Ky-Dembele et al. 2021; Jepsen et al. 2024). In Western sub-Saharan Africa, farmers often retain shea trees as part of their parkland agroforestry systems (Jepsen et al. 2024). On farmlands and agroforestry parklands, the main agricultural systems in the shea belt, shea trees are often protected from clearance by farmers. These areas are sequential farm-fallow systems where crops are cultivated on the same areas as shea trees, followed by temporary fallow periods, where the trees remain while the fields remain uncultivated to allow for soil regeneration (Jepsen et al. 2024). Integration of trees into land-use systems provides an essential source of livelihoods and income for local populations (Choungo Nguekeng et al. 2021).

*V. paradoxa* is easily propagated from both fresh seed (fruiting within 7–15 yrs after planting) and grafted scions (fruiting within 3–5 yr; Lovett 2018). Parkland restoration using assisted natural regeneration with enrichment can be a viable option, but requires support from tenurial changes, skill transfer and financing solutions. Incentives need to be offered for commercial shea nurseries and the breeding of early maturation, regular and high-yield varieties. On-farm trials of intercropped shea, FMNR and replanting of shea with other indigenous trees can be a part of climate-smart agroforestry programs that can increase annual tree and crop productivity (Lovett 2018).

Based on a project in Northwest Ghana, using a semi-mechanized production system can substantially raise income from shea-based livelihoods above the minimum annual wage in Ghana and contributed significant improvements of living conditions for women and their households. (Tanzile et al. 2023).

## Trade and marketing

*V. paradoxa* is the foundation of a billion dollar global industry. Approximately 800,000 metric tonnes of shea kernels are collected each year, with increasing investment in expanding supplies and processing (Global Shea Alliance 2025). In 2023, annual shea nut exports were around 500,000 metric tonnes, an increase of more than 600% from a decade earlier, highlighting shea nuts as a strategic commodity in international food and cosmetics markets (Adu 2025). The highest international demand is in confectionary industry, where it is used as an alternative to cocoa butter (Lovett 2018). In Ghana 94,000 metric tons of shea nuts are produced annually, making it the world's fourth-largest shea producer (CBI 2021).

The shea sector is dominated by women. An estimated 16 million women, half of them in West Africa, work in shea-related activities (Choungo Nguekeng et al. 2021). In Ghana, earnings from shea butter products in 2015 reached USD 64 million, a 23 percent growth from USD 52 million in 2014; while in Burkina Faso, the sector contributed CFA 10 billion (USD 17 million) through kernel sales in 2012 (Rousseau, Gautier, and Wardell 2015).

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# L. *Garcinia kola* (Bitter kola)

## Locations for economic models and ANR scenarios

The cost-benefit model for *Garcinia kola* was based in Odigbo LGA in Ondo State, Nigeria (148 m a.s.l.), where trees were abundant in densely populated areas in mature and secondary forests in the 1990s (Aiyelaagbe and Adeola 1993). The production, collection, and marketing of *Garcinia kola* contribute significantly to the livelihoods of the people in the rainforest ecological zones of Ondo State (Agbelade and Onyekwelu 2013). The area had 94% cover by native forests in 2020 (Global Forest Watch, 2025). The average smallholder farm in the area is 5.0 ha. Prevalent crops in the region are cocoa, oil palm, cassava, maize and tomatoes.

In Odigbo and most rural areas of Nigeria, land and tree tenure is primarily governed by customary practices, where communities collectively own land and resources like trees (Ezeh et al. 2022). However, the National Land Use Act of 1978 also influences land tenure security by vesting all land in the state government. Although this law officially recognizes community forest rights in principle, it allows the government to appropriate forest land for public use, which can bypass community rights and lead to conflicts.

## ANR cost-benefit models, scenarios and assumptions

The cash-flow analysis of ANR with enrichment of *Garcinia kola* shows highly favorable economic indicators with a net present value over 30 years of US$71,145 and a 59.2 % internal rate of return (Figure L1). The benefit-cost ratio is 24.03. Payback time is 7 years, whereas net revenue peaks in year 10. This baseline cost-benefit model for *G. kola* is based on a density of 46 trees/ha and a 10% discount rate. Total costs of ANR with *G. kola* are USD 8,078, of which 47% are management costs.

Among the 14 target species modelled, enrichment of ANR with *Garcinia kola* provides the third-highest levels of net revenue over 30 years, reflecting both low costs of production and high gross revenues. These findings are supported by the local studies on the profitability of *G. kola* in Nigeria (see final section on Trade and Marketing). Revenues remain positive even at discount rates of 15% (Figure L2).

