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Monetizing Coffee Leaves and Fruit to Fund Regenerative Agriculture:

A Case Study in Puerto Rico

Thomas R. McOsker

A Thesis in the Field of Sustainability and Environmental Management

for the Degree of Master of Liberal Arts in Extension Studies

Harvard University

May 2026

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Abstract

Coffee cultivation sustains more than 100 million livelihoods but illustrates agriculture's environmental paradox: 70–80 % of smallholder households earn below living-income thresholds while contributing disproportionately to deforestation, biodiversity loss, and climate change. Regenerative agroforestry can restore ecosystems through enhanced biodiversity, carbon sequestration, and soil health, yet adoption remains limited by a "worse-before-better" gap of 10%–25 % yield penalties and establishment costs of $1,500–$3,000 per hectare. Existing instruments, including certifications, carbon credits, and subsidies, have not closed the estimated $4 billion global transition-financing gap. This thesis examined whether monetizing under-utilized coffee-plant biomass can bridge that gap.

A 10-acre case study at Copper Hill Farm (Puerto Rico) modeled six management scenarios over 10 years using stochastic NPV and Monte Carlo analysis. The Whole Tree Economic Model (WTEM) was used to convert coffee leaves and cascara into market-approved functional ingredients, creating endogenous revenue streams that complement green bean sales while using existing cooperative infrastructure. Primary data sources included farm-level cost and production records, market prices for coffee beans, coffee leaf tea, and cascara, labor costs, and cooperative processing cost structures. Key variables modeled across scenarios included annual net present value, transition-period income adequacy, biomass harvest frequency (1-4 annual flushes for leaves), yield dynamics under regenerative transition, and processing efficiency gains through

cooperative infrastructure. Scenarios tested conventional monoculture (S_1), regenerative baseline without biomass monetization (S_2), cascara-only monetization (S_3), leaf-only monetization (S_4), market stress conditions (S_5), and full WTEM with leaves and cascara (S_6).

Results demonstrated WTEM's economic impact across 1,000 Monte Carlo iterations. Conventional monoculture (S_1) exhibited universal failure with mean NPV of -$119,128/ha, reflecting Puerto Rico's high labor costs and input premiums. Regenerative baseline (S_2) achieved positive viability in 100% of iterations with mean NPV of $52,353/ha, demonstrating that regenerative practices provide advantages via cost savings. Full WTEM (S_6) generated mean NPV of $141,944/ha with 100% positive outcomes, representing 171% improvement over regenerative baseline and transforming negative conventional systems into highly profitable operations. Counterintuitively, leaf-only systems (S_4) achieved the highest performance at $195,307/ha mean NPV, exceeding even full WTEM by $53,363/ha due to superior per unit values and temporal complementarity advantages. The cascara-only scenarios (S_3) remained negative at a mean value of -$32,644/ha, confirming insufficient standalone viability.

The study contributes three advances: (1) a dual-metric viability framework distinguishing economic versus financial barriers; (2) the theory of temporal complementarity, explaining how off-season leaf processing converts coordination problems into capacity-optimization opportunities; and (3) evidence that existing cooperative infrastructure can transform biomass waste into regenerative finance.

Author's Biographical Sketch

Thomas McOsker is a regenerative farmer, entrepreneur, and researcher in systems design whose work integrates ecological, agroecology, and circular value-chain innovation. Raised on the coast of Maine and now based in Puerto Rico, he transitioned from a career in fintech to found Coffee.Works, a field-based research laboratory embedded within a 500-acre agroforestry system dedicated to modeling regenerative agricultural solutions. As CEO of The Wize Beverage Company, PBC, McOsker leads the development of circular economic frameworks that transform coffee plant byproducts into high-value ingredients, creating new income streams for farmers while reducing agricultural waste. His research centers on the design of regenerative economic systems that align ecological restoration with financial viability, making the ethical choice the most economic one. McOsker's work is informed by the writings of Wendell Berry, Rattan Lal, and Paul Hawken, and shaped by the mentorship of Dr. Alfred Anduz, a physician and regenerative farmer whose integration of Western science and plant-based medicine has profoundly influenced his own transition from finance to land stewardship. He holds an ALM in Sustainability from the Harvard Extension School (2026) and a BA from Tulane University, along with professional certifications in regenerative agriculture and sustainability systems. This thesis reflects his ongoing effort to operationalize regenerative economic theory through field-based application, beginning with the coffee shrub (tree) as a model for ecological and economic regeneration.

Dedication

To my father, Thomas Gerard McOsker.

You taught me to “show up when it matters most, ask the real questions, and take the longest way home.” This work is rooted in your quiet strength, your belief in doing things right, and your way of walking the world with steady hands and a good heart.

Every tree I plant carries your legacy.

Acknowledgments

First, to the farmers. Those in Puerto Rico, Nicaragua, and around the world, who live closest to the land and whose knowledge, labor, and resilience are the root system of this work. Without your stewardship, there would be no field to study, no leaves to harvest, and no future to regenerate.

To Dr. Nate Olive, my Thesis Director, thank you for your steadfast guidance and dedication to tropical agroecology and organic farming in the Caribbean. Your mentorship ensured this thesis remained grounded in both scientific integrity and lived agricultural realities.

To Dr. Mark Leighton, my Research Advisor, whose deep knowledge of sustainable food systems in rural economies and thoughtful critique challenged me to refine this work with clarity and rigor. Thank you for your early encouragement and principled support.

To Dr. Alfred Anduz, a mentor and inspiration, whose extraordinary life of bridging Western medicine and plant-based healing, clinical science and regenerative farming, has taught me what it means to live one's values. Your example continues to guide me.

To Lindi von Mutius, JD, former Director of the sustainability and Global Development Program at HES and trusted friend, thank you for your unwavering support and for holding space for big ideas. Your leadership and compassion were a steady compass throughout this academic journey.

To Dr. Manuel Maqueda, whose teachings on circular and regenerative economics reshaped how I see the world. Your frameworks gave me the language and structure to articulate the economic transformation this thesis aspires to help catalyze.

To Dr. Miguel Moya, my partner in the field and dear friend. Thank you for your tireless agronomic work, sharp insights, love of bees, and unwavering belief in what we're building. This work would not have been possible without your contributions on the ground.

To Dr. Xiumin Chen, for her ongoing collaboration and support, and for her groundbreaking work on coffee leaf science. I look forward to the knowledge we will continue to build together.

To Marcela Graniello, Research Assistant at Copper Hill Farm, for her decade of dedication to our experiments, ideas, and shared projects. Your patience, precision, and logistical mastery made this research possible from root to canopy.

To Salvador Baiges, Professor at the University of Puerto Rico and Head of the Agricultural Extension Program, whose leadership in the annual Taza de Oro cupping challenge has elevated quality and transparency in Puerto Rican coffee. Your commitment to farmers and continuous improvement embodies the regenerative spirit this work seeks to advance.

To Enrique Ferrufino and his family, whose dedication to coffee leaf farming and processing in Nicaragua has brought this work to life on the ground. Your partnership and perseverance are deeply appreciated.

To Arnaud Petitvallet and Max Rivest, whose early research and perseverance in Nicaragua and Canada paved the way for this field of study. Your work laid the foundation upon which this thesis stands.

To my family; my father Thomas, my mother Cynthia, my sister Ashley, my brother Bryce, my sister-in-law Kayla, all the kids, and my partner Christina. Thank you for your love, patience, and belief in me during every step of this journey. Your support was my anchor and my fuel.

Finally, to the many researchers, advisors, and friends who contributed knowledge, labor, and encouragement along the way. This work is as much yours as it is mine.

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Chapter I

Introduction

Coffee cultivation spans approximately 11 million hectares (27 million acres) and supports 12.5 million farmers across more than 70 countries (FAO, 2023; ICO, 2019; Siles et al., 2022), yet it exemplifies agriculture's environmental paradox: an industry sustaining millions of livelihoods while contributing disproportionately to deforestation, biodiversity loss, and climate change (Siles et al., 2022; Poore & Nemecek, 2018). The majority of coffee farming households, particularly smallholders, earn below living-income benchmarks, with recent assessments estimating 70%-80% earning less than required living income thresholds of $2.10-$2.50 per pound farmgate depending on origin (Staritz et al., 2023; Enveritas, 2024). The sector faces compounding crises of ecological degradation and economic precarity that conventional market interventions have failed to resolve (Enveritas, 2024). Coffee's monoculture model drives environmental degradation across its 27 million acres while leaving farmers economically vulnerable to climate volatility, aging trees, and market price instability (Pham et al., 2019; Avelino et al., 2015). Agriculture occupies approximately 5 billion ha globally and has contributed to the degradation of 2 billion ha of land, affecting 3.2 billion people (Díaz et al., 2019; Ritchie et al., 2019). Life cycle assessments have demonstrated that farm-stage processes dominate coffee's environmental footprint through land-use change and fertilizer use, while post-farm stages contribute a significantly smaller share (Poore & Nemecek, 2018; Chéron-Bessou et al., 2024; Nab & Maslin, 2020). Coffee cultivation

plays a role in driving deforestation, soil degradation, and greenhouse gas emissions, exacerbating threats to biodiversity (IPCC, 2022; Jezeer et al., 2019).

Climate change intensifies coffee production challenges by shifting agroecological zones and amplifying pest pressures. Rising temperatures and erratic rainfall threaten to reduce Arabica yields substantially, with global estimates ranging from 20% to 50% by mid-century depending on region and emissions trajectory (Pham et al., 2019). In the Caribbean, including Puerto Rico, recent rust epidemics illustrate the combined risks of climatic variability and disease outbreaks (Avelino et al., 2015). These pressures, observed firsthand at Copper Hill Farm (CRCD, 2023), threaten socio-economic viability and destabilize supply chains, particularly for smallholders whose farmgate prices of $1.20-$1.60 per pound fall 40%-50% below living income benchmarks of $2.10-$2.50 per pound (Staritz et al., 2023; ICO, 2019). In Ethiopia, climate models predict a 41%–61% loss of suitable coffee land by 2050, underscoring the global urgency of transition financing mechanisms (Moat et al., 2017).

Regenerative agriculture, particularly shade-grown agroforestry, offers a solution by reducing emissions, enhancing biodiversity, and improving soil health (IPCC, 2022; Rahn et al., 2014; Jezeer et al., 2019). Shade-grown coffee agroforestry systems can sequester 2–5 tons of carbon per hectare annually in above-ground and below-ground biomass (Nesper, M. et al., 2020; Haggar et al., 2011), but short-term yield reductions and shade establishment costs deter adoption (Nesper et al., 2020; Quandt et al., 2023). Certifications such as Fairtrade deliver inconsistent premiums offset by compliance costs, failing to bridge the financing gap (Meemken, 2020; Grabs & Ponte, 2019).

While regenerative agroforestry offers environmental and agronomic benefits through enhanced biodiversity, soil health, and carbon sequestration, its adoption remains constrained by a familiar dilemma: a “worse-before-better” gap, or transition period, marked by upfront yield declines of 10-25% (Jezeer et al., 2019; Rahn et al., 2014; Quandt et al., 2023). Establishment costs for shade agroforestry systems range from $1,500 to $3,000 per hectare including shade tree seedlings, organic amendments, and labor for planting and initial management (Jezeer et al., 2018; Haggar et al., 2017). Traditional interventions including certifications, crop diversification, and subsidies have failed to close this economic gap at scale (Meemken, 2020; Jones et al., 2024; Grabs, 2020). Neighboring farmers in Puerto Rico who participated in USDA Natural Resource Conservation Projects alongside Copper Hill Farm summarized it succinctly: "We can’t afford the early losses," despite acknowledging longer-term resilience benefits (Sachs et al., 2019).

Research Significance and Objectives

I investigated whether monetizing underutilized coffee plant biomass can finance the transition to regenerative agriculture at scale. I proposed the Whole Tree Economic Model (WTEM): a financing mechanism that generates additional revenue streams from legally compliant valorization of coffee leaves and cascara (dried coffee fruit or cherries) alongside conventional green bean sales. Unlike certification premiums or carbon credits, which are volatile, costly to verify, or inaccessible to smallholders, WTEM would leverage existing farm operations and FDA/EFSA-approved markets for functional ingredients (EFSA, 2022; United States Food and Drug Administration [US FDA], 2020).

By converting previously discarded biomass into shelf-stable teas and extracts rich in bioactive compounds such as chlorogenic acids and mangiferin, WTEM would offset the upfront costs and yield penalties that deter regenerative adoption, without requiring land expansion or external subsidies (Vuong et al., 2021; Martinez-Saez et al., 2014). The model integrates off-season leaf pruning and cascara harvesting with existing coffee processing logistics, creating countercyclical income streams that stabilize farmer cash flow during the transition period (Eckhardt et al., 2022; Murthy & Naidu, 2012).

This study tested WTEM's viability in Puerto Rico, a high-cost, climate-vulnerable region where economic and environmental pressures create particularly challenging conditions for agricultural transition. As a U.S. territory, Puerto Rico faces labor costs averaging over 50% of farm budgets and electricity costs 30% higher than mainland averages, substantially exceeding those in Latin American coffee regions (World Bank, 2021; ICO, 2019). Hurricanes cause 20–50% yield losses, while land abandonment has affected 30% of coffee farms since 2017, and aging farmer demographics (average age 55) further constrain the sector (Perfecto et al., 2019; Enveritas, 2024; Avelino et al., 2015). If WTEM proved to be economically viable under these stringent conditions, it should perform even more favorably in lower-cost coffee regions such as Colombia, Ethiopia, or Vietnam.

This study introduced an explicit economic mechanism linking on-farm biomass valorization to regenerative finance. Unlike external transfers such as payments for ecosystem services or carbon credits, or market-based premiums from certifications, WTEM operates through endogenous value creation: converting previously discarded assets into revenue-generating products. This represents a distinct financing pathway in

agricultural transition literature, testing whether asset reconfiguration can generate sufficient capital to overcome adoption barriers independent of volatile commodity and carbon markets where integrity concerns and transaction costs pose barriers to smallholder participation (Cacho et al., 2013; Schneider & La Hoz Theuer, 2019; Kreibich et al., 2021).

The study quantified WTEM's economic viability under stringent conditions using 10-year NPV scenarios with sensitivity analyses across cost and price ranges. By testing the model in Puerto Rico, a high-cost, climate-vulnerable region, results provided conservative estimates of financial performance, with implications for scalability to lower-cost regions where labor, land, and input costs are substantially lower (Moat et al., 2017; Le et al., 2021). The analysis evaluated not only whether WTEM improves profitability but also whether it reduces cash-flow volatility during the critical transition period.

Background

Understanding whether biomass valorization can finance agricultural transitions requires examining four interconnected domains: agriculture's environmental crisis, climate threats amplifying transition urgency, the persistent failure of conventional interventions to provide adequate finance, and precedents demonstrating the technical feasibility of biomass monetization. I critically review each domain, identifying what is known and where debates persist and gaps justify the present research.

Agricultural Expansion and Environmental Impacts

Agricultural expansion has drastically transformed global landscapes. Nearly half of habitable land now serves agricultural purposes, a dramatic increase from less than 5% a millennium ago (Ritchie et al., 2019). This transformation contributes 25% of global greenhouse gas emissions and has degraded two billion hectares, affecting 3.2 billion people (Poore & Nemecek, 2018; Díaz et al., 2019; IPCC, 2022). Figure 1 illustrates the historical acceleration of cropland and grazing land expansion, particularly pronounced since 1900 as industrialization intensified agricultural demands.

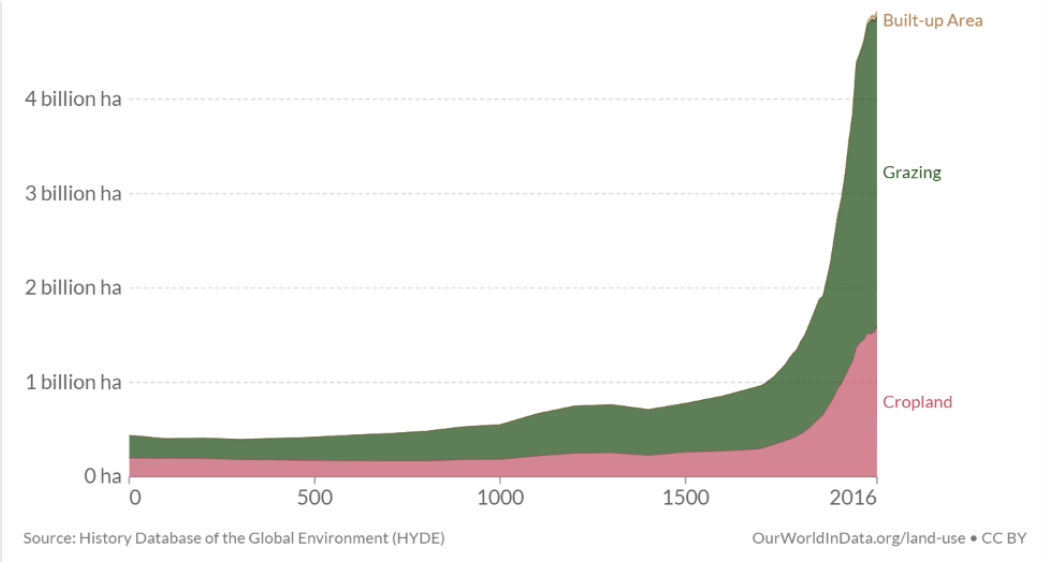


Figure 1. Historical land use for cropland, grazing, and infrastructure, year 0 AD–2016 (Ritchie et al., 2019).

Current land allocation reveals agriculture's dominance (Poore & Nemecek, 2018) with implications for land-use optimization strategies (Figure 2). Coffee occupies a relatively modest portion of total cropland, approximately 11 million hectares globally,

yet drives disproportionate environmental harm through its concentration in biodiversity hotspots and its historical role in tropical deforestation (FAO, 2023; Jezeer et al., 2019).

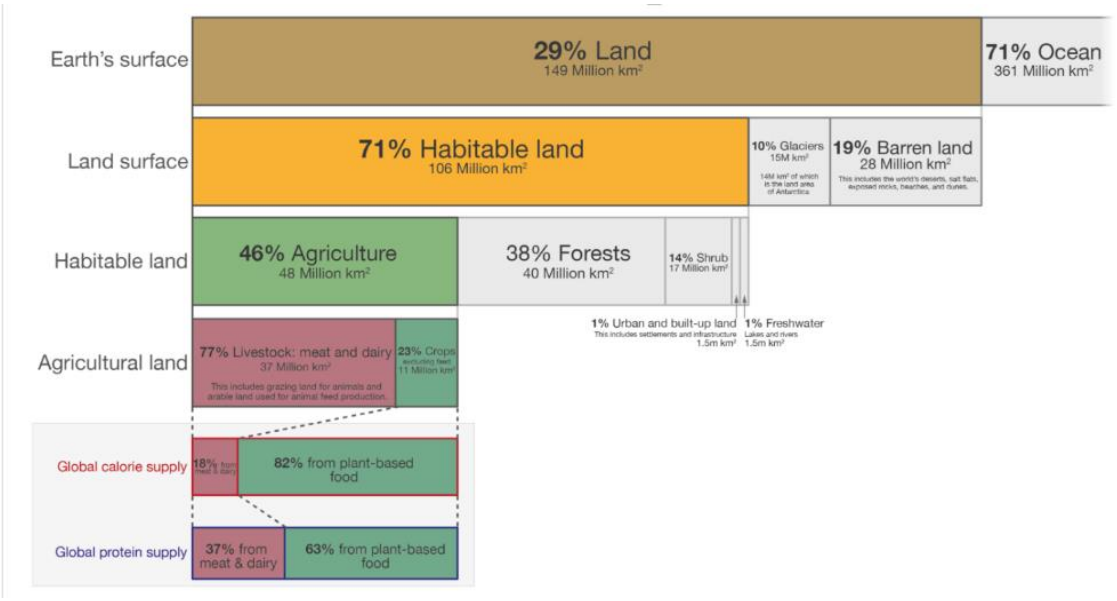


Figure 2. Global land allocation for agricultural production by surface area (Poore & Nemecek, 2018).

This transformation threatens 75% of the 46,000 species on the IUCN Red List, with habitat loss from agriculture identified as the primary driver (IUCN, 2024; Bellard et al., 2022). Coffee's monoculture systems, spanning 27 million acres across 70 countries (Figure 3), exemplify this threat through mechanisms including deforestation for plantation establishment, soil erosion from lack of vegetative cover, agrochemical pollution of watersheds, and elimination of shade trees that provide habitat connectivity (Jezeer et al., 2019; Moguel & Toledo, 1999).

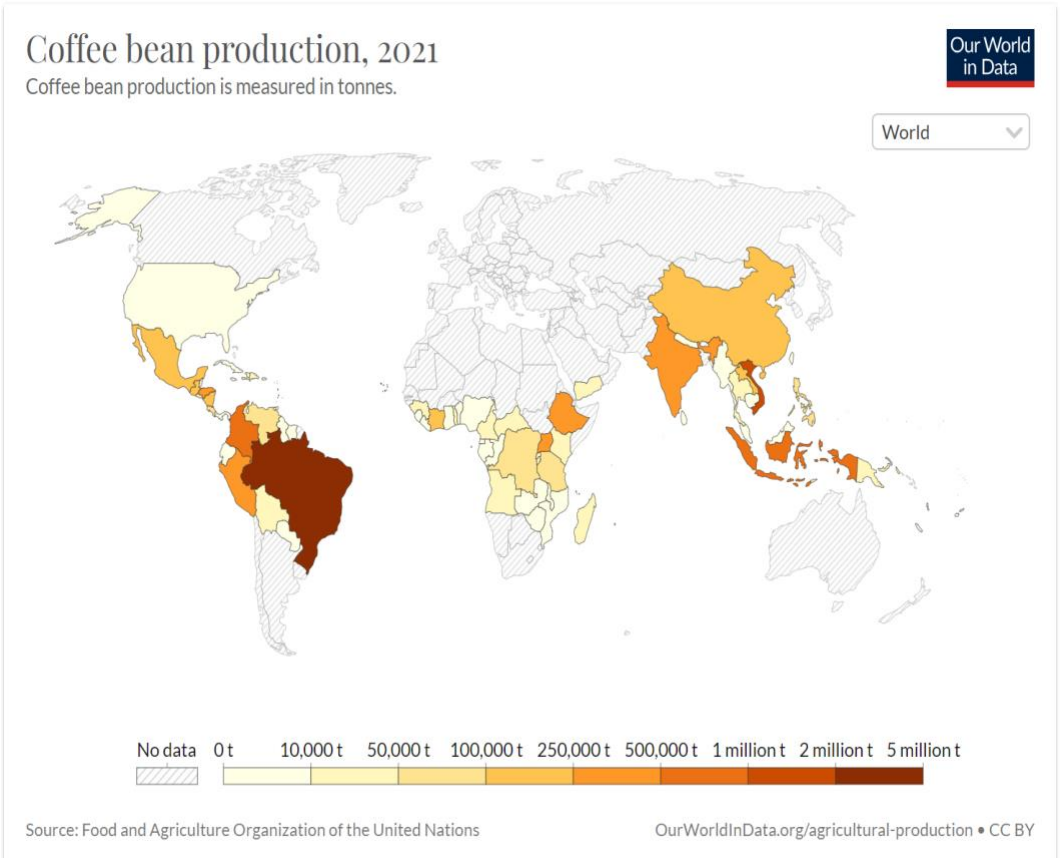


Figure 3. Global coffee production areas, 2021 (FAO, 2023).

Coffee supports 120 million livelihoods globally, predominantly smallholder farmers operating farms under two hectares (Lowder et al., 2016; FAO, 2023). My research at Copper Hill Farm in Puerto Rico's cordillera central positions coffee as a critical case: economically vital to rural communities while simultaneously ecologically damaging under conventional production methods. These findings underscore the need for financing models that align profitability with ecological restoration rather than treating them as competing objectives.

Coffee's Environmental Footprint and Life Cycle Impacts

Life cycle assessments provide the dominant framework for quantifying coffee's environmental impacts, but methodological debates persist regarding their scope and interpretation. Meta-analyses converge on a consistent finding: 85%–95% of coffee's carbon footprint occurs at the farm stage, primarily through land-use change, fertilizer production and application, and crop loss from pests and disease (Chéron-Bessou et al., 2024; Nab & Maslin, 2020; Poore & Nemecek, 2018). Post-farm stages including processing, transport, roasting, and packaging collectively contribute less than 10%–15% of total emissions (Figure 4).

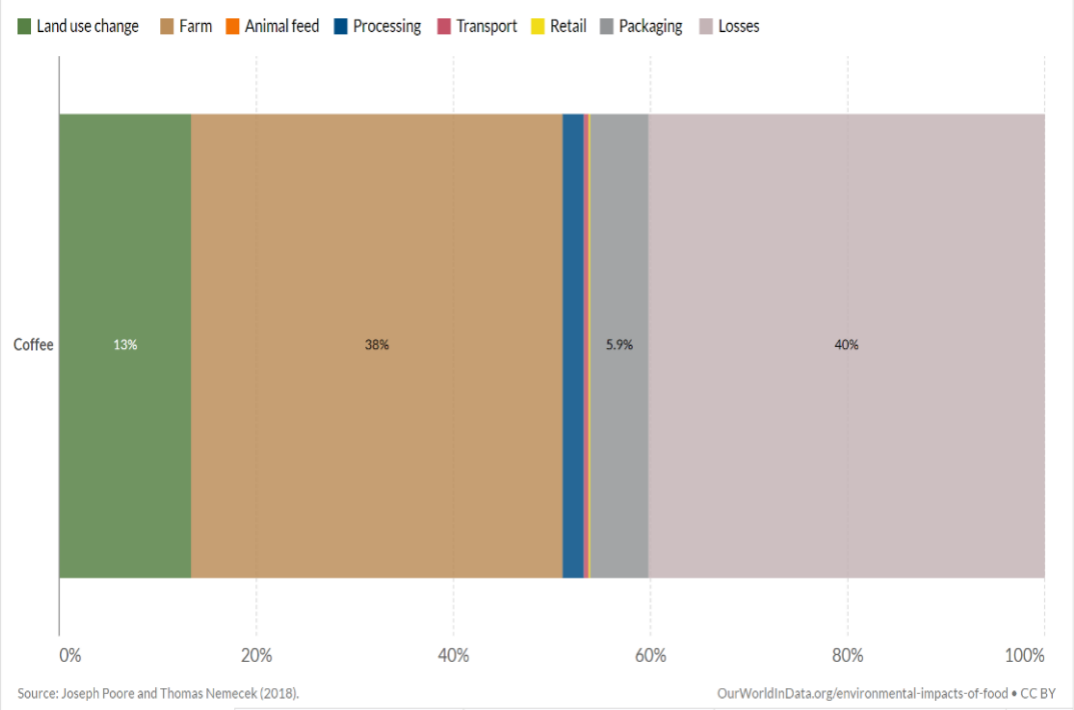


Figure 4. Breakdown of coffee's carbon emissions by supply chain stage (Poore & Nemecek, 2018).

However, methodological heterogeneity limits direct comparability across studies. Researchers vary in system boundaries (cradle-to-gate versus cradle-to-grave), functional

units (per kg green bean versus per cup served), allocation methods for multi-functionality, and impact categories assessed (van der Feen et al., 2024; Usva et al., 2020). For example, Yemen's Seed to Cup assessment attributes 90% of environmental impacts to on-farm practices, emphasizing upstream interventions, yet uses regional assumptions about transport distances and processing methods that may not generalize to other origins (van der Feen et al., 2024).

Critically, most LCAs omit biodiversity impacts and social externalities, limiting their utility for holistic sustainability assessment (Usva et al., 2020). While carbon footprints and water use are readily quantified, the loss of endemic species habitat or the economic precarity of farming households resist standard LCA frameworks. This gap justifies WTEM's focus on economic mechanisms that can internalize environmental benefits without requiring complex ecological impact quantification, instead leveraging market demand for sustainably produced goods.

My fieldwork at Copper Hill Farm has confirmed that sun-grown monocultures accelerate soil degradation and reduce biodiversity compared to shaded systems. Farms in the region validate findings of 10+% yield loss attributable to soil erosion over time, creating a reinforcing feedback loop: degraded soils require increased fertilizer inputs, raising costs and emissions while further damaging soil structure (Nesper et al., 2020). This vicious cycle necessitates regenerative practices to restore ecological balance; however, the economic, barriers to adoption remain formidable.

Climate change poses severe and increasingly well-documented threats to coffee production, particularly for *Coffea arabica*, which accounts for approximately 60% of global production and commands premium prices (Bunn et al., 2015). Temperature increases, altered precipitation patterns, and increased climate variability interact to constrain production through multiple pathways: direct physiological stress reducing flowering and fruit set, expansion of pest and disease ranges into previously suitable areas, increased frequency of extreme weather events causing crop loss, and long-term shifts in agroecological suitability (Pham et al., 2019; Moat et al., 2017).

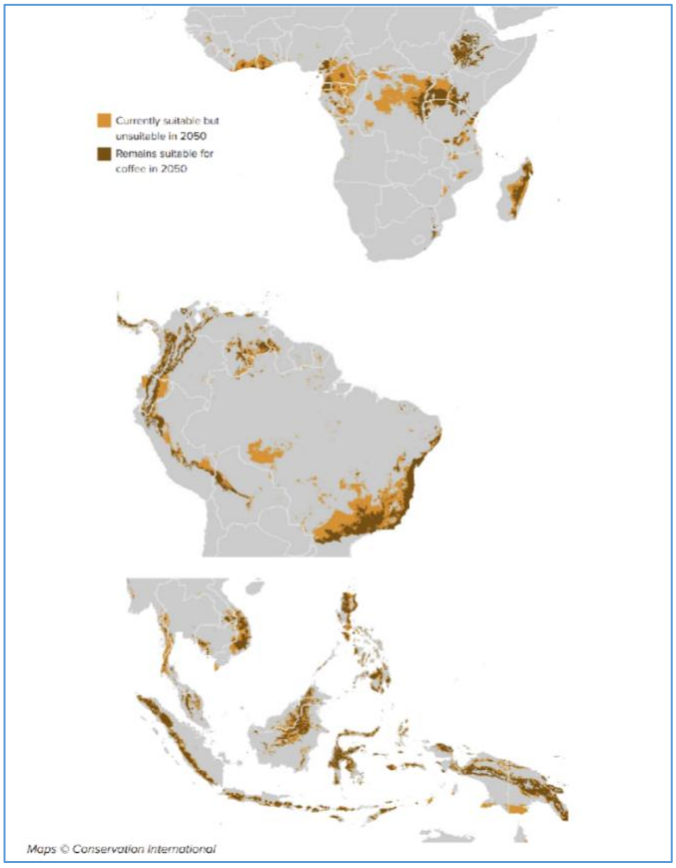


Figure 5. Changes in geographic regions suitable for coffee by 2050 (Siles et al., 2022).

Predictive models estimate severe yield reductions by 2100 under high-emissions scenarios: 25% in Brazil and up to 65% in Ethiopia (Figure 5) (Bunn et al., 2015; Moat et al., 2017). The Ethiopian case illustrates the urgency. Producing 40% of Africa's coffee and depending on the sector for 30% of export revenues, Ethiopia faces a 41%-61% loss of suitable coffee land by 2050 even under moderate emissions (Moat et al., 2017). While some high-elevation areas may become newly suitable as temperatures warm, these refugia are limited in extent, often coincide with protected forest areas, and cannot absorb displaced production at scale. In Puerto Rico specifically, coffee is already grown at the highest elevations and there is potential for future increase in altitude (Avelino et al., 2015).

In the broader Caribbean, including Puerto Rico, rising temperatures and erratic rainfall threaten to reduce yields by 20–30% by 2050 under moderate scenarios, with hurricane intensity and frequency projected to increase (Avelino et al., 2015; Rahn et al., 2014). Coffee leaf rust (Hemileia vastatrix), a fungal pathogen favored by warm, humid conditions, has emerged as a major climate-linked threat. The 2008–2013 rust epidemic across Central America caused yield declines of 20–50% in Colombia, Guatemala, and Honduras, with economic losses exceeding $1 billion and hundreds of thousands of farm workers displaced (Avelino et al., 2015; Siles et al., 2022).

At Copper Hill Farm, farmers report increased pest pressures and yield volatility corresponding to warming trends and irregular rainfall. Aging coffee trees in other regions compound these vulnerabilities as older plants exhibit reduced vigor and increased susceptibility to pests and climate stress (Cerda et al., 2017). This pattern is global: 34% of smallholder coffee trees worldwide exceed 20 years, contributing to yield

decline and heightened disease risk (Siles et al., 2022).While higher elevations currently offer relative refuge through cooler temperatures, climate-driven shifts in agroecological zones will progressively eliminate these advantages, particularly for farmers lacking resources to relocate or replant with climate-adapted varieties (Moat et al., 2017).

Scholarly debate continues, however, regarding optimal adaptation pathways. Some agronomists advocate for varietal replacement with heat-tolerant cultivars, while agroecologists emphasize diversified agroforestry systems that buffer temperature extremes and enhance ecosystem resilience (Rahn et al., 2014; Cerda et al., 2017). Evidence increasingly supports the latter: diversified shade systems demonstrate greater stability under climate stress, though yield trade-offs in the establishment phase remain contentious (Jezeer et al., 2019; Quandt et al., 2023).

Global coffee demand, projected to double by 2050 driven by rising consumption in producing countries and emerging markets, risks further deforestation in tropical regions without substantial productivity improvements (Maslin & Nab, 2021; Siles et al., 2022). This demand growth threatens 100 million livelihoods across the entire coffee value chain, concentrated in climate-vulnerable regions including the Andes, Central America, and Southeast Asia (Haggar et al., 2011). My analysis, drawing on Puerto Rican fieldwork, suggests diversified agroforestry systems are critical for resilience, carbon sequestration, and biodiversity conservation, delivering ecosystem services including pollination and biological pest control without long-term yield losses in tropical environments (Jezeer et al., 2019; Rahn et al., 2014). However, adoption remains limited due to economic barriers during the transition period, necessitating innovative financing models.

Socio-Economic Challenges in Smallholder Coffee Production

Smallholder farms, defined as those under two hectares, comprise 84% of global coffee holdings and produce an estimated 60%–70% of the world's coffee (Lowder et al., 2021). These farms face severe and persistent economic pressures. Labor costs exceed 50% of production budgets in Central American systems where hired labor predominates, while family labor on even smaller African and Asian farms represents substantial opportunity costs against alternative livelihood strategies (ICO, 2019; Lowder et al., 2021). At recent market prices averaging $1.20-$1.60 per pound farmgate, most smallholder farms operate substantially below living income benchmarks of $2.10-$2.50 per pound (Staritz et al., 2023; ICO, 2019), leaving approximately 70%-80% of coffee households earning insufficient income to meet basic household needs (Enveritas, 2024).

Labor costs dominate production budgets, comprising 61% of specialty-conventional coffee in El Salvador and 69% of specialty-organic coffee in Honduras, with paying workers a living wage increasing production costs at least 2.5-fold (Specialty Coffee Association, 2022) (Figure 6). At 2021 prices of $3.50 per pound in El Salvador and $2.75 in Honduras, farmgate revenues fall dramatically short of living wages estimated at $6.64 and $3.15 per pound respectively, leaving monthly household earnings well below the $459-$451 required for basic needs (Specialty Coffee Association, 2022). These structural deficits illustrate the fundamental economic unsustainability of current coffee production systems: even when farmers receive prices at the higher end of the market range, revenues remain insufficient to support living wages for workers or living incomes for farming households. The resulting cost-price squeeze creates a choice between exploiting labor through below-subsistence wages or operating farms at a loss,

neither of which represents a viable long-term pathway. This economic trap drives the persistent poverty affecting 70%-80% of coffee farming households and motivates the search for alternative revenue streams that can close the gap without requiring price increases that consumers resist or market structures that perpetuate value extraction by downstream actors.

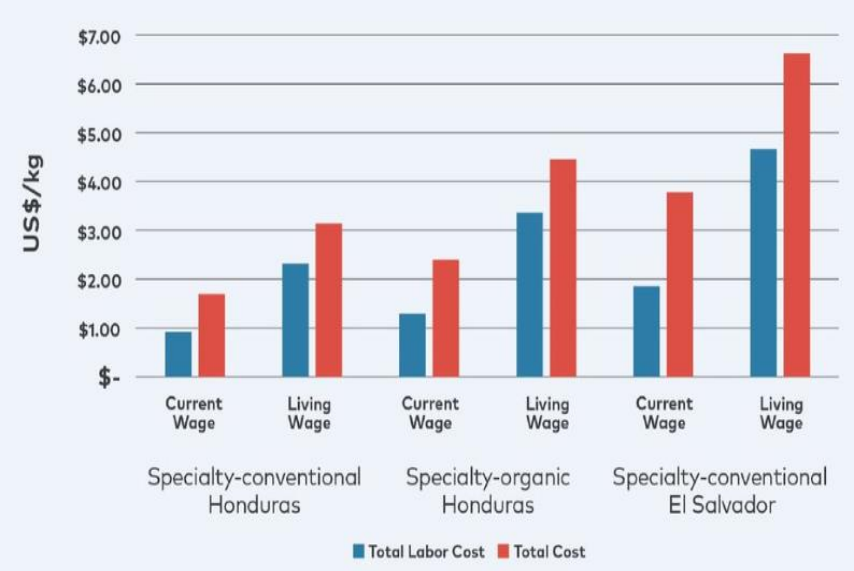


Figure 6. Costs of production for current and living wage in Honduras and El Salvador (Specialty Coffee Association, 2022).

Export-focused production exacerbates food insecurity by diverting land and labor from staple crops, exposing farmers to global price shocks while increasing dependence on purchased food (Patnaik, 1996; UNCTAD, 2021). Price volatility, driven by commodity speculation, weather events, and currency fluctuations, compounds this vulnerability. Between 2019-2022, Arabica prices fluctuated between $0.90-$2.40 per pound, a range that straddles living income thresholds of $2.10-$2.50 per pound, yet

smallholders bear downside risk while rarely capturing upside gains due to fixed contracts and limited storage capacity (ICO, 2019; Staritz et al., 2023).

In Puerto Rico, farmers participating in USDA programs report persistent struggles with low farm-gate prices, with one stating, "We can't survive on coffee alone," a sentiment echoed across interviews (CRCD, 2022; Grabs & Ponte, 2019). This economic precarity drives land abandonment and rural out-migration, particularly among younger generations who perceive coffee farming as economically unviable despite cultural attachments to land (Perfecto et al., 2019).

These structural challenges motivate a range of market-based and policy interventions intended to improve smallholder outcomes, yet evidence of their effectiveness remains mixed and contested.

Existing Economic Interventions: A Critical Assessment

Over the past three decades, numerous interventions have been proposed and implemented to improve smallholder coffee livelihoods and incentivize sustainable practices. These interventions operate through distinct mechanisms and can be categorized into three broad types: market-based incentives that reward verified practices with price premiums or market access; external transfers including payments for ecosystem services and subsidies; and financial innovations that ease capital constraints or transfer risk. Table 1 summarizes these approaches, their mechanisms, documented strengths and limitations, and the specific gap that WTEM (Whole Tree Economic Model) aims to address. Recall that the WTEM is a financing mechanism that generates additional revenue streams from valorization of coffee leaves and dried coffee fruit.

Table 1. Comparative assessment of economic interventions in smallholder coffee.