FIGURE L1. **30-yr cash flow model for ANR with enrichment of *Garcinia kola***

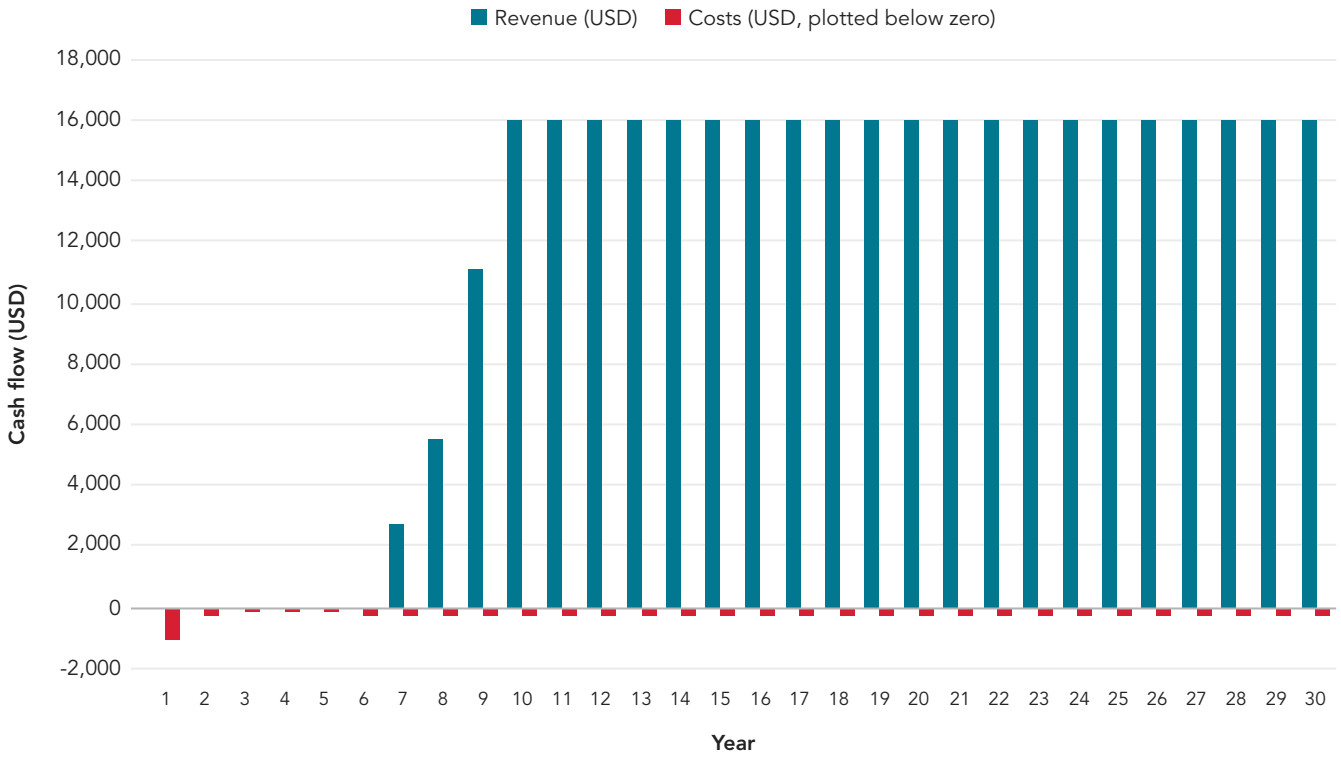
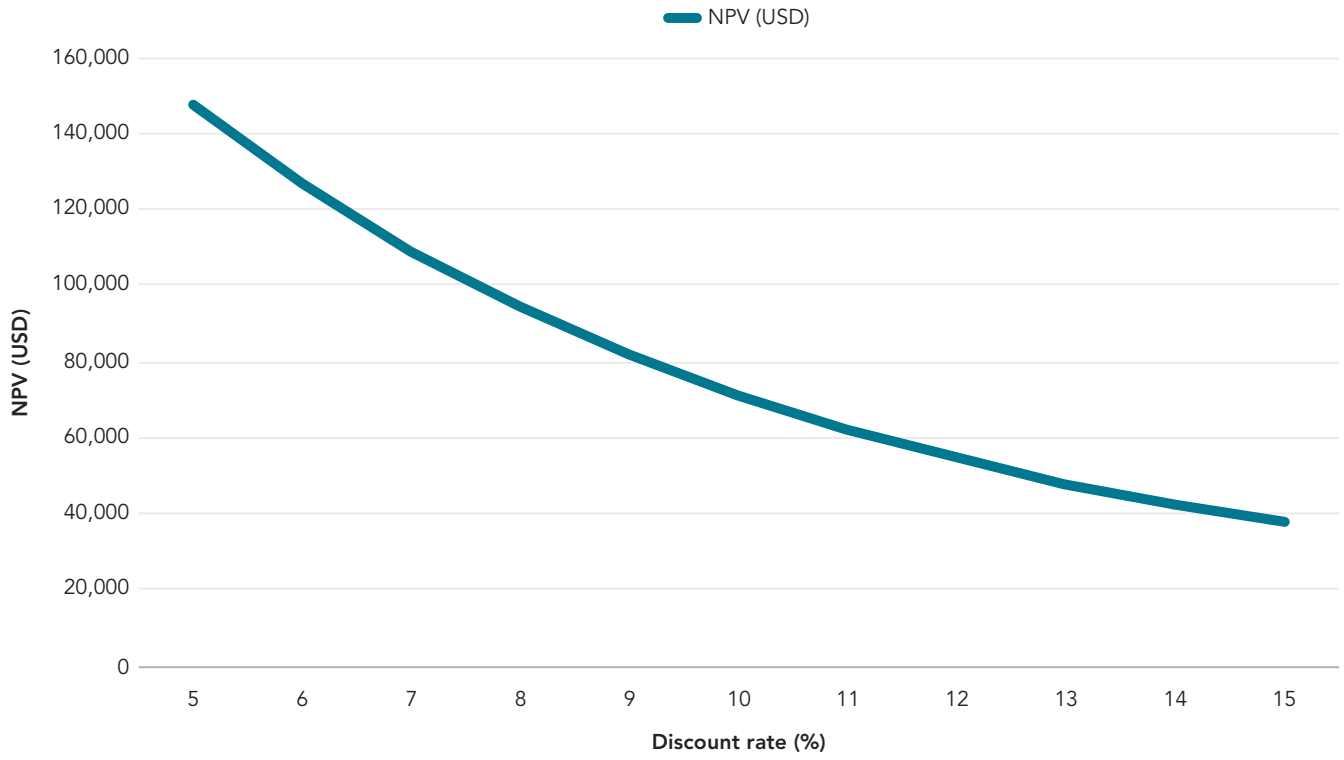


FIGURE L2. **Sensitivity of NPV to discount rate for ANR with enrichment of *Garcinia kola***




## Carbon storage models

Carbon sequestration in aboveground biomass from ANR with enrichment of *G. kola* is estimated to reach 70.82 Mg/ha, which is lower than 101.18 Mg/ha for ANR without enrichment, but similar to minimally assisted natural regeneration (74.57 Mg/ha). Management of *G. kola* trees in ANR is estimated to reduce forest biomass by 30%. At this location, the land uses with the highest values of carbon sequestration are ANR without enrichment and solid wood plantations.

## Alternative production models

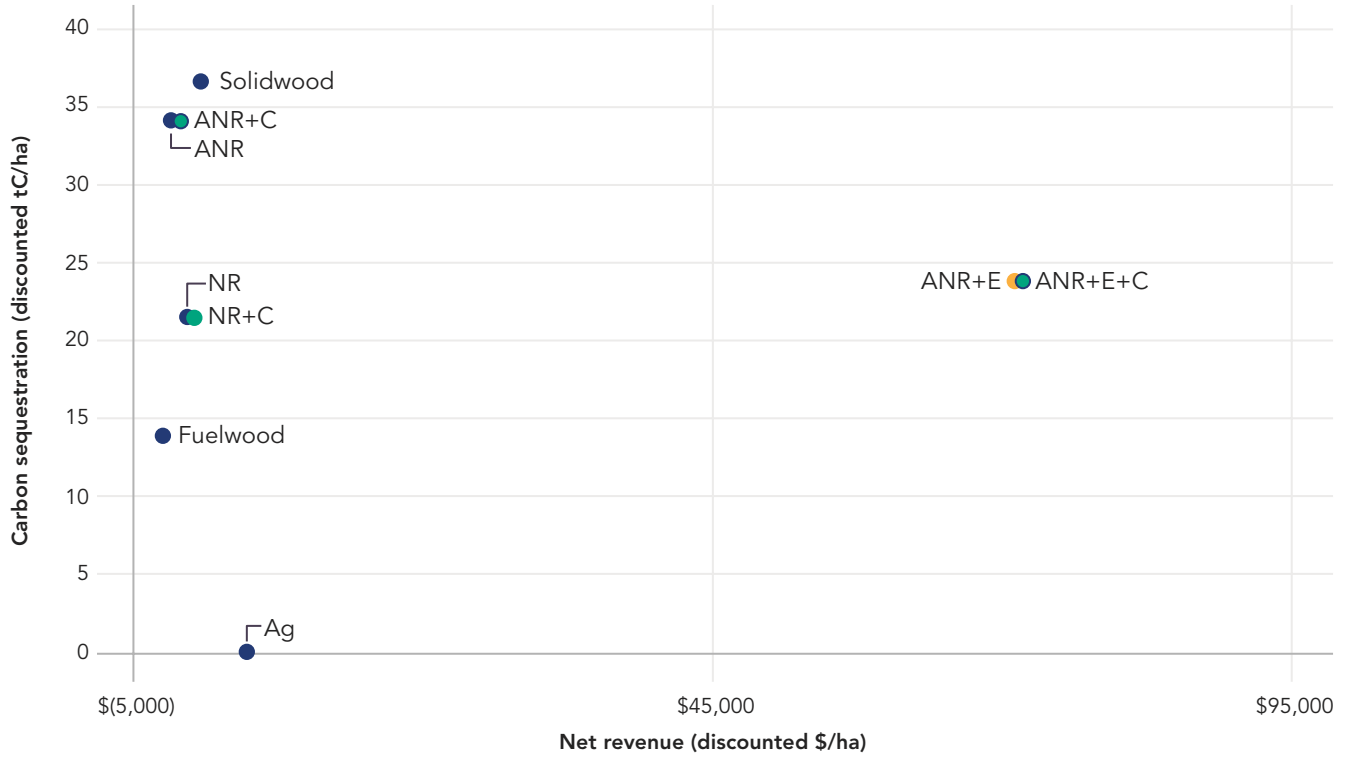
For *G. kola*, net revenue from ANR with enrichment is estimated to be 14.7x higher than that of the most profitable alternative land use, agriculture, at the same site in Nigeria (Figure L3). Including revenue from carbon credits increases net discounted revenue by USD 524/ha. However, revenue from carbon sequestration is below that of ANR without enrichment and timber plantations for solid wood production, at the same site.

## Species ecology and ethnobotanical information

*Garcinia kola* (Bitter kola) is an evergreen subcanopy tree species in the Clusiaceae family that grows up to 30 meters in height. Its natural habitat is subtropical or tropical moist lowland forests up to 300 m above sea level in Central and West Africa, from Congo to Sierra Leone. It is most abundant in Cameroon and Nigeria (Maňourová et al. 2019). *Garcinia kola* typically occurs in zones classified as tropical rainforest climate, tropical monsoon climate or tropical savannah climate. In these climate zones, daily temperatures usually vary between 21 and 31°C, and mean annual rainfall ranges from 2,000 to 2,500 mm per year with atmospheric humidity about 76% (Babalola and Agbeja 2010). The species can withstand various types of soils with a slight preference for sandy loams. Fine roots were found to harbor an arbuscular mycorrhiza (Bechem et al. 2014).

For centuries, the plant's fruits, seeds, nuts and bark have been used in folk medicine to treat a range of ailments, from coughs to fevers. It is also used as a remedy for osteoarthritis (Adegbehingbe et al. 2008). The seed and leaf have antibacterial activity and are also used to treat chest colds (Farombi and Owoeye 2011). The seeds (or nuts) of *Garcinia kola* are an important trade product in markets throughout West and Central Africa and have high cultural importance for three ethnic groups (Yoruba, Igbos and Hausa) in Nigeria (Figure L4). They are chewed as a stimulant, bitter astringent, and aphrodisiac. Stems and twigs of the plants are used as chewing sticks to prevent tooth decay in many parts of Africa (Akpona et al. 2009). The bark, after it is soaked in water, can be used as a treatment for intestinal worms and to cure stomach pain (Agbelade and Onyekwelu 2013).

FIGURE L3. **Net discounted revenue and carbon storage for ANR with enrichment of *Garcinia kola* compared to alternative land uses**




*See Chapter 2 for full description of land uses.*

FIGURE L4. ***Garcinia kola* fruits (left) and cleaned nuts and chewing sticks (right)**



*Photo credits:* Hiobson, Wikipedia CC 4.0 (left); T.K. Naliaka, Wikipedia CC 4.0 (right).

## Cultural and livelihood importance

*Garcinia kola* is very culturally important as it is used for wedding and naming ceremonies, housewarming and traditional festivals (Olujobi et al. 2024). The fruits of *Garcinia kola* are integral components of rural livelihoods. The fruits contribute cash earnings as they are sold in both rural and urban areas. The economic value of the seed from bitter kola trees makes it an important component in compound farming and agroforestry systems in Nigeria. Women are more engaged than men with the collection of fruits and marketing of seeds in local rural markets and social gatherings (Olujobi et al. 2024).

## Conservation status

In 2004, the species was classified as Vulnerable (VU) due to habitat loss, slow-growing seedlings, continuous felling, and overexploitation of the tree in West Africa (Cheek 2004). *Garcinia kola* is listed as one of the priority species for conservation in the Sub-Saharan Forest Genetic Resources Program (Tchoundjeu et al. 2006) and was selected as one of six preferred tree species by the World Agroforestry Centre (ICRAF) for domestication in West and Central Africa (Franzel and Kindt 2012). In Ondo State, local populations are being decimated due to harvesting of roots and bark for herbal remedies (Osowe Clement O, personal communication).

## Production and harvesting

In Omo forest reserve in Nigeria, close to 70% of the bitter kola production is harvested from government forest reserves (mature and secondary forests), where people living in or near forest reserves collect the fruits and extract and wash the seeds for trade (Figure L5). The remaining 30% is grown on farms, gardens, and fallow fields (Adebisi 2004). Wild seedlings occur in secondary forests, but regeneration from seed is poor (Agwu et al. 2018). In fact, many farmers who have trees on their farms indicated that they spared them during land preparation for farming, rather than planting them themselves (Babalola and Agbeja 2010).

FIGURE L5. **Farmers drying nuts of *Garcinia kola* in Ofosu, Ondo, Nigeria**




*Photo credit:* Osowe Clement O.

Raising *G. kola* seedlings under shade significantly enhances their growth compared to those grown in open fields, indicating that the species thrives better in environments with dense shade and limited light during its early growth stages (Akintan et al. 2022). About 58% of the farmers interviewed in Ijebu-Ode, Ogun State would like to cultivate *G. kola* trees on their farms, but are not aware of new improved production methods (Agwu et al. 2018). In Ifedore Local Government, Ondo State, however, 92% of respondents grow *Garcinia kola* in mixed plantations (alongside cocoa, oil palm, plantain, kola nut and other cash crops), whereas only 8% harvest products from natural forests (Olujobi et al. 2024). Given that bitter kola regenerates naturally in secondary forests and has a high demand in local markets, it is a strong candidate for enrichment planting in assisted natural regeneration systems in Southern Nigeria.

Trees grow relatively slowly and produce fruits after 10–14 years using traditional seed planting methods, however, use of grafted cuttings can reduce this period to 4–7 years. Mature trees produce an average of 834 fruits that yield 2,627 nuts per tree (Adebisi 2004). In protected areas, trees yield significantly more fruits compared to unprotected areas, suggesting that conservation efforts and the establishment of protected areas enhance productivity of this economically valuable species (Agwu et al. 2020). Fruits are produced from July through October. Once they are washed of pulp, seeds can be air dried and stored or sold fresh.

FIGURE L6. ***Garcinia kola* in Ifondo community, Akpabuyo Local Government, Cross River State, Nigeria**



*Photo credit:* Charles Ojong Nkpena.

## Trade and marketing

In southern Nigeria. the trade of *G. kola* nuts is more profitable than trade in other non-timber forest products, such as wonder cola (*Buccholzia coriacea*), sponge (*Acanthus montanus*) and cola nuts (*Cola nitida/acuminata*), because of its high amenability to storage, both fresh and dried (Babalola and Agbeja 2010). In Ondo State, Nigeria, women comprised 91% of individuals involved in marketing of *Garcinia kola* fruits in rural markets and 100% in urban markets. Most marketers are 20–50 yrs old. Sales of *Garcinia kola* seeds generated higher annual income in derived savanna ecosystem compared to rainforest areas (Agbelade and Onyekwelu 2013).

In Enugu State, Nigeria the net returns from the sales of Garcinia kola were reported to be ₦1,791.80 during the on-season and ₦9,843.80 during the off-season, with profitability indices of 1.17 and 1.85 respectively, indicating a profitable return for marketers (Eze and Eze 2007). In Ijebu-Ode, Ogun State, the gross profit varied significantly between markets, from ₦3,293.75 to 8,500. Despite these variations, 90% of respondents confirmed the profitability of trading in bitter kola (Adedokun, Adegbenjo, and Oyelakin 2021). In Nkwerre Local Government Area, Imo State, a net profit of ₦200,157.00 was recorded from the sales of bitter kola, highlighting its economic importance to local traders (Unaeze, Oladele, and Agu 2013).