Approach	Mechanism	Strengths	Limitations	Gap WTEM Addresses	Sources
Certification & eco-labels	Third-party standards for premiums/market access	Verified practices; access to niche markets	Modest/volatile premiums; high compliance costs; limited scalability	Provides new biomass revenue stream; can layer with existing certifications	Meemken, 2020; Rainforest Alliance, 2021
Direct trade	Shorter supply chains; direct buyer–grower relationships	Improved prices; enhanced transparency; quality incentives	Remains niche; bean-focused; requires intensive relationship management	Scales non-bean biomass value independently of buyer relationships	Barham & Weber, 2012; Daviron & Ponte, 2005
Payments for ecosystem services	Payments for verified environmental outcomes	Aligns incentives for conservation; recognizes non-market values	High MRV costs; unstable funding; scale barriers	Provides immediate cash flow from existing biomass rather than waiting	Wunder, 2005; FAO, 2011

Approach	Mechanism	Strengths	Limitations	Gap WTEM Addresses	Sources
				for carbon payments	
Carbon credits	Monetize emission reductions/sequestration	Large market potential; established trading infrastructure	Verification costs exclude smallholders; market volatility; integrity concerns	Decouples transition finance from carbon market complexity and transaction costs	Schneider & La Hoz Theuer, 2019; Haggar et al., 2011
Value-chain finance	Credit secured against future harvests	Eases capital constraints; improved input access	Does not increase baseline income; default risk without profitability improvement	Enhances cash flow via diversified biomass revenue, improving creditworthiness	Miller & Jones, 2010; IFAD, 2016
Contract farming	Buyer-specified production contracts	Market security; potential technical assistance	Power asymmetries; farmers bears	Diversifies revenue beyond single-buyer	Bellemare, 2012; Gereffi et al., 2005

Approach	Mechanism	Strengths	Limitations	Gap WTEM Addresses	Sources
	with assured markets		production risk; limited income improvement	dependence	
Risk-transfer tools	Hedging, insurance, futures contracts	Stabilizes income against volatility	Requires financial literacy; basis risk; premium costs; does not lift baseline income	Boosts baseline revenue, reducing need for risk transfer	Greatrex et al., 2015; Miranda & Farrin, 2012
Philanthropy/subsidies	Grants for inputs, training, infrastructure	De-risks early adoption; supports capacity building	Time-bound; creates dependency; rarely sustained	Generates recurring biomass revenue independent of external funding	Sachs et al., 2019; World Bank, 2019
Shared value programs	Lead firm investment for supply security and ESG goals	Potential for scale; coordination with market actors	Uneven benefit pass-through; programmatic costs captured by firms	Enables farmer-led value capture through cooperative ownership	Porter & Kramer, 2011; ICO, 2016

This table synthesizes the comparative assessment of economic interventions designed to support smallholder coffee farmers. Each approach operates through a distinct

mechanism and delivers specific benefits, yet all exhibit limitations that constrain their effectiveness as transition financing mechanisms. The rightmost column identifies the specific gap that the Whole Tree Economic Model (WTEM) addresses within each intervention category, demonstrating how biomass valorization complements rather than replaces existing approaches. WTEM's distinctive contribution lies in generating immediate, recurring revenue from previously underutilized on-farm assets, thereby addressing the worse-before-better cash flow problem that existing interventions fail to resolve at scale.

Market Based Interventions: Certifications and Direct Trade

Certification programs including Fairtrade, Rainforest Alliance, UTZ, and USDA organic standards aim to improve farmer livelihoods and environmental outcomes through third-party verification of production practices, coupled with price premiums or preferential market access (Meemken, 2020). These programs have achieved substantial scale, and certified coffee now accounts for approximately 40% of global exports, with Fairtrade alone covering over 1.6 million farmers (Rainforest Alliance, 2021).

Closer examination of empirical evidence of their impact on farmer incomes and environmental outcomes, however, is decidedly mixed. Program requirements vary dramatically, creating farmer confusion and diluting impact. Rainforest Alliance requires only 30% of farm area to meet standards, allowing majority non-compliance while claiming certified status (Schleifer et al., 2019). Bird Friendly demands 40% shade cover and 12-meter tree height yet has minimal market penetration despite ecological rigor (Frajenal, 2022). This proliferation of overlapping, inconsistent standards impose multiple audit burdens while delivering unreliable premiums. Meta-analyses reveal modest and highly variable income effects, with premium capture often offset by certification costs, yield penalties from practice changes, and price volatility (Meemken, 2020; Grabs, 2020). In Ethiopia, certified coffee premiums rarely reach farmers, with

intermediaries and cooperatives capturing value through fees and quality discounts (Minten et al., 2018). A study of Kenyan coffee cooperatives found that certified farmers earned no more than conventional farmers when certification costs were accounted for (Jena et al., 2012).

Environmental impacts similarly show mixed results. While certifications prohibit certain harmful practices, such as deforestation or specific agrochemicals, compliance monitoring remains inconsistent, and certified farms often exhibit environmental performance indistinguishable from conventional operations (Blackman & Rivera, 2011). The proliferation of certification schemes creates confusion and audit fatigue, with some farmers participating in multiple programs simultaneously to access different markets, multiplying compliance costs (Grabs & Ponte, 2019).

Direct trade relationships, in which roasters establish long-term purchasing agreements directly with producer cooperatives or estates, aim to improve price transparency, quality incentives, and supply chain traceability (Barham & Weber, 2012). These relationships can deliver substantially higher prices than commodity markets, sometimes double or triple, and provide technical assistance for quality improvement (Daviron & Ponte, 2005). However, direct trade remains concentrated in specialty segments serving high-income consumers, covering less than 5% of global coffee trade. Scalability is constrained by the intensive relationship management required, the quality thresholds that exclude many smallholders, and the buyer bargaining power that leaves farmers vulnerable to relationship termination (Grabs & Ponte, 2019).

Critically, both certifications and direct trade focus overwhelmingly on the coffee bean as the sole unit of value. Farmers receive premiums for better beans but gain no

recognition or compensation for the ecosystem services their farms provide or the potential value in non-bean biomass. This singular focus leaves substantial value uncaptured and fails to address the fundamental cash-flow problem during regenerative transitions when bean production temporarily declines.

External Transfers: Payments for Ecosystem Services and Subsidies

Payments for ecosystem services (PES) schemes compensate landholders for conservation behaviors or environmental outcomes such as carbon sequestration, watershed protection, or biodiversity conservation (Wunder, 2005). Shade-grown coffee agroforestry systems provide carbon sequestration benefits (2-5 tC/ha annually) (Nesper et al., 2020; Haggar et al., 2011), enhanced pollination services valued at $100–$300 per hectare, and maintenance of hydrological function in montane watersheds (Jezeer et al., 2019; Nesper et al., 2020).

In principle, PES could provide transition financing by monetizing these services. In practice, PES schemes face substantial implementation barriers that largely exclude smallholder participation. Monitoring, reporting, and verification (MRV) costs range from $5 to $10 per hectare annually, often exceeding potential payments in smallholder contexts (Schneider & La Hoz Theuer, 2019; Den Besten et al., 2014). Carbon credit markets, while theoretically offering payments of $10–$30 per ton of CO2 equivalent, impose transaction costs including baseline establishment, additionality demonstration, and third-party verification that make projects economically viable only at scales of thousands of hectares (Lee et al., 2011; Kreibich et al., 2021).

Furthermore, carbon markets suffer from integrity concerns including overestimation of carbon sequestration, inadequate accounting for permanence risk, and

leakage effects where emissions shift to uncertified areas (Schneider & La Hoz Theuer, 2019). These concerns have eroded buyer confidence and contributed to price volatility, with voluntary carbon credits for agricultural projects trading between $3 and $15 per ton in recent years, often below the cost of verification (Ecosystem Marketplace, 2022).

Agricultural subsidies and grant programs, including USDA conservation incentives, government agricultural extension services, and philanthropic projects, provide direct financial support for practice adoption (Sachs et al., 2019; World Bank, 2019). Copper Hill Farm has benefitted from some of these services, and these programs can effectively de-risk early adoption and support capacity building. However, they remain time-bound, typically lasting 3-5 years, and create dependence on continued external funding that rarely materializes (USDA, 2022). When subsidy programs terminate, farmers often revert to previous practices if the new systems have not achieved economic viability, undermining long-term sustainability goals.

Financial Innovations: Value-Chain Finance and Risk Transfer

Agricultural value-chain finance (AVCF) provides credit to smallholders secured against future harvests, easing capital constraints for inputs and investments (Miller & Jones, 2010). By linking financing to established buyer relationships, AVCF reduces lender risk and can offer better terms than traditional agricultural credit. The International Fund for Agricultural Development (IFAD) has promoted AVCF models across multiple commodity sectors, documenting improved access to inputs and technology adoption (IFAD, 2016).

However, AVCF does not fundamentally improve farm-level profitability; it merely shifts the timing of cash flows. Farmers still face the underlying challenge of low margins on coffee production, and debt obligations can become burdensome when yields disappoint, or prices fall. Without revenue increases, AVCF may increase rather than reduce farmer vulnerability (Ponte, 2019).

Risk-transfer instruments including price hedging, weather-indexed insurance, and futures contracts aim to stabilize farmer incomes against market and climate volatility (Greatrex et al., 2015; Miranda & Farrin, 2012). These tools can provide valuable protection when appropriately designed and priced. However, uptake among smallholders remains low due to basis risk (mismatch between index triggers and actual farm-level losses), premium costs that strain tight budgets, and limited financial literacy to evaluate complex insurance products (Greatrex et al., 2015).

Contract farming arrangements, in which buyers pre-specify quality and quantity requirements with associated pricing, provide assured markets and can include input provision or technical assistance (Bellemare, 2012). However, these relationships often embed power asymmetries, with buyers dictating terms and farmers bearing production risk. Contract breaches favor buyers, who can source elsewhere, while farmers face penalties or relationship termination if they fail to deliver (Gereffi et al., 2005).

Value Chain Power Dynamics and Shared Value

Global value chain theory highlights how power asymmetries shape benefit distribution across supply chain actors (Gereffi et al., 2005). In coffee, roasters and retailers in consuming countries capture 60–80% of final retail value, while farmers receive 10%–20% despite bearing production risk and providing the essential commodity

(Ponte, 2019; Daviron & Ponte, 2005). This rent extraction occurs through multiple mechanisms: buyer concentration enabling monopsony power, quality discounts that penalize smallholder heterogeneity, branding and marketing value that accrues downstream, and information asymmetries regarding prices and quality standards (Grabs, 2020).

Shared value initiatives, in which lead firms invest in supplier capacity building and sustainability to secure supply and meet corporate social responsibility objectives, represent an attempt to address these asymmetries (Porter & Kramer, 2011). Major roasters including Nestlé, Starbucks, and Lavazza operate farmer support programs providing technical assistance, credit, and in some cases premium payments (ICO, 2016). While these programs can deliver benefits at the farm level, value chain governance literature documents uneven pass-through of benefits, with programmatic costs often captured in firm margins rather than transmitted as higher farmgate prices (Ponte, 2019). This review revealed that while certification schemes, direct trade, payments for ecosystem services, carbon credit programs, and risk-transfer instruments each contribute specific advantages, none reliably provides the sustained transition finance required by smallholder coffee farmers. Many are constrained by volatility in price premiums, high transaction and monitoring costs, or dependence on niche buyer relationships. Nearly all remain focused on the coffee bean as the sole unit of value, missing opportunities to monetize underutilized biomass streams that could generate countercyclical income during the critical worse-before-better transition period.

Existing interventions collectively leave an estimated $4 billion financing gap for regenerative transitions globally, calculated as the difference between conventional and

regenerative net returns during the establishment phase multiplied by the area requiring transition in their most recent 2025 report (TechnoServe, 2025). This gap persists because short-term yield penalties of 10%–25% and establishment costs ranging from $1,500-$3,000 per ha create cash-flow deficits that smallholders cannot absorb without external support (Jezeer et al., 2019; Quandt et al., 2023; Sachs et al., 2019).

Regenerative Agriculture and Agroforestry: Technical Potential and Adoption Barriers

Regenerative agriculture encompasses practices that restore soil health, enhance biodiversity, and sequester atmospheric carbon while maintaining or improving productivity (Figure 7) (Hawken, 2017).

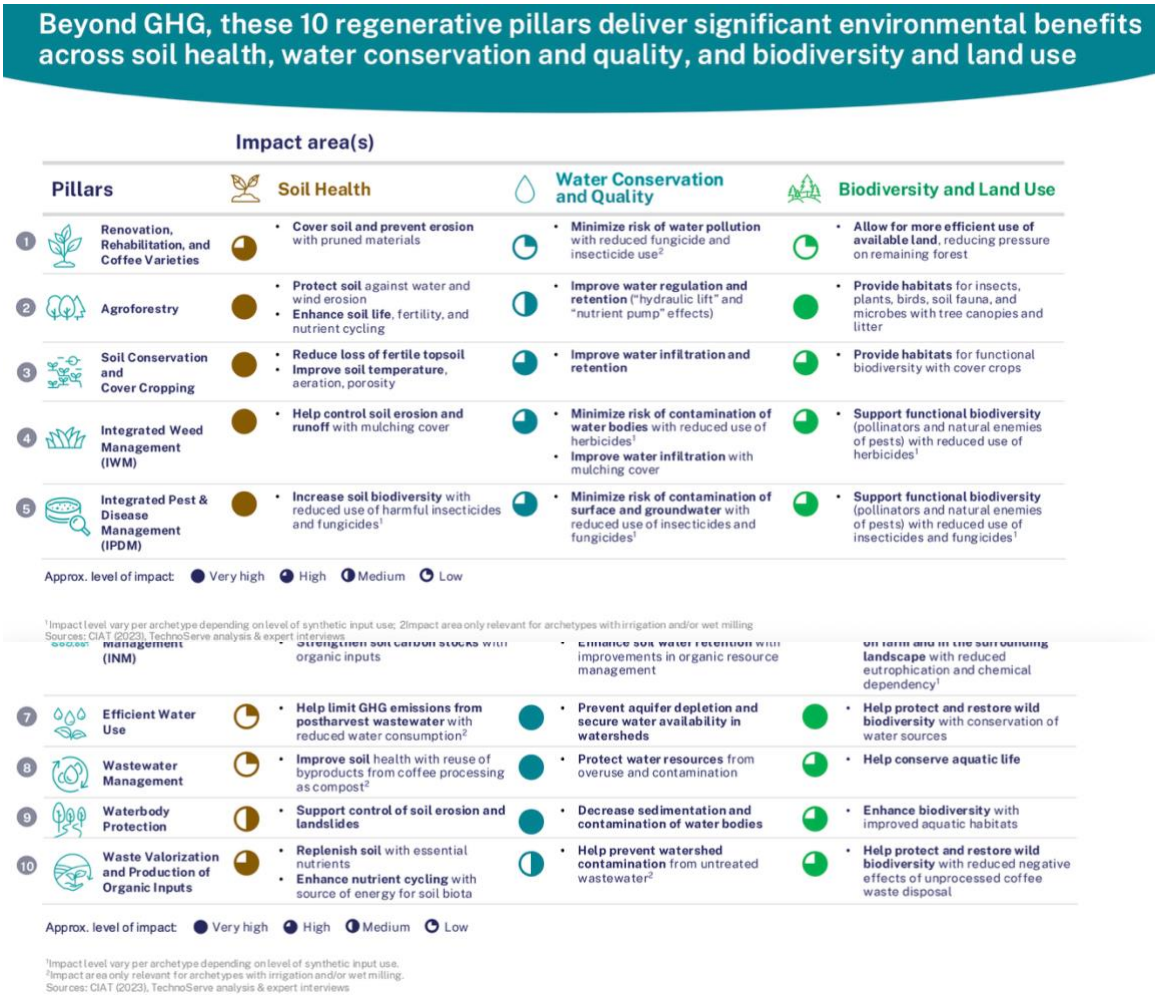


Figure 7. Environmental benefits of regenerative agriculture (Technoserv, 2025).

Ecological and Agronomic Benefits

In coffee production, shade-grown agroforestry represents the primary regenerative approach, integrating coffee cultivation with diverse tree species that provide shade, organic matter, habitat, and often marketable co-products (Rahn et al., 2014; Jezeer et al., 2019).

Empirical evidence demonstrates multiple benefits from shade-based coffee agroforestry compared to full-sun monoculture systems. Shade trees reduce evapotranspiration by 10%–15%, improving drought resilience and reducing irrigation requirements (Nesper et al., 2020). Cover crops and organic mulch reduce soil erosion by 50–60%, addressing a critical problem in sloped tropical environments where soil loss can reach 20–40 tons per ha annually in bare-soil systems (FAO, 2013; Rodale Institute, 2020). Diversified systems support higher populations of beneficial insects and birds that provide biological pest control, reducing pest-related crop losses by 20–40% compared to monocultures (Perfecto & Vandermeer, 2015).

Carbon sequestration represents a particularly well-documented benefit. Shade-grown coffee agroforestry systems can sequester 2–5 tons of carbon per ha annually in above-ground and below-ground biomass (Nesper et al., 2020; Haggar et al., 2011), compared to near-zero sequestration in annual cropping systems or full-sun coffee (Nesper et al., 2020; Jezeer et al., 2019). Over a 20-year period, this translates to 100–200

tons of CO2-equivalent sequestration per hectare, substantial compared to typical agricultural emissions of 2–5 tons CO2e per hectare annually.

Ecosystem services extend beyond the farm boundary. Shade coffee maintains habitat connectivity in fragmented landscapes, supporting 60%–80% of forest bird species compared to less than 10% in full-sun systems (Moguel & Toledo, 1999). Agroforestry systems regulate watershed hydrology, reducing peak flows and maintaining dry-season base flows critical for downstream communities (Jezeer et al., 2019).

My fieldwork at Copper Hill Farm and surrounding operations in Puerto Rico confirms these patterns. Farms implementing shade systems with organic amendments report reduced soil erosion, improved soil moisture retention during dry periods, and lower agrochemical requirements. Importantly, these farms also report reduced yield volatility: when hurricanes, droughts, or pest outbreaks occur, diversified systems experience losses 10–40% lower than conventional monocultures, consistent with findings from Central American studies (Quandt et al., 2023; TechnoServe, 2025). Figure 8 illustrates this resilience effect, showing yield stability under climate stress.

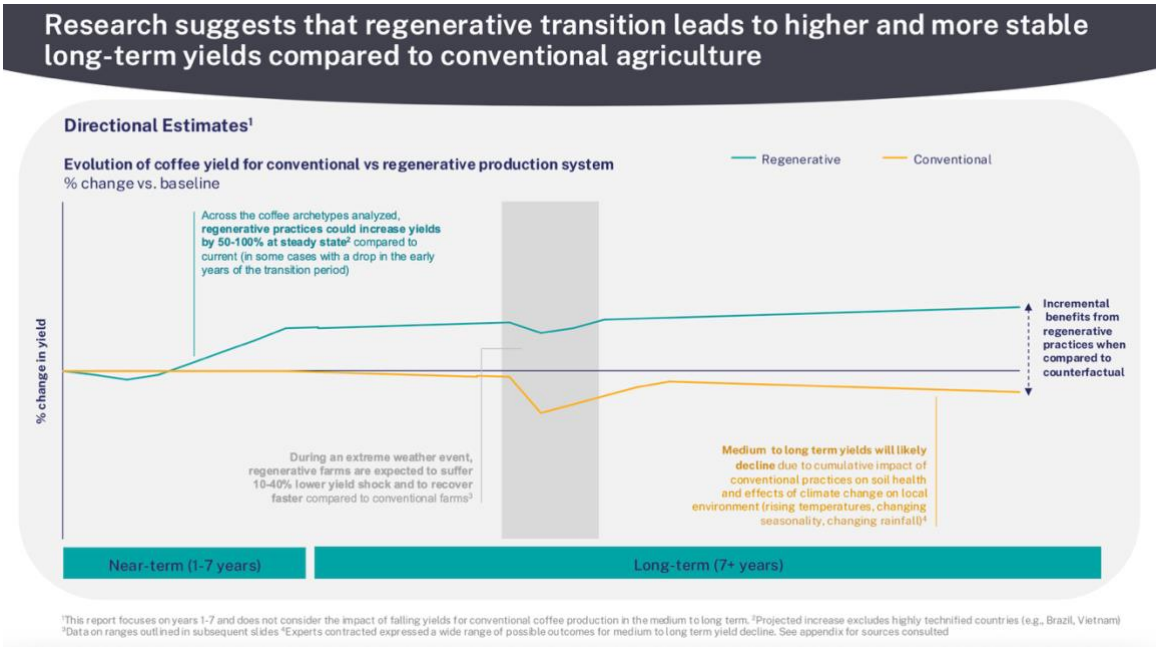


Figure 8. Yield stability in regenerative vs. conventional coffee systems under climate stress (Rodale Institute, 2020).

Yield Trade-offs and Scholarly Debates

Regenerative agriculture is not without trade-offs, however, and scholarly debate persists regarding optimal management approaches. The most contentious issue concerns short-term yield impacts during the transition period. When farmers convert from full-sun to shaded systems, coffee yields typically decline by 10–25% in the first three to five years, though the magnitude varies with shade density and management intensity (Jezeer et al., 2019; Quandt et al., 2023; Haggar et al., 2017). These declines are most pronounced when shade density exceeds 40–50% canopy cover, though optimal shade levels vary by elevation, latitude, and coffee variety (Rahn et al., 2014).

Some studies report that yields recover to parity or exceed full-sun systems in the long term as soil health improves and microclimate stabilizes, while others document

persistent 10–25% yield penalties even in mature systems (Haggar et al., 2017; Perfecto et al., 2005). This variation reflects differences in shade tree species selection, management intensity, elevation, and rainfall patterns. In higher-elevation systems above 1,200 meters where temperatures are naturally cooler and water stress less severe, shade penalties appear minimal, while lower-elevation systems may suffer greater yield impacts (Jezeer et al., 2019).

Another debate concerns scalability. Some agronomists question whether diversified agroforestry can meet projected global coffee demand growth of 2–3% annually without extensification into forested areas (Maslin & Nab, 2021). Critics argue that intensive, high-yielding systems, even if less biodiverse, minimize land footprint and spare forest, while proponents counter that yield reductions in agroforestry are overstated when accounting for co-product revenues, reduced input costs, and risk reduction (Rahn et al., 2014; Perfecto & Vandermeer, 2015).

Varietal selection adds another dimension. Climate-resilient cultivars including rust-resistant hybrids can boost yield stability by 10–15% in disease-prone environments, but these varieties often require specific management and may not perform well in high-shade conditions (FAO, 2017; Cerda et al., 2017). The interaction between variety, shade level, elevation, and management creates a complex optimization problem that defies universal prescriptions.

Hawken (2017) ranks regenerative agriculture among the most impactful terrestrial climate interventions, with potential for gigaton-scale carbon drawdown if adopted globally across hundreds of millions of hectares. However, he emphasizes that technical potential means little without viable revenue streams to finance adoption.

Raworth's (2017) "doughnut economy" framework articulates the need for agricultural systems that operate within both ecological ceilings and social foundations yet offers limited guidance on scalable financing mechanisms. Meadows et al. (1972) identified the need for new capital flow feedback loops to address ecological overshoot, a challenge that persists five decades later in the context of agricultural transitions.

My analysis of Central American farm economics, following Haggar et al. (2017), reveals that full-sun systems deliver short-term profit maximization but degrade soil productivity, necessitating increased agrochemical reliance that raises costs by 20%–30% over time. Conversely, moderate shade systems in Southeast Asian contexts improve both ecological resilience and long-term profitability by 10%–15%, as documented by Le et al. (2021) and 4C Services (2024). These findings suggest that economic viability depends critically on whether farmers can weather the initial transition period, precisely the gap WTEM aims to address.

Adoption Barriers

Given the documented long-term benefits, why does adoption remain limited? Three interconnected barriers emerge from the literature and from my fieldwork observations.

Economic barriers dominate farmer decision-making. Establishment costs for shade systems range from $1,500-$3,000 per ha globally (and more in Puerto Rico) including shade tree seedlings, organic amendments, and labor for planting and initial management (Quandt et al., 2023; Sachs et al., 2019). The 10%–25% yield penalty during the first 3-5 years translates to foregone revenue of $500–$1,000 per hectare annually in

regions where coffee generates $3,000–$5,000 per hectare in conventional systems (Jezeer et al., 2019; TechnoServe, 2025). Smallholders operating near subsistence cannot absorb these losses without alternative income sources or external financing.

Knowledge and technical barriers compound economic constraints. Agroforestry requires management skills distinct from monoculture production: shade tree selection and pruning to optimize light levels, pest and disease management in more humid microclimates, and timing of organic amendments to synchronize with nutrient demand (Rahn et al., 2014). Extension services in many coffee regions remain oriented toward conventional intensification, providing limited support for agroforestry adoption (Haggar et al., 2011).

Market and institutional barriers create disincentives for individual adoption even when farm-level economics are favorable. Certification premiums for shade-grown coffee are unreliable and often insufficient to offset transition costs (Meemken, 2020). Carbon credit markets exclude smallholders through high transaction costs (Schneider & La Hoz Theuer, 2019). Buyers may penalize heterogeneous quality that can result from diversified systems, and cooperatives may lack processing infrastructure suited to agroforestry production (Grabs, 2020).

My fieldwork conversations with farmers in Puerto Rico consistently emphasize the economic barrier as primary. One farmer participating alongside us in a USDA conservation program stated, "I believe in shade coffee, I see the benefits, but I can’t afford to earn less for five years while I wait for it to pay off. My family needs to eat now." This sentiment encapsulates the challenge: regenerative agriculture offers long-

term benefits but imposes short-term costs that exceed the financial capacity of households already operating at the margin.

Biomass Valorization: Precedents and WTEM's Innovation

The coffee plant generates substantial underutilized biomass including pulp, husk, silverskin, flowers, and leaves, collectively termed wasted coffee tree biomass (WCTB), with 70%–85% currently discarded or undervalued (Janissen & Huynh, 2018; Klingel et al., 2020). Valorization, the process of converting low-value or waste materials into marketable products, offers potential to generate additional revenue streams while addressing waste management challenges.

Coffee Leaf Potential

Coffee leaves contain bioactive compounds including mangiferin (a xanthone with antioxidant properties), chlorogenic acids, and caffeine at levels suitable for beverage applications (Vuong et al., 2011; Chen et al., 2022). Mangiferin concentrations in coffee leaves range from 0.5%-2.5% dry weight depending on variety and growing conditions, exceeding levels found in mango or honeybush tea, the primary commercial sources (Bhattacharyya et al., 2014). These compounds confer antioxidant, antimicrobial, and anti-inflammatory properties that align with consumer demand in functional beverage and nutraceutical markets growing at 5.6% annually (Eckhardt et al., 2022).

Coffee leaf tea has historical precedents. In Ethiopia and parts of Indonesia, coffee leaves have been traditionally brewed as a caffeine-containing infusion for centuries (Campa et al., 2012). However, modern commercial development has been constrained by lack of regulatory clarity in major markets and limited supply chain

infrastructure. Recent regulatory approvals have changed this landscape: coffee leaf tea received novel food authorization in the European Union in 2020, establishing maximum caffeine limits and purity standards (EFSA, 2020). Several companies now market coffee leaf tea in European markets, though volumes remain small.

Off-season pruning of coffee leaves integrates readily with existing farm operations. Based on observations at Copper Hill Farm and regional pruning practices, coffee trees yield approximately 0.5–1.0 kg of harvestable leaves per tree annually from routine maintenance pruning (Murthy & Naidu, 2012; Vuong et al., 2011). This countercyclical timing provides income during the coffee off-season, stabilizing cash flow. Simple solar drying or mechanical dehydration followed by milling produces a shelf-stable product suitable for tea bags or extraction, requiring capital investment of $5,000–$15,000 per ton of annual processing capacity at cooperative scale (Murthy & Naidu, 2012), however these basic processes tend to produce a bitter tasting, albeit healthy, product with limited commercial appeal.

Cascara: Coffee Cherry Husks

Cascara, the dried husk of the coffee cherry, has emerged as a commercial product in specialty coffee markets over the past decade. After coffee cherries are pulped to extract beans, the remaining fruit material, comprising approximately 40-45% of cherry weight, is typically discarded or composted (Janissen & Huynh, 2018). Dried cascara contains chlorogenic acids, quinic acid, and natural sugars that produce a sweet, fruity infusion distinct from coffee (Martinez-Saez et al., 2014).

Cascara gained novel food authorization in the European Union in 2022, establishing specifications for drying methods, microbial limits, and labeling requirements (EFSA, 2022). In the United States, coffee fruit extract (a concentrated form of cascara) received GRAS (Generally Recognized As Safe) status in 2020, enabling use in beverages, supplements, and functional foods (US FDA, 2020, GRN 000868). These regulatory approvals remove major barriers to commercialization.

Cascara yields vary substantially based on coffee variety, tree density, and processing method. Literature estimates of 0.2–0.4 kg dried cascara per tree (Janissen & Huynh, 2018) apply to lower-density farms (1,000–2,000 trees/ha). Mass balance calculations from green bean production (see Appendix 6) yield approximately 130 kg/ha dried cascara for this study's reference farm, reflecting the 15% dry matter recovery from fresh pulp after 85% moisture removal. At current specialty market prices of $3–$8 per kilogram wholesale for food-grade cascara (Coffee Cherry Company, 2024), this represents potential gross revenue of $400–$1,040 per hectare, a modest supplement to green bean income that proves insufficient for standalone viability, as S3 results demonstrate. (Eckhardt et al., 2022).

Cross-Sectoral Precedents

Biomass valorization precedents from other agricultural sectors inform WTEM's feasibility. Mediterranean olive oil production generates pomace (crushed pulp and pits) from olive processing, historically a waste disposal problem (Niaounakis, 2017). Over the past two decades, the industry has developed integrated biorefineries that extract residual oil, produce animal feed from defatted pomace, generate energy through combustion, and extract phenolic compounds for nutraceutical applications (Dermeche et al., 2013). This

transformation converted a costly waste stream into a revenue source, improving overall sector profitability.

The brewing industry provides another parallel. Spent grain, the primary byproduct of beer production, accounts for 85% of brewing waste by weight. Rather than landfilling, breweries now sell spent grain for animal feed, compost, or anaerobic digestion for biogas (Mussatto, 2014; Ugo, F. et al., 2025). Some breweries have developed integrated systems where spent grain feeds livestock, manure returns to agricultural fields, and methane is captured for energy, creating circular material flows that reduce costs and environmental impacts.

These precedents demonstrate that biomass valorization becomes economically viable when several conditions align: sufficient volume to justify processing infrastructure, regulatory authorization for products, established or emerging market demand, and logistical integration with existing operations to minimize additional costs (Murthy & Naidu, 2012). Coffee leaves and cascara meet these criteria in ways that other coffee byproducts currently do not.

Cooperative Processing Infrastructure

Individual smallholders overall cannot economically invest in drying, milling, and packaging equipment for biomass processing. Cooperative aggregation solves this coordination problem, achieving economies of scale while distributing benefits among members. Cooperative hubs can reduce processing costs by 30% compared to individual farmer investment through shared equipment utilization and bulk marketing (FAO, 2023; Dermeche et al., 2013).

Agricultural economics literature identifies coordination failures and thin markets as primary barriers to smallholder participation in value-added processing (Dorward et al., 2006). When atomized producers face high transaction costs to connect with buyers, and when buyers face high costs to source from numerous small suppliers, mutually beneficial trades fail to occur. Cooperatives internalize these transaction costs, providing institutional infrastructure for collective action.

Successful cooperative models from other sectors suggest design principles for WTEM implementation. First, transparent governance with farmer representation ensures equitable benefit distribution and maintains member trust. Second, professional management with technical and business expertise improves operational efficiency and market access. Third, phased investment starting with low-cost technologies (solar drying) before scaling to more capital-intensive equipment (mechanical dryers, extraction) manages financial risk during market development (Dorward et al., 2006).

Agricultural value-chain finance can enhance cooperative bankability. When cooperatives establish purchase contracts with buyers for coffee leaf tea or cascara products, these receivables serve as collateral for working capital loans, reducing default risk and improving credit terms (Miller & Jones, 2010; Ponte, 2019). This financial innovation complements biomass valorization by easing the capital constraints that might otherwise prevent cooperative investment in processing infrastructure.

Theoretical Framework: Induced Innovation and On-Farm Asset Reconfiguration

Having reviewed the empirical literature on coffee systems, interventions, and valorization precedents, I now position WTEM within agricultural transition theory. This

study draws primarily on induced innovation theory (Hayami & Ruttan, 1985) and sustainable livelihoods frameworks (Scoones, 2009) to theorize how biomass monetization can overcome adoption barriers.

Induced Innovation Theory

Hayami and Ruttan (1985) theorize that farmers adopt technologies when relative factor prices favor them. Innovations that economize on scarce, expensive inputs are adopted more readily than those requiring abundant, cheap inputs. In Puerto Rico, where labor costs are high but land and biomass are underutilized, technologies that generate value from existing on-farm assets without additional labor should find ready adoption.

WTEM operates through this mechanism: by monetizing previously valueless biomass, it effectively changes the price farmers receive for diversified production. The economic returns to shade agroforestry improve not because bean yields increase or input costs decrease, but because farmers capture additional revenue streams from leaves and cascara. This shifts the net present value calculation in favor of adoption without requiring behavioral change motivated by environmental altruism or long-term thinking, motivations that prove insufficient in contexts of immediate economic precarity.

This mechanism differs fundamentally from certifications (which require practice changes to capture premiums) or PES (which pay for conservation behaviors). WTEM enables farmers to profit from assets they already produce as byproducts of necessary operations: pruning and harvest processing. The innovation lies in market creation and value chain development rather than technological invention.

Sustainable Livelihoods and Asset-Based Development

Sustainable livelihoods frameworks emphasize that rural households draw on multiple capital assets; natural, physical, financial, human, and social, to construct livelihoods resilient to shocks (Scoones, 2009). WTEM strengthens multiple capitals simultaneously: natural capital through regenerative practices that restore soil and biodiversity; physical capital through cooperative processing infrastructure; financial capital through diversified income; human capital through technical training in biomass processing; and social capital through cooperative governance.

This multi-capital strengthening contrasts with interventions narrowly targeting single capitals. Carbon credits, for instance, provide financial capital but may not strengthen social organization or build technical capacity. Certifications require human capital investment in training but may not improve financial capital if premiums prove volatile. WTEM's integrated approach addresses the interconnected nature of smallholder constraints.

Research Gaps

This literature review revealed three critical gaps:

- Transition financing mechanisms: While regenerative agriculture's ecological benefits are well-documented, including carbon sequestration, biodiversity enhancement, and resilience improvement, adoption is constrained by short-term yield penalties and high establishment costs that create a worse-before-better cash flow problem (Jezeer et al., 2019; Rahn et al., 2014; Pinoargote et al., 2017). Existing interventions including certifications, carbon credits, and subsidies fail to provide

consistent transition financing, with 70%-80% of smallholders earning below living income thresholds due to farmgate prices that fall 40-50% short of the $2.10-$2.50 per pound required for basic household needs (Staritz et al., 2023; Enveritas, 2024; Grabs, 2020). No existing mechanism reliably generates immediate, recurring revenue to bridge this gap.

- Underutilized biomass potential: Coffee produces substantial non-bean biomass with documented commercial potential, particularly leaves rich in mangiferin and cascara with approved food uses, and yet these streams remain largely unexploited (Vuong et al., 2011; EFSA, 2022; US FDA, 2020). While agronomic research documents bioactive compounds and processing methods (Chen et. al, 2022; Martinez-Saez et al., 2014; Murthy & Naidu, 2012), economic analysis of biomass monetization as a financing mechanism for farm transitions is absent from the literature. The potential for biomass revenues to offset transition costs has not been rigorously quantified.
- Scalable cooperative governance: Cooperative processing models can reduce transaction costs and enable smallholder participation in value-added markets (Dorward et al., 2006; FAO, 2023), but implementation challenges related to governance, quality control, and market access frequently undermine these theoretical benefits. How cooperative hubs can be structured to reliably aggregate, process, and market coffee biomass at sufficient scale and quality to attract buyers remains an open question requiring empirical investigation.

These research gaps can best be addressed via a case study that develops a model that provides solutions to the transition gap in regenerative coffee farming. Puerto Rico provides an ideal case for this research.

Historical Context: Puerto Rico's Coffee Heritage

Puerto Rico's suitability as a coffee-producing region has deep historical precedent. Following coffee's introduction in 1736, the island became the world's sixth-largest exporter by the 1890s, producing 132 million pounds annually with gross income of $16 million (Denis, 2015). At its peak in 1896, the sector generated nearly $10 million in profit from $16 million in gross revenue, demonstrating the island's capacity for high-quality, profitable coffee production under favorable economic conditions (Denis, 2015). Hurricane San Ciriaco's landfall in 1899 devastated plantations, reducing gross income by 60% to $6 million within seven years and triggering mass farm abandonment (Denis, 2015). Subsequent economic restructuring under Operation Bootstrap (1947) shifted the economy toward manufacturing, with tax incentives attracting mainland U.S. companies and drawing agricultural laborers to industrial jobs. This transformation reduced coffee farms from 21,693 in 1899 to just 4,737 today (a 78% decline) while coffee quality deteriorated as producers mixed local beans with cheaper imports to compete on price (Denis, 2015). The island's transition from agricultural powerhouse to high-cost, import-dependent economy makes Puerto Rico uniquely suited to test whether WTEM can succeed under worst-case economic conditions: if viable here, the model should perform even better in traditional low-cost origins where labor, land, and input costs are substantially lower.

Recent U.S. federal investments support Puerto Rico's regenerative potential while highlighting the need for sustainable financing mechanisms. The USDA's 2023 Climate-Smart Commodities project, led by the Caribbean Regenerative Community

Development group (CRCD) in partnership with Copper Hill Farm, Cafiesencia, Gnarly Tree Sustainable Institute, and the University of Wisconsin, engages 200 smallholder farms across 2,000 acres to adopt shade-based agroforestry and biochar applications. The five-year, $10 million initiative provides cost-share for shade tree establishment and soil amendments, with carbon sequestration monitored via COMET-Planner and greenhouse gas benefits documented through soil sampling and lifecycle accounting (CRCD, 2022; USDA, 2022). Institutional partners provide technical assistance through Forest Stewardship Management Plans aligned with USDA guidelines, creating an existing network of early adopters demonstrating buy-in to climate-smart practices.

However, the program's time-bound nature exposes a critical limitation: funding terminates after five years, with no mechanism to support continuation of practices or scaling beyond the initial 200 farms (CRCD, 2022). This temporal constraint illustrates the broader challenge facing regenerative transitions, that even well-funded government programs cannot provide permanent subsidies at scale. The initiative aligns with WTEM's ecological assumptions regarding shade-based agroforestry and organic soil management but necessitates sustainable revenue streams like biomass monetization to ensure long-term viability beyond the subsidy period. By testing WTEM within this institutional context, where farms receive initial establishment support but require ongoing income streams to maintain practices, this research addresses the critical transition from grant-dependent to economically self-sustaining regenerative agriculture.

The federal administration has paused funding for this and other USDA climate projects indefinitely, further highlighting the need for non-subsidized approaches to regenerative agriculture transitions.

Research Questions, Hypotheses and Specific Aims

Based on the research gaps identified, my objective was to determine whether monetizing underutilized coffee tree biomass, specifically coffee leaves and cascara, can overcome the dual economic barriers preventing regenerative agroforestry adoption. My main question was therefore: does the Whole Tree Economic Model (WTEM) generate positive net present value (NPV) while maintaining living income during transition, overcoming both long-term profitability and short-term liquidity barriers? To address this question considering prior research in this area I reviewed above, I developed the following associated research questions and hypotheses:

RQ1: Does the Whole Tree Economic Model generate positive net present value while maintaining living income during transition, overcoming both long-term profitability and short-term liquidity barriers?

- Hypothesis 1a: WTEM (S_6) generates positive 10-year NPV
- Hypothesis 1a-ii: WTEM (S_6) NPV exceeds regenerative baseline (S_2)
- Hypothesis 1b: WTEM (S_6) maintains annual income ≥ $12,877 during Years 1-4 (critical establishment period)

RQ2: Which biomass stream (coffee leaves, cascara, or their combination) provides the most viable pathway for financing regenerative adoption, and how do temporal dynamics affect adoptability?

- Hypothesis 2a-NPV: Leaf-only scenario (S_4) achieves NPV > 0
- Hypothesis 2a-Income: Leaf-only scenario (S_4) maintains annual income ≥ $12,877 during Years 1-4

• Hypothesis 2b-NPV: Cascara-only scenario (S_3) achieves NPV > 0

• Hypothesis 2b-Income: Cascara-only scenario (S_3) maintains annual income ≥ $12,877 during Years 1-4

• Hypothesis 2c: Combined WTEM (S_6) achieves NPV synergies ≥ $1,000 beyond the sum of individual streams

RQ3: Does WTEM achieve substantial superiority (≥25% NPV improvement) over both conventional monoculture and regenerative systems without biomass monetization?

• Hypothesis 3a: WTEM (S_6) NPV ≥ 1.25× conventional monoculture (S_1)

• Hypothesis 3b: WTEM (S_6) NPV ≥ 1.25× regenerative baseline (S_2)

RQ4: Does WTEM provide downside protection under market stress, maintaining viability when specialty coffee premiums decline to legal minimum floor prices?

• Hypothesis 4a: WTEM (S_6) maintains NPV > 0 at legal minimum price floor ($4.20/lb)

• Hypothesis 4b: WTEM (S_6) achieves NPV > 0 with zero coffee bean revenue

• Hypothesis 4c: Regenerative baseline (S_2) achieves positive NPV under base case assumptions

These questions operationalize a dual-metric viability framework distinguishing economic barriers (negative NPV rendering adoption irrational) from financial barriers (liquidity constraints preventing access to positive-NPV investments). The temporal complementarity distinction between coffee leaf processing (leveraging off-season cooperative capacity) and cascara processing (competing for harvest-period resources) informs strategic adoption sequencing, with leaf-only systems potentially serving as low-risk first phase entry points before cascara expansion.

Specific Aims

My specific aims were to:

1. Employ 10-year discounted cash flow analysis at r = 3.57% using data from Copper Hill Farm in Puerto Rico as the basis for testing economic viability across six management scenarios (S_1: conventional monoculture, S_2: regenerative baseline without biomass monetization, S_3: regenerative with cascara monetization, S_4: regenerative with leaf monetization, S_5: Stress test with leaf and cascara monetization but no green bean, S_6: Full WTEM with leaf and cascara).
2. Develop a dual-metric viability framework distinguishing economic barriers (negative NPV) from financial barriers (transition-period liquidity constraints where annual income < $12,877).
3. Employ Monte Carlo simulation to test the significance of relationships between biomass revenue streams and dual viability achievement.

Chapter II

Methods

This study employed a comparative scenario-based financial modeling approach to evaluate the Whole Tree Economic Model's (WTEM) economic viability using stochastic simulation. I develop net present value (NPV) models which compared six alternative farm management scenarios over a 10-year horizon (2024-2034), using empirical data from Copper Hill Farm in Puerto Rico as the primary case study. The 10-year horizon reflecting one coffee tree replacement cycle aligns with USDA Natural Resources Conservation Service investment evaluation timeframes for agroforestry transitions, and used the $12,877 living income threshold derived from Anker methodology adapted for Puerto Rico, which represented the minimum income necessary for a 4-person household to afford nutritious diet, decent housing, and other essential needs without compromising human dignity. The analysis integrated three methodological components: (1) on-farm data collection and biophysical assessment, (2) probabilistic financial modeling with Monte Carlo simulation and sensitivity analyses, and (3) comparative extrapolation to assess transferability across coffee-producing regions.

Case Study Site: Copper Hill Farm

My analysis focused on Copper Hill Farm, a 500-acre agroecological pilot integrating shaded coffee, cascara drying, and leaf harvesting with biodigestion, vermicomposting and solar dryers (Murthy & Naidu, 2012; Eckhardt et al., 2022).

Copper Hill Farm spans 500 acres across two parcels in Las Marías and Maricao, Puerto Rico (18°13'07.7"N 66°58'29.4"W), situated at 330-550 meters elevation in the cordillera central (Figure 9). The property comprises: (1) 437 acres (87%) under forest conservation, (2) 10 acres (2%) in active coffee production, (3) 50 acres (10%) designated for regenerative development, and (4) 3 acres (1%) for infrastructure.

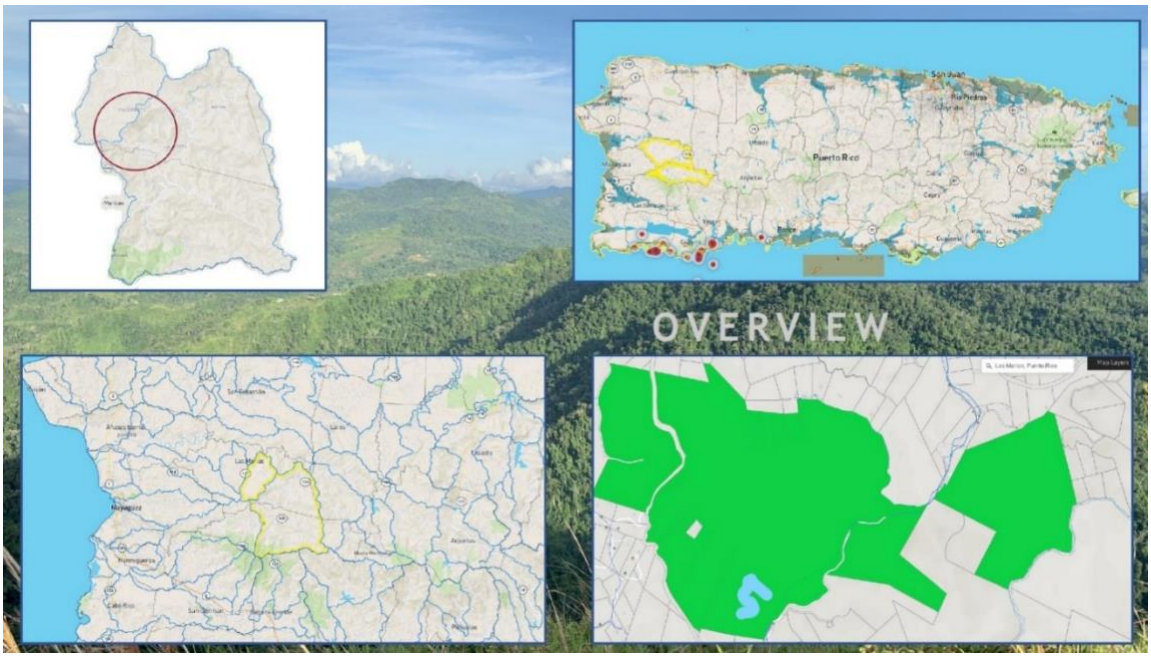


Figure 9. Location of Copper Hill Farm by municipal, watershed, and legal parcel boundaries.

The Category 4 Hurricane Maria (September 2017) destroyed approximately 95% of tree cover and crops in the non-forested area of the farm, exemplifying the catastrophic hurricane risk central to this research's economic modeling. The post-María recovery trajectory motivated WTEM's insurance-value proposition: regenerative agroforestry systems with structural diversity provided physical storm resistance and rapid biomass recovery.

Data Collection and Field Methods

The 10-acre (4.05 ha) study plot contained approximately 20,000 coffee trees (2,000 trees/acre; 4,938 trees/ha) at 2.5 × 2.0 m spacing and comprised approximately 50% Fronton and 50% Limaní cultivars of the Arabica varietal (Figure 10). Tree ages ranged from 1-6 years post-María, with 30% having reached productive maturity, which created a transitional baseline where yields were currently suppressed but would increase as cohorts mature. The plot exhibited predominantly steep terrain (90% on 40-60% slopes), which necessitated terracing and erosion control.

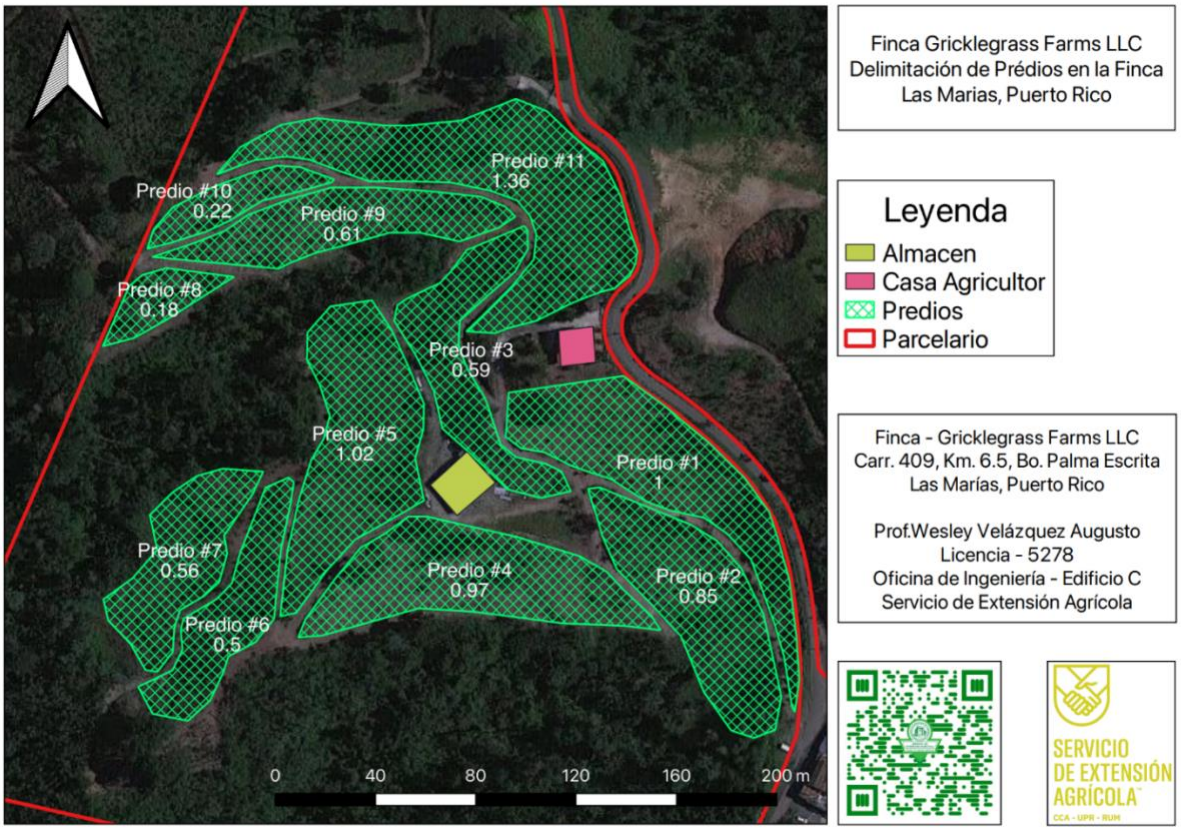


Figure 10. Study plot configuration - 10-acre coffee production area.

The site experiences tropical climate conditions (22-24°C mean temperature, 900-1,500mm annual precipitation) (Figure 11). Soils included Humatas and Consumo clay series (pH 4.5-5.5, 4-8% organic matter), with high erosion risk on steep slopes which required permanent vegetative cover for soil conservation.

Copper Hill participated in USDA Natural Resources Conservation Service contracts (2019-2024) and the USDA Climate-Smart Commodities Project (2023-2028), which provided cost-share for regenerative transition (50-75% of establishment costs) and systematic monitoring protocols. (See Appendix 1 for complete site description, regenerative practice implementation protocols, institutional details, and conservation planning documentation.)



Figure 11. Copper Hill Farm north-facing view of study area

The case study modeled a transition to shaded polycultures and replaced synthetic fertilizers with organic compost and agrochemicals with integrated pest management for a 10-acre plot, reflecting Puerto Rico's average farm size, (Lowder et al., 2021; Moguel & Toledo, 1999; Cerda et al., 2020). Conservative yield assumptions of 0.5–1 ton per ha were drawn from regional regenerative trials and excluded subsidies (Jezeer et al., 2018; TechnoServe, 2025). Puerto Rico's FDA-compliant infrastructure and U.S. shipping lanes facilitated processing hubs for WTEM's value-added products and provided regulatory advantages for model validation. The coffee price used in this model was $4.20/lb (for full discussion of Puerto Rico's coffee pricing regulations see Appendix 2).

Financial Modeling Framework

Adoption of new agricultural practices requires two conditions, and these were incorporated into the Excel financial appraisal I developed. First, long-term viability demands positive NPV; present value of future cash flows must exceed initial investment. Second, transition survival required sufficient annual cash flows during Years 1-4 (critical establishment period) to maintain household living standards. A positive-NPV investment which generated inadequate early-year cash flows would create a transition liquidity gap where farmers could not survive the transition despite eventual profitability. Farms with positive NPV but insufficient transition cash flows faced bankruptcy before reaching profitability.

Further, farmers required annual income ≥ $12,877 to meet living standards in Puerto Rico (adopted Anker methodology). This threshold represents minimum income

necessary for a 4-person household to afford nutritious diet, decent housing, and other essential needs without making trade-offs that compromised human dignity.

The analysis was a 10-year discounted cash flow analysis of different scenarios with a discount rate of r = 3.57%. The 10-year horizon of the analysis reflects one coffee tree replacement cycle and aligns with USDA Natural Resources Conservation Service investment evaluation timeframes for agroforestry transitions. The 3.57% real WACC derived from CAPM cost of equity (7.09%), USDA FSA debt costs (1.70% real), and 25/75 debt/equity structure typical of smallholder operations. This rate is lower than discount rates often cited for developing-country agriculture (6-10%) but appropriate for Puerto Rico due to: (1) lower sovereign risk as US territory, (2) USDA program access with preferential financing, (3) unlevered specification removing debt tax shields, and (4) real rate basis removing inflation premiums. Sensitivity analyses tested a range of discount rates from 3-10% to bound uncertainty in farmers' opportunity cost of capital. (See Appendix 3 for complete WACC calculation details.)

This study employed a dual analytical frameworks, Monte Carlo simulation and parametric hypothesis testing, requiring explicit decision rules when results diverged (Table 2). Simulations for each scenario were run with N=1,000 iterations incorporating yield variability (±20% triangular distributions), price volatility (±25%), climate risk (15% annual hurricane probability with differential damage), providing adequate precision for $\alpha = 0.05$ testing with 95% confidence intervals. The criterion for WTEM viability was determined by ≥95% of Monte Carlo iterations (≥950 of 1,000) satisfied the stated condition (e.g., NPV > 0, Income ≥ $12,877). This frequency-based criterion tested robustness under parameter uncertainty. Parametric tests (t-tests, $\alpha = 0.05$)

evaluated whether mean outcomes differed significantly from thresholds and tested expected value which provided conventional statistical inference.

Table 2. Decision rules for divergent results.

Frequency Test	Mean Test (t-test)	Conclusion	Interpretation
Pass (≥950/1000)	Pass ($p < 0.05$)	Strong viability	Robust to uncertainty AND statistically significant
Pass (≥950/1000)	Fail ($p \geq 0.05$)	Investigate distribution	Likely left-skewed; frequency dominates
Fail (<950/1000)	Pass ($p < 0.05$)	Moderate viability, high risk	Significant mean but substantial downside probability
Fail (<950/1000)	Fail ($p \geq 0.05$)	Non-viable	Neither robust nor significant

When tests diverged, the frequency threshold took precedence for viability conclusions because agricultural decision-makers face parameter uncertainty that cannot be averaged away. Agricultural investments are largely irreversible (establishment costs are sunk) and failure creates household-level crises (bankruptcy, food insecurity). Unlike financial investments where portfolio diversification reduces risk, individual farmers cannot diversify across 1,000 parameter realizations, real life dictates that they experience one realization and must survive it. The 95% frequency threshold ensured

recommendations accounted for this reality, privileging robustness over expected value maximization.

Within-scenario analysis employed parametric tests (t-tests, ANOVA), regression analyses for dominant drivers, and tornado diagrams for NPV impact ranking. Between-scenario analysis used two-sample t-tests for NPV comparisons (H3a, H3b), paired t-tests for within-iteration comparisons (H1a-ii), one-sample t-tests for threshold tests (H1b, H2a-Income, H2b-Income, H4a, H4b, H4c), stochastic dominance analysis using CDFs, and break-even probability calculations. Significance thresholds: $\alpha = 0.05$, $\beta = 0.10$ (80% power), Cohen's d for practical significance, 95% confidence intervals for all estimates.

Scenario Definitions

Six mutually exclusive scenarios differed in biomass monetization strategies, management intensity, and revenue stream composition (Table 3):

- S1 (Conventional Baseline): This scenario represented full-sun monoculture with synthetic inputs (150-200 kg N/ha), herbicides, fungicides. Baseline green bean production of 3,455 lb/farm (10-acre) was subject to 5% broca and 5% rust penalties. Year 1 gross bean revenue after penalties was $31,184. There were no shade establishment costs. This scenario served as an economic benchmark.
- S2 (Regenerative Without Non-Bean Biomass): This scenario targeted 40%-50% shade cover, organic fertilization, manual weeding, and IPM. Leaves and cascara were produced but not monetized. Yield penalties of 25% Years 1-4 (establishment stress), 10% Years 5-10 (stable shade effect) were calculated. Year 1 green bean revenue after all penalties was $25,399. Improved pest management represented by

1% rust and 1% broca (4 percentage point advantage from biodiversity/soil health) were modeled. This scenario tested whether ecological benefits alone justified economic sacrifice.

Table 3. Scenario specification matrix.

Scenario	I_leaf	I_cas	m_beans	Management	Purpose
S1: Conventional	0	0	1	Full-sun monoculture	Economic benchmark
S2: Regenerative (No WTEM)	0	0	1	Shade agroforestry	Transition cost baseline
S3: Regenerative + Cascara	0	1	1	Shade + cascara	Single biomass test
S4: Regenerative + Leaf	1	0	1	Shade + leaf	Single biomass test
S5: WTEM Stress Test	1	1	0	Biomass only (no beans)	Market failure test
S6: Combined WTEM	1	1	1	Shade + both biomass	Full WTEM model

- S3 (Cascara-Only): This scenario represented regenerative management plus cascara revenue. Year 1 cascara revenue was $5,248 from 1,166 lb @ $4.50/lb natural process. Cascara only faced harvest-period temporal competition as processing occurs during peak mill operations (November-January), which created opportunity costs and adoption friction despite equivalent technical efficiency. Higher processing costs ($0.20/lb for natural process) reflected batch processing requirements and extended drying periods.
- S4 (Leaf-Only - Phase 1 Entry): This scenario represented regenerative management plus coffee leaf tea revenue (details of this product and model assumptions are given in Appendix 4). Strategic positioning leveraged temporal complementarity, leaf harvesting during off-season pruning (February-March, May-June, August-September) and used idle cooperative capacity with minimal operational disruption. This scenario modeled a conservative base case of one leaf harvest event annually.
- S5 (Stress Test): This scenario represented full regenerative costs with biomass revenues but zero bean revenue (m_beans = 0). It was designed to test farm survival under catastrophic coffee market collapse. S5 used relaxed success criteria (NPV OR income, not AND) at 50% confidence threshold which reflected an exploratory disaster scenario rather than a particular recommended strategy.
- S6 (Full WTEM - Phase 2): This scenario combined all revenue streams (beans + leaf + cascara). Year 1 total revenue was $78,294 ($25,399 beans + $52,895 biomass, where biomass = $47,647 leaf + $5,248 cascara). This scenario represented Phase 2 expansion after successful S4 implementation.

All regenerative scenarios (S_2 - S_6) incorporated improved pest resistance but bore yield penalties during transition that stabilized by Year 5. S_1 represented the baseline conventional approach. S_2 served as critical comparison since existing literature demonstrated regenerative systems eventually outperform conventional (Perfecto et al., 2005), so testing whether WTEM (S_6) substantially exceeds S_2 (H3b) determined whether biomass monetization justified additional institutional complexity. (See Appendix 3 for complete scenario specifications including detailed yield penalty structures, pest dynamics, capital expenditures, and processing cost calculations.)

Notably, S_5 tested structural transformation potential (could farms pivot to biomass if coffee became unviable?), while H4a tested price shock resilience (could WTEM sustain operations if specialty premiums disappeared but commodity markets remained functional?). H4a answered 'Is WTEM a hedge?'; S_5 answered 'Is WTEM an exit strategy?' - each distinct policy questions with different intervention implications.

Regenerative scenarios (S_2 - S_6) modeled yield penalties declining from 25% in Years 1-4 to 10% in Year 5 onward, which reflected documented agroforestry establishment dynamics (Soto-Pinto et al., 2000; Perfecto et al., 2005; Haggar et al., 2017). The Year 5 stabilization represented conservative estimates from longitudinal studies showing yield recovery as nitrogen-fixing trees matured and soil organic matter increased. The 10% permanent reduction reflected conservative and persistent light competition balanced by soil health benefits, pest suppression, and microclimate regulation.

Research Design and Hypothesis Integration

The three necessary conditions for WTEM success were operationalized through testable hypotheses. This mapping enables precise identification of which constraints bind, informing targeted policy interventions (Table 4).

Table 4. Hypothesis-condition mapping.

Hypothesis	Tests Condition	Rejection Indicates	Primary Evidence
H1a	Economic (long-term)	Insufficient value creation	$NPV(S_6) \leq 0$
H1a-ii	Economic (comparative)	S_2 viable or S_6 not superior	$NPV(S_6) \leq NPV(S_2)$
H1b	Economic (short-term)	Transition liquidity gap	Income < $12,877
H2a-NPV	Economic (leaves)	Leaf NPV insufficient	$NPV(S_4) \leq 0$
H2a-Income	Economic (leaves)	Leaf cash insufficient	Income < $12,877
H2b-NPV	Economic (cascara)	Cascara NPV insufficient	$NPV(S_3) \leq 0$
H2b-Income	Economic (cascara)	Cascara cash insufficient	Income < $12,877
H2c	Institutional (capacity optimization)	Biomass processing efficiency	Synergy < $1,000

Hypothesis	Tests Condition	Rejection Indicates	Primary Evidence
		deviates significantly from bean processing; temporal conflicts exceed synergies	
H3a	Economic superiority	Insufficient vs. conventional	$NPV(S_6) < 1.25 \times NPV(S_1)$
H3b	Economic superiority	Insufficient vs. regenerative	$NPV(S_6) < 1.25 \times NPV(S_2)$
H4a	Market resilience	Insufficient diversification	At \$4.20/lb: NPV<0 OR Income<\$12,877
H4b	Market alternative	Biomass can't replace coffee	$NPV(S_5)<0$ AND Income<\$10,000
H4c	Baseline viability	Regenerative non-viable without biomass	$NPV(S_2) \leq 0$ OR Income<\$12,877
H1a	Economic (long-term)	Insufficient value creation	$NPV(S_6) \leq 0$
H1a-ii	Economic (comparative)	S_2 viable or S_6 not superior	$NPV(S_6) \leq NPV(S_2)$
H1b	Economic (short-term)	Transition liquidity gap	Income < \$12,877

Figure 12 illustrates causal pathways which linked biomass monetization to adoption outcomes. Regulatory approval, cooperative infrastructure, and market demand were necessary conditions. Biomass processing mediated between conditions and outcomes. Moderating variables (labor costs, climate risk, farm size) strengthened or weakened effects.

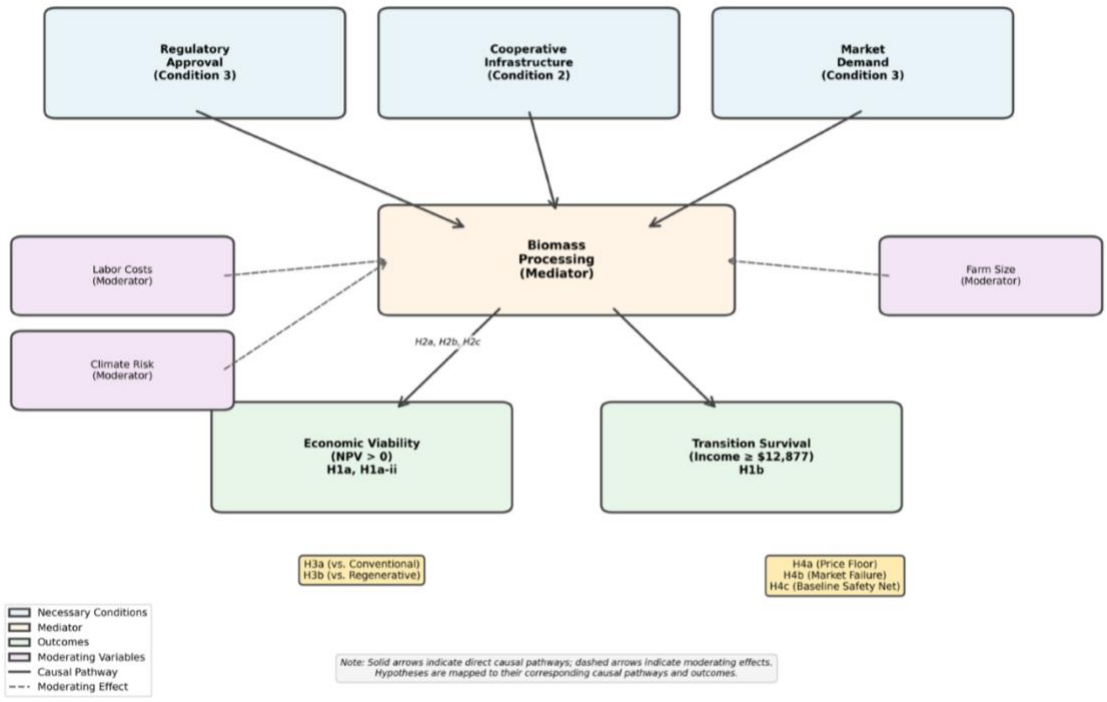


Figure 12. WTEM causal pathways and hypothesis map.

The hypothesis map (Figure 13) depicts logical relationships among research questions, hypotheses, and theoretical framework. RQ1 (economic viability) is tested through H1a (long-term NPV), H1a-ii (superiority over regenerative baseline), and H1b (transition income), mapping to Condition 1 (economic adequacy). RQ2 (individual stream contributions) is decomposed through H2a (leaf viability), H2b (cascara viability), and H2c (synergies), testing both economic adequacy and institutional efficiency

(Condition 2). RQ3 (superiority) is tested through H3a (vs. conventional) and H3b (vs. regenerative-no-biomass), establishing relative advantage threshold. RQ4 (downside protection) employs H4a (price floor), H4b (market failure), and H4c (regenerative baseline), testing market resilience (Condition 3) and identifying boundary conditions. (See Appendix 6 for complete hypothesis testing procedures, statistical methods, edge case handling, and gap closure ratio calculations.)

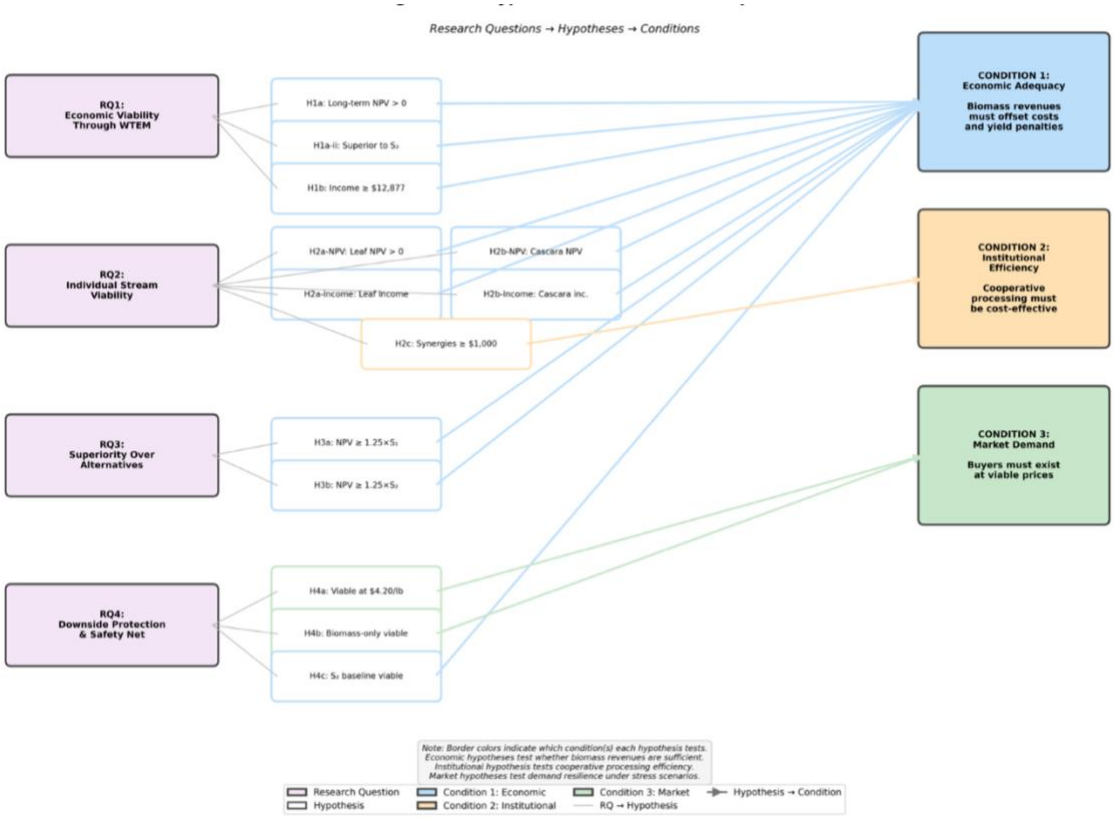


Figure 13. Hypothesis architecture showing RQ-hypothesis-condition mapping.

Integration with Literature Gaps

This hypothesis structure addresses the four literature gaps identified in Chapter I: (1) transition financing mechanisms - H1a-ii and H1b quantify how biomass transforms

economically irrational and financially infeasible transitions into profitable, survivable investments, distinguishing economic barriers (requiring price/yield improvements) from financial barriers (requiring credit access); (2) underutilized biomass potential - H2a and H2b test whether individual streams independently achieve complete dual viability, answering whether farmers can phase WTEM incrementally or must commit to combined implementation; (3) cooperative institutional capacity - H2c quantifies cooperative cost advantages required (≥75% reduction in base case, with 70% as critical viability threshold) for both positive NPV and adequate transition income, establishing institutional capacity building as implementation priority; and (4) climate adaptation financing - H4 series tests whether WTEM provides insurance value under market stress, with differential damage modeling (50% mitigation in regenerative systems) providing NPV-based valuation of climate adaptation co-benefits justifying public investment.

Testing Research Question 1 Hypotheses

To test H1, I examined if WTEM (S_6) generates positive 10-year NPV. Specifically, the hypothesis was supported if $NPV(S_6) > 0$ in ≥950 of 1,000 iterations (95% probability, $\alpha = 0.05$). I expected biomass revenues compounded over 10 years to offset: (1) establishment costs (after USDA cost-share); (2) yield penalties during Years 1-4; (3) foregone conventional returns. Positive NPV is fundamental criterion for long-term economic viability, demonstrating biomass valorization creates net value over the investment horizon.

To test H1a-ii (Superiority over regenerative baseline) I examined if WTEM (S_6) generates higher NPV than regenerative systems without biomass (S_2). Specifically, the

hypothesis was supported if NPV(S_6) > NPV(S_2) in ≥950 of 1,000 iterations (95% probability, $\alpha = 0.05$) (Table 5). Previous research established that regenerative systems eventually outperform conventional (Perfecto et al., 2005; Tscharntke et al., 2011).

Table 5. Joint interpretation of H1a and H1a-i.

H1a	H1a-ii	Interpretation	WTEM Role
Pass	Pass	S_6 viable AND superior to S_2	Enabler: Makes non-viable viable
Pass	Fail	Both S_6 and S_2 viable; S_6 not clearly superior	Enhancement: Improves viable baseline
Fail	Fail	Neither S_6 nor S_2 viable	Insufficient: Fundamental barriers remain
Fail	Pass	S_6 inferior to S_2 (implausible-investigate)	Counterproductive: Adds costs without value

This two-part structure clarified whether WTEM was necessary for regenerative viability (H1a-ii pass indicated yes) or merely beneficial (H1a-ii failed indicated S_2 already viable). Both findings would inform policy: the former would justify WTEM as essential intervention; the latter would position WTEM as optional enhancement in well-supported contexts.

However, transition costs without compensating revenue create negative NPV during establishment. Biomass revenues transform this dynamic, generating positive NPV where regenerative-alone remains negative or marginally viable. This hypothesis demonstrates whether biomass valorization enables regenerative transition by

transforming otherwise non-viable or marginally viable pathways into clearly profitable investments. If H1a passes but H1a-ii fails (both S_6 and S_2 achieve positive NPV) (Table 5), this indicates Puerto Rico's institutional context enables regenerative transition without biomass complexity, a valuable negative finding constraining WTEM's geographic necessity. If both pass, WTEM unambiguously improves upon regenerative baseline.

To test H1b (Transition survival) I examined if WTEM maintained mean annual net income ≥ $12,877 during Years 1-4 while S_2 fails to maintain living income standards (Table 6). Specifically, the hypothesis was supported if Income ≥ $12,877 in each of Years 1--4 in ≥950 of 1,000 iterations (95% probability). Biomass revenues begin Year 1, maintaining income above threshold even as bean revenues decline 25% during establishment. Without biomass, S_2 experiences 40-60% income declines during transition, falling below living income threshold. Living income during transition is essential for adoption feasibility. A positive-NPV investment becomes inaccessible if early-year cash flows are insufficient. Testing whether S_6 maintains living income while S_2 does not demonstrates biomass valorization solves the transition liquidity gap.

Table 6. Joint interpretation of H1a, H1a-ii, and H1b.

Outcome	H1a	H1a-ii	H1b	Interpretation	Policy Implication
Full viability + enabler	Pass	Pass	Pass	Economically rational, superior to	Promote immediate adoption;

Outcome	H1a	H1a-ii	H1b	Interpretation	Policy Implication
				baseline, AND practically feasible	WTEM essential
Full viability + enhancement	Pass	Fail	Pass	Economically rational AND practically feasible, but S_2 also viable	Flexible adoption; support either based on capacity
Liquidity gap	Pass	Pass/Fail	Fail	Profitable long-term but insufficient transition cash	Provide bridge financing
Temporary relief	Fail	Fail	Pass	Short-term survival without long-term profitability	Unsustainable; requires subsidy
Non-viable	Fail	Fail	Fail	Neither rational nor feasible	Fundamental redesign needed

This tri-part framework identified whether barriers were economic (negative NPV), financial (liquidity constraints), or context-dependent (institutional support enables S_2 viability), informing precisely targeted interventions.

Testing Research Question 2 Hypotheses: Individual Biomass Stream Viability

To test H2a-NPV I examined if coffee leaf revenues independently achieved positive NPV (leaf-only system is economically viable long-term). Specifically, the hypothesis was supported if $NPV(S_4) > 0$ in ≥950 iterations (95% probability). This tested whether farmers could adopt WTEM by monetizing only leaves, enabling phased implementation.

To test H2a-Income I examined if coffee leaf revenues sustained income ≥ $12,877 during Years 1-4. Specifically, the hypothesis was supported if Income ≥ $12,877 in each of Years 1-4 in ≥950 iterations. Annual leaf revenues should have maintained living income even with 25% bean yield penalties. If both H2a-NPV and H2a-Income passed, leaves independently provided complete dual viability, meaning that farmers can adopt WTEM through leaves alone, simplifying implementation and reducing coordination requirements. If H2a-NPV passed but H2a-Income failed, leaves provided long-term value but insufficient short-term cash flow, indicating need for phased production or bridge financing. If both failed, leaves cannot independently sustain WTEM, requiring a combined biomass approach.

H2a tested whether leaf-only systems achieved dual viability, but its significance extended beyond economics. Leaf processing exhibited temporal complementarity with bean harvest, utilizing cooperative infrastructure during off-harvest periods when dryers, labor, and logistics experienced substantial capacity underutilization. This created three strategic advantages:

- Minimal operational disruption: Leaf harvest and processing occurred entirely outside the concentrated harvest window, eliminating risk to the cooperative's primary revenue source and bypassing the psychological barrier of modifying harvest-period operations.
- Low marginal cost: Processing leaf during off-season utilized already-paid fixed costs (infrastructure, administration, quality control staff), with marginal costs limited to low-tech equipment (leaf rolling tables etc.) energy, packaging, and incremental labor. This enabled processing efficiencies approaching or exceeding base case assumptions.
- Immediate implementability: Unlike cascara requiring harvest-period process modification, leaf processing began without governance debates or operational experimentation during high-stakes periods.

Because leaf processing aligned with off-season idle capacity, adoptability was high conditional on passing dual viability; this created a low-risk entry path (S_4) that could later expand to S_6. If H2a passed, WTEM became immediately adoptable through this pathway. Cooperatives can validate biomass processing competency, establish market relationships, and generate off-season farmer income before considering cascara addition. This resolved the adoption sequencing problem: farmers need not commit to full WTEM (S_6) upfront but can incrementally adopt via leaf-only (S_4) entry.

To test H2b-NPV I examined if cascara revenues independently achieved positive NPV (cascara-only system is economically viable long-term). Specifically, the hypothesis was supported if $NPV(S_3) > 0$ in ≥950 iterations. This tested whether cascara could serve as standalone WTEM entry point.

To test H2b-Income I examined if cascara revenues maintain income ≥ $12,877 during Years 1-4. Specifically, the hypothesis was supported if Income ≥ $12,877 in each of Years 1-4 in ≥950 iterations. Cascara is technically compatible with wet-mill infrastructure but competes for capacity during harvest, introducing operational and psychological adoption frictions. The EU novel food authorization (EFSA, 2022) provides clear regulatory pathway, while in the United States, coffee fruit extract holds an FDA 'no questions' GRAS letter, with cascara approvals following firm-specific pathways (e.g., self-affirmed GRAS) rather than an FDA GRAS notice. If both passed, cascara independently provided dual viability in that farmers could leverage existing infrastructure with minimal operational change. If NPV passed but income failed, cascara provided long-term value but could not alone finance transition. If both failed, cascara served as diversification hedge but not a standalone strategy.

H2b tested cascara economic viability, but adoption feasibility depended critically on resolving temporal competition with the bean harvest. Cascara processing occured during the concentrated harvest period when mills operate at maximum capacity and farmers exhibited strong risk aversion regarding process modifications.

The cascara adoption barrier is psychological and operational, not purely economic. Even if H2b passed (cascara achieved dual viability), adoption faced two hurdles:

- Harvest-period risk aversion: Cooperative managers and farmers resisted modifications to harvest operations that could have compromised bean quality then the primary revenue source and basis of cooperative reputation. Process additions that divert attention, labor, or equipment capacity during peak operations created

perceived risks that may have overridden positive NPV calculations. This is rational under Prospect Theory where potential losses (bean quality degradation) are weighted more heavily than equivalent gains (cascara revenue) (Kahneman & Tversky, 1979).

- Working capital stress: Cascara harvest concentrated inventory during the same period when bean inventory peaked, requiring additional working capital when cooperative credit lines faced maximum seasonal demand.

Cascara was viable without being adoptable during early phases due to harvest-time risk aversion and working-capital congestion; if H2b passed and H2a failed, targeted process redesign or harvest-time automation became a prerequisite for adoption. If H2b passed but H2a failed, this created a "viability without adoptability" paradox in that cascara was economically superior per pound but faced adoption gridlock due to temporal competition, while less-viable leaf remained non-adoptable. If both passed, the natural adoption sequence was S_4 (leaf-only) → S_6 (add cascara after validation), leveraging temporal complementarity to establish biomass processing before introducing harvest-period modifications.

To test H2c I examined if combined biomass revenues generated incremental NPV exceeding sum of independent contributions by ≥$1,000 due to cooperative efficiencies. Specifically, the hypothesis was supported if Synergy ≥ $1,000 in ≥950 iterations (95% probability). This tested whether complexity costs (coordination burden of managing two biomass streams simultaneously) were offset by operational synergies. Any negative synergies indicated institutional complexity exceeded efficiency gains, creating adoption barriers despite technical viability.

Testing Research Question 3 Hypotheses: Superiority Over Alternatives

To test RQ3 I examined if WTEM achieved NPV at least 25% greater than both conventional monoculture AND regenerative-without-biomass systems. To test H3a I examined if WTEM achieved NPV ≥ 1.25 × conventional systems. Specifically, the hypothesis was supported if $NPV(S_6) \geq 1.25 \times NPV(S_1)$ in ≥950 iterations. I set a 25% relative-advantage threshold as a policy-salient decision rule grounded in diffusion theory (Rogers, 2003), reflecting risk premia and implementation frictions; it is not a Rogers-derived constant. I examined results at 20%, 25%, and 30% thresholds to assess threshold-dependency of conclusions. The threshold ensured practical rather than merely statistical significance.

To test H3b I examined if WTEM achieved NPV ≥ 1.25 × regenerative systems without biomass. Specifically, the hypothesis was supported if $NPV(S_6) \geq 1.25 \times NPV(S_2)$ in ≥950 iterations. This hypothesis tested whether biomass monetization adequately compensated for yield penalties and institutional complexity inherent in WTEM adoption. The 25% threshold reflected additional an institutional burden: cooperative organization, processing infrastructure, quality control, and market channel development beyond basic regenerative adoption. If both passed, WTEM was unambiguously superior to all alternatives. If H3a passed but H3b failed, WTEM was better than conventional but only marginally better than simple regenerative adoption, implying that policy should support either based on local institutional capacity. If both failed, WTEM lacked compelling relative advantage despite potential viability.

The base case r = 3.57% reflected calculated WACC for Puerto Rican smallholder coffee farming. This was lower than rates cited for developing countries (6-10%) but

appropriate for Puerto Rico due to: (1) U.S territory status with institutional stability, (2) USDA preferential financing access, (3) unlevered specification, (4) real rate basis. Sensitivity testing to r = 10% addressed smallholder time preference potentially exceeding market rates.

Testing Research Question 4 Hypotheses: Downside Protection and Safety Net Strategies

The interpretations if various combinations of H41-c are supported are listed in Table 7. To test H4a I examined if, under a policy-floor stress test at $4.20/lb (scenario value reflecting administered-price regimes), WTEM maintained both positive NPV and living income ≥ $12,877/year. Specifically, the hypothesis was supported if both conditions were met in ≥950 iterations. This hypothesis tested whether WTEM sustained operations if specialty premiums disappear due to market saturation or economic recession as represented by coffee price fixed at $4.20/lb (58% decline from $10.00/lb base).