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# M. *Gnetum africanum* (*Afang, Nkani, Ukasi, Eru, Okok,* Wild Spinach)

## Locations for economic models and ANR context

The cost-benefit model is based in Nsan Community in Akamkpa Local Governmant Area of Cross River State, Nigeria. In this area, some form of domestication on farms has already been started, so there are sources of seeds and technical knowledge available. Akamkpa Local Government Area is the largest forest area in the state with fertile land and stable water supplies by many rivers, streams and springs. Elevation ranges between 500–1,000 m a.s.l. There are several agricultural estates in the area, specializing in oil palm, rubber and cocoa production, as well as other forest products that are essential for industrial development of the entire state and country. Land holdings are from 2.5 to 115 ha. The vegetation is mainly humid tropical rainforest with the largest forest area in the state. Natural forests cover 85% of the area in this region (Global Forest Watch 2025). The region has fertile soils with many rivers and streams with a large tract of reserved forest, *Gmelina* plantations as well as privately owned rubber and oil palm plantations. *Gnetum africanum* occurs naturally in forest fallows. It is a climber that requires other vegetation to survive and grows best under partial shade. Ideally, it would be planted at a relatively low density (200/ha) into early regrowth forests with some clearance around trees that would act as supports.

In Cross River State, Nigeria, land and tree tenure is primarily a communal system governed by customary practices, where communities collectively own land and resources like trees. However, the national Land Use Act of 1978 also influences this by vesting all land in the state government, while still recognizing customary rights. Cultivation has been particularly significant for women, who constitute the majority of *Gnetum* farmers and traders in Nigeria. In many traditional systems, women face limitations in acquiring land through inheritance. However, because *Gnetum* is often classified as a vegetable crop, there are fewer tenure restrictions on planting it on rented land, or women can acquire land through purchase, which provides them more secure access and ownership opportunities (Udoh and Inyang 2012).

## ANR cost-benefit models, scenarios and assumptions

The costs of enrichment planting of *G. africanum* were substantially higher than the revenues, showing a negative NPV of USD -23,148 over 30 years and a benefit-cost ratio of 0.23. (Figure M1). Total ANR costs are very high (USD 82,262) and 73% of the costs are related to management activities including replanting after 10 years, fertilization, and fencing. Based on these high costs, cultivation of *Gnetum africanum* in ANR would require economic incentives or price subsidies to be financially beneficial for smallholder farmers. Further research on costs is needed, as the figures we used may be overestimates based on more intensive plantings in plantations. NPV becomes less negative with increases in discount rate, but remains negative at a rate of 15% (Figure M2).

## Carbon storage models

Carbon storage is high in this topical moist forest ecosystem, reading 110 MgC/ha within 30 years in ANR (with and without enrichment). We estimated 23% higher carbon storage in ANR compared to minimally assisted NR.

## Alternative production models

The highest net revenue from land use in this site is from agricultural land use ($3,933/ha), which provides slightly higher revenue than solidwood timber plantations (Figure M3). Additional revenue for carbon credits, $935/ha do not compensate for the costs of ANR with or without enrichment.

## Species ecology and ethnobotanical information

*Gnetum africanum* Welw. is an evergreen leafy climber in the Gnetaceae that grows across the Congo Basin in forest openings, secondary forest, fallow farmlands, and are increasingly being cultivated on farmholdings (Clark and Sunderland 2004). *G. africanum* grows in humid tropical forests below 1500 m elevation from Nigeria through Cameroon, Central African Republic, Gabon, Democratic Republic of Congo and Angola (Figure M4). *Gnetum buchholzianum* has similar distribution, ecology and uses, but is less commonly traded commercially. In Nigeria, both *Gnetum* species are called *ukasi* by the Igbo tribe and *afang* by the Efik/Ibibio tribes (Shiembo 1999).

*Gnetum africanum* is slow growing and shade-tolerant but does grow as well in full sunlight (Shiembo 1997). It is abundant in degraded forest, bush fallows and crop fields, where it is favored by forest disturbance (Fondoun and Tiki Manga 2000; Mialoundama 1993). In five provinces of Cameroon, *G. africanum* is distributed relatively homogenously in areas where secondary forests predominate (Clark et al. 2004).

FIGURE M1. **30-yr cash flow for ANR with enrichment of *Gnetum africanum***

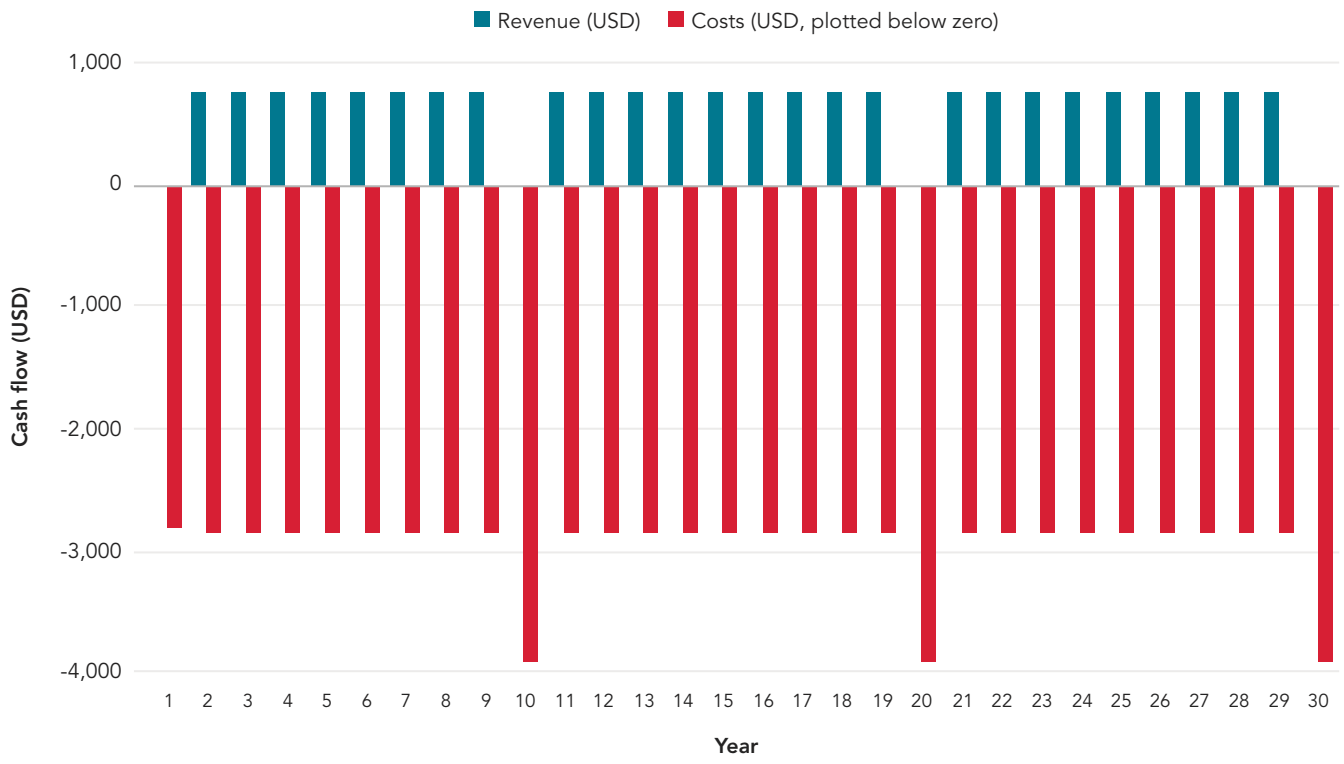



FIGURE M2. **Sensitivity of NPV with discount rate for ANR with enrichment of *Gnetum africanum***