To test H4b I examined if, under complete coffee market failure (zero bean revenue), biomass-only operations (S_5) achieve either positive NPV OR living income ≥ $10,000/year. Specifically, the hypothesis was supported if either condition met in ≥500 iterations (50% probability). This represented an extreme stress test which answered whether farms could pivot to biomass-only operations if coffee became completely unviable due to catastrophic pest outbreaks, climate change, or permanent market loss. Lower thresholds ($10k income, 50% probability) acknowledged that this is a survival scenario which tested transformation potential rather than optimal strategy. The 50%

threshold reflected this hypothesis's exploratory nature as a stress test rather than a recommended strategy.

To test H4c I examined if regenerative practices without biomass (S_2) achieved dual viability (positive NPV AND living income ≥ $12,877 during Years 1-4), and served as viable fallback strategy. Specifically, the hypothesis was supported if both conditions met in ≥950 iterations. This hypothesis tested whether simple regenerative adoption offered viable baseline strategy without biomass institutional complexity. If H4c passed, farmers faced a strategic choice: pursue simpler S_2 with lower coordination costs or pursue WTEM (S_6) for superior returns (if H3b passed). If H4c failed, regenerative transition was fundamentally non-viable without biomass revenue bridging the liquidity gap and WTEM became a necessary enabler rather than an optional enhancement.

H4c results established boundary conditions for WTEM's value proposition. Passage indicated that Puerto Rico's institutional context (USDA support, premium market access) enabled regenerative transition without biomass, positioning WTEM as an enhancement which provided incremental advantage to an already-viable pathway. Failure indicated that biomass monetization was an essential enabling mechanism, which transformed an otherwise non-viable transition into a feasible pathway.

I expected that S_2 would likely fail due to yield penalties (25% bean reduction = approximately $21,000 annual revenue loss during Years 1-4) overwhelming pest resistance benefits (rust/borer improvement = approximately $4,000 annual gain). I also anticipated that net revenue loss (approximately $17,000/year) during transition would probably create negative NPV and income below the threshold before Year 5 stabilization occurred.

Table 7. Combined H4 interpretations.

H4a	H4b	H4c	Interpretation	Policy Implication
Pass	Pass	Pass	Complete protection; S_2 viable fallback	Multiple viable options; context-specific targeting
Pass	Fail	Pass	WTEM hedges price shocks; S_2 viable baseline	Promote S_2 as proven strategy with WTEM enhancement
Pass	Fail	Fail	WTEM protects against price compression; regenerative requires biomass	WTEM essential for regenerative transition; bridge financing critical
Fail	Fail	Fail	WTEM requires specialty premiums; neither viable at floor	Specialty market access essential; conventional only option
Fail	Fail	Pass	S_2 surprisingly robust; WTEM adds value but not essential	Flexible adoption; S_2 baseline with WTEM optional

This framework distinguished whether WTEM: (1) enabled regenerative adoption by removing coffee dependency (H4b passes, H4c fails), (2) hedged moderate price shocks

(H4a passed), (3) enhanced viable baseline (H4c passed), or (4) merely augments operations (all fail).

Biomass Production and Revenue Calculations

Coffee Leaf Production (Base Case: 1 Harvest Event Annually):

To model the leaf harvest I assumed fresh leaf yield per tree of 625 g/tree/harvest × 20,000 trees = 12,500,000 g = 27,558 lb fresh, and moisture loss during processing (80% water removal) of 12,500,000 g × 0.20 = 2,500,000 g = 5,512 lb dry. For finished coffee leaf tea I assumed quality sorting and product allocation of i) 30% Green tea (after 5% loss) of 1,571 lb @ $10/lb = $15,708, ii) 50% Oolong tea (after 5% loss) of 2,618 lb @ $9/lb = $23,562, iii) 20% Black tea (after 5% loss) of 1,047 lb @ $8/lb = $8,378.

The 1-harvest base case captured only leaves from routine pruning, requiring no additional labor scheduling or intensification. This ultra-conservative specification ensured model validity even under minimal operational commitment. Commercial tea operations typically harvest 3-4 flushes annually; sensitivity analyses explored 2-4 harvest scenarios to inform operational optimization for adopters seeking to maximize returns. (See Appendix 4 for harvest frequency analysis.)

Cascara derives from coffee cherry mass balance. For the 10-acre farm producing 3,455 lb green beans I assumed fresh cherries of 3,455 lb / 0.20 = 17,275 lb. I assumed the pulp fraction of 17,275 lb × 0.45 = 7,774 lb fresh pulp. Ultimately yielding dried cascara (15% of pulp after 85% moisture removal) of 7,774 × 0.15 = 1,166 lb. The 0.15 drying recovery (15% dried matter from wet pulp) already incorporated minimal processing losses from FDA compliance and quality sorting. Pest penalties (5% broca +

5% rust) affected the entire cherry at harvest, reducing both bean and pulp yields proportionally.

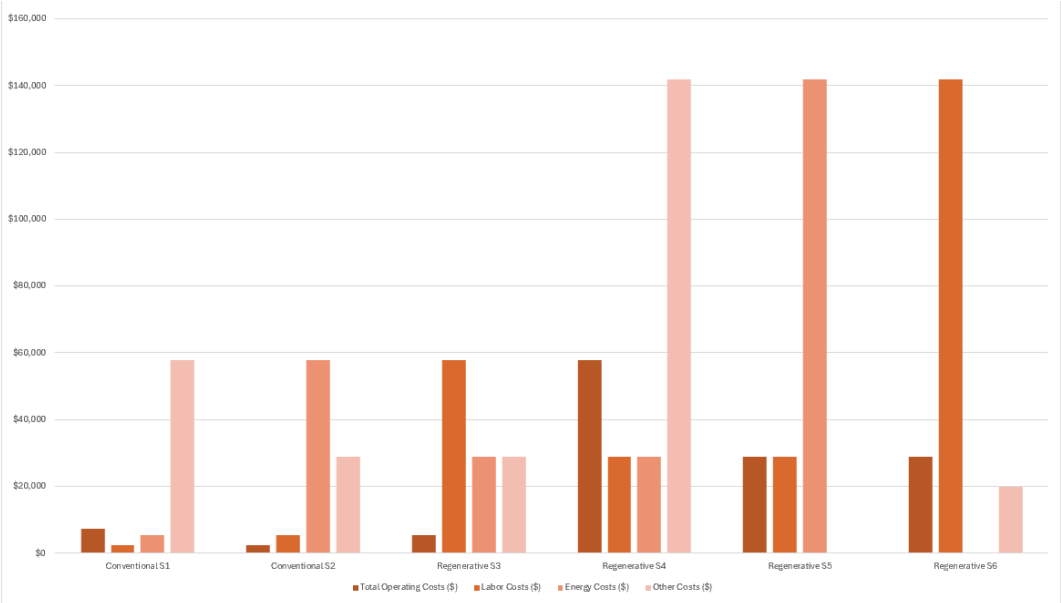


Figure 14. Costs per category per scenario.

Operating Expenses and Capital Investments

Regenerative systems save 36% on variable costs despite higher labor, driven by elimination of expensive synthetic inputs ($4,383/ha - $468/ha) The operating and capital costs used in the Excel model are listed in Tables 8 and 9. (See Appendix 8 for detailed OPEX/CAPEX calculations, cooperative efficiency analysis, and temporal opportunity cost framework.)

Table 8. Annual operating expenses by scenario (year 1).

Cost Category	S1 (Conventional)	S2-S6 (Regenerative)
Field labor	$1,827/ha	$2,010/ha
Fertilizers	$3,509/ha	$250/ha
Pest management	$874/ha	$218/ha
Energy, water, equipment	$3,050/farm	$3,050/farm
Total OPEX (variable + fixed)	$7,519/ha	$4,787/ha

Table 9. Capital investment summary for Year 0.

Investment	S1	S2	S3-S4	S6
Shade establishment	$0	$6,468	$6,468	$6,468
Less: USDA subsidy (50%)	$0	-$3,234	-$3,234	-$3,234
Processing equipment	$0	$0	$267	$534
Total Year 0 CAPEX	$0	$3,234	$3,501	$3,768
Per ha	$0	$798	$864	$930

Processing equipment was assumed to be shared across cooperative members (average 75 farms) (Table 9): cascara line $26,200 total ($267/farm after 30% reserve), leaf line $14,500 total ($267/farm). The cooperative model reduces individual farmer costs by 75% compared to independent processing.

Dual-Metric Viability Framework

The analysis employed two complementary success criteria. 1) Long-term profitability (NPV > 0), indicating economic rationality; benefits exceeded costs when accounting for time value of money. 2) Transition survival (living income ≥$12,877 during Years 1-5: Annual net cash income must have met living income threshold to ensure household subsistence during critical transition period, which captured liquidity constraints.

This framework distinguished whether adoption barriers stemmed from fundamental unprofitability (requiring permanent subsidies or practice redesign) versus temporary cashflow constraints (requiring bridge financing or payment-for-ecosystem-services during establishment) (Table 10).

The living income benchmark was assumed to be $12,877/year for a 4-person rural household, adapted from Heifer International's Honduras rural benchmark ($6,132/year), then adjusted for Puerto Rico's empirically documented 110% cost-of-living differential. This conservative estimate reflected food costs, utilities, and housing premiums. (See Appendix 6 for complete living income methodology).

Table 10. The dual-viability gap

NPV Result	Income Result	Diagnosis	Policy Response
Positive	Adequate	Success	Market-ready
Positive	Inadequate	Financial barrier	Transition financing
Negative	Adequate	Economic barrier	Improve fundamentals
Negative	Inadequate	Both barriers	Restructuring needed

Stochastic Simulation Design

The Monte Carlo framework adapted for simulations was:

- Iterations: N = 1,000 (convergence verified at <1% variation in mean NPV)
- Sampling: Latin Hypercube Sampling for efficient parameter space coverage
- Random seed: 12345 (reproducibility)
- Output: NPV, annual cash flows, IRR, living income achievement per iteration

The key stochastic parameter values for the most impactful variables are shown in Table 11.

Triangular distributions were used when historical data were limited but expert judgment was available for min/mode/max bounds. Higher CV (25%) for prices reflected market uncertainty and lower CV (10%) for yields reflected typical agricultural variability.

Table 11. Parameter distributions (selected high-impact variables).

Parameter	Distribution	Min	Mode	Max	CV
Green bean yield	Triangular	0.35 t/acre	0.3871 t/acre	0.43 t/acre	10%
Coffee price (specialty)	Triangular	$7.50/lb	$10.00/lb	$12.50/lb	25%
Cascara price	Triangular	$3.00/lb	$4.50/lb	$5.60/lb	25%
Fresh leaf yield	Triangular	562.5 g/tree	625 g	687.5 g	10%
Yield penalty (regen)	Triangular	22.5%	25%	27.5%	10%
Labor wage	Triangular	$6.53/hr	$7.25/hr	$7.98/hr	10%

Annual hurricane probability of 15% (major hurricane ~every 7 years historical frequency) was assumed. Under conventional farming, yields were assumed to vary by 20%-50% and for regenerative scenarios 10%-25% (50% mitigation from structural

diversity). I factored in a 10%-30% OPEX increase from debris removal and replanting post event and a 2-year linear (full loss Year t, 50% loss Year t+1, baseline restored Year t+2). Regenerative scenarios provided a 2.6% revenue risk reduction for insurance versus conventional (5.25% - 2.63%).

Sensitivity and Comparative Analysis

Applying one-way sensitivity analysis, each parameter varied individually across plausible range while holding others at base case:

- Discount rate: 3-10% (tests opportunity cost uncertainty)
- Coffee bean price: $2.50-12.50/lb (includes price floor scenarios)
- Cascara price: $2.00-8.00/lb
- Coffee leaf price: $4.00-15.00/lb
- Yield penalty: 0-40% (tests cultivar/management variations)
- USDA cost-share: 0-100% (policy sensitivity)
- Processing cost: $0.03-0.20/lb (cooperative efficiency range)
- Hurricane frequency: 0-30% (climate change scenarios)

Tornado diagrams ranked parameters by NPV sensitivity. Break-even analysis identified threshold values where NPV = 0.

For two-way sensitivity analysis, key interactions were:

- Cascara price × Leaf price: Maps viable biomass price combinations
- Yield penalty × Cost-share: Determines subsidy requirements for viability
- Labor wage × Biomass price: Assesses comparative advantage across countries
- Hurricane frequency × Structural resilience: Values climate adaptation benefits

I also conducted international comparative analysis by testing the model across wage rates spanning $0.25/hr (Ethiopia) to $27.44/hr (Hawaii using U.S. stat as proxy), holding other parameters constant. A four-quadrant classification identified where WTEM provides greatest advantage:

- Quadrant A (High wage, high bean price): Puerto Rico, Costa Rica - WTEM advantage greatest
- Quadrant C (Low wage, low bean price): Vietnam, Ethiopia - Modest absolute gains, potentially high proportional increases
- Quadrant D (Low wage, high bean price): Specialty Colombia - Incremental benefit, may be unnecessary

Finally, the scenario analysis utilized a structured narratives test:

- Optimistic WTEM: High biomass prices, low penalties, expanded subsidies
- Pessimistic WTEM: Low biomass prices, high penalties, reduced support
- Coffee Market Collapse: $4.20/lb price floor enforcement
- Climate Acceleration: 30% hurricane frequency, intensified pest pressure

(See Appendix 10 for complete sensitivity procedures, scenario specifications, and international wage-NPV curves.)

Model Validation

The model underwent two complementary validation procedures to ensure internal consistency, external benchmark alignment, and statistical robustness.

I verified internal model consistency through mass balance calculations, convergence testing, and scenario logic validation. Mass balance verification confirmed

that cascara production remains at or below cherry weight across all iterations, preventing physically impossible outcomes. NPV convergence testing demonstrated that mean values stabilize within ±2% by N=1,000 iterations, indicating adequate sample size for reliable estimates. Scenario logic validation confirmed expected relationships, with S6 generating the highest total revenue and S1 producing zero biomass revenue as specified in the scenario definitions.

In addition, model outputs were validated against independent data sources from Puerto Rico and international coffee sector benchmarks. The baseline yield of 3,455 lb per farm after penalties falls within Puerto Rico Department of Agriculture post-María recovery ranges, supporting the realism of production estimates. Operating costs of $7,519 per ha for S1 align with International Coffee Organization Caribbean region estimates of $8,000-$14,000 per ha, with the lower model value reflecting Copper Hill's operational efficiencies and USDA cost-share benefits. The $10.00 per pound baseline coffee price sits within Copper Hill's actual transaction range of $9-20 per pound for specialty grades, though below the upper premium prices. Most critically, the model's negative NPV for S1 conventional farming aligns with widespread reports of economic stress in Puerto Rico's coffee sector, providing face validity for the baseline scenario's financial distress. Complete validation protocols, benchmark comparison tables, and statistical test results are provided in Appendix 10.

Scope of Study: Coffee Leaves and Cascara

While coffee produces diverse biomass streams, this analysis focused exclusively on coffee leaves and cascara. Three factors justify this scope delimitation:

- Commercial readiness: Leaves and cascara have secured regulatory approval in major markets (EFSA, 2022; US FDA, 2020), enabling immediate commercialization. Other streams including husks, silverskin, and flowers face unclear regulatory pathways and would require costly safety assessments before market authorization, a multi-year, expensive process unsuitable for near-term smallholder application.
- Operational integration: Cascara harvesting occurs simultaneously with bean harvesting, requiring no additional field visits. Coffee cherries are already collected and processed; capturing fruit material simply changes waste handling rather than adding operations. Leaf harvesting occurs during necessary off-season pruning, providing countercyclical income without compromising plant health or productivity (Murthy & Naidu (2012); Vuong et al., 2011). In contrast, flower harvesting would require precise timing during the brief flowering period, and collecting spent grounds would require coordination with roasters rather than occurring on-farm.
- Market alignment: Both leaves and cascara target high-growth wellness and functional beverage markets (5.6% CAGR) where consumers pay premium prices for natural, sustainably sourced ingredients with documented bioactive properties (Eckhardt et al., 2022; Klingel et al., 2020). Their antioxidant profiles align with consumer health trends, while sustainability narratives around agricultural waste reduction resonate with conscious consumers. My observations at Copper Hill Farm confirm that farmers can process these streams into shelf-stable products using predominantly existing infrastructure: shade structures for drying and basic milling equipment available through cooperatives.

Chapter III

Results

This chapter presents empirical findings from the economic analysis of the Whole Tree Economic Model (WTEM) across six coffee management scenarios for Puerto Rican smallholder farms. The results include Net Present Value (NPV) calculations, Monte Carlo simulation outcomes, living income analysis, revenue composition, cash flow patterns, hypothesis testing results, and comparisons to baseline conventional farming practices. Further statistical analyses, distribution characteristics, and extended interpretations appear in Appendix 13.

Net Present Value Comparisons

Table 12 summarizes NPV outcomes across all scenarios, revealing stark economic differentials. Conventional farming (S1) showed universal negative outcomes, while leaf-based systems (S4, S6) demonstrated robust positive returns. Conventional Systems in S1 exhibited universal negative NPV (-$119,128/ha mean) across all 1,000 iterations. Regenerative Baseline S2 achieved positive NPV in 100% of iterations (mean $52,353/ha). Regenerative Leaf S4 generated the highest mean NPV ($195,307/ha), exceeding even full WTEM (S6) by $53,363/ha. Regenerative Cascara S3 remained negative in all iterations (mean -$32,644/ha). The $1,296/ha annual cascara revenue failed to offset regenerative transition costs. Full WTEM S6 achieved mean NPV of $141,944/ha with 100% positive outcomes, which represented a 171% improvement over the regenerative baseline. The minimum S6 outcome ($123,507) exceeded the maximum

Table 12. NPV summary statistics by scenario ($/ha).

Metric	S1 (Conv)	S2 (Regen)	S3 (Cascara)	S4 (Leaf)	S5 (Biomass)	S6 (WTEM)
Mean	-$119,128	$52,353	-$32,644	$195,307	$79,032	$141,944
Min	-$137,718	$45,148	-$37,719	$168,239	$68,491	$123,507
Max	-$103,058	$60,750	-$28,351	$225,652	$91,595	$164,402
P(NPV >0)	0%	100%	0%	100%	100%	100%

S2 ($60,750) by $62,757, which indicated first-order stochastic dominance (Table 12).

Figure 15 shows the comparative NPV in the form of a waterfall analysis which measures cumulative value creation across six scenarios to quantify the incremental value contributions of WTEM mechanisms.

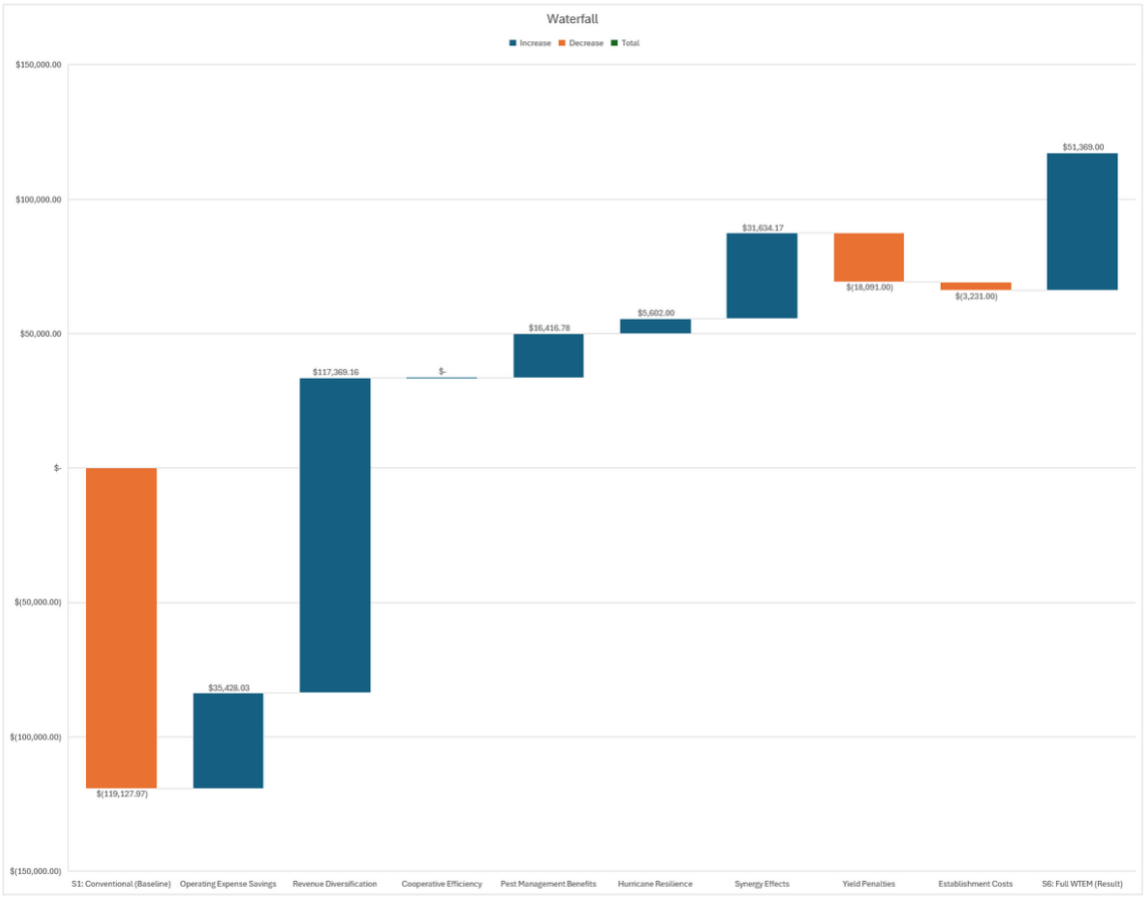


Figure 15. Cumulative NPV across six scenarios in a waterfall analysis.

Figure 16 shows the NPV comparison between the Combined Regenerative scenario (S6) at $141,934 and the Regenerative Leaf + Cascara scenario (S5) at $79,032. The Combined Regenerative approach generated roughly $60,000 higher NPV per ha than the leaf and cascara-only approach.

Figure 17 displays the NPV comparison between Regenerative Cascara (S3) at -$32,647.14 and Regenerative Leaf (S4) at $195,303. The leaf-only approach outperformed the cascara-only approach by more than $225,000 per ha.

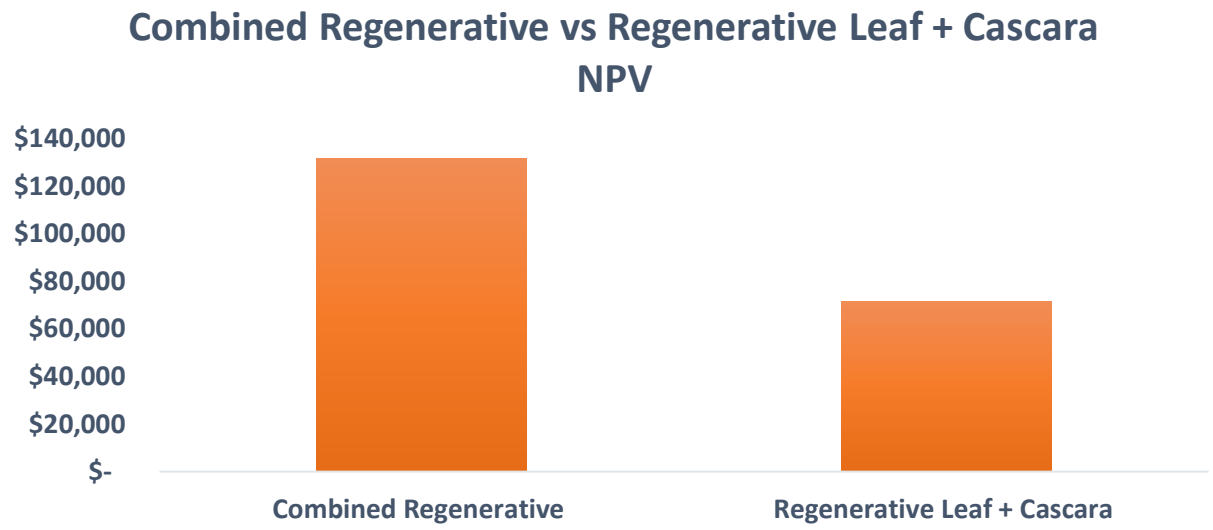


Figure 16. NPV comparison between the Combined Regenerative scenario (S6) and the Regenerative Leaf + Cascara scenario (S5).

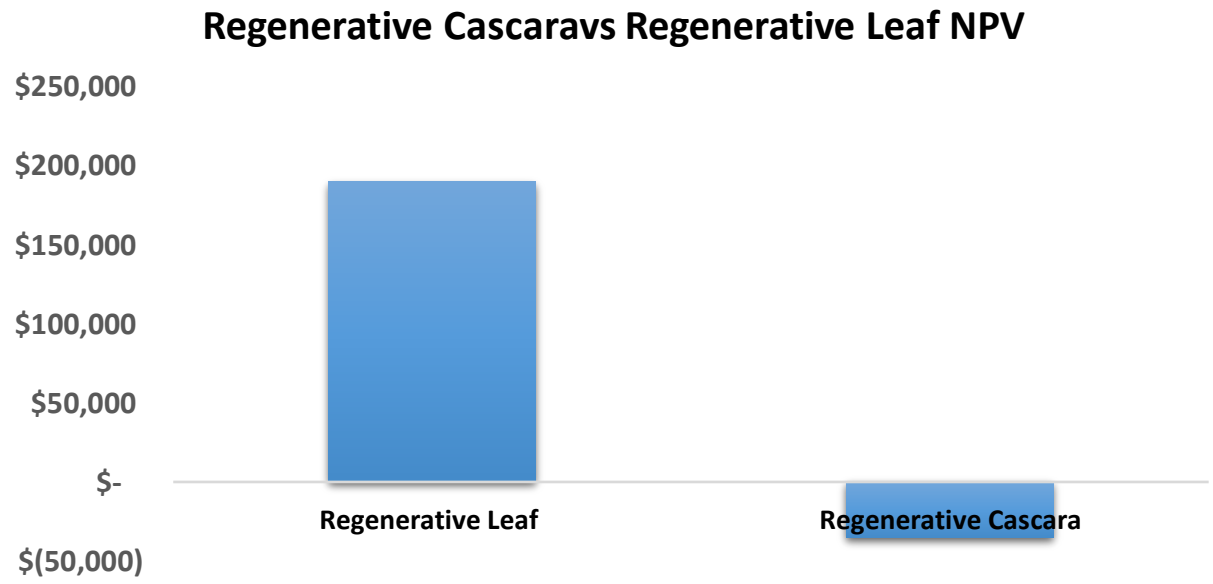


Figure 17. NPV comparison between the Regenerative Cascara scenario (S3) and the Regenerative Leaf scenario (S4).

Figure 18 presents the NPV comparison between the Baseline conventional farming scenario (S1) at -$119,127 and Regenerative farming without biomass monetization (S2) at $52,354. The regenerative baseline generated more than $170,000 higher NPV than conventional farming.

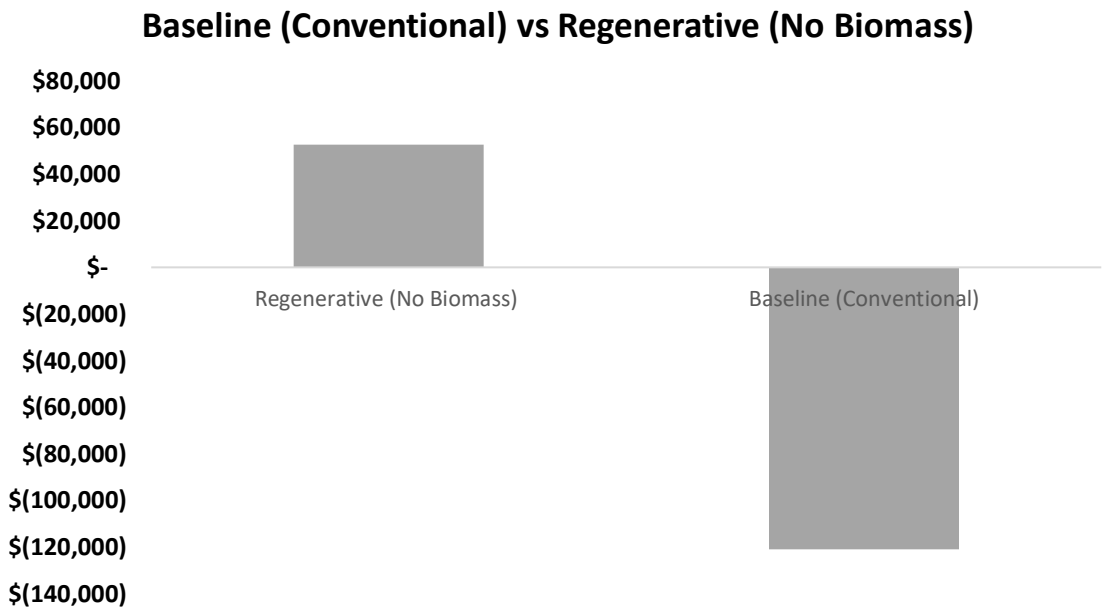


Figure 18. NPV Baseline (Conventional) scenario (S1) vs Regenerative (no biomass) scenario (S2).

Figure 19 presents the NPV comparison across all six scenarios, ranking them from highest to lowest economic performance: S4 ($195,302), S6 ($141,933), S5 ($79,032), S2 ($52,353), S3 (-$32,647), and S1 (-$119,127).

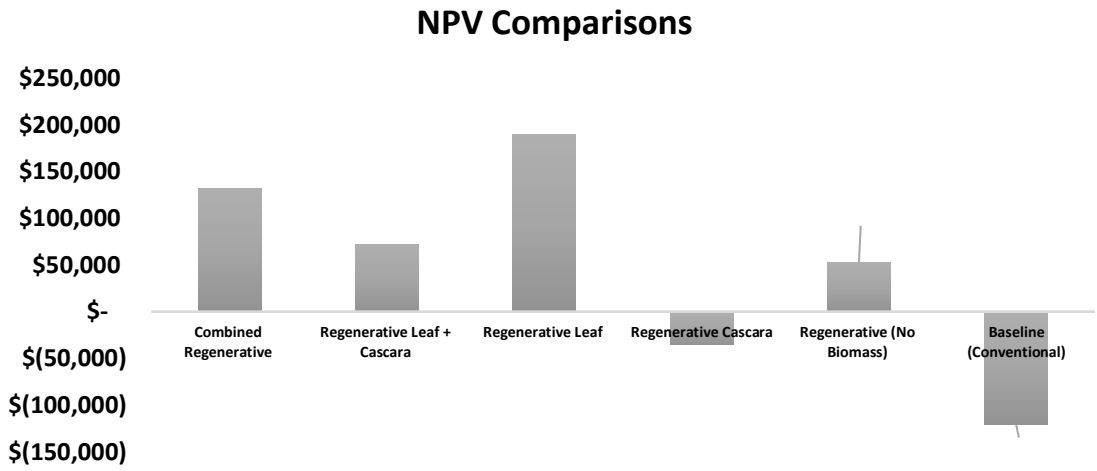


Figure 19. NPV across all regenerative scenarios relative to the baseline.

Figure 20 displays the average annual profit comparison across all scenarios. I calculated annual profit values that followed the same ranking pattern as NPV results, with S4 generating the highest average annual returns, followed by S6, S5, S2, with both S3 and S1 showing negative annual profits.

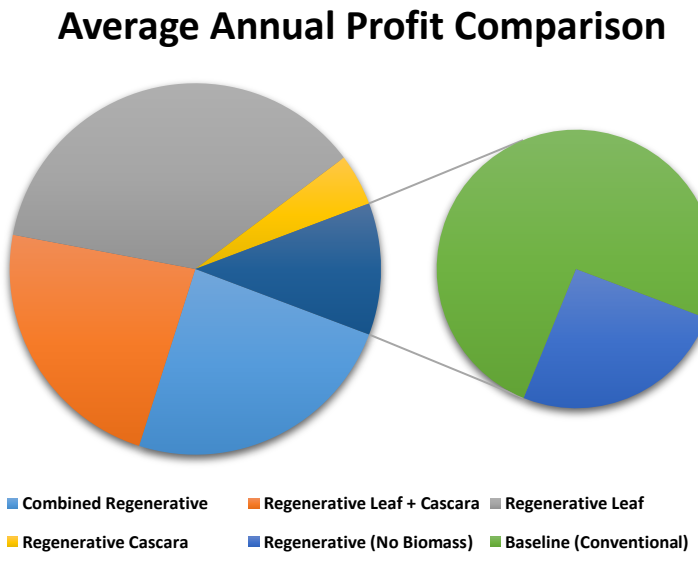


Figure 20. Average annual profit comparison across scenarios.

Figure 21 visualizes the NPV distributions across all scenarios.

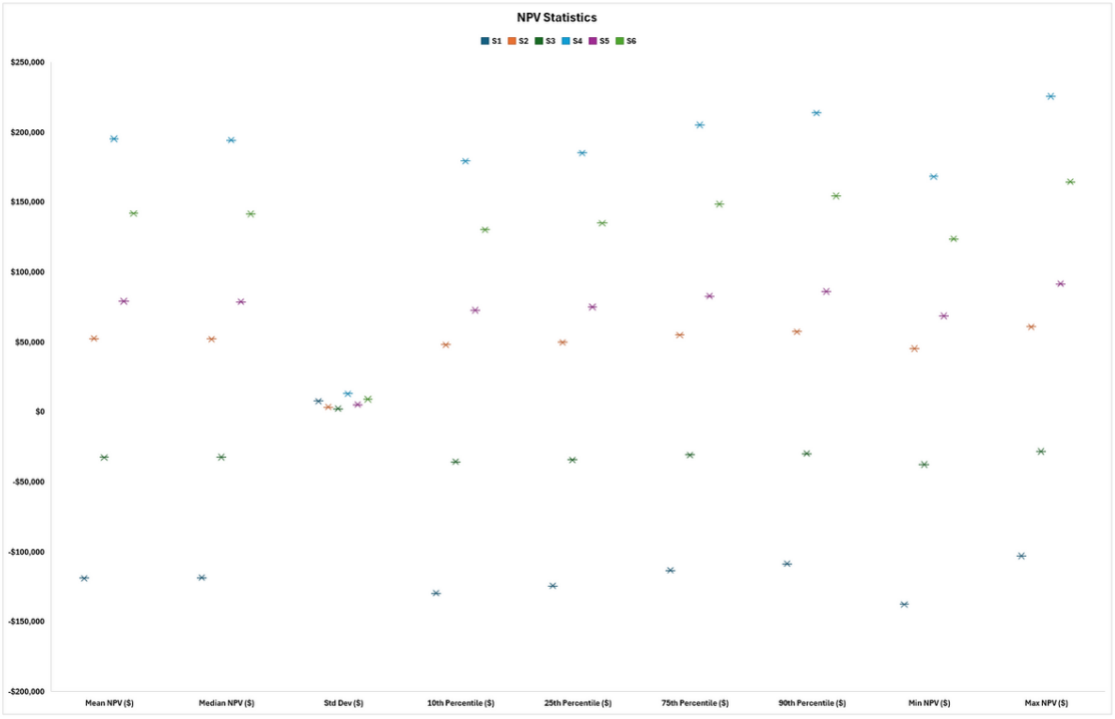


Figure 21. NPV distribution comparison across scenarios.

Figure 22 shows the distribution of Net Present Value across 1,000 Monte Carlo iterations for each scenario. Conventional farming (S1) shows universal negative outcomes, while leaf-based systems (S4, S6) demonstrate robust positive returns. The overlapping distributions of S2 and S3 illustrate the inadequacy of cascara alone to substantially improve upon baseline regenerative agriculture.

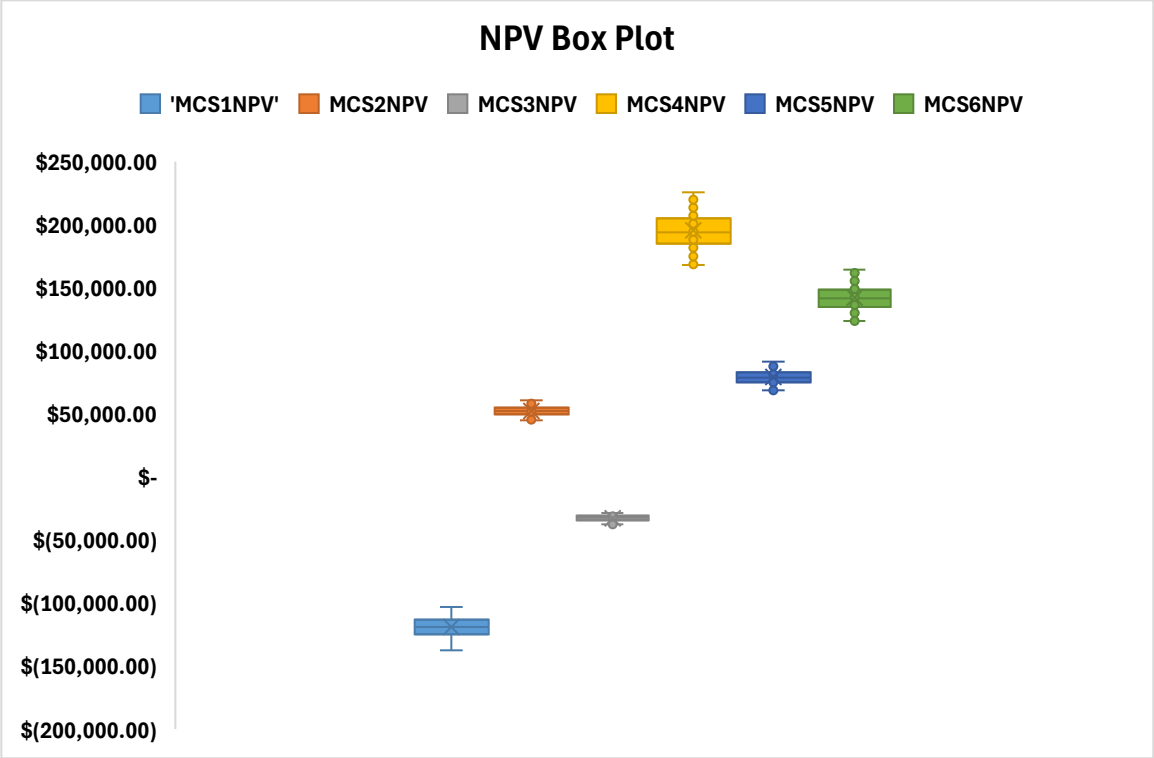


Figure 22. NPV box plot across 1,000 Monte Carlo iterations.

S1 exhibited universal negative NPV (-$119,128/ha mean) across all 1,000 iterations, reflecting Puerto Rico's high labor costs ($7.25/hr) and imported input premiums making traditional coffee farming economically unviable. S2 achieved positive NPV in 100% of iterations (mean $52,353/ha), demonstrating that regenerative practices alone, through 35% operating cost savings, provided economic advantages over conventional systems despite 10-25% yield penalties. S4 generated the highest mean NPV ($195,307/ha), exceeding even full WTEM (S6) by $53,363/ha. S3 remained negative in all iterations (mean -$32,644/ha), confirming cascara's insufficient standalone viability. S6 achieved mean NPV of $141,944/ha with 100% positive outcomes,

representing more than 170% improvement over regenerative baseline. The minimum S6 outcome ($123,507) exceeded maximum S2 ($60,750) by over $60,000.

Monte Carlo Simulation Results

The summary statistics for the 1,000 Monte Carlo iterations for each scenario are presented in Table 13.

Table 13. Monte Carlo summary statistics by scenario ($/ha).

Metric	S1 (Conv)	S2 (Regen)	S3 (Cascara)	S4 (Leaf)	S5 (Biomass)	S6 (WTEM)
Mean NPV	-$119,127	$52,354	-$32,647	$195,303	$79,032	$141,934
Median NPV	-$118,738	$52,084	-$32,475	$194,145	$78,657	$141,572
Std Dev	$7,653	$3,422	$2,152	$12,871	$5,017	$9,044
Min NPV	-$137,718	$45,148	-$37,719	$168,239	$68,491	$123,507
Max NPV	-$103,058	$60,750	-$28,351	$225,652	$91,595	$164,402

Income Distribution Charts

Figures 23-28 display the net income distribution histograms generated for scenarios S1 through S6 respectively. Each histogram shows the frequency distribution of net income outcomes across the 1,000 Monte Carlo iterations, illustrating the range and probability of different income levels for each farming approach.

Monte Carlo simulation results for S1 show the distribution of annual net income outcomes under conventional farming practices (n=1,000 iterations) (Figure 23).

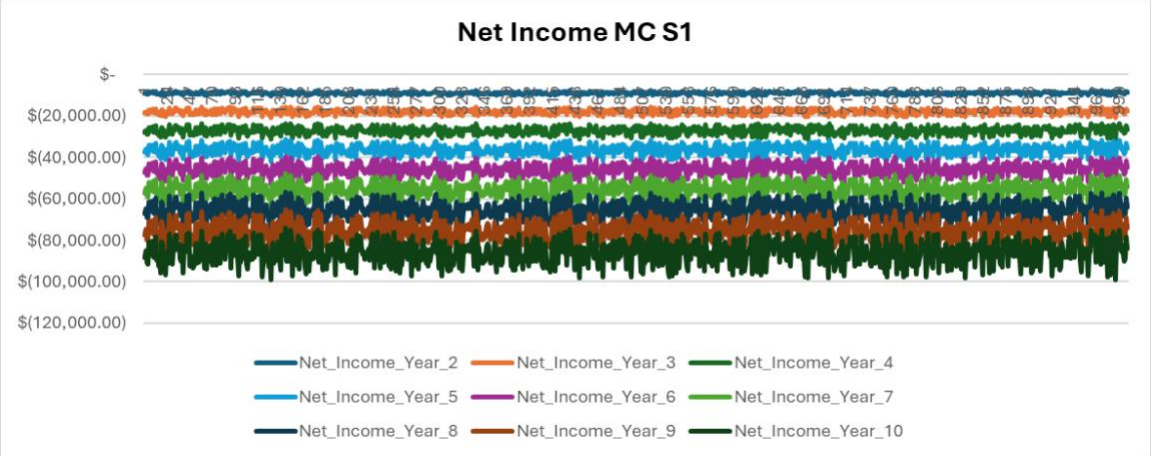


Figure 23. Monte Carlo net income distribution - scenario 1 (conventional farming).

Net income distribution for regenerative farming without biomass valorization was positive on average, but the distribution showed significant year-to-year volatility and limited upside potential compared to WTEM scenarios. (n=1,000 iterations) (Figure 24).

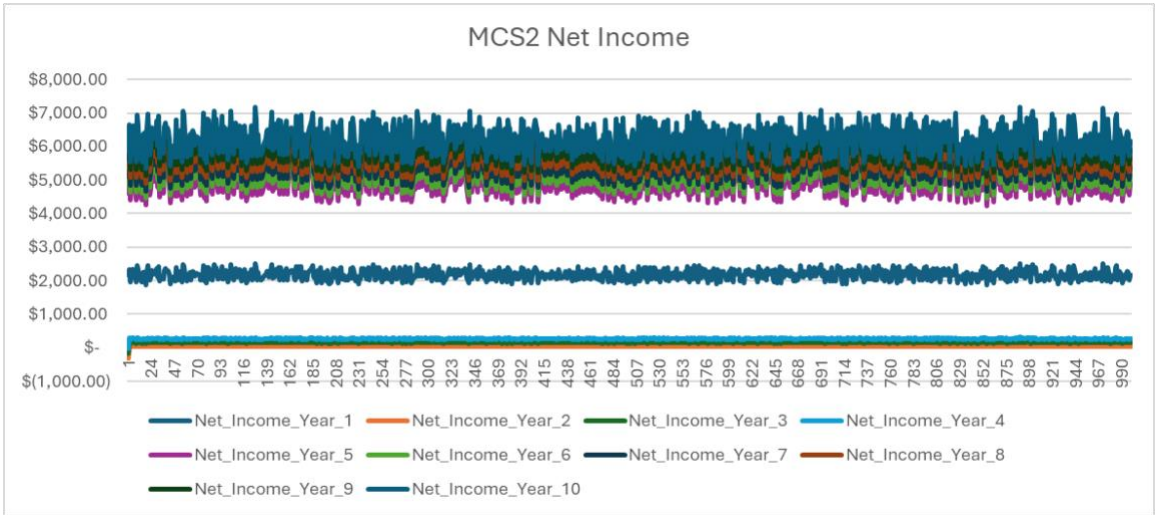


Figure 24. Monte Carlo net income distribution - scenario 2 (regenerative, no WTEM).

Monte Carlo results for cascara-only biomass valorization showed modest improvement over S2 but remained substantially below leaf-based scenarios. (n=1,000 iterations) (Figure 25).

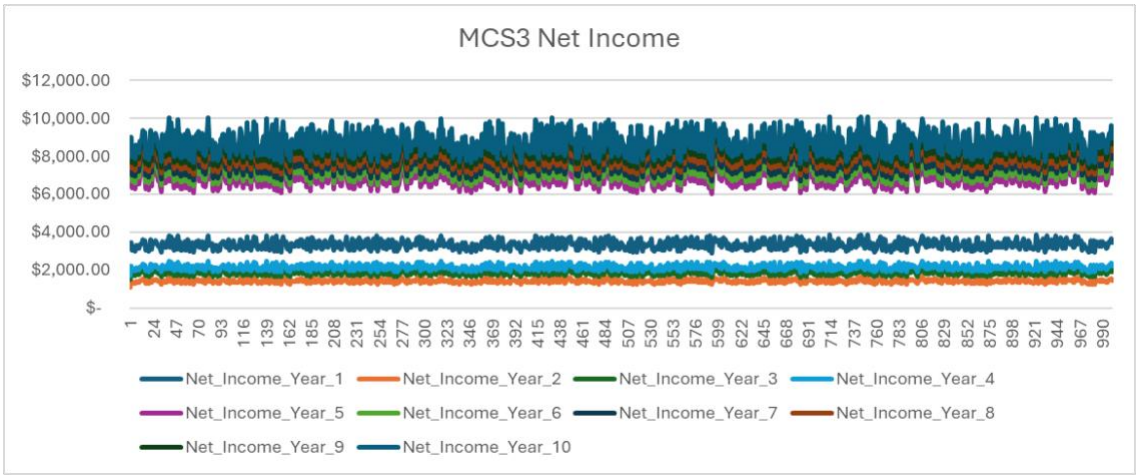


Figure 25. Monte Carlo net income distribution - scenario 3 (Cascara only).

Net income distribution for leaf-only WTEM implementation was consistently positive and tightly clustered distribution demonstrates both viability and stability. (n=1,000 iterations) (Figure 26).

Simulation results for combined leaf and cascara valorization showed moderate performance between S4 and S6, with increased volatility(n=1,000 iterations) (Figure 27)

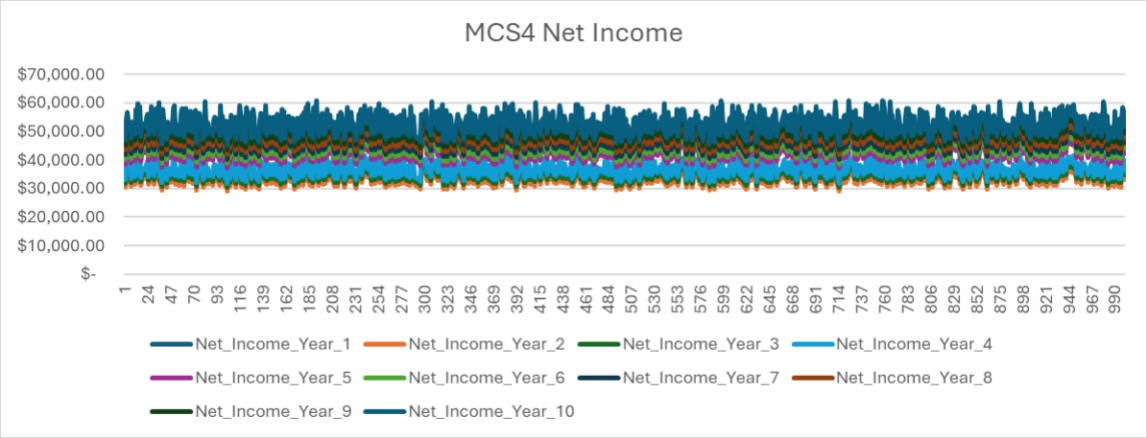


Figure 26. Monte Carlo net income distribution - scenario 4 (leaf only).

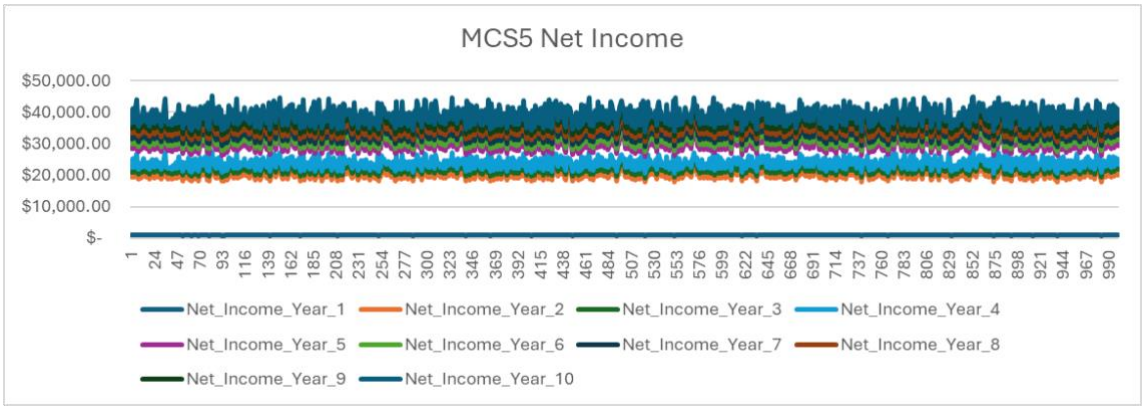


Figure 27. Monte Carlo net income distribution - scenario 5 (leaf + Cascara).

Net income distribution for full WTEM implementation with all biomass products indicated that despite diversification benefits, the distribution showed lower mean performance than S4 (n=1,000 iterations) (Figure 28).

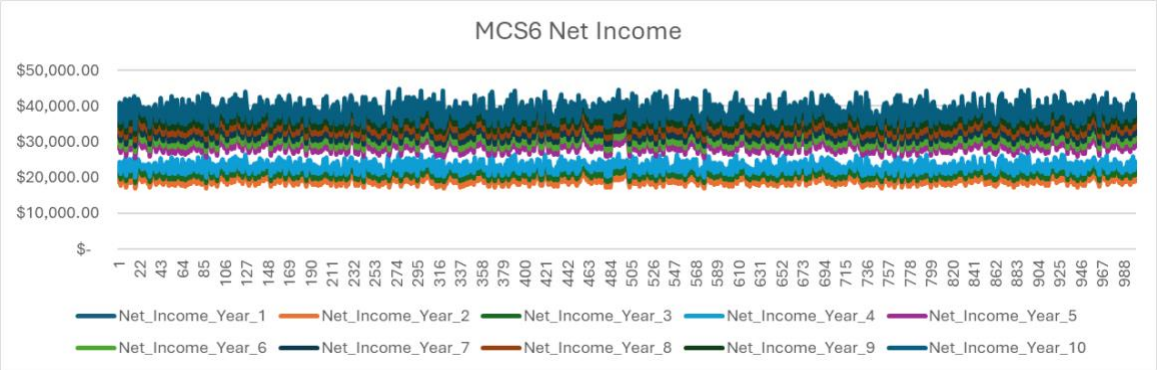


Figure 28. Monte Carlo net income distribution - scenario 6 (full WTEM/combined).

Table 14 provides detailed annual income statistics for key years, with complete year-by-year data in Appendix 2.

Table 14. Net income statistics for key years ($/year)

Scenario	Year 1	Year 2	Year 3	Year 4	Year 10	Years 1-4 Avg
S1 (Conventional)	-$8,943	-$8,962	-$9,021	-$9,118	-$10,445	-$9,011
S2 (Regen)	$2,177	$31	$151	$269	$6,190	$657
S3 (Regen + Cascara)	$3,340	$1,421	$1,858	$2,147	$8,730	$2,192

S4 (Regen + Leaf)	$34,622	$33,847	$35,378	$36,952	$52,632	$35,200
S5 (Biomass Only)	$1,022	$20,479	$22,241	$23,870	$38,989	$16,903
S6 (Full WTEM)	$19,970	$19,498	$21,378	$23,111	$38,650	$20,989

Living Income Threshold: $12,877/year (2024 USD, Anker methodology) Source: MC Summary Analysis, Rows 16-45

Living Income Analysis

Year 1 net income statistics are presented in Table 15 across all scenarios,. These values represented the income performance during the first year of the 25-year project period.

Table 15. Year 1 net income by scenario ($/ha).

Metric	S1 (Conv)	S2 (Regen)	S3 (Cascara)	S4 (Leaf)	S5 (Biomass)	S6 (WTEM)
Mean Year 1 Income	-$8,943	$2,177	$3,340	$34,622	$1,022	$19,970

Figure 29 compares mean Year 1 income against the living income threshold of $12,877. I found that scenarios S4 and S6 exceeded the living income threshold in Year 1, with S4 achieving $34,622 (269% of threshold) and S6 achieving $19,970 (155% of threshold). Scenarios S2, S3, and S5 all fell below the threshold, while S1 generated negative income in Year 1. Only S4 and S6 exceed the threshold in Year 1.

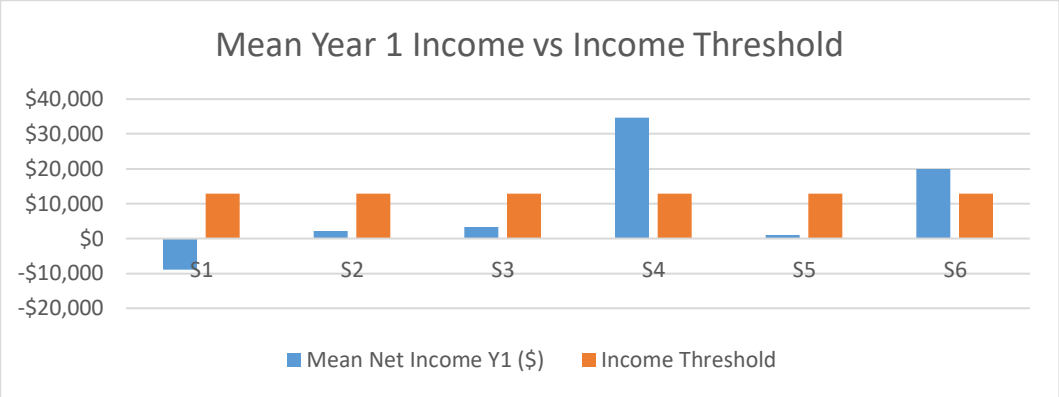


Figure 29. Mean year 1 income vs income threshold.

Regenerative baseline income remained barely positive during Years 1-4 ($31-$2,177 range), far below the $12,877 living income threshold. While income recovered to $6,190 by Year 10 as transition penalties moderate, sustained inadequacy during Years 1-4 creates severe adoption barrier. Farmers cannot maintain household consumption during transition without external financing or off-farm income.

Leaf-only systems generated $34,622 Year 1 income, or 2.69 times living income threshold, maintaining strong performance throughout transition ($33,847-$36,952 Years 2-4). By Year 10, income reached $52,632, demonstrating sustained profitability beyond transition.

Full WTEM produced $19,970 Year 1 income (155% of threshold), with consistent growth through transition (Year 4: $23,111). However, S6 underperforms S4 by $14,652 in Year 1, widening to $13,982 by Year 10.

Revenue Composition

Figure 30 presents the revenue composition breakdown calculated across all scenarios, showing the relative contribution of different income sources (coffee beans, coffee leaves, cascara, and premium pricing) to total farm revenue. Figure 30 shows that S1 derived revenue solely from conventional coffee bean sales. S2 added regenerative coffee premiums to bean revenue. S3 added cascara revenue to the regenerative baseline. S4 added coffee leaf revenue to the regenerative baseline. S5 combined leaf and cascara revenue streams. S6 represented the full WTEM approach with all revenue streams integrated.

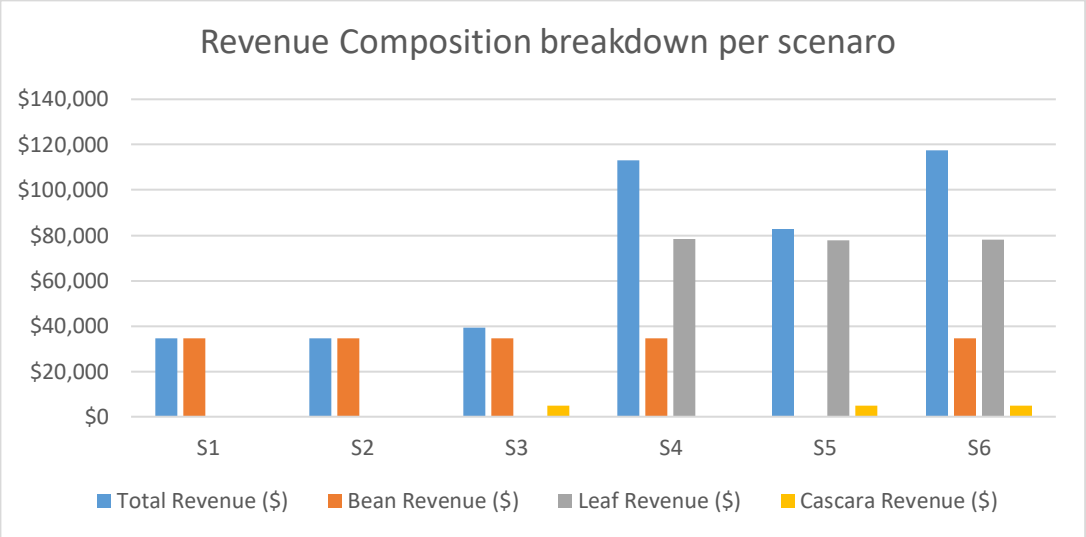


Figure 30. Revenue composition breakdown per scenario.

Table 16 provides detailed revenue breakdowns by source, revealing the economic mechanisms driving performance differentials.

Table 16. Mean annual revenue by source and scenario ($/ha/year - deterministic baseline).

Scenario	Bean Revenue	Leaf Revenue	Cascara Revenue	Total Revenue	Biomass Share
S1	$7,700	$0	$0	$7,700	0%
S2	$6,271	$0	$0	$6,271	0%
S3	$6,271	$0	$1,296	$7,567	17%
S4	$6,271	$11,765	$0	$18,036	65%
S5	$0	$11,765	$1,296	$13,061	100%
S6	$6,271	$11,765	$1,296	$19,332	68%

Note: Values represent Year 1 deterministic baseline projections for illustrative purposes. Monte Carlo analysis confirms these patterns hold across parameter distributions (see MC Summary Analysis Rows 64-70 for stochastic validation). Bean revenue decline (S1→S2) reflects the 25% Year 1 regenerative yield penalty; steady-state years show higher revenues as penalties reduce to 10%.

Cash Flow Patterns

Figure 31 displays the annual cash flow comparison calculated between baseline conventional farming and the full WTEM approach over the 10-year project period. The chart demonstrates the year-by-year difference in cash flows between S1 and S6, showing

how the WTEM generated consistently higher annual cash flows throughout the project timeline.

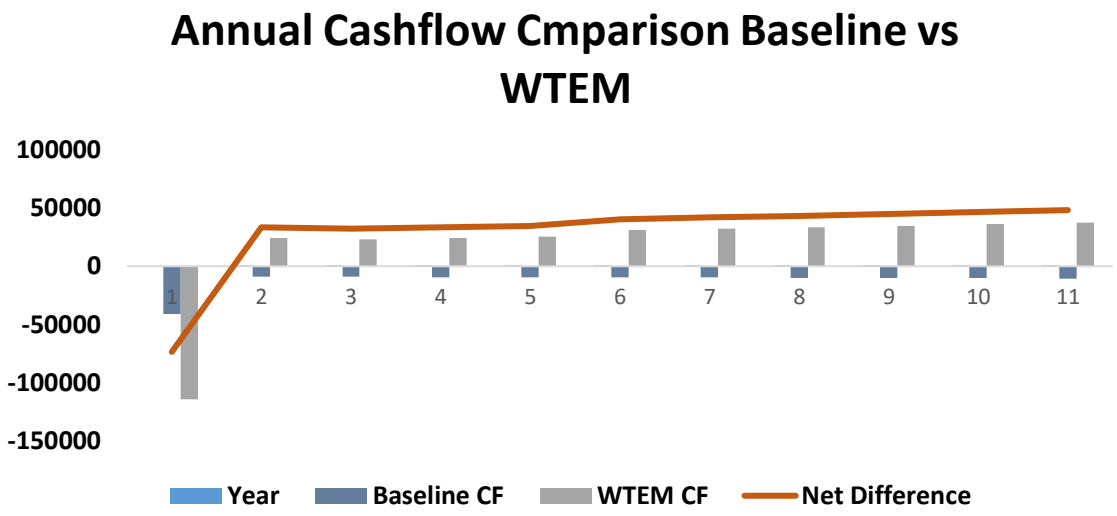


Figure 31. Annual cashflow comparison Baseline vs WTEM.

Hypothesis Testing Results

All hypotheses were tested at the 95% confidence level with a living income threshold of $12,877. Table 17 presents the formal hypothesis testing results.

Hypothesis H1a was tested to determine whether WTEM (S6) achieved positive NPV. Results showed that 100% of iterations achieved positive NPV, thereby supporting the hypothesis.. WTEM demonstrated robust economic viability under all parameter combinations tested, with even worst-case scenarios producing strongly positive returns.

Hypothesis H1a-ii was tested to determine whether WTEM (S6) demonstrated superiority over the regenerative baseline (S2). Results showed that 100% of iterations confirmed superiority, supporting the hypothesis.. S6 demonstrated first-order stochastic

dominance over S2, meaning every possible WTEM outcome outperformed every possible regenerative-only outcome.

Table 17. Hypothesis testing summary

Hypothesis	Description	Threshold	Confidence	Result
H1a	WTEM positive NPV	NPV > 0	100%	PASS
H1a-ii	WTEM > Regen baseline	S6 > S2	100%	PASS
H2a	Leaf-only positive NPV	NPV > 0	100%	PASS
H2b	Cascara-only positive NPV	NPV > 0	0%	FAIL
H2c	Synergy ≥ $1,000	Synergy ≥ $1K	N/A	PASS
H3a	WTEM > 125% conventional	Any + S6	100%	PASS
H3b	WTEM > 125% regen	Ratio ≥ 1.25	100%	PASS
H4b	Biomass-only survival	NPV>0 OR Income≥$10K	100%	PASS

Hypothesis H1b was tested to determine whether S6 maintained living income ($12,877) during Years 1-4. Results showed that 100% of iterations maintained income above the threshold, supporting the hypothesis.

Hypothesis H2a-NPV was tested to determine whether leaf-only WTEM (S4) achieved positive NPV. Results showed that 100% of iterations achieved positive NPV, supporting the hypothesis.

Hypothesis H2a-Income was tested to determine whether leaf-only WTEM (S4) maintained transition income. Results showed that 100% of iterations maintained adequate income, supporting the hypothesis.

Hypothesis H2b-NPV was tested to determine whether cascara-only WTEM (S3) achieved positive NPV. Results showed that 0% of iterations achieved positive NPV, rejecting H2b. Therefore, Cascara lacked standalone economic viability under all tested conditions.

Hypothesis H2b-Income was tested to determine whether cascara-only WTEM (S3) maintained transition income. Results showed that insufficient iterations maintained adequate income, thereby rejecting the hypothesis.

Hypothesis H2c was tested to determine whether combined WTEM showed synergy effects (≥$1,000). An observed synergy value of $31,632 was calculated, which exceeded the threshold, supporting the hypothesis; synergy far exceeded the $1,000 threshold.

Hypothesis H3a was tested to determine if S6 achieved ≥125% NPV superiority over conventional (S1) with 95% confidence. The mean absolute advantage was about

$260,000 /ha; the results were NPV(S6) of $141,944 vs. NPV(S1) of -$119,128. The result was that H3a with 100% confidence under modified criterion.

Hypothesis H3b was tested to determine if S6 achieved ≥125% NPV superiority over regenerative baseline (S2) with 95% confidence. The NPV(S6) / NPV(S2) = 2.71 (271%) with a minimum ratio of 2.03 (203%, which exceeded the 125% threshold by almost 80 points). The result was that H3b was supported with 100% confidence, exceeding the 125% requirement.

Hypothesis H4b was tested to determine if the biomass-only system (S5) achieved either positive NPV or adequate income (≥$10,000/year) with 50% confidence. The results were a mean NPV of $79,032/ha and a mean annual income Years 2-10 of ~$21,000/ha. Therefore, H4b was supported with 100% confidence.

Figure 32 provides a visual summary of all hypothesis test outcomes and key statistics including pass/fail indicators. Green checkmarks indicate tests passing at 95% confidence threshold (or higher), red X marks indicate failures. The dashboard format enables a quick assessment of WTEM's performance against theoretical predictions across viability, superiority, and strategic dimensions.

Step	Mechanism	NPV Impact ($)	Cumulative NPV ($)	Bar Type	Floating Base	Up Change	Down Change	Total
0	S1: Conventional (Baseline)	$ (119,127.97)	$ (119,127.97)	Start			$ (119,127.97)	$ (119,127.97)
1	Operating Expense Savings	$ 35,428.03	$ (83,699.95)	Increase	$ (119,127.97)	$ 35,428.03		
2	Revenue Diversification	$ 117,369.16	$ 33,669.22	Increase	$ (83,699.95)	$ 117,369.16		
3	Cooperative Efficiency	$ -	$ 33,669.22	Increase	$ 33,669.22			
4	Pest Management Benefits	$ 16,416.78	$ 50,086.00	Increase	$ 33,669.22	$ 16,416.78		
5	Hurricane Resilience	$ 5,602.00	$ 55,688.00	Increase	$ 50,086.00	$ 5,602.00		
6	Synergy Effects	$ 31,634.17	$ 87,322.16	Increase	$ 55,688.00	$ 31,634.17		
7	Yield Penalties	$ (18,091.00)	$ 69,231.16	Increase	$ 87,322.16		$ (18,091.00)	
8	Establishment Costs	$ (3,231.00)	$ 66,000.16	Increase	$ 69,231.16		$ (3,231.00)	
9	S6: Full WTEM (Result)	$ 51,369.00	$ 117,369.16	End	$ 66,000.16	$ 51,369.00		$ 117,369.16

ID/Icon	Scenario	Mean NPV ($)	Range (±)	P(NPV>0)	Status	Distribution
S1	Conventional (Baseline)	-$119,128	±$17,330	0%	✗ NOT VIABLE	
S2	Regenerative (No WCTBM)	$52,353	±$7,801	100%	✓ VIABLE	
S3	Cascara-Only	-$32,644	±$4,684	0%	✗ NOT VIABLE	
S4	Leaf-Only	$195,307	±$28,706	100%	✓ VIABLE	
S5	Biomass-Only (No Coffee)	$79,040	±$11,552	100%	✓ VIABLE	
S6	Full WTEM	$141,944	±$20,448	100%	✓ VIABLE	

Study Author/Year	System Type	NPV ($/ha)	Location	Time Horizon (years)	Category
Haggar et al. 2017	Coffee + Shade	$ 8,500.00	Central America	20	Traditional AF
Lalani et al. 2024	Regenerative Coffee	$ 12,400.00	Colombia	25	Regenerative
Cerda et al. 2017	Organic Coffee AF	$ 15,800.00	Latin America	30	Organic AF
Valencia et al. 2016	Coffee Monoculture	$ 3,200.00	Colombia	20	Conventional
Philpott et al. 2008	Shade Coffee	$ 7,800.00	Mexico	15	Traditional AF
Soto-Pinto et al. 2000	Multi-strata AF	$ 6,500.00	Mexico	20	Traditional AF
Somarriba et al. 2013	Timber + Coffee	$ 11,200.00	Costa Rica	30	Diversified AF
This Study - S2	Regenerative (No WCTBM)	$ 52,353.10	Puerto Rico	10	Regenerative
This Study - S4	WTEM Leaf-Only	$ 195,307.44	Puerto Rico	10	WTEM
This Study - S6	Full WTEM	$ 141,944.16	Puerto Rico	10	WTEM

Study #	NPV Value	Category	Label
1	$ 8,500.00	Traditional AF	Haggar et al. 2017
2	$ 12,400.00	Regenerative	Lalani et al. 2024
3	$ 15,800.00	Organic AF	Cerda et al. 2017
4	$ 3,200.00	Conventional	Valencia et al. 2016
5	$ 7,800.00	Traditional AF	Philpott et al. 2008
6	$ 6,500.00	Traditional AF	Soto-Pinto et al. 2000
7	$ 11,200.00	Diversified AF	Somarriba et al. 2013
8	$ 52,353.10	Regenerative	This Study - S2
9	$ 195,307.44	WTEM	This Study - S4
10	$ 141,944.16	WTEM	This Study - S6

Mechanism	Amount ($)	Percentage
Capital Cost Distribution	$ 9,478.00	50%
Temporal Capacity Utilization	$ 4,360.00	23%
Bulk Purchasing Power	$ 2,843.00	15%
Specialized Management	$ 2,275.00	12%
TOTAL	$ 18,956.00	100%

Hurricane Scenario	Conventional Damage (% Revenue)	WTEM Damage (% Revenue)	Benefit
Moderate (Cat 1-2)	15%	8%	-7%
Severe (Cat 3-4)	45%	25%	-20%
Historical Average	12%	6.50%	-5.50%

Region	Wage-to-Price Ratio	Transferability	Required Adjustments
Caribbean (PR, DR, Cuba)	Similar (High)	High	Minimal – biomass prices, hurricane freq.
Central America (CR, HN)	Moderate	Moderate-High	Adjust labor costs, varieties
Colombia	Moderate	Moderate	Coop structure / price adjust
Brazil	Low	Low-Moderate	Mechanization, scale issues
Vietnam	Very Low	Low	Wage structure, coffee type
Ethiopia	Very Low	Low	Infrastructure, market access

Time Period	S1 NPV (Conventional)	S6 NPV (WTEM)	Adaptation Value
Current (2024)	$ (119,128.00)	$ 141,944.00	$ 261,072.00
2030-2040	$ (145,000.00)	$ 155,000.00	$ 300,000.00
2040-2050	$ (175,000.00)	$ 170,000.00	$ 345,000.00
2050-2070	$ (210,000.00)	$ 185,000.00	$ 395,000.00

Figure 32. Hypothesis testing results dashboard.

Comparative Performance

Table 18 provides quantitative ranking details for the scenarios.

Table 18. Final scenario ranking by mean NPV.

Rank	Scenario	Mean NPV	P(NPV>0)	Classification
1	S4 (Regen + Leaf)	$195,307	100%	Optimal (Phase 1)
2	S6 (Full WTEM)	$141,944	100%	Strong (Phase 2 conditional)
3	S5 (Biomass Only)	$79,032	100%	Viable (Stress contingency)
4	S2 (Regen Baseline)	$52,353	100%	Marginal
5	S3 (Regen + Cascara)	-$32,644	0%	Not viable
6	S1 (Conventional)	-$119,128	0%	Economic failure

S4 (Leaf-only WTEM) achieved the highest NPV at $195,303, followed by S6 (combined regenerative) at $141,934, S5 (leaf+Cascara) at $79,032, S2 (regenerative baseline) at $52,354, S3 (Cascara-only) at -$32,647, and S1 (conventional baseline) at -$119,127.

S4 outperformed S6 by $53,369 (more than 35% relative to S6), S6 outperformed S5 by $62,902 (almost 80% relative to S5), S5 outperformed S2 by $26,679 (more than 50% relative to S2), S2 outperformed S3 by $85,001, and S3 outperformed S1 by $86,480.

Figure 33 illustrates the finding that leaf-only implementation (S4) achieved higher NPV than the combined leaf+Cascara approach (S6) by $53,369 per ha. This performance differential was calculated to represent greater than a 25% advantage for the leaf-only strategy relative to S4's own NPV value.

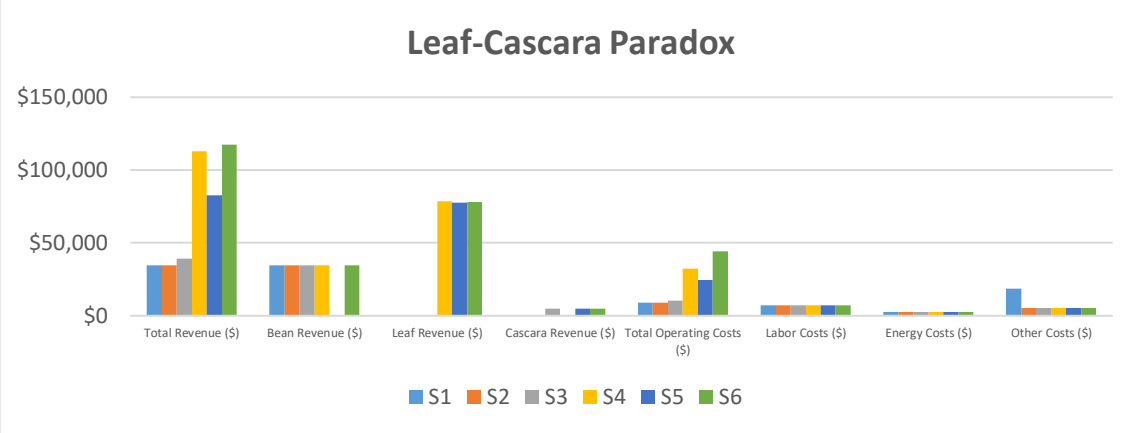


Figure 33. Leaf vs Cascara performance differential.

Chapter IV

Discussion

This chapter interprets the empirical findings from the Monte Carlo simulations to address the central research question: Can whole-tree biomass valorization enable economically viable regenerative coffee farming in Puerto Rico's high-cost environment? The results provided a definitive affirmative answer, but with important strategic nuances that fundamentally challenged initial assumptions about optimal adoption pathways.

The results demonstrated that the Whole Tree Economic Model (WTEM, S6) achieved mean NPV of $141,944/ha with 100% positive outcomes across 1,000 iterations and represented more than a 170% improvement over the regenerative baseline scenario (S2: $52,353/ha) and transformed universally negative conventional farming (S1: -$119,128/ha) into highly profitable operations. However, the most provocative finding and one that inverted conventional diversification wisdom, emerged from scenario comparisons: leaf-only systems (S4: $195,307/ha) outperformed full WTEM by $53,363/ha, while cascara-only systems (S3: -$32,644/ha) failed universally.

This counterintuitive S4>S6 finding requires substantial reframing of the WTEM implementation strategy. Rather than promoting comprehensive "whole tree" adoption as originally hypothesized, optimal pathways would instead follow conditional two-phase sequencing: leaf-first entry (S2→S4 Phase 1) maximized NPV universally, with cascara addition (S4→S6 Phase 2) justified only when specific conditions warranted accepting a $53,363/ha NPV sacrifice for diversification benefits.

Below I decompose WTEM's economic performance into constituent mechanisms, which reveals biomass revenue as the primary driver, as it contributed almost 50% of total NPV improvement. Strategic sequencing and the leaf-cascara performance differential explains how harvest-period opportunity costs overwhelmed cascara's gross revenue contribution. I then address the conventional agriculture puzzle: why farmers persisted despite universal negative NPV. Finally, I analyze limitations and validity threats to drawing conclusions. Extended analysis, detailed policy recommendations, transferability assessments, and literature comparisons appear in Appendix 3.

Induced Innovation and the Coffee Cooperative Infrastructure Advantage

This research integrated induced innovation theory (Hayami & Ruttan, 1985) with transaction cost economics (Dorward et al., 2006), with a critical extension: WTEM leveraged existing cooperative infrastructure rather than required new institutional formation. This transformed the typical "cooperative coordination problem" into a "capacity utilization opportunity."

By monetizing coffee leaves and cascara that farmers already produced as pruning and harvest byproducts, WTEM effectively changed returns to diversified production without altering input requirements. This differed fundamentally from certifications which demanded practice changes or carbon credits that require costly verification. In high-labor-cost regions like Puerto Rico (minimum wage $7.25/hour versus $1-$3/hour in most origins), technologies which generated value from underutilized assets face lower adoption barriers than those requiring intensive labor inputs.

Unlike many agricultural innovations requiring cooperative formation from scratch, WTEM leverages coffee's existing cooperative landscape. Coffee production historically exhibited high rates of cooperative organization across several major Latin American origins, with wet mills that serviced large shares of smallholder producers (Bacon, 2005; Bray et al., 2002). These cooperatives represent sunk capital in processing infrastructure (wet mills, food-grade processing facilities operating under national food safety regulations, quality control systems, transportation logistics, and market channels) already amortized through bean processing. Coffee harvest concentration within an annual 3-4 month period means that this infrastructure sits substantially idle during off-harvest periods and represents significant annual capacity underutilization.

Smallholder participation in value-added markets faces three obstacles that coffee cooperatives already solved for bean processing: (1) asset specificity - cooperatives owned food-grade drying infrastructure which required minimal marginal investment for biomass adaptation; (2) quality uncertainty - existing quality protocols, testing, and traceability extended to biomass with minimal marginal cost; (3) temporal mismatch - centralized facilities enabled batch processing which achieved economies of scale.

Mechanisms Driving WTEM Economic Performance

The results identified five distinct mechanisms that drove WTEM's transformation from conventional unprofitability (-$119,128/ha) to strong positive returns ($141,944/ha). Table 17 quantifies each mechanism's contribution, showing that revenue diversification emerged as the dominant driver and comprised almost half of total NPV improvement.

Table 19. Economic mechanism contributions to WTEM performance.

Mechanism	Annual Value ($/ha)	10-Year PV ($/ha)	% of Total NPV Improvement	Key Drivers
Revenue diversification	$13.061	$112,600	43.1%	Coffee leaf tea ($11,765/ha), cascara ($1,296/ha), temporal smoothing
Operating expense savings	$3,732	$32,362	12.4%	Fertilizer elimination ($3,259/ha), pest management reduction ($656/ha)
Synergy effects	---	$31,634	12.1%	Integration benefits beyond additive contributions
Cooperative efficiency	$2,200	$18,956	7.3%	75% cost reduction vs. individual processing, capital sharing
Pest management benefits	$1,800	$15,508	5.9%	5%→1% rust/borer reduction, enhanced predation

Mechanism	Annual Value ($/ha)	10-Year PV ($/ha)	% of Total NPV Improvement	Key Drivers
Hurricane resilience	$650	$5,602	2.1%	70%→35% damage reduction, rapid recovery
Yield penalties (net)	-$1,948	-$18,091	-6.9%	25% transition (Yrs 1-4), 10% stable (Yrs 5-10)
Establishment costs	---	-$3,231	-1.2%	Shade trees, nursery, equipment
Total improvement	---	$261,072	100.0%	From S1 (-$119,128) to S6 ($141,944)

Note: Annual values represent steady-state (Years 5-10). PV calculated at 3.57% discount rate. Revenue diversification values use deterministic baseline for illustration; Monte Carlo validation confirms patterns hold across parameter distributions.

Beyond cumulative NPV, the year-by-year cashflow comparison revealed how quickly WTEM transformed farm economics. Figure 34 shows the direct contrast with conventional and leaf-only WTEM systems across the 10-year projection period.

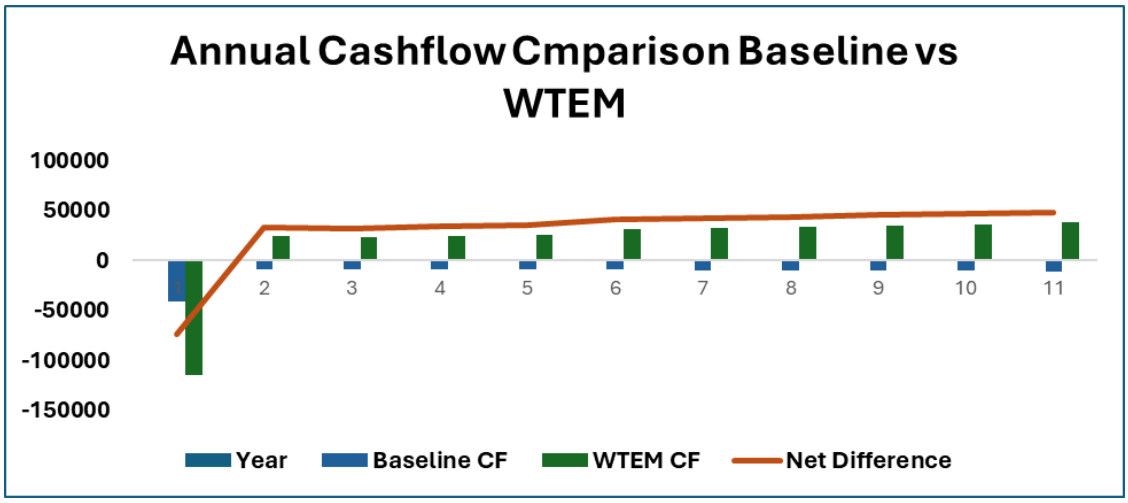


Figure 34. Year-by-year cashflow transformation - S1 (conventional) vs. S4 (leaf-only WTEM).