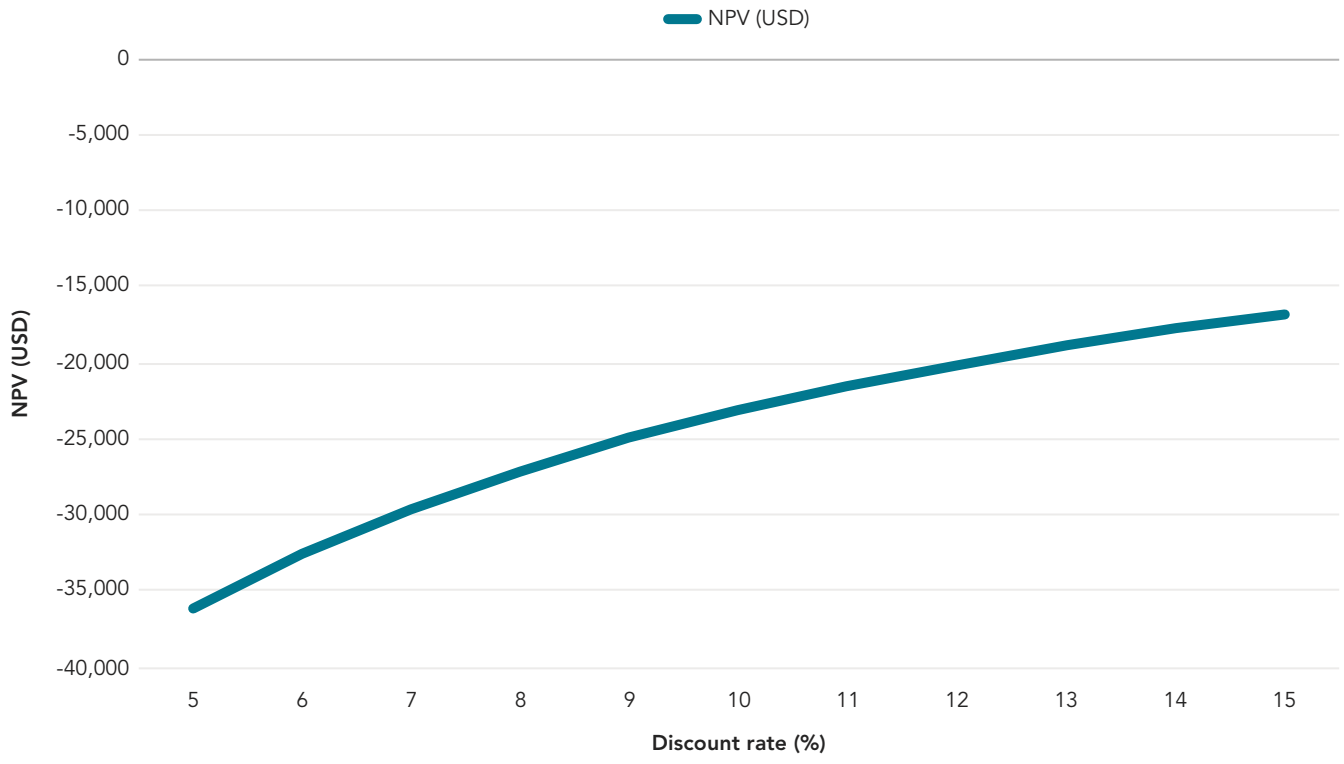


FIGURE M3. **Net discounted revenue and carbon storage for ANR with enrichment of *Gnetum africanum* compared to alternative land uses**




*See Chapter 2 for full description of land uses.*

FIGURE M4. **Distribution of *Gnetum africanum* in the Congo Basin (left); Leaf and ripe fruit (right)**





*Photo credit:* Marco Schmidt; CC BY-SA 2.5.

*Gnetum africanum* is one of the most commonly consumed plants found growing wild in Central Africa. The leaves, produced year-round, are a popular and highly valued vegetable in many parts of Africa (Udoh and Inyang 2012)). They are widely harvested from the wild and commonly sold in local markets, where they are often a major item of trade. The leaves are either eaten raw or are finely shredded and added to soups and stews (Burkill 1994); Figure M5) and they are rich in minerals and protein (Ndam, Nkefor, and Blackmore 2001). *G. africanum* plays a significant nutritional and social role across the region and is consumed by people of all social strata (Mialoundama 1993). In Nigeria, the leaves are used to treat enlarged spleen, sore throats, hemorrhoids and high blood pressure (Okafor, Okolo, and Ejiofor 1996; Schippers 2000; Ndam, Nkefor, and Blackmore 2001) and as a purgative and tonic (Clark et al. 2004).

Gnetum is dioecious, with flowers displayed in whorls in spikelike inflorescences (Clark et al. 2004). Birds, bats and rodents eat ripe and unripe fruit in the forest canopy (Shiembo 1997) reducing the availability of seeds for regeneration. Leaves of G. africanum and G. buchholzianum are consumed by gorillas in the Nouabali-Ndoki forest of the Republic of Congo. Suckering can be quite prolific in the wild, suggesting that vegetative regeneration is important.

## Cultural and livelihood importance

*Gnetum africanum* plays an important role in the livelihood of most rural and even urban communities of South-South region of Nigeria (Umoh, Nkeme, and Ekanem 2019). Gnetum dishes are greatly valued as part of the experience of traditional culture, and their presence is required at many traditional occasions (Shiembo 1999). Women dominate the *Gnetum africanum* trade and are engaged with gathering leaves, brokering sales, transport, and marketing. Participation in this economic activity is particularly important for young or uneducated women, as it provides their primary income (Shiembo 1999, Clark and Sunderland 2004; Figure M5).

## Conservation status

Once plentiful across their ecological ranges, *G. africanum* and *G. buchholzianum* have been overexploited and threatened by habitat loss. The species have a "near threatened" conservation status by IUCN, but this has not been recently updated (Wikipedia). *G. africanum* is increasingly difficult to find in the forest, raising concerns about overharvesting (Clark and Sunderland 2004). In areas of Nigeria and southern Cameroon, *Gnetum africanum* is likely to disappear from the wild due to over-exploitation. National populations of the plant are so depleted that Nigeria now imports *G. africanum* leaves from neighboring Cameroon (Madsen, Attard, and Wez 2020).

FIGURE M5. **A woman selling *Gnetum africanum* leaves for income**



*Photo credit:* Hnkamwa, CC BY-SA 4.0).

## Production and harvesting

Most of the *Gnetum* consumed in Nigeria is still harvested from the wild, while an increasing amount is imported from Cameroon (Patrick, Bassey, and Peter 2017). Pressures on wild-grown populations have led to programs to cultivate *G. africanum* on farms (Figure M6). The recommended method of planting *G. africanum* is by roots, vines and seeds. *Gnetum africanum* is not difficult to cultivate. Principal requirements are shade, a support for the vine to climb on, suitable soil type and sufficient rainfall (Udoh and Inyang 2012).

The life span of *G. africanum* is estimated at about 10 years with 3-4 harvests per year (Udoh and Inyang 2012). Cultivating *Gnetum africanum* can pave a way for permanent ownership of land by women. In Akwa Ibom State, Nigeria the cultivation of *Gnetum africanum* on-farm and on homestead was introduced to farmers in 1995 by the Akwa Ibom Agricultural Development Programme (Udoh and Inyang 2011). *Gnetum* production in Akwa Ibom was profitable and was primarily undertaken by women (Patrick et al. 2017). The Limbe Botanical Garden, Cameroon has also promoted domestication of both *Gnetum* species (Ndam et al. 2001).

FIGURE M6. **Small scale domestication of *Gnetum africanum* in Ikot Effanga Village in Akpabuyo Local Government**



*Photo credit:* Charles Ojong Nkpena.

Leaves are harvested and available in markets throughout the year (Clark and Sunderland 2004). Prices for the leaves fluctuate depending on season, price of fuel, and the currency exchange rates; leaves can be stored fresh for about a week and are usually traded in this form (Clark et al. 2004). In Southern Cameroon, harvesting of *Gnetum africanum* from secondary forests generates an average of US$2,630 household/year (Fondoun and Manga 2000).