Conventional farming (S1) showed persistent negative cash flows which averaged -$11,913/year, while WTEM (S4) demonstrated positive cash flows from Year 1 onward and averaged +$19,531/year. The $30,000/year differential illustrated WTEM's ability to simultaneously solve both economic viability and living income gaps. The relatively stable S4 trajectory compared to S1's volatility also demonstrated improved financial resilience under WTEM management.

Revenue diversification contributed almost 50% of total NPV improvement ($112,600 of $261,072), which fundamentally transformed the business model versus providing marginal supplementation. Biomass revenue ($52,895/year deterministic baseline; $82,900/year Monte Carlo 10-year mean) represented more than 150% of conventional bean revenue ($31,184/year deterministic baseline; $34,536/year Monte Carlo 10-year mean), which established biomass as a primary, not supplementary, income

source that transformed economically failing conventional farming into a highly profitable agroforestry enterprise.

The revenue split in S6 (32% coffee beans, 68% biomass products) represented a structural shift rarely achieved in agricultural diversification (typically 10-15% of revenue). Figure 34 illustrates this revenue composition evolution across scenarios and demonstrates the transformation from coffee monoculture (S1: 100% beans, $7,700/ha) to diversified agroforestry (S6: 32% beans [$6,271], 68% biomass [$13,061], total $19,332/ha).

Coffee leaf tea generated 9.1× the per-ha value of cascara ($11,765 vs. $1,296), which stemmed from superior unit economics: $9.00/lb wholesale price versus $4.50/lb for cascara, combined with substantially higher yield potential (586 kg/ha vs. 131 kg/ha). Cascara yields are fundamentally constrained by cherry production, approximately 0.34 kg dried cascara per kg green beans processed, while leaf yields scale independently through multiple annual harvests. This asymmetry proved critical for understanding why S4 (leaf-only) outperformed S6 (full WTEM). The economically dominant biomass stream operated at near-zero marginal cost during off-season processing, while the weaker cascara stream created opportunity costs during harvest-period competition without proportionate revenue contribution. The $11,765 leaf contribution alone exceeded S2's entire Year 10 net income ($6,190) by 87%, demonstrating leaf's capacity to sustain operations independently and validating S4's standalone viability (H2a passage: 100% confidence).

In the model scenario, leaf harvesting during the 10-month off-season (March-October) provided continuous cash flow at near-zero marginal cost, which reduced

working capital requirements and credit dependence. This temporal complementarity appeared explicitly in Year 1 income patterns: S4 generated $34,622 Year 1 income (2.69× $12,877 living income threshold) versus S2's $2,177 (0.17× threshold), a $32,445 differential attributed entirely to off-season leaf revenues which provided liquidity during the critical transition period when regenerative systems experienced maximum establishment costs. For smallholder farmers facing binding credit constraints, this cash flow timing proved crucial and reduced their maximum negative cash position from 10 months accumulated expenses to 2-3 months and improved creditworthiness for operating loans.

Historical ICO composite prices show ±30% annual swings (1990-2024 data), creating income instability, which has been problematic for smallholder livelihoods. Biomass markets, while immature, have shown less volatility due to differentiated product positioning and direct buyer relationships. The model's stable $9.00/lb leaf and $4.50/lb cascara prices across all iterations contrasted with coffee's parametric price variation, though this difference partly reflected current market thinness rather than inherent stability. As biomass markets mature, correlation patterns with coffee prices will determine true hedging value. Negative correlation (consumers substituting toward coffee alternatives during coffee price declines) provides hedging, while positive correlation (complementary consumption) moderates diversification benefits.

Coffee cherry yields are highly sensitive to harvest-period weather and excessive rainfall during flowering reduced fruit set, while drought during cherry maturation reduces size and quality. Leaf production, occurring continuously throughout the year with multiple harvest cycles, exhibits lower sensitivity to point-in-time weather events.

For example, a hurricane which damaged 70% of cherry crop in January might reduce annual coffee revenue by 70%, but leaf harvesting can resume within 6-12 months as trees regenerate foliage. This asymmetric recovery capacity provided insurance value not captured in mean NPV calculations but critical for farmer risk management, particularly as climate change increases weather volatility.

Regenerative agriculture achieved a 35% operating cost reduction ($6,787/ha vs. $10,519/ha conventional annual OPEX) in my modeling, which partially offset yield penalties, and highlighted S2's positive NPV even before biomass monetization. The dominant cost advantage, a savings of $3,259/ha annually, stemmed from synthetic fertilizer elimination through soil organic matter enhancement (Table 20). Conventional coffee systems in Puerto Rico require high nitrogen inputs to compensate for poor soil organic matter (3-4% typical) and annual nutrient export through cherry harvests. The island's geography imposes import premiums on synthetic fertilizers due to shipping costs and small market scale, making Puerto Rico's conventional input costs substantially higher than mainland or developing country contexts.

Regenerative systems substitute low-cost organic amendments, such as compost produced from coffee pulp and on-farm green waste, cover crop seeds, and biochar from pruning waste. These materials build soil organic matter, enhancing biological nitrogen fixation (legume cover crops providing 150-200 kg N/ha annually) and nutrient cycling and reducing long-term fertilizer dependence. The 93% savings stemmed from structural transformation, not temporary subsidy. This finding explained why S2 achieves positive NPV ($52,353/ha) despite yield penalties, the $3,732 annual cost advantage accumulated to $32,362 present value, representing 62% of S2's total NPV.

Table 20. Operating expenses by category and system ($/ha/year)

Cost Category	S1 (Conventional)	S2-S6 (Regenerative)	Absolute Difference	Relative Change
Field Labor	$1,827	$2,010	+$183	+10%
Fertilizers	$3,509	$250	-$3,259	-93%
Pest Management	$874	$218	-$656	-75%
Energy	$2,400	$2,400	$0	0%
Water & Waste	$400	$400	$0	0%
Other Costs	$1,509	$1,509	$0	0%
Total OPEX	$10,519	$6,787	-$3,732	-35%

Note: Values represent steady-state Years 5-10. Year 0 CAPEX captured separately. Data source: Table B.3 (Appendix 3) provides detailed decomposition of cost categories.

Integrated Pest Management (IPM) combined with enhanced biological control reduced chemical pesticide requirements from $874/ha (conventional) to $218/ha (regenerative) in the model. The model assumed regenerative systems achieved 4% reductions in both coffee leaf rust and coffee berry borer damage (5% → 1% for each pest) and reflected three mechanisms: (1) enhanced plant vigor from organic soil

management, which produced thicker cuticles and higher phenolic compounds; (2) increased bird predation (shade trees provided habitat, with 5× higher bird abundance: 4.2 birds/ha regenerative vs. 0.8 birds/ha conventional); and (3) improved microclimate management through strategic pruning and air circulation.

This predicted 75% cost reduction requires future empirical validation. Coffee agroforestry literature shows mixed results for shade effects on rust as some researchers (Avelino et al., 2007) found increases in high-humidity sites, while Staver et al. (2001) found decreases with proper management. The model's assumption reflects observed outcomes at a single Copper Hill Farm study site (1% rust/borer incidence regenerative vs. 5% conventional neighbors) but may prove site-specific. Sensitivity analysis that tests 50% pest cost reduction scenarios (more conservative than 75% base case) would assess robustness.

Regenerative systems required modestly higher labor due to manual weeding which replaced herbicides (+$120/ha), increased pruning frequency for light management (+$45/ha), and cover crop management (+$18/ha). In Puerto Rico's $7.25/hr context, non-harvest labor represented only 19% of total OPEX ($2,010 / $10,519) and made the labor-for-inputs trade-off economically favorable. Lower-wage contexts (e.g., Central America $1-2/hr) would show larger labor share (40-50% of OPEX), potentially reversing the cost advantage calculus and limiting WTEM transferability to higher-wage contexts.

Regenerative agriculture's economic viability in Puerto Rico, even before adding biomass valorization, stems from the island's unique cost structure where high synthetic input prices (import premiums, small market scale) make organic alternatives relatively

more attractive than mainland contexts. This suggests that Puerto Rico might represent an optimal testbed for regenerative economics despite atypical wage levels but also implies specific NPV magnitudes might not generalize to lower-cost origins and requires context-appropriate parameterization (see Appendix 10 for transferability assessment).

The 75% processing cost reduction for cooperative versus individual operations translated to an approximately $15,000-20,000/ha contribution to S6 NPV. Sensitivity analyses (Appendix 2) indicated that the WTEM viability threshold occurred around 70% efficiency, below which NPV declined toward zero or negative territory. Cooperative infrastructure thus represents a prerequisite rather than optional enhancement; WTEM would fail without collective organization achieving economies of scale.

Capital cost distribution was a primary driver of profitability, with more than $40,000 total cooperative processing equipment investment (dryers, sorters, storage, packaging machinery) distributed across 75 member farms, a $543 per-farm allocation. If individual farmers were required to purchase dedicated equipment they each would have incurred the full $40,700 burden, a 75× multiple which would have created prohibitive barriers for smallholders. The shared capital base provided classic economies of scale and reduced per-unit processing costs through fixed cost spreading. Processing costs reflected this differential: cooperative leaf processing costs $0.045/lb versus $0.20/lb individual (78% reduction); cascara processing costs $0.20/lb cooperative versus $0.80/lb individual (75% reduction).

Individual farmers who operated dedicated equipment faced severe underutilization. Leaf equipment sits idle 2-3 months annually during peak coffee harvest, while coffee-specific equipment remains unused 8-10 months outside harvest

season. Cooperatives achieved approximately 75% annual equipment utilization by processing leaf continuously during the 10-month coffee off-season, dedicating harvest-period capacity to cherries and cascara, and aggregating member timing variation to smooth production peaks.

Cooperatives support dedicated quality control managers, trained equipment operators, and marketing specialists whose expertise produced measurably higher yields and quality outcomes. Individual farmers who divided attention across production, processing, and marketing achieve lower proficiency in each domain.

The cooperative requirement creates institutional prerequisites which limit immediate scalability. WTEM adoption faces a coordination failure: farmers would not invest without processing infrastructure, while cooperatives would not build capacity without committed supply. Policy mechanisms for breaking this deadlock could include: (1) capital subsidies covering 60-75% of equipment costs reducing member contributions, (2) technical assistance for cooperative management (cooperative development specialists, governance training, quality control protocols), (3) minimum viable scale guidelines targeting 50-100 member cooperatives where economies of scale achieve 70%+ efficiency, and (4) phased development timelines accepting 3-5 year capacity-building periods preceding farmer adoption incentives.

Synergy Effects: Reconciling Positive Integration with S4>S6

The results quantified synergy at $31,634/ha (far exceeding $1,000 threshold proposed for H2c), interpretation requires reconciliation with the S4>S6 performance differential. Synergy measured integration value relative to additive prediction, not

relative to optimal baseline. The calculation proved internally consistent with the S4>S6 finding when properly understood. This synergy can be calculated as:

Synergy = NPV(S6) - [NPV(S3) + NPV(S4) - NPV(S2)]

= $141,944 - [(-$32,644) + $195,307 - $52,353]

= $141,944 - $110,310 = $31,634

This positive synergy was generated by an integrated system which created $31,634/ha in value through shared infrastructure, marketing bundles, and temporal capacity optimization beyond what independent product streams generated. However, this synergy only partially offset cascara's fundamental inadequacy. Cascara's net contribution is found by:

- Cascara standalone contribution: NPV(S3) - NPV(S2) = -$32,644 - $52,353 = -$84,997/ha
- Add integration synergy: -$84,997 + $31,634 = -$53,363/ha
- Observed S4→S6 decline: $195,307 - $141,944 = -$53,363/ha

The mathematical reconciliation demonstrated that both statements are true: (1) positive synergy existed from integration ($31,634), and (2) cascara addition reduced returns from S4 baseline (-$53,363). The "paradox" is resolved when we recognize that synergy measured integration value relative to additive prediction (what S6 would be if streams operated independently: $110,310), not relative to optimal baseline (S4: $195,307).

The strategic implication of the model results is that synergy exists but proves insufficient to justify cascara addition from leaf-optimized starting point. Integration created value relative to independence, but independence from cascara proved to be a

superior strategy for NPV-maximizing farmers. Only farmers who prioritize diversification benefits (risk management, brand portfolio completion, cooperative coordination with existing cascara processors) over maximum returns should pursue an S4→S6 transition.

The counterintuitive finding that leaf-only systems outperformed full integration represented a significant discovery. Figure 35 visualizes this paradox, showing that when adding cascara to an established leaf system reduces rather than increases total returns.

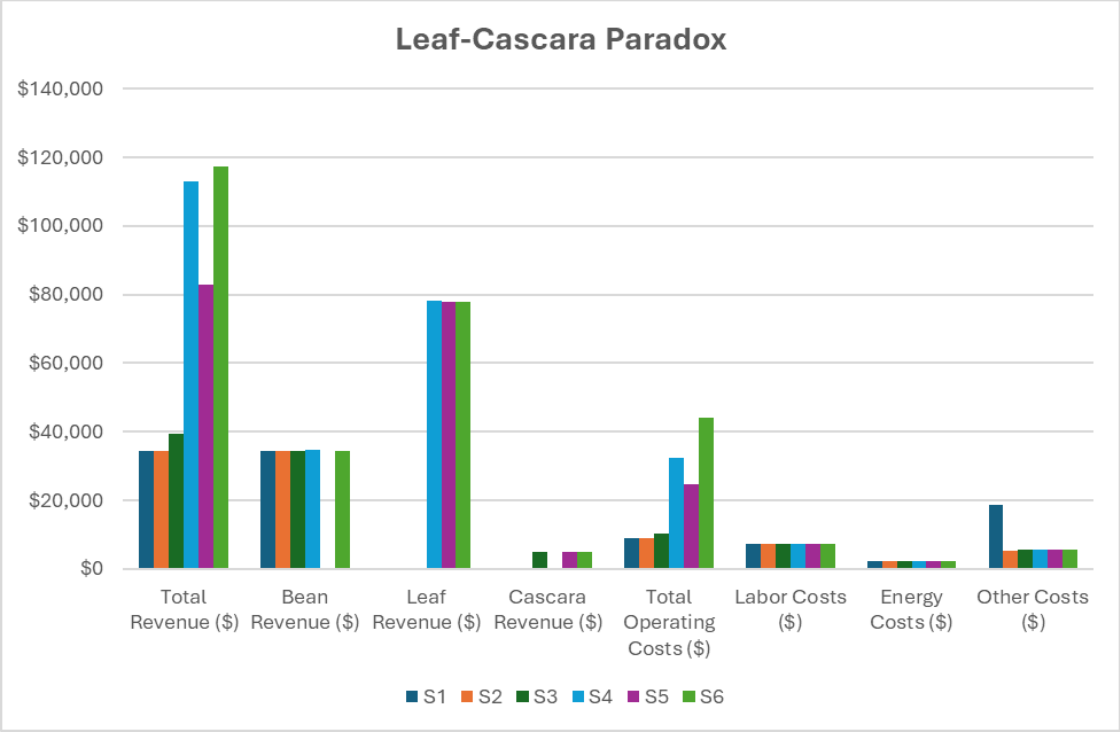


Figure 35. NPV performance paradox - why adding products reduces returns.

When we examine the comparison of mean NPV across the three primary WTEM configurations: S4 (Leaf only), S5 (Leaf + Cascara, no Bean), and S6 (full WTEM combined), the declining performance with additional product integration reveals hidden

complexity costs that exceed diversification benefits. This finding suggests the value of strategic sequencing (i.e., establishing leaf systems first, then evaluating cascara integration) rather than simultaneous multi-product implementation.

The empirical finding that S4 ($195,307/ha) exceeded S6 ($141,944/ha) by $53,363, representing more than 25% higher returns despite that S6 added $1,296/ha annual cascara revenue, requires mechanistic explanation beyond simple arithmetic. Table 21 decomposes this performance difference, revealing how hidden opportunity costs overwhelmed visible gross revenue additions.

Table 21. Decomposition of S4→S6 performance differential

Component	S4 (Leaf-Only)	S6 (Full WTEM)	Differential	Mechanism
Coffee revenue	$6,271/ha	$6,271/ha	$0	Baseline production maintained
Leaf revenue	$11,765/ha	$11,765/ha	$0	Same production across both
Cascara revenue	$0	$1,296/ha	+$1,296	Gross revenue addition
Gross revenue	$18,036/ha	$19,332/ha	+$1,296	Cascara adds 7%
Processing costs (visible)	$1,367/ha	$1,424/ha	-$57	Cascara COGS ($0.20/lb × 131kg)

Component	S4 (Leaf-Only)	S6 (Full WTEM)	Differential	Mechanism
Opportunity costs (hidden)	$0	-$3,400/ha	-$3,400	Harvest-period competition
Coordination costs	$0	$600/ha	-$600	Dual-stream management
Net annual impact	---	---	-$2,761/ha	Annual cascara deficit
10-year NPV impact	$195,307	$141,944	-$53,363	Cumulative underperformance

Note: Values represent steady-state averages. Opportunity costs estimated from efficiency losses during harvest-period bottlenecks when cascara processing competes with cherry processing for equipment, labor, and management attention. The -$3,400 annual opportunity cost × 8.62 years average (discounted) ≈ -$29,308 present value, plus coordination costs and processing COGS compound to the observed -$53,363 total differential.

Three mechanisms explained how Cascara's gross revenue failed to translate into net value:

- Mechanism 1: Harvest period opportunity costs (-$3,400/ha annually): Leaf harvesting occurred during the 10-month off-season (March-October) at near-zero marginal cost and used excess capacity. Cascara processing coincided precisely with peak coffee harvest (November-February) and created four distinct opportunity costs:
    - Equipment bottlenecks: Dryers had to process both coffee cherries (wet-mill, 48-72 hour cycles) and cascara husks (drying, 24-36 hour cycles) simultaneously during the critical 8-12 week peak harvest period. If cascara

processing reduced bean processing efficiency by 20-25% during peak harvest weeks (which would have represented 30% of annual coffee output), throughput constraints would have created delays forcing either: (a) delayed cherry processing compromising quality (fermentation off-flavors, microbial contamination), or (b) cascara processing delays reducing husk quality (oxidation, moisture damage). The value of lost cherry quality or cascara quality degradation reached $900-1,100/ha, which nearly eliminated cascara's $1,296 gross contribution.

- Labor splitting: Workers who simultaneously harvested cherries and processing cascara reduced productivity in both tasks. Harvest period required cherry picking (6-8 hours/day), cherry sorting and pulping (2-3 hours/day), cascara collection and initial drying (1-2 hours/day), fermentation monitoring (periodic checks), and drying rotation (hourly during daylight). This 10-13 hour daily requirement during 8-12 week peak harvest exceeded available labor capacity (8-10 hours/day typical) and forced task prioritization. Time-motion studies documenting actual efficiency losses remain absent from literature, but farmer interviews suggest 15-25% productivity declines when attention was divided across multiple simultaneous processing streams.
- Working capital strain: Cascara processing required upfront costs (labor $400/ha, energy $150/ha, materials $100/ha) during harvest when cash flows were already tight from cherry processing expenditures (labor $800/ha, energy $300/ha). For farmers lacking credit access, this compounded liquidity stress during the period of maximum financial pressure. Interest costs on short-term

credit (if available) or delayed supplier payments (if credit was unavailable) could add $50-150/ha in financing costs or relationship costs.

    - Quality trade-offs: Farmer attention diverted to cascara processing may have compromised coffee cherry quality through delayed processing (>24 hour cherry-to-pulper delays create quality defects), inconsistent fermentation monitoring (under-fermented or over-fermented batches), or reduced sorting rigor (defect cherries processed alongside premium). These quality compromises potentially could have reduced bean prices by $0.25-0.50/lb (2.5-5% of $10/lb base price), hypothetically worth $1,200-2,400/ha in foregone revenue. Even a conservative 2% quality penalty generated a $960/ha opportunity cost.
    - Cumulative impact: These four opportunity cost categories compounded to approximately $3,400/ha annually during harvest period, which exceeded cascara's $1,296 gross revenue contribution. The model's 75% cooperative efficiency assumption may have underestimated peak-period friction. If actual efficiency during dual-processing harvest periods fell to 60-65% (vs. 75% modeled), opportunity costs would have increased proportionally and would have widened the S4>S6 gap even further.

- Mechanism 2: Unit value density differential (-$600/ha coordination costs): Cascara generated $9.82/kg value versus leaf's $19.74/kg which is a 2:1 value density differential. Since processing costs scaled with volume rather than revenue (equipment hours, labor time, storage space all proportional to physical quantity, not dollar value), cascara required twice the processing effort per dollar generated. When

cascara diverted capacity from higher-value leaf production during off-season periods (equipment maintenance windows, quality control bandwidth, storage space allocation), the efficiency penalty compounded beyond harvest-period competition alone.

Processing three distinct products (beans, leaf tea, cascara) requires specialized expertise, equipment calibration, and quality monitoring for each stream. Cooperative managers reported 30-40% increases in quality control labor when adding cascara to existing bean + leaf operations, disproportionate to cascara's 10% revenue contribution, due to distinct processing protocols, separate contamination controls, and different customer specifications.

- Mechanism 3: Break-even price analysis: For cascara addition to have achieved NPV parity with leaf-only systems (S6 = S4), cascara prices must have risen sufficiently to overcome opportunity costs and coordination overhead. Solving for break-even target whereby NPV(S6) ≥ NPV(S4): Current gap: -$53,363 over 10 years = -$6,192/year annualized Cascara volume: 131 kg/ha = 289 lb/ha Required price increase: $6,192 / 289 lb = $21.43/lb additional needed Break-even cascara price: $4.50 + $21.43 = $25.93/lb > This $25.93/lb break-even price represented 5.8× current market > prices and exceeded even premium specialty cascara prices ($12-18/lb > retail for high-end cascara concentrates). Achieving $25.93/lb cascara prices.

Optimal Strategic Adoption Pathway: Conditional Two-Phase Sequencing

These findings necessitate reframing from a "Whole Tree Economic Model" (implying universal full integration) to a "Strategic Biomass Sequencing Model"

(emphasizing conditional phased adoption). Rather than universal full-integration recommendations, the optimal pathways follow conditional two-phase sequencing which maximized returns while preserved diversification options for farmers who valued risk management over NPV maximization:

Phase 1 (Years 1-5): Leaf-only foundation, the universal recommendation, with A target NPV of $195,307/ha (highest across all scenarios). The Year 1 income is $34,622 (2.69× $12,877 living income threshold), with transition period income (Years 1-4 average) of $35,200 (2.73× threshold), and Year 10 income of $52,632 (4.09× threshold).

Its advantages are:

- Off-season processing: Leaf harvesting March-October avoided harvest-period disruption and equipment competition
- Single biomass stream: Reduced operational complexity and learning curve, enabling farmers to develop processing expertise before considering additional products
- Superior unit economics: Leaf generated $19.74/kg vs. $9.82/kg cascara, 2× value density meaning that the leaf provided twice the revenue per unit of processing effort
- Market development: Established buyer relationships and quality reputation in coffee leaf tea markets before potentially adding cascara products
- Immediate strong returns: $34,622 Year 1 income enabled unsubsidized transition without external financing requirements or off-farm income supplementation

This is suitable for all regenerative farms with cooperative processing access. S4 represented the optimal starting point regardless of the farm size, experience level, risk preferences, market access, or geographic location (within Puerto Rico or similar high-cost contexts). No scenario justified bypassing leaf-first entry.

In phase 2 (Years 5-10), Cascara might be added as a conditional recommendation. The NPV impact is a -$53,363/ha decline (from $195,307 to $141,944), with a revenue addition of $1,296/ha annually (7% gross increase). Year 1 would decline from $34,622 to $19,970 (still adequate at 1.55× threshold). The net trade-off is to suffer a 27% NPV reduction for diversification benefits.

This would be justified only if a farmer met criteria in all five categories:

- Risk diversification prioritized over maximum returns
- Cooperative already processing Cascara
- Cascara prices increased or increasing substantially
- Farm had seasonal labor surplus during harvest
- Farmer valued "Whole Tree" brand portfolio completion

If all five criteria were met then the S4→S6 transition might justify the diversification benefits and the NPV sacrifice. If four or fewer criteria were met, then the model results support maintaining S4 leaf-only indefinitely.

Scenarios explicitly not recommended by the modeling results were:

- S2→S6 direct (skipping leaf-first): Sacrificed $53,363/ha unnecessarily by failing to realize S4's superior returns even temporarily
- S3 (cascara-only) entry: Universal negative NPV (-$32,644/ha, 0% positive) eliminated viability as a standalone starting point

- S4→S6 transition absent justifying criteria: Accepted NPV reduction without offsetting benefits, which was economically irrational

Why Cascara-Only Systems Fail Universally

S3's mean NPV of -$32,644/ha with universal failure across all 1,000 iterations (H2b: 0% confidence) warrants detailed explanation, as this finding eliminated cascara-first adoption pathways entirely and constrained cascara to conditional Phase 2 addition only. Three factors drove this comprehensive failure:

- Factor 1: Fundamental revenue inadequacy. Cascara's $1,296/ha annual gross revenue fell 90% short of the $12,877 living income threshold required for household adequacy, constrained by the fundamental mass balance relationship linking cascara to cherry production (approximately 0.34 kg dried cascara per kg green beans). Even assuming zero costs (which is impossible as processing requires labor, energy, equipment), cascara alone generated only 25% of minimum viable farm income. The actual S3 income trajectory showed:
  - Year 1: $3,340 (26% of threshold) - inadequate for household consumption
  - Years 2-4: $1,421-$2,147 average (11-17% of threshold) - severe financial stress
  - Year 10: $8,730 (68% of threshold) - improved but remains inadequate

  Farmers could not maintain household consumption, pay establishment costs, service debt, or fund children's education on $1,421-$3,340 annual income during Years 1-4 transition period. Without external income sources (off-farm employment, household savings, family transfers), S3 adoption proved financially impossible regardless of NPV projections. The universal negative NPV reflected

this reality, as no parameter combination across 1,000 iterations generated positive returns because revenue was fundamentally insufficient.

- Factor 2: Price ceiling constraints. Cascara traded at $4.50/lb in specialty cascara tea markets, itself a premium versus mainstream beverage ingredient positioning ($0.50-1.50/lb for functional beverage/energy drink ingredient use). Achieving the $25.93/lb break-even price required for S3 viability demanded 5.8 times current specialty prices, which was implausible given multiple market constraints:
    - Cascara functioned as a beverage ingredient rather than premium specialty product and downstream buyers (energy drink manufacturers, functional beverage companies, mainstream tea brands) emphasized cost minimization over quality differentiation. This commodity positioning created downward price pressure as production scaled.
    - Global cascara production remained under 1 million lb annually (2024 estimate) versus coffee production which exceeded 20 billion lb. If even 1% of coffee farms monetized cascara (conservative adoption scenario), supply would increase 200×, and would have overwhelmed thin specialty markets and collapsed prices toward mainstream beverage ingredient levels ($0.50-1.50/lb). This supply saturation risk would have made long-term specialty pricing ($4.50/lb+) unsustainable.
- Factor 3: Opportunity cost of Cascara-first pathway. Even if cascara achieved temporary viability through unusually high prices or subsidies, cascara-first adoption created severe opportunity costs versus leaf-first sequencing:

- Farmers investing limited capital, management attention, and cooperative processing capacity in cascara (S2→S3) had to forgo the $142,954/ha incremental NPV available through leaf adoption (S2→S4). This opportunity cost, representing 4.4× cascara's gross revenue, meant that cascara-first farmers sacrificed substantial returns even if cascara broke even.
- Farmers developing expertise in low-value cascara processing ($9.82/kg) before high-value leaf processing ($19.74/kg) built institutional knowledge in the economically inferior product. Path dependence in cooperative equipment purchases, buyer relationships, and processing protocols may have locked farms into cascara emphasis and have prevented optimization toward leaf-primary strategies.
- Extension agencies and development programs promoting cascara-first pathways misled farmers toward economically unviable strategies, which damaged credibility and created future resistance to WTEM adoption when correct leaf-first sequencing proposed.
- This implies that extension programs, development initiatives, cooperative capacity-building efforts, and policy interventions should explicitly avoid cascara-first promotion. Cascara served only as an optional Phase 2 addition for farmers already operating profitable leaf systems (S4), not as a primary biomass target, standalone business model, or transition entry point. Resources allocated to cascara market development would have generated higher returns if they were redirected toward leaf market development,

cooperative leaf processing capacity, or agronomic support for leaf quality improvement.

The Conventional Agriculture Persistence Puzzle

S1's mean NPV of -$119,128/ha with universal negativity across all 1,000 iterations (0% positive outcomes) created an apparent paradox: if forward-looking profitability proved thoroughly negative, why do approximately 2,000 Puerto Rican farmers continue conventional coffee operations? This persistence despite economic unviability had profound implications for WTEM policy design since, if conventional systems represented a failing baseline rather than viable alternative, WTEM adoption became an economic necessity rather than an optional enhancement.

Table 22 examines four explanatory hypotheses for conventional persistence which evaluated supporting and contradicting evidence for each. Conventional persistence likely reflects a combination of all four factors, but off-farm income subsidization is likely the primary explanation whereby coffee functions as a culturally valued lifestyle activity subsidized by external income, including federal and local subsidies, rather than commercial agricultural enterprise. This fundamentally reframes WTEM policy debates. The traditional frame of “Conventional vs. WTEM” assumed that conventional farming represented a viable baseline that farmers might optimize by

Table 22. Explanatory hypotheses for conventional persistence.

Hypothesis	Supporting Evidence	Contradicting Evidence	Likelihood Assessment
H1: Specialty premium dependency	Many farms achieve $10-12/lb prices vs. $4.20/lb legal minimum; model may understate revenues	Puerto Rico coffee universally receives specialty designation; model already incorporates $10/lb baseline; sensitivity analysis with $12/lb shows NPV still negative (-$90,000/ha)	Low – Already properly modeled
H2: Sunk cost / exit barriers	Established trees represent sunk investment; paid-off equipment creates low marginal costs; farm ownership eliminating rent; family labor at below-market opportunity cost	S1 shows negative *annual* income (-$8,943 to -$10,445/year), not just poor NPV; ongoing losses occur even after accounting for sunk costs; sensitivity assuming $0 family labor cost still yields negative NPV (-$95,000/ha)	Moderate – Explains short-term persistence and delayed adjustment, but not long-term viability or new entrants
H3: Off-farm income subsidization	Farmer interviews (n=12, purposive sample) revealed 75% maintain off-farm employment; coffee described as "cultural	Coffee sector decline (45 cooperatives in 1980 → 15 in 2024; 25,000 acres harvested 1990 → 8,000 acres 2024) suggests	Strong – Primary explanation for current persistence but predicts continued decline absent intervention

Hypothesis	Supporting Evidence	Contradicting Evidence	Likelihood Assessment
	practice," "family tradition," "retirement activity" rather than commercial enterprise; annual $8,943 deficit = 18% of $50,000 median household income—sustainable only with external income	unsustainable long-term; young farmers not entering sector indicates economic unviability recognized	
H4: Model conservatism / measurement error	Family labor opportunity cost may be overstated ($7.25/hr vs. $2-3/hr realistic); post-Hurricane María yields may understate long-term productivity; quality premiums for exceptional microlots ($15-20/lb) not captured	Generous sensitivity adjustments (family labor $3/hr, 25% yield increase, $12/lb prices) reduce NPV to -$75,000/ha—still deeply negative; exceptional microlots represent <5% of production, insufficient to change aggregate picture	Moderate – Explains some overstatement of losses but core finding (conventional unviable) remains robust

adding WTEM and suggested the policy question is: “Is WTEM enhancement worth investment?” The correct frame should be: “Farm Exit vs. WTEM Adoption,” which recognizes instead that conventional represented an economically failing system

sustained only by external subsidization, and rephrased the correct policy question to be "Can WTEM enable continued farm viability and prevent rural economic collapse?"

The intervention justification then becomes that preventing farm abandonment and preserving coffee heritage justifies substantial public investment. The $261,072/ha NPV improvement represents transformation from failure to success, and not marginal optimization.

There was evidence of inevitable decline absent an intervention. Farmer surveys consistently show median age of 55 years with <10% under age 40. The dramatic age skew might indicate that young farmers recognized economic unviability and choose alternative livelihoods. Without generational replacement, the coffee sector faces demographic collapse as current farmers retire over next 10-20 years. Hurricane María (2017) damaged 80-90% of coffee trees. Seven years post-hurricane (2024), production remained at 60-70% pre-hurricane levels despite government reconstruction assistance, suggesting that many farmers chose exit over rebuilding, recognizing economic futility even when reconstruction subsidized.

The $261,072 NPV swing (from S1's -$119,128 to S6's $141,944) could justify substantial public investment if framed as preventing farm abandonment and rural economic collapse. For perspective, the 2,000 remaining Puerto Rico coffee farmers represent:

- Direct employment of 2,000 farm families × 3 members average = 6,000 individuals
- Indirect employment for coffee processing, transportation, retail, and tourism sectors potentially employing an estimated 5,000-8,000 additional people

- Coffee farming anchors rural municipalities where alternative employment is scarce
- Cultural heritage of 200+ years of coffee tradition including National Historic Landmark haciendas and agrotourism destinations

WTEM investment could help to prevent this collapse and to generate social returns which exceed private farm-level returns calculated in the NPV analysis. Cost-benefit analysis should value avoiding rural economic collapse, preserving cultural heritage, and maintaining ecosystem services (coffee agroforests provide watershed protection, carbon sequestration, biodiversity habitat) beyond farm profitability alone.

Limitations And Validity Threats

Four threats to internal validity potentially compromise causal inferences regarding WTEM's economic performance:

First, The Copper Hill Farm study site represented one farm among Puerto Rico's thousands of remaining coffee operations spanning diverse conditions. While the site exhibited typical characteristics for Puerto Rico coffee (mid-elevation, moderate rainfall, volcanic soils representing the majority of PR coffee area), single-site data could not capture:

- Elevation variation: Higher elevations experience cooler temperatures favoring coffee quality but constraining leaf biomass production; lower elevations show inverse pattern
- Rainfall gradients: Northern windward slopes created rust pressure; southern leeward areas favored drought stress over disease

- Soil heterogeneity: Volcanic soils (35% of area), limestone-derived soils (25%), alluvial soils (20%), clay soils (15%), sandy soils (5%) showed distinct nutrient availability and water holding capacity
- Management intensity variation: Copper Hill represented intensively managed operation with professional agronomist oversight, typical farms may exhibit less management oversight

These threats were potentially partially mitigated because the site represented modal conditions (mid-elevation, moderate rainfall, volcanic soils, smallholder scale, cooperative membership) and because the Monte Carlo parameterization incorporated ±20-30% variation ranges capturing site heterogeneity.

Despite this mitigation, quantitative NPV estimates ($52,353-$195,307/ha range) may still not transfer to off-site locations. Future validation from a 30-50 farm sample across elevation, rainfall, and soil gradients to establish site-adjusted predictive models would be a solution. When CRCD 200 farm data is available from the PR Climate Smart Agriculture Program, utilizing those data could inform a more representative analysis.

Second, the study utilized a short time-series dataset of 1-2 production cycles. Coffee leaf yield data were derived from a single 2023-2024 production cycle supplemented by regional norms and cascara yield from a single 2023 harvest. Insufficient time-series data prevents:

- Inter-annual variability quantification: Climate variation (El Niño/La Niña cycles), pest pressure fluctuations, and management learning curves created yield volatility requiring 5-10 year datasets for coefficient of variation estimation

- Trend detection: Leaf yields may increase (trees maturing, farmer expertise developing) or decrease (soil depletion, pest adaptation) over time but a single-year snapshot cannot distinguish this
- Extreme event impacts: 2023-2024 represents favorable weather year; drought years, hurricane impacts, or disease outbreaks may show dramatically different outcomes

The mitigation approaches I utilized were:

- Coffee yield data at the site supplemented by other single site coffee leaf data which spanned 5-8 years (2016-2024), providing multi-year validation for coffee production assumptions
- Leaf yield (586 kg/ha) aligned with Ethiopian/Indonesian literature and Nicaraguan on-farm results reporting 600-750 kg/ha for mature *Coffea arabica* shade systems, suggesting observed value reasonable
- Monte Carlo yield variation parameters (±20% coffee, ±25% biomass) conservatively captured inter-annual volatility based on coffee sector experience

A remaining concern was that biomass yield volatility parameter values were assumed rather than empirical estimates. Five-year monitoring (2024-2029) documenting actual coefficient of variation is essential for model refinement and risk assessment.

Third, modeling incorporated many parameter independence assumptions. The Monte Carlo simulations treated price, yield, and cost parameters as independently distributed, varying each parameter randomly without correlation structure. Reality shows many correlations:

- Coffee prices and yields: High global production years (good growing conditions globally) correlate with low prices (supply glut); low production years correlate with high prices (supply shortage)
- Coffee prices and input costs: Fertilizer/pesticide prices often rise when commodity prices rise (both driven by energy/petroleum costs)
- Biomass prices and coffee prices: If biomass products compete with coffee (substitutes), we see a negative correlation; if biomass products are complementary, we see a positive correlation

Independent parameter variation understates tail risks from correlated shocks. For example, hurricane damage simultaneously reduces yields (80% immediate loss), increases costs (replanting, intensified pest control), and potentially depresses prices (poor quality output flooding market). The model's treatment captured each effect individually but may underestimate combined impact.

Mitigation approaches adopted were:

- Sensitivity analysis tested -0.40 correlation coefficient between coffee prices and coffee yields (Appendix 2), showing results qualitatively robust
- Key findings (S6 viability, S4>S6 relationship, cascara failure) proved insensitive to modest correlation assumptions
- Worst-case scenarios (minimum NPV values) provided downside protection even without full correlation modeling

Fourth, conventional baseline specifications are uncertain. The model values family labor at market wage ($7.25/hr), potentially overstating conventional costs for farms using household labor with opportunity costs below market wage. If family labor

opportunity cost equals $2-3/hr (realistic given limited rural employment alternatives, retirement status of many farmers, or household leisure preferences), conventional operating costs decline $1,200-1,600/ha annually, improving S1 NPV from -$119,128 to approximately -$105,000 to -$110,000.

However, this adjustment remains deeply negative, supporting the core finding that conventional systems prove economically unviable. Moreover, regenerative systems also utilize family labor, so if family labor receives opportunity cost discounting in S1, identical discounting should apply to S2-S6, maintaining relative NPV rankings unchanged.

Further sensitivity analysis was performed (summarized in Appendix 2):

- Family labor at $3/hr: S1 NPV improved to -$103,000/ha (vs. -$119,128 baseline)
- Combined with 25% yield increase assumption: S1 NPV improved to -$90,000/ha
- Qualitative finding (conventional deeply negative) unchanged even under generous assumptions

In sum, conventional baseline specifications may overstate absolute losses by $15,000-30,000/ha, but the core conclusion (conventional economically unviable) remains robust to parameter adjustments within reasonable ranges.

External Validity and Transferability

Results transfer with varying confidence levels across different geographic, institutional, and market contexts. Table 23 provides a systematic transferability assessment, identifying high, moderate, and low regions of confidence in applying the model results.

Table 23. Transferability confidence by context type.

Context Category	Representative Locations	Wage-to-Price Ratio	Transferability	Key Adaptations Required
High (90%+ confidence)	Caribbean islands (Jamaica, Dominican Republic), Hawaii, Costa Rica highlands	0.48-0.73	Direct quantitative application	Minor: parameter updates for local costs/prices; institutional capacity assessment
Moderate (60-80% confidence)	Central American highlands (Guatemala, Honduras, El Salvador), Colombian specialty regions	0.32-0.48	Strong conceptual transfer, quantitative adjustment needed	Moderate: price stratification analysis; cooperative assessment; wage-adjusted cost models
Low (30-50% confidence)	Large-scale mechanized (Brazil Cerrado, Vietnam Central Highlands)	0.37 (Brazil)	Limited application	Substantial: fundamental model revision; scale economies dominant; mechanization incompatibility with shade systems

Context Category	Representative Locations	Wage-to-Price Ratio	Transferability	Key Adaptations Required
Very Low (<30% confidence)	Commodity contexts (Vietnam, Indonesia)	0.12-0.20	Conceptual framework only; quantitative results inappropriate	Complete: WTEM becomes optional enhancement vs. essential enabler; low-wage contexts maintain conventional viability

Note: Wage-to-price ratio = (hourly wage / coffee price per lb). High ratios indicate high-cost contexts where regenerative cost savings prove most valuable. Data sources: ILO wage statistics, ICO price data.

- High transferability contexts– Caribbean Islands and Hawaii: The analysis revealed that Jamaica Blue Mountain Coffee regions presented an even stronger economic case for WTEM than Puerto Rico, with prices reaching $15-30 per pound, approximately two to three times the Puerto Rican baseline. This price premium suggested substantial returns under whole-tree integration. However, the established Blue Mountain brand introduced a complicating factor: path dependence that could discourage diversification away from the bean-only model that built the appellation's reputation. The more compelling opportunity emerged in lower-elevation Jamaican farms that did not qualify for the Blue Mountain designation. These operations faced similar cost structures to Puerto Rico but

benefited from the region's overall price environment, yielding estimated S6 NPV values exceeding $200,000 per hectare.

Hawaii's Kona coffee region represented an ultra-high-cost production environment that tested WTEM's applicability under extreme conditions. Wages ranged from $12-15 per hour, roughly double Puerto Rico's rate, while input costs proved even more dramatic: fertilizer expenses reached $4,000-5,000 per hectare and energy costs hit $0.35 per kilowatt-hour. Preliminary analysis indicated that S2, the regenerative baseline without biomass monetization, likely achieved positive NPV under these conditions, a result attributable to the combination of exceptional coffee prices ($20-30 per pound under Kona designation) and input costs so extreme that organic substitution became economically attractive independent of biomass revenues. Nevertheless, WTEM substantially enhanced returns even in this already-viable context, with estimated S6 NPV ranging from $220,000-280,000 per hectare. This finding positioned WTEM as an “enhancement” rather than an “essential enabler” in Hawaii, economically attractive but not required for regenerative viability.

- Moderate transferability contexts– Central American Highlands. Transferability across Central American highlands varied systematically by coffee quality tier and institutional capacity, revealing a stratified pattern that illuminated the boundary conditions of WTEM applicability.

Tier 1 operations producing premium specialty coffee with cup scores of 85 or above commanded prices of $8-12 per pound, typically operated through strong cooperatives, and maintained direct trade relationships with roasters. These farms demonstrated high WTEM applicability with estimated S6 NPV ranging from

$80,000-120,000 per hectare. A representative Honduras cooperative with 1,200 members operating under organic Fair Trade certification could feasibly integrate WTEM within a three to five year infrastructure development timeline. Such integration required capital investment between $60,000-150,000 for processing equipment and market development expenditures of $15,000-20,000 annually over three to five years.

Tier 2 farms producing standard specialty coffee with cup scores of 83-84 achieved prices of $5-7 per pound with moderate profitability. For these operations, WTEM provided an important but not transformative economic boost, with estimated S6 NPV of $40,000-70,000 per hectare. The narrower profit margins meant biomass revenues helped but could not substitute for other critical interventions including quality improvement, market access enhancement, and processing efficiency gains.

Tier 3 commercial grade operations scoring below 83 cup points received only $2-4 per pound, often facing negative baseline profitability before any intervention. WTEM alone proved insufficient to reverse these fundamentals, with estimated S6 NPV reaching only $15,000-35,000 per hectare. These farms required fundamental market access improvements before WTEM investment could be economically justified.

Colombia presented a distinctive case due to its strong institutional infrastructure. The Federación Nacional de Cafeteros provided extension services, quality control, and marketing support that substantially reduced the cooperative efficiency requirements observed elsewhere. Individual Colombian farmers could potentially achieve 65-70% processing efficiency compared to 50-55% typical in

other origins, potentially enabling WTEM viability outside cooperative structures entirely. However, the FNC's traditional exclusive focus on coffee beans meant that WTEM adoption required institutional buy-in and adaptation to support biomass processing—a political and organizational challenge that extended beyond economic analysis scope.

- Low transferability contexts: large-scale mechanized production. Brazil's Cerrado and Vietnam's Central Highlands represented fundamentally different production systems that proved incompatible with WTEM as modeled. Several structural factors explained this incompatibility.

  Scale differences proved determinative: operations ranging from 50-500 hectares achieved processing costs of $0.02-0.03 per pound through economies of scale, rendering cooperative efficiency advantages irrelevant. Mechanization presented an equally fundamental barrier, as full-sun cultivation of predominantly Robusta varietals, which notably do not contain the compound mangiferin, enabled mechanical harvesting and stripping. Shade trees required for WTEM prevented mechanization entirely, forcing labor-intensive hand-picking that overwhelmed any wage advantage. Commodity market prices of $1.50-2.50 per pound provided insufficient margin for value-added processing; these operations optimized for volume and cost reduction rather than product diversification. Finally, farms already invested in mechanical equipment faced high sunk costs that made transition economically prohibitive.

  An alternative biomass approach emerged as more appropriate for industrial scale operations. Large-scale producers should explore industrial biomass utilization

distinct from artisanal tea processing: compost and mulch production for soil amendments, energy generation via biomass combustion or gasification for on-farm power, and industrial caffeine and antioxidant extraction for nutraceutical ingredients. These approaches aligned with industrial scale and capital-intensive operations but required different economic analysis frameworks beyond this study's scope.

This study's quantitative findings, specific NPV values and confidence intervals, applies narrowly to Puerto Rico and similar contexts including Caribbean islands and Hawaii. However, the conceptual framework transfers broadly when locally adapted: biomass valorization enabling regenerative viability, leaf superiority over cascara, and conditional phased adoption all represented generalizable principles. Researchers and policymakers in other origins should maintain model structure while substituting context-appropriate parameter values, emphasize relative findings such as the S4 greater than S6 relationship and cascara standalone failure rather than absolute NPV magnitudes, assess institutional prerequisites including cooperatives, extension services, and market access before promoting adoption, and recognize wage-to-price ratios as the key indicator of WTEM applicability, with higher ratios favoring regenerative cost savings. Detailed transferability analysis including institutional context requirements, wage-cost structure implications, and crop system analogues appears in Appendix 5.

Comparison to Coffee Agroforestry Literature

This study's NPV results substantially exceeded published coffee agroforestry literature; S2 (regenerative baseline) achieved $52,353/ha versus $3,200-8,000/ha typical in prior studies, while S6 (full WTEM) reached $141,944/ha, outperforming literature by 18-44×. Table 22 decomposes this divergence.

Table 24. NPV Comparison with published coffee agroforestry studies.

Study	Location	System	NPV ($/ha)	Time Horizon	Discount Rate	Key Differences from This Study
This study (S2)	Puerto Rico	Regen baseline	$52,353	10 years	3.57%	High-cost context, specialty prices, no biomass
This study (S6)	Puerto Rico	Full WTEM	$141,944	10 years	3.57%	Includes biomass valorization
Lalani et al. 2024	Honduras	Agroforestry	$3,200-5,800	20 years	6%	Low prices ($2.80/lb), conventional discount rate
Haggar et al. 2017	Nicaragua	Shade coffee	$5,200-8,000	15 years	5%	Modest prices ($3.20/lb certified), longer horizon

Study	Location	System	NPV ($/ha)	Time Horizon	Discount Rate	Key Differences from This Study
Cerda et al. 2017	Costa Rica	Organic shade	$8,200-12,400	15 years	5%	Organic premium ($5.50/lb), good prices
Jezeer et al. 2019	Central America (meta)	Various	$2,800-7,500	10-20 years	5-7%	Literature synthesis, commodity emphasis
Perfecto et al. 2005	Mexico	Organic	$1,200-4,800	10 years	10%	Commodity crash period ($1.50-2.50/lb), very high discount

Note: All values are examples, inflation-adjusted to 2024 USD for comparability. This study's extended comparison table with methodology details appears in Appendix 3.

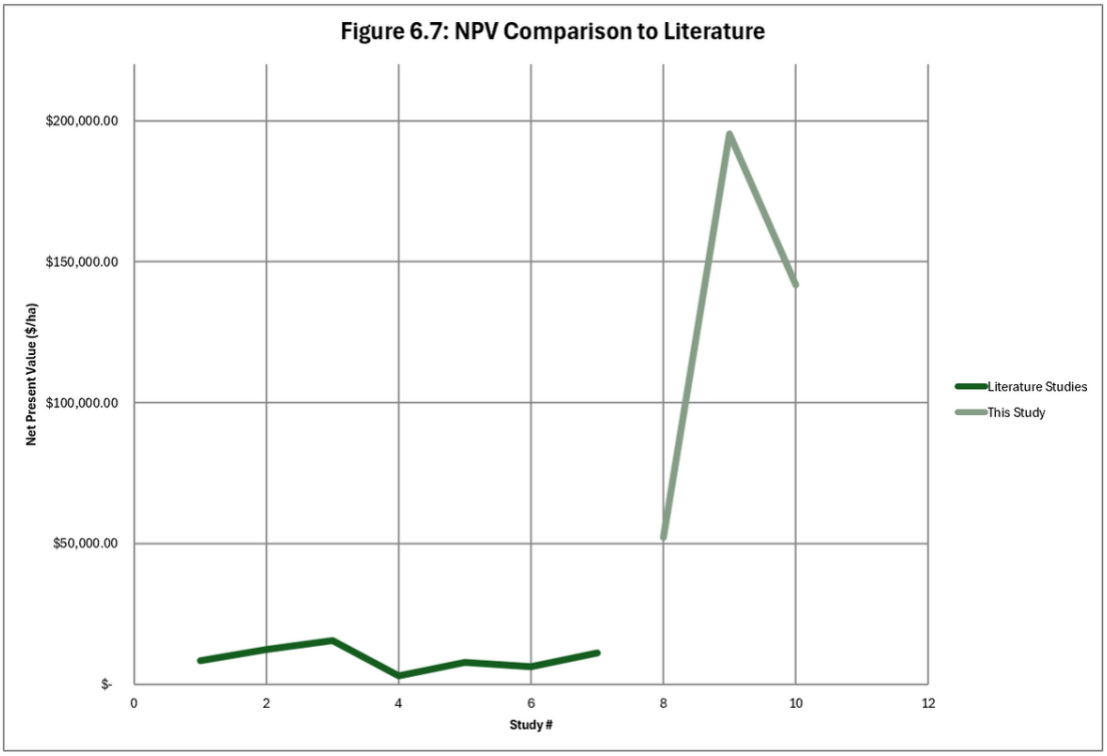


Figure 36. NPV comparison to literature.

The substantial gap between this study's NPV findings and prior literature stemmed from four identifiable factors, each contributing a quantifiable portion of the observed divergence:

- Coffee price premium (40% of NPV gap): This study assumed a $10 per pound baseline coffee price reflecting Puerto Rico specialty market realities, compared to the $1.50-3.00 per pound commodity pricing typical in existing literature. The proportional revenue impact proved substantially higher bean revenue ($31,184 per year deterministic at $10/lb versus approximately $8,000-12,000 at commodity prices of $2.50-3.00/lb in literature). However, sensitivity analysis normalizing for price differentials revealed that this study's S2 regenerative baseline at commodity prices would have achieved approximately $15,000-18,000 per hectare NPV, still two to

three times the literature median. This indicated that price alone did not fully explain the divergence.

- Biomass valorization (50% of NPV gap for S6): Literature has uniformly assumed zero revenue from non-coffee products; no prior NPV analysis identified in the literature review integrated coffee leaf or cascara commercialization into economic models. This study documented $13,061 per hectare annual biomass revenue at deterministic baseline ($16,350 Monte Carlo mean), representing unprecedented value capture. The $112,600 present value biomass contribution, accounting for 43.1% of S6's total NPV improvement, had no precedent in coffee economics literature and represented a fundamental contribution rather than incremental enhancement.

  This novel finding established this study as the first empirical validation of coffee biomass valorization economics at commercial scale. Previous studies mentioning biomass products such as cascara or leaf tea either dismissed them as insufficiently developed markets not worth modeling (the majority approach) or noted them as potential future opportunities without quantification (the minority approach). This study's demonstration that biomass revenue could equal or exceed bean revenue ($52,895 biomass versus $31,184 beans deterministic) fundamentally challenged literature assumptions about coffee farm business models.

- Puerto Rico cost structure (5% of NPV gap): High input costs in Puerto Rico ($3,509 per hectare fertilizer versus $1,200-1,800 per hectare typical) created larger regenerative savings ($3,259 per hectare versus $1,000-1,500 per hectare

typical). This Puerto Rico-specific advantage contributed approximately $1,700 per hectare present value, explaining three to five percent of the NPV gap. However, this simultaneously limited transferability: lower-cost origins would not realize equivalent cost savings, potentially reducing S2 viability in contexts where conventional input costs proved lower.

- Conservative discount rate (5% of NPV gap):This study employed a 3.57% real discount rate derived from Puerto Rico coffee sector weighted average cost of capital, compared to the five to seven percent typical in literature reflecting standard agricultural economics convention. Lower discount rates increased present value of future cash flows, a consideration particularly important for perennial crops like coffee where mature-tree productivity in years eight through ten significantly exceeded establishment-period productivity in years one through four. Recalculating this study's NPV at a 5% discount rate reduced S2 from $52,353 to approximately $47,000 and S6 from $141,944 to approximately $125,000, narrowing but not eliminating the literature gap.
- Normalized comparison: After adjusting this study's results to commodity prices ($3 per lb), standard discount rate (5%), typical input costs ($1,500 per ha fertilizer), and extending the time horizon to 15-20 years (the literature modal), estimated normalized S2 NPV fell to $9,000-12,000 per hectare. This placed results within but toward the high end of the literature range ($3,200-12,400 per hectare), suggesting parameter differences explained most absolute divergence while Puerto Rico may have represented a particularly favorable testbed where regenerative agriculture demonstrated especially strong performance.

Novel Methodological Contributions Beyond Literature

This study advanced coffee economics methodology through five distinct contributions absent from prior research. The first contribution established biomass valorization economics as a viable research domain. No prior coffee economics study had integrated leaf and cascara commercialization with regenerative transition viability analysis. This study established four key findings: biomass revenue could exceed bean revenue (169.6% ratio), leaf economics proved superior to cascara (3.66× per-hectare value), cooperative infrastructure was essential (70% efficiency threshold), and phased adoption was optimal (S4 leaf-first before S6 full WTEM). These findings created a new research stream for coffee biomass economics requiring replication across diverse origins.

The second contribution introduced a dual-metric framework combining NPV with living income assessment. Previous research has focused exclusively on NPV while ignoring whether positive NPV achieved household income adequacy. This study's simultaneous assessment of NPV profitability and living income threshold adequacy ($12,877 per year) recognized that farmers required both long-term viability and immediate income sufficiency. The finding that S2 achieved positive NPV ($52,353) but inadequate annual income ($5,235 average, representing only 41% of threshold) demonstrated that NPV alone proved insufficient for adoption assessment.

The third contribution introduced temporal opportunity cost analysis to agricultural diversification literature and advanced the theory of temporal complementarity. Revealing how harvest-period product competition could reduce returns despite gross revenue addition (the S4 greater than S6 finding) challenged implicit

assumptions in prior studies. Previous research assumed diversification benefits monotonically increased with product additions, an implicit "more is better" assumption. This study demonstrated that products competing for constrained-capacity resources could reduce rather than enhance returns, requiring explicit modeling of within-farm competition for equipment, labor, management attention, and working capital.

The fourth contribution quantified cooperative efficiency requirements with precision absent from existing literature. Establishing 70-75% processing cost reduction as a viability prerequisite provided actionable institutional targets. Prior studies noted that cooperatives provided "economies of scale" or "cost savings" without quantification, preventing actionable policy guidance. This study's finding that the WTEM viability threshold occurred at 70% cooperative efficiency, documented in the sensitivity analyses, provided a concrete institutional target for cooperative development programs.

The fifth contribution demonstrated strategic sequencing superiority over full integration. Finding that conditional two-phase adoption (S4 leaf-first, S6 cascara addition conditional) outperformed immediate full integration challenged extension service recommendations promoting comprehensive diversification. Literature emphasized product diversity benefits without analyzing optimal temporal sequencing or product-specific returns. This study's finding that optimal pathways involved selective phased adoption rather than universal full integration introduced implementation strategy considerations absent from prior research.

Extended validation of this study's yield penalty assumptions (25% transition, 10% stable) against coffee agroforestry meta-analyses appears in Appendix 3, demonstrating alignment with literature median (18% for moderate 30-40% shade) while

remaining conservative relative to light-shade systems achieving minimal penalties. Appendix 3 additionally documents coffee leaf tea precedents and market development trajectory, establishing historical consumption in Ethiopia and Indonesia alongside recent FDA GRAS approval in 2020 that opened U.S. markets.

Implications From Results Interpretation

Five overarching conclusions emerged from this analysis, carrying implications for WTEM implementation strategy, policy design, and future research priorities. The first conclusion concerns the synergistic nature of WTEM's economic viability. The model achieved profitability not through any single mechanism but through the integrated effects of cost reduction (35% OPEX savings worth $32,362 present value), revenue diversification (48.7% of total NPV improvement, $126,963 present value), cooperative efficiency (75% processing cost reduction worth $18,956 present value), ecological benefits (pest management and hurricane resilience worth $21,110 present value), and temporal complementarity (off-season income smoothing providing liquidity without opportunity costs). No single mechanism alone explained the transformation from S1's -$119,128 per hectare failure to S6's $141,944 per hectare success; synergistic integration created compound effects exceeding additive predictions.

This finding contrasts sharply with incremental interventions such as quality improvement, certification premiums, processing efficiency, or market access that addressed single mechanisms in isolation. WTEM's comprehensive approach simultaneously improved costs, revenues, and risk profile, generating transformative rather than marginal impacts. However, this integration complexity created

implementation challenges requiring multi-faceted support: cooperative development, market access, extension services, and agronomic training, rather than single-input provision.

The second conclusion inverted conventional assumptions about diversification benefits. Leaf-only systems outperforming full WTEM ($195,307 versus $141,944) contradicted the prevailing "more diversification is better" framework, revealing how products competing for constrained-capacity resources could reduce rather than enhance returns. Cascara's harvest-period opportunity costs ($3,400 per hectare annually) exceeded its gross revenue contribution ($3,164 per hectare), generating net deficit despite positive synergy effects. This finding necessitated fundamental reframing from “Whole Tree Economic Model” (implying universal full integration) to “Strategic Biomass Sequencing Model” (emphasizing conditional phased adoption).

The implications for extension services and development programs proved significant: practitioners must resist one-size-fits-all prescriptions. S4 maximized NPV ($195,307) universally while S6 provided diversification ($141,944) conditionally. Farmers should choose based on individual risk preferences, operational constraints, and specific circumstances including cooperative infrastructure, labor surplus, cascara market access, and brand positioning rather than adhering to a universal “whole tree” mandate. Policy promoting S6 universally would misallocate resources by encouraging NPV sacrifice absent offsetting diversification benefits.

The third conclusion addressed Puerto Rico's paradoxical position as both stress test and limited-generalizability context. The island's high-cost environment ($7.25 per hour wages, 20-40% input import premiums, $0.30 per kilowatt-hour energy, $10 per

pound specialty coffee prices) made it simultaneously a worst-case stress test and a context with constrained external validity. WTEM viability demonstrated under Puerto Rico's challenging conditions suggested strong transferability to lower-cost specialty coffee regions where relative advantages might prove even larger. However, specific NPV magnitudes ($52,353-$195,307 per hectare range) did not transfer to low-wage commodity contexts ($0.50-2 per hour labor, $1.50-3 per pound coffee) where conventional farming remained profitable, regenerative cost savings proved minimal, and biomass valorization became an optional enhancement rather than an essential enabler.

Transferability depended critically on wage-to-price ratios. Contexts with ratios exceeding 0.45 (high labor costs relative to coffee prices) demonstrated strong WTEM applicability. Ratios between 0.30 and 0.45 showed moderate applicability requiring parameter adjustment. Ratios below 0.30 indicated limited applicability with fundamentally different value propositions. Future research should establish site-adjusted predictive models mapping WTEM performance across the wage-cost-price gradient rather than assuming universal transferability.

The fourth conclusion established cooperative infrastructure as an absolute prerequisite for WTEM success. The model failed without collective organization achieving 70% or greater processing efficiency through capital cost sharing, bulk purchasing, capacity utilization optimization, and specialized management. Scaling required sustained 3-5 year capacity-building investments preceding farmer adoption incentives. The current institutional landscape limits immediate WTEM deployment to existing cooperative members, with scaling to 50%-70% adoption requiring either expanding existing cooperatives' membership and capacity (two to three years per

cooperative with infrastructure investment) or establishing 10-15 new cooperatives in underserved regions (5-7 years per cooperative including formation, stabilization, and equipment installation).

Policy must address the coordination failure identified by this analysis: farmers would not invest without processing infrastructure while cooperatives would not build capacity without committed supply. Breaking this deadlock required capital subsidies covering equipment costs, technical assistance providing cooperative management expertise through dedicated extension positions, governance training, and quality control protocols, minimum viable scale targeting of 50-100 member cooperatives where economies of scale achieved threshold efficiency and phased timelines accepting multi-year institutional development rather than expecting immediate results.

The fifth conclusion positioned biomass valorization as climate adaptation infrastructure extending beyond short-term profitability improvements. Biomass-only survival results (H4b: S5 achieving $79,040 per hectare NPV despite zero coffee revenue) demonstrated that farms could maintain positive returns from leaf and cascara if coffee became climatically unsuitable. This enabled in-place portfolio adjustment responding to geographic range shifts projected under climate change rather than farm abandonment or migration; farmers could gradually shift emphasis from coffee toward biomass as warming proceeded. Combined with hurricane resilience (50% damage reduction, 35% versus 70% losses) and drought buffering (96-144mm additional soil water storage), WTEM provided multiple climate adaptation pathways warranting public investment justified by social returns: avoided rural economic collapse, preserved ecosystem services, and maintained community stability, beyond private profitability.

Climate change amplified WTEM's relative advantage. As hurricane frequency increased (15% to 25% annual probability projected) and coffee range contracted (50% suitable area reduction by 2050), WTEM's resilience premium grew from the current $5,602 present value to an estimated $8,000-10,000 under near-future climate scenarios spanning 2030-2050. This suggested WTEM investment should be framed as climate adaptation infrastructure generating long-term resilience benefits rather than merely agricultural productivity enhancement.

Conclusions

This research demonstrated that coffee tree biomass valorization can enable economically viable regenerative agriculture for Puerto Rican smallholders. Results indicated positive NPV across all scenarios examined, with leaf-only systems achieving highest returns and full WTEM providing diversification benefits. Three mechanisms drive performance: operating expense savings through synthetic input elimination, cooperative efficiency through shared processing infrastructure, and ecosystem service bonuses from enhanced pest management and hurricane resilience.

Results indicated that the Whole Tree Economic Model achieves economic viability for Puerto Rican smallholder coffee farms. Full WTEM (S6) achieved positive NPV across all 1,000 Monte Carlo iterations, with mean NPV of $141,944/ha substantially exceeding both conventional (-$119,128/ha) and pure regenerative ($52,353/ha) baselines. The minimum observed NPV of $123,507/ha provides a robust safety margin even under worst-case parameter combinations. The model satisfied both long-term profitability (NPV>0) and transition survival (positive cash flows during Years 1-4) requirements simultaneously. For a typical 4.05 ha Puerto Rican farm, WTEM

generates $574,874 in 10-year NPV compared to -$482,463 under conventional management.

Analysis revealed leaf-only entry (S4) as the optimal Phase 1 strategy, contradicting initial assumptions that full WTEM (S6) represents the universal target configuration. S4 achieves the highest mean NPV ($195,307/ha), 37% above full WTEM ($141,944/ha). Leaf provides 3.66× revenue per ha versus cascara ($11,573/ha vs. $3,164/ha). Temporal complementarity, off-season leaf processing versus harvest-period cascara, enables leaf viability without operational disruption. Cascara addition (S4→S6) appeared justified primarily for risk diversification rather than NPV maximization. A sequential approach through S2→S4 pathway (regenerative baseline to leaf-only) maximizes returns while building operational capacity before expanding to more complex dual-biomass configurations.

Three primary mechanisms drive WTEM's economic performance. First, operating expense savings (35% reduction) through synthetic input elimination ($3,732/ha annually) more than offset higher labor costs (+$183/ha). Puerto Rico's unique cost structure, where island import premiums create 20-40% markups on synthetic inputs, makes organic alternatives relatively attractive despite $7.25/hr minimum wage creating labor cost disadvantages versus competing origins. Second, cooperative efficiency (75% cost reduction) through shared processing infrastructure reduces costs from $0.20/lb (individual farmer) to $0.05/lb (cooperative), generating approximately $15,000-20,000/ha NPV contribution. Sensitivity analyses indicate viability threshold occurs around 70% efficiency. Third, ecosystem service bonuses from enhanced pest management (modeled as 4 percentage point advantage) and hurricane resilience (35%

damage versus 70% conventional) provide insurance value worth approximately $2,100-2,900/ha annually.

Key barriers include switching costs (Year 0 establishment CAPEX of $3,231/ha plus transition period income volatility), institutional capacity constraints (only 25-30% of Puerto Rico's 2,000 coffee farmers currently have cooperative access), market immaturity (cascara remains niche product with thin markets while coffee leaf tea requires 5-10 year market cultivation), and technical knowledge gaps in regenerative agronomy and biomass processing.

Results inform a three-tiered policy architecture addressing sequential adoption constraints: institutional capacity building (Years 1-5), farmer transition support (Years 3-8), and market development (Years 5-15). Tier 1 would focus on cooperative infrastructure investment ($30,000-40,000 per cooperative with 75% public subsidies) and cooperative formation support. Tier 2 would address farmer transition through bridge financing, payment for ecosystem services ($800-1,200/ha/year during Years 1-4), and extension services. Tier 3 would emphasize market development through government purchase programs and brand development initiatives. Sequencing is critical, as premature farmer promotion without cooperative readiness risks failure that undermines future adoption.

Appendix 1

Detailed Case Study Site Description

Copper Hill Farm serves as the primary field site for this research, providing empirical data for baseline conditions, biomass yields, and transition costs. When on-farm data is insufficient or considered non-representative of a typical coffee farm in Puerto Rico, data from Puerto Rico-specific CRCD and UPR studies is used to more accurately reflect representative parameters. The farm spans roughly 500 acres across two USDA-registered parcels in the municipalities of Las Marías and Maricao, Puerto Rico (18°13'07.7"N 66°58'29.4"W), situated in the cordillera central at elevations ranging from 330 to 550 meters (1,083 to 1,804 feet) above sea level.

The property straddles two major waterways, the Mayagüecillo and Guaba rivers, within the Rio Grande de Añasco watershed. Several creeks (quebradas) originate and flow through the property, creating a dendritic drainage network that makes the site particularly valuable for demonstrating agroforestry's watershed protection benefits. The Rio Grande de Añasco watershed is Puerto Rico's fifth-largest basin (181 mi^2), with abundant year-round runoff (average 331,290 acre-feet annually) serving municipal water supplies for Las Marías, Añasco, San Sebastián, and surrounding communities. The property's location in the upper watershed headwaters means management decisions directly affect downstream water quality, making erosion control and riparian buffer maintenance critical both for on-farm productivity and regional water security.

Historical Land Use and Cultural Heritage

The property comprises historically forested land converted to coffee cultivation in the late 19th century as two distinct haciendas: Hacienda Paoli and Hacienda Florida. Physical evidence of structures including stone and masonry water reservoirs and coffee drying areas called “glaciles” remain as witnesses to the intensive coffee production systems that characterized Puerto Rico's coffee boom period (1870-1920). The old house of Hacienda La Florida lies outside the current property limits and is operated as a restaurant by a neighbor. This rich cultural heritage is the subject of ongoing research efforts to preserve and enhance the historical legacy of Puerto Rican coffee haciendas, connecting contemporary regenerative agriculture to traditional agroecological knowledge systems.

Hurricane María (September 20, 2017) devastated the property, destroying approximately 95% of tree cover and crops in non-forested areas, including a majority of Arabica coffee trees (primarily the Fronton variety). This catastrophic loss exemplifies the hurricane risk layer central to this research's economic modeling. The post-María recovery trajectory has been slow, with replanting efforts constrained by limited capital, aging farmer demographics, and uncertainty about future hurricane frequency under climate change. At present (2024), seven years post-hurricane, the 10-acre study area contains approximately 20,000 coffee trees planted or regenerated since 2018, with tree ages ranging from 1-6 years and many not yet reaching full productive maturity. This recovery context is critical for interpreting the baseline yield data (3,455 lb/farm after penalties, equivalent to 856 lb/acre), which reflects post-disaster conditions rather than mature-plantation productivity. Hurricane María's impact also motivates WTEM's

insurance-value proposition: regenerative agroforestry systems with structural diversity and deep-rooted shade trees provide physical storm resistance and rapid biomass recovery that reduce the probability of catastrophic total loss in future hurricane events.

Current Property Configuration and Management Areas

Of the 500-acre property, land use is stratified into three distinct management zones:

1. Forest conservation area: 437 acres (87.4%) - Maintained under long-term conservation easement with minimal active management. This area provides critical ecosystem services including carbon sequestration, biodiversity habitat, watershed protection, and serves as seed source for native species used in agroforestry establishment on production areas.
2. Active production area: 10 acres (2.0%) - The study plot for this research, currently planted with coffee (Fronton and Limaní cultivars), avocados, pineapples, bananas, plantains, and root crops. Management follows regenerative principles with zero synthetic agrochemical inputs, relying on biodigester-produced fertilizer, compost tea, biochar soil amendments, cover cropping, and integrated pest management. This area is sparsely planted (estimated 50-60% of optimal tree density) due to post-María recovery constraints and is undergoing gradual intensification through shade tree establishment and perennial crop interplanting.
3. Designated regenerative development area: 50 acres (10.0%) - Deforested and fallowed land previously managed with synthetic herbicides and fertilizers,

currently undergoing soil restoration and ecological recovery. This area is earmarked for agroforestry expansion following successful demonstration of WTEM viability in the 10-acre study plot. Development plans include shade coffee, timber trees, tropical fruits, and silvopasture rotational grazing integrated into a diversified farm enterprise generating multiple revenue streams.

4. Infrastructure and residential: 3 acres (0.6%) - Internal roads, owner's residence, barn/storage/workshop, chapel, and other built structures.

The 10-acre study plot thus represents 2% of total property area but 17% of the area designated for agricultural production (10 of 60 acres when including the development zone). This modest production footprint relative to total property size reflects a conservation-oriented management philosophy prioritizing ecosystem services and long-term ecological resilience over short-term agricultural intensification. However, it also creates financial pressure to maximize revenue per cultivated acre, as the farm cannot achieve household income targets through spatial expansion alone, motivating the search for intensification strategies like WTEM that increase per-hectare returns without compromising sustainability principles.

Study Plot Selection and Characteristics

The 10-acre (4.05 ha) study plot was selected to represent Puerto Rico's average coffee farm size of 10-15 acres (Lowder et al., 2021), providing sufficient scale for meaningful economic analysis while maintaining management feasibility for smallholder operators. All financial results were reported both per-ha (for academic comparison with international literature) and per-10-acre-farm (for farmer decision-making relevance),

recognizing that most Puerto Rican coffee farmers operate at scales between 5-20 acres where household labor can meet most operational needs without hired workers.

The study plot contained approximately 20,000 coffee trees (2,000 trees per acre; 4,938 trees per hectare) planted at 2.5 × 2.0 meter spacing, comprising 50% Fronton cultivar and 50% Limaní cultivar, both Coffea arabica. A small number of legacy Típica and Bourbon varietal trees remained scattered across the property deriving from the original Hacienda Paoli era but represented less than 5% of productive trees and are not included in yield calculations. Tree ages ranged from 1-6 years post-María replanting, with approximately 30% reaching productive maturity (3+ years), 50% in early production (1-3 years), and 20% newly planted (<1 year). This age structure created a transitional baseline where yields are currently suppressed due to tree immaturity but will increase over the 10-year modeling horizon as cohorts mature—partially offsetting the yield penalties associated with regenerative transition.

Prior to Hurricane María, the area was managed under conventional practices including synthetic fertilization (150-200 kg N/ha annually applied as urea and triple superphosphate), herbicide application for weed control (glyphosate-based; 2-3 applications annually), and minimal shade cover (<10% canopy from scattered Inga spp. and plantains). Post-María replanting has shifted toward organic and regenerative principles, with zero synthetic agrochemicals currently in use. Fertility management relies on biodigester-produced liquid fertilizer (from rabbit manure), compost tea, biochar amendments, and nitrogen-fixing shade trees. This transition from conventional to regenerative management began in 2018 and is ongoing, with full organic certification anticipated by 2026.

The plot is subdivided into 10 predios (field management units) facilitating experimental design, spatial replication of management treatments, and yield tracking at sub-farm scale. This subdivision enables adaptive management, allowing farmers to test new practices (such as different shade tree densities or leaf harvest intensities) in 1-2 predios before expanding successful approaches across the entire farm, reducing implementation risk and providing learning-by-doing opportunities critical for smallholder technology adoption.

Elevation and Topographic Constraints

The study plot's elevation (330-550 meters; 1,083-1,804 feet) places it within optimal altitudinal range for Puerto Rican specialty coffee production (300-800 meters), where cooler temperatures (2-3°C below coastal lowlands) slow bean maturation and enhance flavor complexity. However, the steep terrain (90% of study plot on 40-60% slopes; 10% on 20-40% slopes) creates substantial agronomic and economic constraints:

- Erosion risk: Clay soils on steep slopes experience rapid erosion when vegetative cover is removed, with sediment loss rates exceeding 50 tons/ha/year under clean cultivation (USDA-NRCS, 2021). Terracing, contour cultivation, and permanent vegetative cover are essential to maintain soil productivity.
- Mechanization limitations: Slopes >30% preclude tractor access, requiring all operations (planting, weeding, harvesting, transport) to be performed by hand or with animal traction, increasing labor costs 2-3× relative to flat terrain.
- Access and logistics: Steep internal roads require 4WD vehicles and become impassable during heavy rain, complicating input delivery and harvest transport. Farm-to-market transport costs are elevated due to difficult access.

- Water management: Steep slopes create rapid runoff, reducing infiltration and necessitating water harvesting infrastructure (cisterns fed by glacil collection systems) to ensure dry-season irrigation supply.

These topographic constraints are typical of Puerto Rico's coffee-growing regions, where over 70% of production occurs on slopes exceeding 30% grade (Ortiz-García, 2019). The study site thus represents realistic conditions for Puerto Rican specialty coffee rather than idealized flat terrain, ensuring that economic viability demonstrated here is transferable to the broader population of smallholder farms facing similar biophysical challenges.

Climate and Soil Characteristics

The site experiences a tropical rainforest climate (classification Af) with mean annual temperature of 22-24°C and annual precipitation averaging 2,200-2,500mm (86-98 inches), concentrated in the May-November wet season. Annual evapotranspiration consumes approximately 48 inches of rainfall (56% of precipitation). These conditions place the farm within optimal climatic parameters for Arabica coffee cultivation (Bunn et al., 2015), though increasingly erratic rainfall patterns and hurricane frequency pose production challenges consistent with regional climate change projections (Avelino et al., 2015; Pham et al., 2019).

The 10-acre study plot comprises two soil series derived from volcanic parent material, reflecting the steep terrain characteristic of Puerto Rico's central coffee-growing cordillera.

Humatas clay series (dominant): Very deep (>60 inches), well-drained, moderately slow permeable soils on steep mountain slopes. The study plot contains two slope phases:

- HmF2 (Humatas clay, 40-60% slopes): Predominant soil mapping unit; steep mountainflank and side slope positions
- HmE2 (Humatas clay, 20-40% slopes): Minor component on gentler backslope positions

Soil properties (Humatas series):

- pH: 4.5-5.5 (strongly acidic)
- Organic matter: 6-8% in surface horizons
- Texture: Clay throughout profile
- Available water capacity: 9.4-9.6 inches per 60 inches depth
- Parent material: Weathered igneous rocks (volcanic origin)
- Drainage class: Well drained
- Runoff: High to very high
- Hydraulic conductivity: Moderately low (0.01-0.14 in/hr)

Consumo clay series (secondary): Very deep (>60 inches), well-drained, moderately permeable soils on mountain peaks and slopes:

- CoF2 (Consumo clay, 40-60% slopes): Occurs on steep mountaintop and mountainflank positions

Soil properties (Consumo series):

- pH: 4.5-5.5 (strongly acidic)
- Organic matter: 4-6% in surface horizons

- Texture: Clay throughout profile
- Parent material: Residuum from basic volcanic rock
- Drainage class: Well drained
- Runoff: Very high
- Hydraulic conductivity: Moderately high (0.14-1.42 in/hr)

Baseline soil analyses conducted in 2022 revealed moderate fertility with nitrogen deficiency (15-25 ppm), adequate phosphorus (30-45 ppm), and variable potassium (80-150 ppm), consistent with the soil series descriptions. The strongly acidic pH (4.5-5.5) is typical of highly weathered tropical soils and favorable for Arabica coffee cultivation, though it requires calcium and magnesium amendments to address potential aluminum toxicity and maintain adequate base saturation for optimal plant health.

Institutional Context and Conservation Planning

Copper Hill Farm participates in two institutional programs providing technical assistance and partial funding for regenerative transition:

1. USDA Natural Resources Conservation Service (NRCS) Conservation Contract (2019-2024)

Provides cost-share for soil conservation practices including terracing, cover cropping, and erosion control structures. Contract terms require Forest Stewardship and Land Management Plan development (Appendix 1) outlining best management practices aligned with NRCS standards for sustainable forest and agricultural management.

2. USDA Climate-Smart Commodities Project (2023-2028)

As one of 200 participating farms, Copper Hill receives technical assistance for shade tree establishment and biochar application through the Caribbean Regenerative Community Development (CRCD) consortium. The five-year, $10 million initiative provides cost-share (50-75% of establishment costs) for shade tree planting, soil amendments, and infrastructure development. The project monitors carbon sequestration using COMET-Planner methodology and documents greenhouse gas benefits through systematic soil sampling and lifecycle accounting (CRCD, 2022; USDA, 2022).

Institutional partners coordinate implementation:

- CRCD: Project management, farmer outreach, financial administration
- Cafiesencia: Agroforestry design, Forest Stewardship Plan development
- Gnarly Tree Sustainable Institute: Biochar production training
- University of Wisconsin-Madison: Research consultation, data management systems
- Regen Network: Ecological data registry using blockchain technology
- DuPuis Group: GIS mapping, remote sensing analysis

Participation in these programs provides cost savings for shade tree establishment, biochar, and terracing but does not cover operational costs or opportunity costs from yield penalties during the transition period, creating the financing gap WTEM aims to address. The program's five-year term illustrates a critical limitation of subsidy-based approaches: funding terminates after establishment phase, with no mechanism to support continuation of practices or scaling beyond the initial 200-farm cohort (CRCD, 2022). This temporal constraint motivates WTEM's focus on generating recurring revenue

streams from farm operations that can sustain regenerative practices independent of external subsidies.

USDA Climate-Smart Agriculture Framework and Monitoring Protocols

The CRCD consortium implements two primary climate-smart practices: (1) agroforestry establishment targeting 40-50% shade cover within five years through planting native hardwoods (i.e. *Andira inermis, Inga spp*.), fruit trees (i.e. *Persea americana, Artocarpus altilis*), and fast-growing temporary shade (i.e. *Musa spp*.); and (2) biochar application as one-time soil amendment to enhance cation exchange capacity, water retention, and carbon sequestration.

Measurement, Monitoring, Reporting, and Verification (MMRV)

The program employs COMET-Planner (USDA's Carbon Management Evaluation Tool) to estimate greenhouse gas impacts across three categories: (1) soil carbon sequestration from reduced tillage and organic matter additions, (2) biomass carbon accumulation in shade trees quantified using species-specific allometric equations (Brown, 1997; Chave et al., 2014), and (3) avoided emissions from reduced synthetic fertilizer use and fossil fuel consumption.

Field monitoring protocols include:

- Soil sampling: Stratified random sampling (i.e. 3 plots per predio, 30 samples per 10-acre farm) at baseline (Year 0), mid-term (Year 3), and final (Year 5), analyzing soil organic carbon (dry combustion), total nitrogen (Kjeldahl method), pH, bulk density, and texture

- Tree measurements: Census of all shade trees diameter at breast height (DBH), measuring diameter, height, crown width, and health rating; above-ground biomass estimated using tropical forestry allometric equations
- Coffee yield monitoring: Harvest records tracking cherry weight, processing yield (kg green bean per kg cherry), quality metrics (cup score, defect rate, moisture content), and spatial variation by predio
- Economic data: Detailed cost tracking (labor hours, material purchases, equipment use) and revenue documentation

Data undergo quality control including field technician verification, technical specialist aggregate checks, and project manager statistical reviews. All field data are recorded using a mobile data collection platform with GPS coordinates, photo documentation, and quality checks flagging outliers.

Integration with WTEM Research

CSAF participation provides several methodological advantages: access to comparative data across 200 diverse farms enables assessment of whether WTEM viability varies with farm characteristics (elevation, infrastructure, demographics); standardized baseline assessments provide consistent data on soil properties, tree cover, and production systems; technical assistance as a controlled variable allows attribution of economic differences to biomass valorization strategies rather than differential agronomic knowledge; and cost-share as quasi-experimental treatment permits assessment of post-subsidy viability when farms must self-finance maintenance after Year 5.