## Trade and Marketing

National and international trade in *Gnetum africanum* is a significant economic activity estimated at USD13.8 million per year in southwest Cameroon and USD1.2 million per year in Kinshasa (DRC) (Mawunu et al. 2021). In Angola, *G. africanum* is among the wild food plants traded in Uíge province. In northern Angola, women are the main participants in the trade of cultivated plants and wild food products, generating employment and income for urban and rural households (Mawunu et al. 2021).

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# N. *Irvingia gabonensis* (Bush mango, *ogbono*)

## Locations for economic models and ANR context

The economic model for *Irvingia gabonensis* is located in Idanre Local Government Area, Ofosu, Nigeria at 375 m asl. Data on costs and revenues of enrichment planting were obtained from practicing farmers in this region by members of the FOLUR team in Nigeria. Average smallholder area is 5 ha. A sizeable population of *Irvingia gabonensis* still exists in the area. The climate has moderate temperatures and significant rainfall, especially during the wet season, and a short dry season. The region has average annual rainfall of around 2,208 mm. In 2020, natural forest covered 84% of area of Idanre LGA (Global Forest Watch 2025), indicating that conditions are suitable for natural regeneration. The ANR interventions used in the model were weed removal, fire prevention, ant control and pest control in addition to enrichment planting. Prevalent crops in the region include cocoa, oil palm, cassava, maize and tomatoes.

In Ofosu and most rural areas of Nigeria, land and tree tenure is primarily governed by customary practices, where communities collectively own land and resources like trees (Ezeh et al. 2022). However, the National Land Use Act of 1978 also influences land tenure security by vesting all land in the state government. Although this law officially recognizes community forest rights in principle, it allows the government to appropriate forest land for public use, which can bypass community rights and lead to conflicts.

## ANR cost-benefit model

The cash-flow analysis of ANR with enrichment of *Irvingia gabonensis* shows favorable economic indicators with a net present value over 30 years of USD 5,559 and a 14.1% internal rate of return (Figure N1). The benefit-cost ratio is 1.22. Payback time is 14 years, whereas net revenue peaks in year 11. This baseline cost-benefit model for *I. gabonensis* is based on a density of 60 trees/ha and a 10% discount rate. Total costs of ANR with enrichment for *Irvingia gabonensis* are USD 95,216, with 70.4% of these costs related to Management activities. NPV is highly sensitive to discount rate, with negative NPV at a discount rate of 14% (Figure N2).

## Carbon storage models

Carbon sequestration in aboveground biomass from ANR with enrichment of *I. gabonensis* is estimated to reach 63.39 MgC/ha, which is lower than 90.36 MgC/ha for ANR without enrichment but similar to minimally assisted natural regeneration. Management of *I. gabonensis* trees in ANR is estimated to reduce forest biomass by 30%. At this location, the land uses with the highest values of carbon sequestration are ANR without enrichment and solid wood plantations.

FIGURE N1. **30-yr cash flow model for *Irvingia gabonensis***

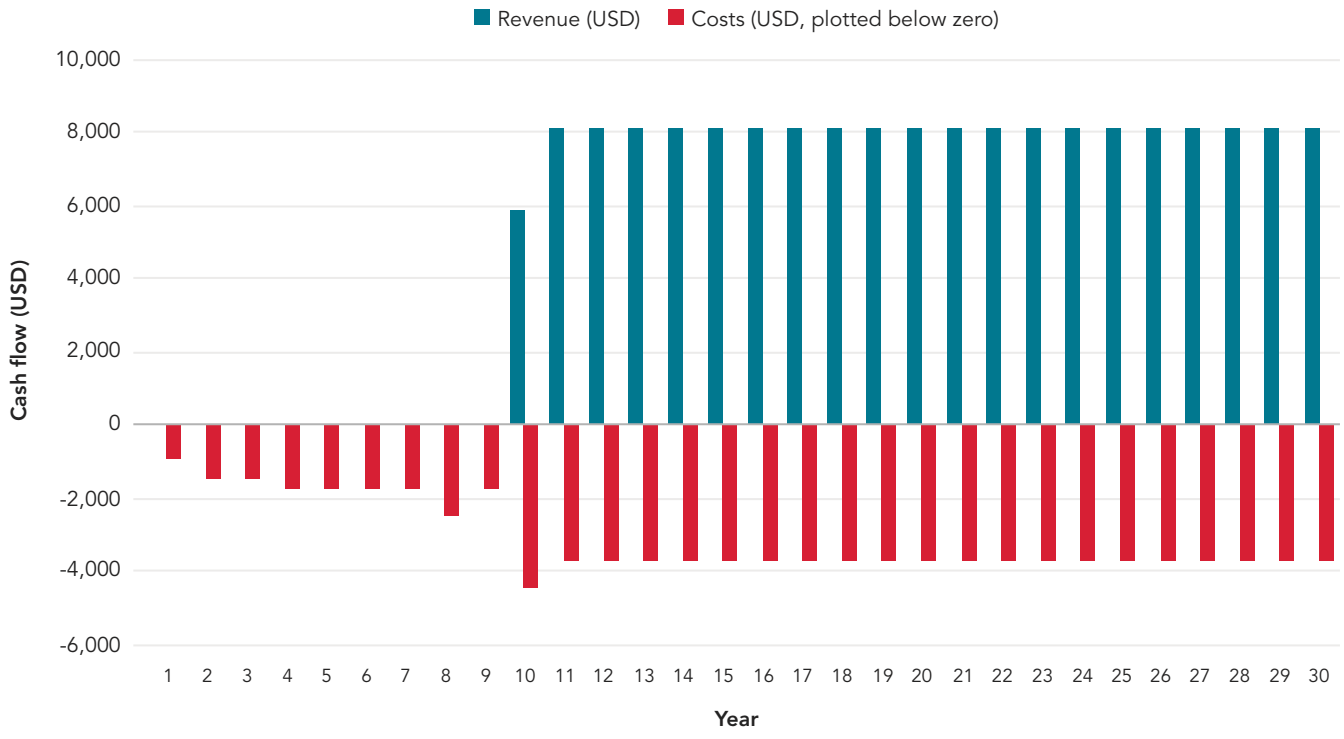
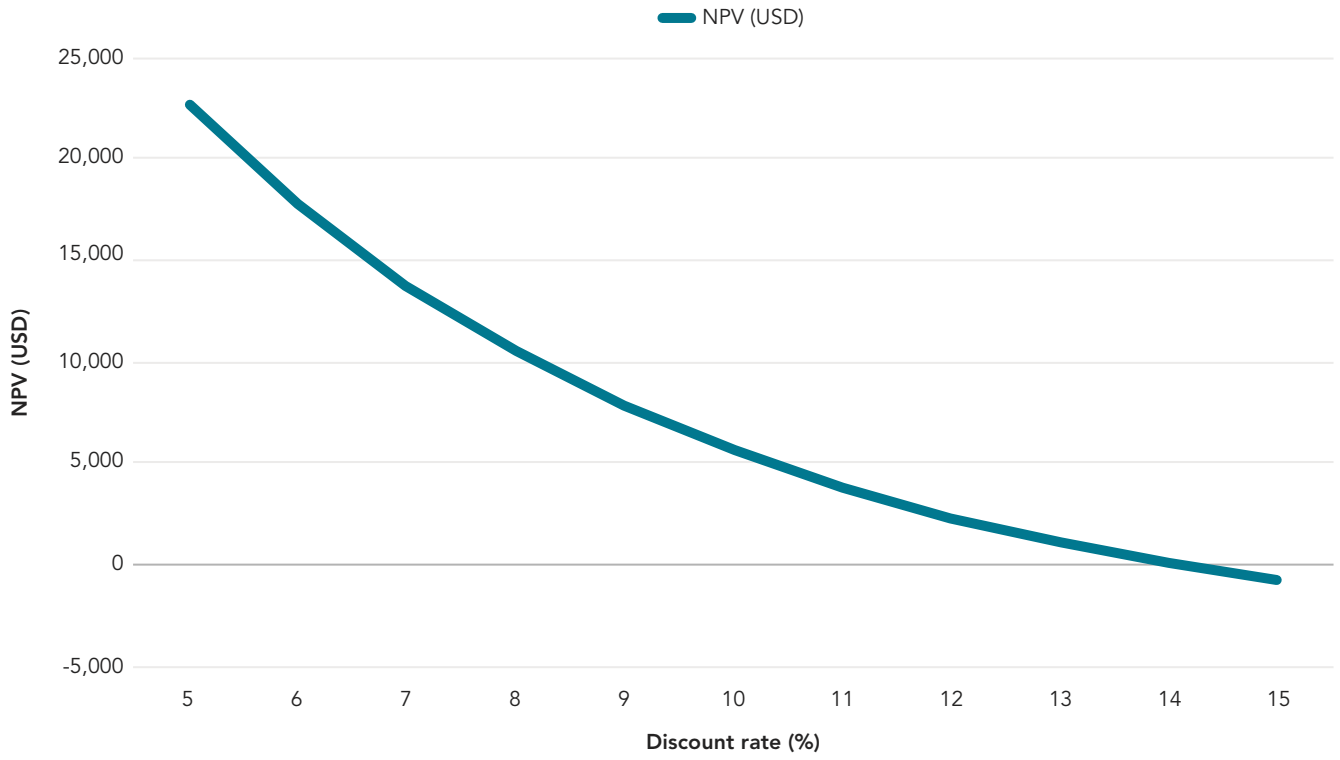


FIGURE N2. **Sensitivity of NPV to discount rate for *Irvingia gabonensis***




## Alternative production models

For *I. gabonensis*, net revenue from ANR with enrichment is estimated to be slightly higher (1.2x) than that of the most profitable alternative land use, agriculture, at the same site in Nigeria (Figure N3). Including revenue from carbon credits increases revenue by USD 568/ha. Revenue from carbon sequestration is below that of timber plantations for solid wood production, at the same site.

## Species ecology and ethnobotanical information

*Irvingia gabonensis* (bush mango) is a large evergreen tree belonging to the family Irvingiaceae. It is widely distributed in moist semi-deciduous forests in West and Central Africa (Figure N4) at elevations below 1,000 m with yearly rainfall of 1,500–3,000 mm and an average yearly temperature of 25–32 °C (Sileshi et al. 2023). Its geographical distribution covers Angola, Cameroon, Central African Republic, Congo, Côte'Ivoire, Democratic Republic of Congo, Equatorial Guinea, Gabon, Ghana, Guinea-Bissau, Liberia, Nigeria, Senegal, Sierra Leone, Sudan and Uganda (Sileshi et al. 2023); Figure N4). It grows to a height of 30–50 m. *Irvingia gabonensis* is a highly valuable and extensively utilized tropical African tree and is classified among the Sub-Saharan Africa's key Non-Wood Forest Products (NWFPs) present in local, regional and international markets (Vihotogbé et al. 2007). The fruit of this tree has been traditionally used for its nutritional and medicinal properties; in recent years it has gained attention for potential weight loss benefits (Olorunfemi and Bamishaye 2023).

This tree is prized for its large kernels, known as 'ogbono' in Nigeria, which are used as a condiment and thickener in soups (Figure N4). *Irvingia* kernels form an important part of the West and Central African diet, providing carbohydrate and protein (Onyeike, Olungwe, and Uwakwe 1995). The seed kernel is also used for medicinal purposes and as a source of oil for making soap (Ayuk et al. 1999). I. *gabonensis* kernels can only be used when fresh, since they become too mucilaginous over time. The kernels are ground with a pestle and mortar or on a stone into a paste or cake called "dika bread" (also known as odiko), which is used as a soup, stew or sauce additive, for flavoring and thickening (Leakey and Newton 1994). Fat extracted from the kernels can be used for food applications, such as margarine or cooking oil, and is also suitable for soap, cosmetics and pharmaceuticals (Ejiofor and Okafor 1997). The juicy and fragrant fruits of some varieties are eaten fresh and are rich in vitamin C. Fruit pulp can be used for making jam, jelly and juice.

This species is an important component of regional trade in West Africa. It is also a source of timber, poles and fodder. The timber of bush mango is used locally for construction (Leakey 1999). The bark is used in the treatment of various ailments such as hernia, yellow fever, dysentery, diarrhoea, and as an antidote for poisons.

FIGURE N3. **Discounted revenue and carbon storage of ANR with enrichment of *Irvingia gabonensis* compared to alternative land uses**

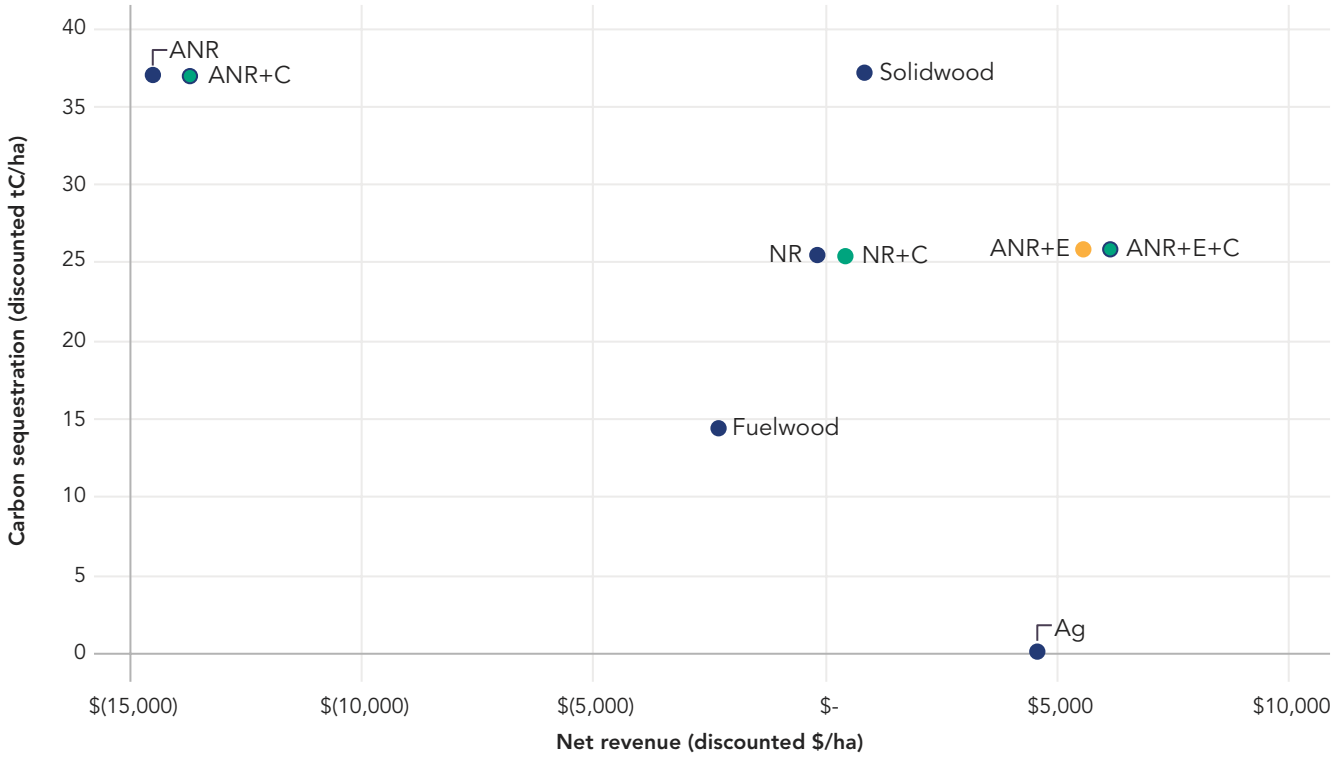



FIGURE N4. **Geographic distribution of *Irvingia gabonensis (left)*; A cup of ogbongo kernels being purchased at a local market (right)**





*Sources:* Wikipedia; CC BY-SA 3.0 (left); Zz411, CC BY-SA 3.0 (right).

Fruits of *Irvingia gabonensis* comprise a significant part of the diet of forest elephants (*Loxodonta africana cyclotis*) (Ainge and Brown 2004). Fruits are also consumed by squirrels and other rodents, as well as red forest hogs (*Potamochoerus porcus*) and gorillas (*Gorilla gorilla gorilla*) (Harris 1996). Wild bees make honey from the nectar of I. gabonensis (Agwu and Akanbi 1986).

## Cultural and livelihood importance

In Akwa Ibom State, Nigeria, *Irvingia gabonensis* is one of the most useful forest trees and is an integral part in the livelihood of the rural communities. The trees improve air quality, windbreak and play important role in soil protection and formation (Esiere et al. 2023). Bush mango is intertwined with the cultural identity of various Nigerian ethnic groups, such as the Ijaw people, where it holds a central place in traditional practices, including rituals and ceremonies. It symbolizes good health, prosperity, and the continuation of cultural heritage. Shared meals of Ogbono soup foster social connections and a sense of togetherness within families and communities. Processing seeds into the dried and ground form used in soups is a labor-intensive process that often involves community participation, reinforcing social bonds. The dried products are used in funeral ceremonies to signify prosperity and the continuation of cultural legacy. Marriage customs among the Ijaw further illustrate the cultural importance of *Irvingia gabonensis* (Ogboin). The larger, more elaborate marriages may see Ogboin products as part of the bride price, highlighting its role in social and economic exchanges (Forum 2025).

Cameroon is a major exporter of *Irvingia gabonensis* seeds to Nigeria, Equatorial Guinea, and Gabon (Ingram, Awono, and Laird 2024). In Cameroon, approximately 5190 people work in the *Irvingia gabonensis* value chain ending in 24 markets in southern Cameroon, with an estimated 4109 tons harvested on average annually between 2007 and 2010. Bush mango income contributes on average 31% of harvester's annual income (Ingram, Awono, and Laird 2024).

## Conservation status

In some regions of Nigeria, such as Cross River State, harvesting of *Irvingia gabonensis* in the wild has reached unsustainable levels (Ishoro et al. 2023). Stocks are diminishing at an alarming rate (Febnteh and Yani 2023). The conservation status of this species is currently near threatened (IUCN, 2020) as the natural habitat for the species is being cleared for agricultural land, and wild trees are over-exploited (Ainge and Brown 2004).

## Production and harvesting

*Irvingia gabonensis* can grow in farmland, semi deciduous forest, and closed bush or gallery forests. In addition to harvest of the seed, many rural people collect and market edible pulp in many parts of the country where the species are in abundance (Esiere et al. 2023). Farmers also protect remnant trees on farms to provide shade for coffee and cocoa and to restore soil fertility (Sileshi et al. 2023). An estimated 41% is harvested from farms and fallows, and the remainder from secondary and primary forests (Laird et al. 2020).

Of the 171 indigenous woody plants of economic importance identified by (Okafor 1980), within the forest zone of Nigeria, *Irvingia gabonensis* ranks amongst five principal fruit trees which occur in traditional farms as compared to natural forests (Onyekwelu and Stimm 2004). Farmers also transplant wild seedlings in farms or grow new seedlings (Ayuk et al. 1999). They select seeds from trees that are known to produce high yields of good fruit, either on their land or on a neighbor's. Farmers collect fruits from their own trees as well as wild and semi-wild forest trees. Cultivated trees are pruned and fertilized, and some pest control is carried out (Ayuk et al. 1999). Women usually gather the fruits, except when climbing is necessary (Ndoye, Ruiz Perez, and Eyebe 1996).

*I. gabonensis* usually reaches maturity and begin flowering at 10–15 years of age (Ladipo et al. 1996). However, fruiting as early as six years of age has been reported (Ladipo et al. 1996). Flowering generally occurs in February–March (Agwu 1985) and fruits are produced in the rainy season from July–September (Ladipo et al. 1996). In Nigeria, *I. gabonensis* is recorded as fruiting twice per year, once in January–February and again in June–August. Okafor (1975) also describes cultivated trees that fruit in both May–July and September–October. On the other hand, some individual trees produce fruit only every other year (Ladipo et al. 1996).

## Trade and marketing

In Onne, Rivers State, Nigeria, production of *Irvingia gabonensis* is a profitable business with a positive NPV of USD 12,838.67 per hectare and an estimated benefit-cost ratio of 2.1 (Larinde and Omokhua 2015). *Irvingia gabonensis* is one of the most widely traded NTFPs in the humid forest zone of Cameroon (Ingram, Awono, and Laird 2024). Trade was estimated to be worth USD 50 million, based on exports to Nigeria, Gabon, and Equatorial Guinea, and onwards in West and Central Africa (Ingram et al., 2010; Clark and Sunderland 2004). Ingram et al. (2017) studied the *Irvingia gabonensis* value chain in three major production areas in Cameroon. Over 5,100 people worked as harvesters and traders, with an estimated 4,109 tons harvested annually from 2007–2010. Incomes from *Irvingia gabonensis* contribute an average of 31% of harvester's annual incomes.

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APPENDIX 2.

# Detailed cost breakdown for total 30-yr costs for all 14 ANR models

Total undiscounted costs are categorized into three main components (1) Implementation: Initial setup costs (Year 1: fencing, seedlings, planting, etc.); (2) Harvest: Costs related to harvesting activities; (3) Management: Ongoing management and maintenance costs (pruning, weeding, fertilization, etc.). Costs are shown in USD.

TABLE A2. **Summary over 30-years**

| Country | Species | Implementation | Harvest | Management | Total |
|---|---|---|---|---|---|
| Brazil | *Aniba rosaeodora* | $2,900 | $22,400 | $207,280 | $232,580 |
| | *Euterpe oleracea* | $3,360 | $15,795 | $44,640 | $63,795 |
| | *Ilex paraguariensis* | $1,716 | $1,592 | $27,264 | $30,572 |
| | *Paullinia cupana* | $7,060 | $13,360 | $8,215 | $28,635 |
| Ecuador | *Ilex guayusa* | $227 | $1,001 | $4,176 | $5,404 |
| Ethiopia | *Aframomum corrorima* | $2,212 | $7,000 | $56,260 | $65,472 |
| | *Oldeania alpina* | $894 | $5,105 | $9,617 | $15,616 |
| | *Piper capense* | $1,673 | $290 | $1,627 | $3,590 |
| Ghana | *Parkia biglobosa* | $60 | $460 | $639 | $1,159 |
| | *Tetrapleura tetraptera* | $411 | $750 | $4,990 | $6,151 |
| | *Vitellaria paradoxa* | $827 | $1,620 | $3,092 | $5,539 |
| Nigeria | *Garcinia kola* | $1,037 | $3,243 | $3,798 | $8,078 |
| | *Gnetum africanum* | $2,608 | $19,595 | $60,459 | $82,662 |
| | *Irvingia gabonensis* | $903 | $27,243 | $67,070 | $95,216 |

APPENDIX 3.

# Survey form for data collection

You can find the Excel Spreadsheet used for data collection for the 14 target species here.

## Partner organizations



















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