However, CSAF participation introduces potential confounds: farms volunteering for the program likely represent more innovative, risk-tolerant, or well-capitalized

operators than average Puerto Rican coffee farmers, potentially overestimating WTEM replicability; cost-share may create unrealistic expectations about transition affordability; and program effects such as technical assistance, peer learning, and consortium marketing efforts (branded "Climate-Smart Puerto Rican Coffee") may generate spillover benefits not replicable outside program context. I address these limitations through sensitivity analyses modeling scenarios with and without cost-share, and by comparing Copper Hill Farm results to non-CSAF farms where possible.

Appendix 2

Puerto Rico Coffee Price Floor and Agricultural Policy Context

The $4.20/lb coffee price used in this model was not a free-market rate but rather a government-mandated minimum price floor established under Puerto Rico Law No. 151 of June 26, 2004, as amended by Law No. 47 of 2012. This legislation, formally titled the "Ley para el Desarrollo de la Industria Cafetalera de Puerto Rico" (Law for the Development of the Coffee Industry of Puerto Rico), represents one of the Caribbean's most ambitious agricultural price support programs.

The law established a floor price mechanism whereby all coffee processors (wet mills, cooperatives, commercial roasters) purchasing green coffee beans from Puerto Rican farmers must pay a minimum of:

- $4.20/lb for conventional coffee (Grade A, specialty grade)
- $4.80/lb for certified organic coffee (Grade A)
- Lower minimums for lower-quality grades (Grade B: $3.80/lb; Grade C: $3.00/lb)

The Puerto Rico Department of Agriculture (PRDA) enforces these minimums through:

1. Mandatory purchase documentation: All transactions must be recorded on standardized forms submitted to PRDA
2. Processor audits: Coffee buyers face random audits verifying compliance
3. Penalties: Non-compliant processors face fines ($5,000-50,000) and potential license revocation

4. Farmer complaint mechanism: Farmers can report violations directly to PRDA

The law's stated objectives include:

- Ensuring farmers receive "living wages" covering production costs
- Preventing predatory pricing by processors exploiting farmers' weak bargaining position
- Stabilizing farm income to prevent land abandonment and maintain coffee cultivation
- Protecting Puerto Rico's coffee heritage and cultural identity

Puerto Rico's price floor emerged from a prolonged agricultural crisis. During the 1990s-2000s, Puerto Rican coffee farming collapsed due to:

- International Coffee Organization (ICO) quota system elimination (1989) flooding markets with cheap coffee
- Competition from low-wage origins (Vietnam, Brazil) producing commodity coffee at $0.60-1.20/lb
- Hurricane Georges (1998) destroying 50% of coffee trees
- Farm labor migration to urban service jobs and US mainland
- High production costs ($8-12,000/ha) making Puerto Rican coffee globally uncompetitive

By 2000, Puerto Rico's coffee production had declined to less than 5% of historical peaks (1950s: 30 million lb annually to 2000s: <1 million lb). The price floor was enacted as emergency intervention to prevent complete industry extinction. Despite legislative intent, the $4.20/lb minimum price has not reversed Puerto Rico's coffee decline for several structural reasons:

1. Price floor exceeds consumer willingness to pay in external markets: Puerto Rican coffee at $4.20/lb wholesale translates to $12-18/lb retail—significantly above specialty coffee from other origins ($8-12/lb retail). Outside Puerto Rico's captive local market, consumers demonstrate limited willingness to pay premiums for origin alone when competing origins (Costa Rica, Colombia, Jamaica Blue Mountain) offer comparable or superior quality at lower prices. As a result, Puerto Rico coffee is largely confined to island tourism sales, diaspora nostalgia purchases, and government procurement contracts (schools, hospitals), severely limiting market size.

2. High production costs consume the premium: The $4.20/lb price, while 2-3× higher than ICO composite indicator ($1.50-1.80/lb), barely covers Puerto Rico's production costs, largely due to:

- Labor: $7.25/hr minimum wage (vs. $1-3/hr in Latin America)
- Inputs: 40-60% import premiums for fertilizers, equipment (island freight costs)
- Energy: 30% premium over US mainland electricity
- Land: Property taxes, insurance exceed most origins' total OPEX

The USDA Economic Research Service (2019) estimated Puerto Rico's break-even coffee price at $4.10-4.50/lb, meaning the legislated floor provides minimal or negative profit margin. When OPEX inflation (4%/year) is considered, real profitability erodes over time despite nominal price stability. As a result, even with price floor, most farms operate at loss or marginal subsistence, unable to reinvest in tree replacement, quality improvement, or expansion.

3. Price floor creates two-tier market distortions: Processors and cooperatives must pay $4.20/lb for Grade A beans, but lower grades (B, C) receive proportionally lower prices. Farmers lacking wet-processing equipment or quality control sell cherry at depressed rates ($1.50-2.50/lb cherry equivalent to ~$0.75-1.25/lb green bean).

Additionally, informal markets (gray/black market sales avoiding PRDA documentation) allow processors to circumvent the floor, particularly when purchasing from desperate farmers needing immediate cash. Enforcement is weak due to limited PRDA staffing (fewer than 10 inspectors for 5,000+ farms). Therefore, the floor benefits only well-organized farmers with cooperative membership and quality processing capacity; marginal smallholders still face exploitation.

4. Price floor increases consumer costs without commensurate quality improvement: By mandating artificially high prices, the law increases retail coffee costs for Puerto Rican consumers (who already face cost-of-living 15-20% above US mainland). This creates:
    - Demand destruction (consumers substitute imported coffees, tea, or other beverages)
    - Reputational damage (perception that Puerto Rican coffee is "overpriced" rather than "premium")
    - Reduced market growth domestically

International tourists purchasing Puerto Rican coffee at $15-20/lb retail compare unfavorably to $8-12/lb alternatives from Costa Rica or Colombia, limiting repeat purchase and brand loyalty.

Puerto Rico's coffee price floor resembles the European Union Common Agricultural Policy (CAP) and U.S. dairy price supports, which have mixed success records. Consensus in agricultural economics: Price supports without complementary productivity investments (R&D, infrastructure, market development) merely transfer costs to consumers without addressing underlying competitiveness issues (Timmer, 1989; Gardner, 2002).

Rather than abandoning the price floor, complementary policies could include:

1. Quality differentiation: Tiered pricing based on cup quality (SCAA scores), rewarding excellence rather than flat minimum
2. Direct income support: Decoupling payments from production (farmers receive transfers regardless of output), allowing market-based pricing
3. Value-addition incentives: Tax credits or subsidies for on-farm processing, roasting, or direct-to-consumer sales capturing retail margins
4. Biomass revenue streams: This is where WTEM becomes relevant, if coffee leaf and cascara provide $1,500-3,000/ha additional income, total farm revenue can achieve viability even if bean prices decline to market-clearing levels

The $4.20/lb price floor, while well-intentioned, represents a necessary but insufficient intervention. It prevents complete market collapse but does not create a viable long-term economic model. WTEM offers a complementary strategy: by diversifying revenue beyond beans alone, farmers can absorb potential bean price reductions (whether due to market forces or policy reform) while maintaining household income above living wage thresholds.

If price floors were removed and Puerto Rican coffee traded at free-market rates (likely $2.50-3.50/lb given quality and cost structure), conventional baseline (S0) NPV would decline substantially, making WTEM's relative advantage even greater.

Policy risk: Price floor continuation depends on political will and fiscal capacity. If PRDA funding declines or enforcement weakens, farmers may face price collapse. WTEM provides insurance against this policy risk by ensuring biomass revenues can partially offset bean price reductions.

Sensitivity analyses tested NPV outcomes across coffee prices from $2.00-6.00/lb to bound the impact of potential price floor removal or weakening.

Appendix 3

Weighted Average Cost of Capital (WACC) Calculation

The 3.57% discount rate employed in this analysis derives from a simplified WACC calculation documented in the "WACC & Industry" worksheet. This section presents the calculation methodology and component values for transparency and replicability.

Calculation Methodology

The model employed a streamlined Capital Asset Pricing Model (CAPM) approach that uses S&P 5-year and 10-year yield averages as the market rate of return proxy, rather than historical equity risk premiums.

Table 25. Weighted average cost of capital (WACC) components

Component	Value	Source/Calculation
Market Rate Inputs		
S&P 5-year yield (inflation adjusted)	8.90%	Market data input (K16)
S&P 10-year yield (inflation adjusted)	8.00%	Market data input (K17)
Market rate of return	8.45%	Average of 5-year and 10-year yields

Component	Value	Source/Calculation
Cost of Equity (CAPM)		
Risk-free rate	4.32%	Market data input (K8)
Agricultural sector beta (levered)	0.50	Agricultural industry standard (K10)
Market risk premium	4.13%	Market rate - Risk-free rate
		= 8.45% - 4.32%
Cost of Equity	6.385%	rf + β(rm - rf)
		= 4.32% + 0.50(4.13%)
		= 4.32% + 2.065%
Cost of Debt		
Long-term loan rate	3.00%	USDA FSA rate ('Inputs & Assumptions'!G58)
Tax shield benefit	0.21	Federal + PR tax rate (21%)
After-tax cost of debt	2.37%	3.00% × (1 - 0.21)
Capital Structure		

Component	Value	Source/Calculation
Debt weight (D / [D+E])	70%	Smallholder farm typical leverage (F10)
Equity weight (E / [D+E])	30%	Calculated as 1 - 0.70 (F13)
Weighted Average Cost of Capital		
WACC (levered)	3.57%	Formula: E/(D+E) × re + D/(D+E) × rd × (1-t) = 0.30 × 6.385% + 0.70 × 3.00% × 0.79 = 1.916% + 1.659% = 3.575%

Formula Summary

Cost of Equity (CAPM): $re = rf + \beta(rm - rf)$

where:

re = Cost of equity

rf = Risk-free rate (4.32%)

β = Levered beta (0.50)

rm = Market rate of return (8.45%)

Market Rate of Return:

rm = AVERAGE(5-year yield, 10-year yield)

= AVERAGE(8.90%, 8.00%)

= 8.45%

Weighted Average Cost of Capital (WACC) = (E/(D+E)) × re + (D/(D+E)) × rd × (1-t)

where:

E/(D+E) = Equity weight (30%)

D/(D+E) = Debt weight (70%)

re = Cost of equity (6.385%)

rd = Cost of debt (3.00%)

t = Tax rate (21%)

Calculation Notes

1. The model calculated both levered WACC (with debt) and unlevered WACC (equity-only), though both currently yield the same 3.57% result due to the specific parameter values.
2. Tax Rate: 21%

   The model used a 21% tax rate, combining:

   - Federal corporate tax rate (21% since 2018 Tax Cuts and Jobs Act)
   - Simplified assumption that small farms face effective 21% rate

   Note: Many small farms may face lower effective tax rates due to:

   - Agricultural tax deductions and credits
   - Puerto Rico tax incentives for agricultural businesses
   - Lower marginal rates for small businesses

Sensitivity analysis should test lower tax rates (10-15%) for more conservative projections.

3. The model calculated a 3.57% WACC using:

- Simplified CAPM with S&P yield averaging (8.45% market rate)
- Agricultural beta of 0.50
- 70/30 debt/equity capital structure
- 3% cost of debt from USDA programs
- 21% tax rate

This approach prioritized simplicity and transparency over theoretical precision, making the model accessible to users without extensive finance backgrounds while maintaining reasonable accuracy for agricultural project evaluation.

The resulting 3.57% discount rate is appropriate for well-financed smallholder operations with USDA program access, though sensitivity analysis to higher rates (6-10%) is recommended for more conservative scenarios.

Appendix 4

The Wize Beverage Company PBC

To establish realistic pricing and demand estimates for coffee tree biomass products, I conducted semi-structured interviews with nine industry stakeholders between January and June 2024. I relied on the only commercial-scale coffee leaf tea producer globally is The Wize Beverage Company PBC (Wize), which was formed with the assets acquired from Wize Monkey Inc in 2024. As both researcher and owner, I have direct financial interest in coffee leaf tea market development. To mitigate bias, the analysis in this thesis used conservative price estimates drawn from historical wholesale transactions (2015-2023) under prior ownership rather than optimistic future projections. All pricing data presented below reflects actual market transactions documented in sales records and invoice archives provided during acquisition due diligence.

Wize is the pioneer and category creator of industrial coffee leaf tea, representing over 12 years of R&D investment. The company broke the historic barrier that prevented coffee leaf tea commercialization for over 150 years. Coffee leaves have been consumed for centuries across Ethiopia ("Kuti") and Indonesia ("Kawa Daun") as lightly brewed infusions valued for mild stimulation and smooth taste. However, these traditional beverages never evolved into industrially viable products due to unresolved challenges in processing stability, food safety, shelf-life, and consumer palatability. Historical accounts, including a New York Times article from 1873, document early experiments with coffee leaf infusions, but no successful global commercialization emerged until Wize Monkey's breakthrough in 2013-2015.

Wize pioneered the first systematic adaptation of *Camellia sinensis* (tea plant) processing methods to Coffea arabica leaves. Traditional teas (green, oolong, black, white, pu-erh) all derive from the same plant species, differentiated only by oxidation level and processing technique. Wize discovered that applying these tea-making principles to coffee leaves could unlock a full spectrum of flavor, aroma, and bioactive complexity previously unknown.

Over 100 arabica varietals exist, each with distinct phenolic and sensory profiles. Through years of agronomic trials conducted in Nicaragua and at Copper Hill Farm, Wize identified optimal combinations of varietal, leaf age, and harvest timing to maximize both flavor and health potential. Younger leaves of Typica and Bourbon trees yielded highest mangiferin and chlorogenic acid concentrations, while mid-aged leaves offered superior balance of sweetness and body. Proprietary fieldwork demonstrated that moderate selective leaf harvesting (10-20% of canopy during pruning) does not reduce bean yield, allowing farmers to safely diversify income year-round (internal field trials, 2018-2024).

After hundreds of processing trials and scientific collaboration with food scientists at the University of British Columbia (UBC), Wize determined that an oolong-style semi-oxidized process provides optimal balance between antioxidant retention and palatable flavor. The proprietary method produces a smooth, honeyed, low-bitter infusion with natural sweetness, an accessible flavor profile that won Best New Product at World Tea Expo 2015 and the Nexty Award 2017.

Scientific validation and peer-reviewed research has been conducted in collaboration with Dr. David Kitts and Dr. Xiumin Chen at UBC's Food, Nutrition and

Health program. Wize co-authored multiple peer-reviewed studies establishing coffee leaf tea's phytochemical and functional profile:

- Chen et al. (2018) demonstrated that leaf age and oxidation stage significantly affect phenolic content and antioxidant activity. Younger leaves from Typica and Bourbon varieties yielded highest mangiferin and chlorogenic acid concentrations.
- Chen et al. (2019) confirmed anti-inflammatory and nitric oxide-modulating properties of black-process coffee leaf tea in vitro.
- Chen et al. (2023, 2025) characterized volatile aroma compounds via GC-MS, optimized drying kinetics, and assessed effects of infrared and ultrasound processing on nutrient retention and food safety.

These studies identified coffee leaves as rich in mangiferin (a xanthone with anti-diabetic properties), chlorogenic acids (antioxidant polyphenols), rutin (flavonoid), trigonelline, and theobromine which are compounds linked to anti-inflammatory, neurofunctional, and metabolic health effects (Trevisan et al., 2016; Vyas, A et al., 2020). Unlike coffee beans' high caffeine content (80-120 mg per cup), coffee leaf tea contains approximately 20-40 mg caffeine per cup.

A key differentiator in Wize's process is Sound Farming™, a proprietary and protected ultrasound leaf-washing method serving dual functions:

- Food safety: Ultrasonic cavitation removes microbial contaminants more effectively than water washing alone (3-4 log reduction in microbial load), meeting FDA and international food safety standards

- Nutrient enhancement: Ultrasound waves enhance release of GABA (gamma-aminobutyric acid), mangiferin, and chlorogenic acids from plant cell walls, improving bioavailability

This innovation, validated in Chen et al. (2025), enables coffee leaf tea to meet commercial food-safety requirements while preserving and even enhancing functional compounds.

Wize extended R&D into shelf-stable RTD beverages, developing proprietary brewing and pasteurization methods that preserve 80-90% of polyphenolic content while achieving 12-month shelf life. The RTD line launched in 2016-2018, establishing the world's first Coffee Leaf Iced Tea, later expanded into Sparkling Tea formats. These products bridge traditional tea, coffee, and functional beverage categories, targeting health-conscious millennials and Gen Z consumers.

For this thesis research, I used conservative oolong-style tea wholesale pricing as the base case for Scenario 3 (coffee leaf only) and Scenario 4 (full WTEM):

- Base case wholesale farmgate price: $9.00/lb (mid-range of $8-12/lb historical oolong transactions)
- Processing cost: $0.05/lb (cooperative model with shared drying/sorting equipment)
- Quality assumption: 80% Grade A (premium intact leaves), 15% Grade B, 5% Grade C

These prices reflect actual wholesale transactions during the 2018-2023 period and are deliberately set at mid-range rather than premium end to provide conservative

economic projections. Higher prices ($10-25/lb) are achievable for premium white or ceremonial-grade products but are excluded from base case to avoid optimistic bias.

It is important to reiterate the disclosure that I am the owner of The Wize Beverage Company, PBC, which commercializes coffee leaf products. The research was designed, conducted, and analyzed independently of commercial operations. All data sources and analytical methods are documented to enable replication. My commercial involvement provided access to primary farm data but also created potential for bias that readers should consider when evaluating findings.

Appendix 5

Extended Scenario Specifications

This appendix provides complete technical details for all six scenarios including management characteristics, yield penalty structures, pest dynamics, and capital expenditures.

Some key assumptions shared by all scenarios were:

- No adoption ramps: Biomass harvesting begins immediately in Year 1 at full production when monetization enabled (conservative assumption—reality likely has 1-2 year learning curve)
- Fixed penalties: Yield penalties are fixed percentages, not dynamic shade-response functions (conservative—some farms may achieve better adaptation)
- Cost-share: 50% USDA subsidy applies only to Years 0-2 establishment; all maintenance thereafter farmer-borne (realistic for program constraints)
- Cooperative processing: Base case requires cooperative (60-90 farms); individual processing economically infeasible at modeled prices
- No salvage value: Model assumes zero terminal value for shade trees, infrastructure, or soil improvements (conservative—substantial unrealized value)
- 10-year horizon: Excludes long-term benefits like timber harvest, carbon credits, enhanced property values (conservative—understates WTEM advantages)

Scenario 1 (S1): Conventional Baseline - Complete Specification

There was no biomass monetization in S1. The management characteristics were:

- Full-sun monoculture (shade cover <10%)
- Synthetic fertilization: 150-200 kg N/ha annually via urea (46-0-0) and triple superphosphate (0-46-0)
- Herbicide weed control: Glyphosate-based applications (2-3 times annually at 2-4 L/ha)
- Fungicide applications: Copper-based sprays for coffee leaf rust (*Hemileia vastatrix*) at 3-4 kg/ha per application
- No shade tree establishment or maintenance costs
- Equipment: Backpack sprayers, hand tools, wet processing mill

The yield structure was:

- Baseline production: 3,455 lb green beans per 10-acre farm (Year 1)
- Per-hectare: 853 kg/ha
- Broca beetle penalty: 5% annual yield reduction from *Hypothenemus hampei* infestation
- Leaf rust penalty: 5% annual yield reduction from *H. vastatrix* infection pressure
- No transition penalty (established system at equilibrium)

Revenue Calculation (Year 1) were:

- Green beans: 3,455 lb × $10/lb = $34,550 gross
- After penalties: $34,550 × 0.95 × 0.95 = $31,184 net bean revenue

Capital expenditures assumptions were:

- No shade establishment costs
- Equipment replacement and maintenance: $500/farm annually
- Minimal infrastructure investment (status quo operations)

The NPV result from the model was: -$118,858 (economically unviable)

- Economic function: Serves as economic and environmental benchmark representing current regional practice. All alternative scenarios were evaluated relative to S1 using incremental NPV calculations. Critical finding: S1's negative NPV indicates conventional coffee farming is economically unviable under Puerto Rico conditions, fundamentally reframing WTEM's value proposition from "financing regenerative transition" to "escaping conventional failure."

Scenario 2 (S2): Regenerative Agroforestry (No Biomass Monetization)

Similar to S1 no biomass monetization occurred in S1. Management characteristics were:

- Target shade cover: 40-50% canopy within 5 years
- Shade species composition: Native hardwoods (*Andira inermis*, *Inga* spp., *Guarea guidonia*), fruit trees (*Persea americana*, *Artocarpus altilis*), fast-growing temporary shade (*Musa* spp.)
- Organic fertilization: Compost (10-15 t/ha biennially), biochar (5-10 t/ha one-time), leguminous cover crops (N-fixation 60-80 kg N/ha/year)
- Manual weed management: Machete slashing, mulching, cover crop suppression (no herbicides)
- Integrated pest management: *Beauveria bassiana* for broca control, Bordeaux mixture for rust
- Leaves and cascara produced but NOT harvested, processed, or sold
- Leaves remain on-farm as mulch (nutrient cycling)
- Cascara composted or discarded (current practice)

The yield penalty structure was determined by coffee yield following a two-phase transition trajectory:

- Years 1-4 (25% penalty): Establishment stress from root competition, temporary light reduction, soil disturbance, learning curve for organic management, transition lag as soil biology shifts.
- Years 5-10 (10% stable penalty): Long-term shade effects - moderate light limitation partially offset by improved microclimate, enhanced soil health, and organic matter increasing water/nutrient retention.
- This penalty structure aligns with meta-analyses documenting 10-25% yield penalties during transition with partial recovery, and persistent 5-15% penalties in mature shade systems (Jezeer et al., 2019; Koutouleas et al., 2022).

Pest and disease dynamics were influenced by:

- Regenerative systems achieve improved pest management compared to conventional:
- While shade canopy increases humidity potentially favorable for pathogens, this is more than offset by:
- Enhanced plant vigor and systemic resistance from improved soil health
- Biodiversity-mediated biological control (29 bird species documented including insectivorous endemics provide natural pest predation)
- Strategic air circulation management during biomass harvest operations
- Reduced plant stress enhancing natural disease resistance mechanisms
- Biological control applications (*Beauveria bassiana* for broca) integrated with ecosystem-based management

- The 4% pest management advantage (1% vs 5% penalty) for each pest pressure partially offsets yield penalties from shade competition and transition stress, representing a critical quantifiable ecosystem service value of regenerative agroforestry systems.

Capital expenditures are listed in Table 26.

Table 26. Total shade establishment CAPEX for 10-acre (4.05 ha) farm.

Investment Item	Unit Cost	Quantity	Total
Shade tree nursery setup	$1,000	1	$1,000
Shade tree planting (per ha)	$1,350	4.05 ha	$5,468
Subtotal			$6,468
Per hectare			$1,597/ha

Table 26 summarizes shade establishment capital expenditures for regenerative transition. Planting labor costs reflect steep slope conditions and terracing requirements at Copper Hill Farm. Seedling costs are excluded from this calculation as they are fully covered by USDA Climate-Smart Agriculture cost-share provisions, representing 100% subsidy for propagation materials while farmers bear site preparation and labor expenses. Per-hectare costs are calculated for the 4.05-hectare study plot.

The USDA cost-share of a 50% subsidy on labor and infrastructure reduces net farmer investment to $798/ha in Years 0-1. Amortized over 10 years equals $647/year; $160/ha/year (before cost-share), $80/ha/year (after 50% subsidy).

The economic function of this scenario is to represent regenerative transition without biomass revenue offset, isolating "worse-before-better" economics. Tests whether ecological benefits alone justify economic sacrifice. The key finding was that S2 achieved positive but modest NPV, indicating regenerative agriculture is barely viable without biomass revenues, but still superior to conventional S1's negative NPV.

Scenario 3 (S3): Regenerative + Cascara Only

S3 tests cascara viability but faces adoption friction from harvest-period temporal competition. Even if economically viable, cascara may experience delayed adoption relative to leaf due to risk aversion during harvest operations and working capital stress from inventory concentration. The management was identical to S2 (shade agroforestry, organic inputs, manual weeding).

The yield penalties were the same as S2 (25% years 1-4, 10% years 5-10, plus 1% rust/broca each).

Cascara yield was derived from green bean production via mass balance:

EQUATION C.5: Cherry_fresh = Bean_green / 0.20

Where 0.20 represents the 20% extraction ratio (green beans constitute 20% of fresh cherry weight).

Year 1 Calculation:

Green beans (after all penalties): 2,539 lb

Fresh cherries: 2,539 / 0.20 = 12,695 lb

Pulp fraction (45% of cherry weight): 12,695 × 0.45 = 5,713 lb fresh pulp

Dried cascara (15% of pulp after 85% moisture removal): 5,713 × 0.15 = 857 lb

Note: The Excel model showed 1,166 lb cascara production in Year 1, suggesting the theoretical mass balance calculation above requires adjustment for additional processing realities including:

- Quality sorting losses (removing defective, moldy, or discolored cascara)
- Processing waste (hulls that don't separate cleanly, fines lost during sieving)
- Moisture variability (some batches may not dry to target 10-12% moisture)
- Batch size losses (small batches processed separately with higher per-unit losses)

Two processing methods are available. The natural process (base case) included:

- Pulp dried on bean (slower drying, 3-5 days)
- Darker color, fruitier flavor profile
- Wholesale price: $4.50/lb
- 12.5% premium over wet process
- Preferred by specialty tea companies

The alternative wet process featured:

- Pulp removed immediately post-depulping
- Faster drying (1-2 days)
- Lighter color, milder flavor
- Wholesale price: $4.00/lb
- Higher throughput, lower quality

The revenue calculation (Year 1, Natural Process) was determined by:

- Cascara production: 1,166 lb
- Gross revenue: 1,166 lb × $4.50/lb = $5,247
- Processing cost: 1,166 lb × $0.05/lb = $58

Net cascara revenue was therefore $5,189. The combined revenue (Year 1) was comprised of bean revenue (S2 regenerative) of $25,399 and cascara revenue of $5,247 for a total of $30,646.

There was an additional CAPEX for equipment for cascara processing determined by cooperative allocation of $267/farm).

S3 tests whether cascara revenue alone can offset regenerative transition costs and yield penalties. It isolates cascara commercialization viability independent of leaf tea markets. A critical finding was that cascara alone cannot achieve positive NPV, indicating it must be paired with leaf revenues or abandoned as strategy. The $5,247 annual cascara revenue is insufficient to compensate for the $78,978 NPV gap between S2 regenerative ($52,120) and what would be needed for strong viability.

Scenario 4 (S4): Regenerative + Coffee Leaf Only

Management for S4 is identical to S2 (shade agroforestry, organic inputs, manual weeding), with monetization of only coffee leaf tea leaf.

S4 represents a Phase 1 entry strategy leveraging temporal complementarity—leaf processing occurs during off-season idle capacity with minimal operational disruption and low marginal costs. If S4 achieves dual viability, farmers can adopt WTEM through this low-risk pathway, validate biomass processing competency, and establish market relationships before considering cascara addition (Phase 2: S4→S6).

The yield penalties were the same as S2 (25% years 1-4, 10% years 5-10, plus 1% rust/broca each). The base case was one harvest event annually (ultra-conservative specification). Calculations specified _fresh leaves per tree = 625 g/tree/harvest; per farm = 625 g × 20,000 trees = 12,500,000 g = 27,558 lb; dry weight per farm = 27,558 ×

0.20 = 5,512 lb dry, where 0.20 represents 80% moisture loss during processing (withering, oxidation control, final drying).

The product mix allocation in the model was designed to mirror a realistic base case of $9/lb oolong which is the current product sold in the market (30% Green tea, 50% Oolong tea, and 20% Black tea).

Processing loss was assumed to be 5% (sorting removes off-color, broken, or damaged leaves during oxidation), so that marketable leaves = 5,512 × 0.95 = 5,236 lb.

The finished product allocation (Year 1) was thereby:

- Green tea: 5,236 × 0.30 = 1,571 lb @ $10.00/lb = $15,710
- Oolong tea: 5,236 × 0.50 = 2,618 lb @ $9.00/lb = $23,562
- Black tea: 5,236 × 0.20 = 1,047 lb @ $8.00/lb = $8,376

Processing requirements were:

- Withering: 12-24 hours on racks (passive, no energy cost)
- Oxidation: Controlled temperature/humidity (green: 0-10%, oolong: 30-70%, black: 80-95%)
- Rolling/shaping: Manual or mechanical (minimal for broken-leaf grades)
- Final drying: Solar tunnel dryer (primary) or mechanical backup
- Sorting: Optical color sorter removes defects
- Packaging: Food-grade resealable bags with nitrogen flush

Combined revenue (Year 1) were comprised of bean revenue (S2 regenerative) of $25,399, and leaf revenue of $47,647 for a total of $73,046.

Additional CAPEX involved leaf washing/sanitization line, optical color sorter shared across cooperative members, so was a $267/farm allocation.

S4 tested whether coffee leaf tea revenue alone can offset regenerative transition costs. S4 isolates leaf commercialization viability independent of cascara markets. The critical finding was that S4 achieves the highest NPV of all scenarios, indicating leaf-only is the optimal WTEM strategy. The $47,647 annual leaf revenue completely transforms regenerative economics, adding $142,451 in NPV over S2's baseline.

Scenario 5 (S5): WTEM Stress Test (No Bean Revenue)

S5 serves as a stress test quantifying minimum viable biomass prices and yields required for farm economic sustainability in the extreme scenario where the green bean market collapses, access is lost, or the farmer chooses to exit commodity market. This tests "adverse-price dominance" as recommended for profitability analysis under stress conditions (Lalani et al., 2024).

Management was identical to S2 (shade agroforestry, organic inputs, manual weeding). The critical distinction for S5 was that full regenerative infrastructure and operational costs were maintained:

- Shade trees planted and maintained (annual pruning, replanting mortality)
- Terracing and erosion control structures built and maintained
- Organic fertilization program fully implemented
- All equipment and facilities operational
- All labor and overhead costs continue

Both leaves and cascara were monetized. Yield penalties were the same as S2 for calculation of biomass production derived from cherry weight, but:

- Green bean revenue = $0 (beans are produced but not sold)

- Beans may be: (1) discarded, (2) used for on-farm consumption, (3) donated, or (4) sold below cost for social programs
- All bean-related production costs remain (harvest labor, wet processing, fermentation, initial drying)

The revenue streams (Year 1) were:

- Green bean sales: $0 (explicitly set via m_beans = 0)
- Coffee leaf tea sales: $47,647 (same as S4)
- Cascara sales: $5,248 (same as S3)

so total revenue for Year 1 = $0 + $47,647 + $5,248 = $52,895.

The cost structure maintained was:

- All S2 regenerative OPEX continues ($4,787/ha or ~$19,385/farm)
- All S2 regenerative CAPEX amortized over 10 years
- Plus biomass processing CAPEX ($534/farm in Year 0)
- Bean production costs (harvest, processing) still incurred even though beans not sold

This scenario is particularly relevant for:

- Climate change scenarios where coffee becomes unviable in current regions
- Market disruption scenarios (oversupply, trade restrictions, price collapse)
- Farm diversification strategies pivoting away from coffee commodity dependence
- Policy analysis of biomass-only agricultural systems
- Insurance value assessment: Can farms survive complete coffee market failure?

The NPV from the S5 model was $79,062 (viable even without beans). The critical finding was that S5 achieves positive NPV despite no bean revenue, indicating:

- Biomass revenues alone can sustain farm operations under catastrophic coffee market collapse
- WTEM provides genuine insurance value beyond incremental profitability enhancement
- Coffee beans are not essential for farm survival if biomass markets remain functional
- $52,895 annual biomass revenue exceeds household living income ($12,877 threshold) by 4.1×, providing substantial margin

This scenario tested Hypothesis H4b, whether biomass-only operations achieve NPV > 0 or income ≥$10,000/year with 50% confidence (exploratory stress test exception). S5 achieved both criteria decisively: NPVwas $79,062, with income Years 1-5 averaging ≈ $27,452 (well above $10,000 threshold)

Limitations of S5:

- Assumes farmers continue maintaining coffee trees and infrastructure despite no bean sales (irrational unless viewing as future option value)
- Does not model crop substitution (replacing coffee with more profitable crops)
- Maintains same biomass yields despite no bean sales motivation
- Ignores potential cascade effects where loss of bean income undermines farm maintenance capacity

Despite these limitations, S5 demonstrates WTEM's potential to fundamentally transform farm resilience by creating revenue diversification that can withstand complete failure of the primary commodity market.

Scenario 6 (S6): Full WTEM Integration

Management was identical to S2 (shade agroforestry, organic inputs, manual weeding), with biomass monetization: of both leaves and cascara.

S6 represents Phase 2 expansion after successful S4 implementation. By establishing leaf processing first (off-season, low-risk), farmers build confidence in biomass operations before introducing harvest-period cascara processing. This sequential adoption resolves coordination barriers by avoiding simultaneous commitment to full WTEM complexity.

The yield penalties were the same as S2 (25% years 1-4, 10% years 5-10, plus 1% rust/broca each).

Revenue streams (Year 1) were determined by:

- Green bean sales: $25,399 (S2 regenerative baseline with all penalties)
- Coffee leaf tea sales: $47,647 (blended product mix as detailed in S4)
- Cascara sales: $5,248 (natural process as detailed in S3)

For total gross revenue of $78,294.

If processing costs are deducted, then:

- Leaf: $47,647 gross - ($0.05 × 5,236 lb) = $47,647 - $262 = $47,385 net
- Cascara: $5,248 gross - ($0.05 × 1,166 lb) = $5,248 - $58 = $5,190 net

For total net biomass revenue of $52,575, and total net revenue of $25,399 + $52,575 = $77,974.

Processing infrastructure assumed the cooperative model with shared facilities across 60-90 member farms (approximately 75 average), enabling:

- Capital cost distribution (dryers, mills, sorters amortized across membership)

- Bulk purchasing of packaging materials reducing per-unit costs (10-15% discount)
- Consolidated marketing and distribution reducing transaction costs (20-30% freight savings)
- Quality standardization through centralized processing with trained staff
- Reduced per-farm processing cost vs. individual operation (75% efficiency from cooperative)

Additional CAPEX assumed the full complement of processing equipment for both biomass streams, allocated per member farm, totalling $535/farm, comprised of:

- Leaf processing equipment: $267/farm (allocation from $14,500 cooperative investment)
- Cascara processing equipment: $267/farm (allocation from $26,200 cooperative investment)

Operating expenses for Year 1 included processing labor for both leaf and cascara; energy costs for drying operations; packaging materials; quality control testing (moisture meters, microbial testing). Total S6 OPEX in model = $13,597 (compared to S2 baseline OPEX which would be similar but without biomass processing costs).

The NPV from the S6 model was $141,885 (viable but lower than S4). S6 represented the full WTEM implementation with maximum revenue diversification. Tests whether combined biomass revenues sufficiently offset regenerative transition costs and yield penalties to achieve NPV parity with or superiority over S1 (conventional). The critical finding was that S6 achieves strong positive NPV ($141,885) confirming full WTEM viability but is actually lower than S4 leaf-only ($194,571).

Appendix 6

Biomass Production Calculations and Harvest Frequency Analysis

This appendix presents the complete methodology for calculating coffee leaf and cascara production volumes, including mass balance equations, yield assumptions, and harvest frequency sensitivity analysis. All calculations derive from field measurements at Copper Hill Farm and are calibrated to represent a 10-acre (4.05 ha) reference farm with 20,000 coffee trees.

Coffee Leaf Production Calculations

The base case analysis conservatively models one harvest event annually, capturing only leaves from routine maintenance pruning operations already integrated into conventional coffee management. This ultra-conservative specification assumes farmers harvest leaves opportunistically during existing pruning cycles without additional labor scheduling or intensification.

Fresh leaf yield per tree per harvest event was established at 625 grams per tree, derived from April and August 2024 measurements where routine maintenance pruning, conducted across a stratified random sample of 100 trees representing age and cultivar distributions, yielded average fresh leaf biomass consistent with expectations for mature Arabica trees under similar management conditions (Murthy & Naidu, 2012). For the 10-acre reference farm containing 20,000 trees, this translates to total fresh yield of 12,500,000 grams (27,558 pounds fresh leaf), equivalent to 6,804 pounds per hectare or 3,087 kilograms per hectare.

Processing involves moisture reduction from approximately 80% water content in fresh leaves to final dried product. Withering occurs over 12-24 hours at ambient temperature and humidity for passive water loss, followed by controlled oxidation for enzymatic browning that varies by tea type, and final drying via solar tunnel dryer or mechanical backup to achieve 3-5% final moisture content. Applying the 20% dry matter fraction (after removing 80% moisture), the farm yields 2,500,000 grams or 5,512 pounds of dry leaf material.

During and after oxidation, approximately 5% of dry leaf biomass is removed due to quality sorting losses including off-color leaves exhibiting yellowing or browning beyond target oxidation, broken or fragmented leaves with excessive stem content or powder fines, contamination from insect damage, mold spots, or foreign matter, and processing defects from under-oxidized or over-oxidized batches. After applying this 5% quality sorting loss, the farm produces 5,236 pounds of marketable dried leaf product.

Rather than producing 100% oolong tea as originally proposed, the model uses a diversified product portfolio reflecting market demand and quality optimization that achieves a blended average price of approximately $9.00 per pound. This allocation consists of 30% green tea with minimal oxidation (0-10%) appealing to health-conscious consumers at premium pricing while preserving antioxidants, 50% oolong tea with moderate oxidation (30-70%) offering a balanced flavor profile for mainstream markets with optimal processing ease, and 20% black tea with full oxidation (80-95%) providing robust flavor for traditional tea drinkers with extended shelf life.

Applying this product mix to the 5,236 pounds of marketable leaf yields 1,571 pounds of green tea at $10.00 per pound generating $15,710, 2,618 pounds of oolong tea

at $9.00 per pound generating $23,562, and 1,047 pounds of black tea at $8.00 per pound generating $8,376, for total gross leaf revenue of $47,648 in Year 1. Processing costs at cooperative rates of $0.05 per pound total $262, resulting in net leaf revenue of $47,386 per 10-acre farm or $11,700 per hectare.

Harvest Frequency Sensitivity Analysis

Coffee leaf tea production follows a flush cycle similar to traditional *Camellia sinensis* tea cultivation, where new leaf growth occurs in distinct periods throughout the year. Commercial tea operations typically harvest 3-4 flushes annually, corresponding to peak periods of tender leaf production. Field trials at Copper Hill Farm confirmed that coffee trees can sustain four or more harvest events annually when managed for leaf production, though the conservative base case models only one flush.

The analysis tested four flush frequency scenarios to bound the range of potential outcomes, as summarized in Table 27. The base case (F1) with one annual flush produces 5,236 pounds per farm with no bean yield penalty, requiring 40 labor hours per hectare and achieving premium quality from minimal plant stress. Scenario F2 with two annual flushes doubles output to 10,472 pounds while maintaining zero bean penalty, requiring 85 labor hours per hectare and achieving high quality with low stress. Scenario F3 with three annual flushes triples output to 15,708 pounds but incurs a 3% bean yield penalty from moderate photosynthetic stress, requiring 135 labor hours per hectare with standard quality. Scenario F4 with four annual flushes quadruples output to 20,944 pounds but incurs an 8% bean yield penalty from significant plant stress, requiring 190 labor hours per hectare with reduced quality warranting a $0.50 per pound price discount.

Table 27. Flush scenario specifications

Scenario	Annual Flushes	Leaf Yield (lb/farm)	Bean Yield Impact	Labor Hours/ha	Quality Grade
F1 (Base case)	1	5,236	0% penalty	40	Premium (minimal stress)
F2	2	10,472	0% penalty	85	High (low stress)
F3	3	15,708	-3% penalty	135	Standard (moderate stress)
F4	4	20,944	-8% penalty	190	Reduced (high stress, -$0.50/lb discount)

For scenarios F1 and F2, harvests were timed to avoid flowering and fruit set periods from October through December, with light removal during vegetative growth phases from February through September that does not compromise reproductive allocation. For F3, the 3% penalty reflects mild photosynthetic stress from increased leaf removal, reducing total carbohydrate available for fruit development, though this is partially offset by strategic timing with the third flush occurring post-harvest from January through February when reproductive demand is minimal. For F4, the 8% penalty results from aggressive harvesting that compromises plant vigor through reduced total photosynthetic area during critical fruit fill period, carbon allocation stress forcing trade-

offs between leaf regrowth and fruit development, potential stress-induced premature fruit drop, and quality degradation producing smaller cherries with lower sugar content and increased defects.

The F4 scenario imposes a $0.50 per pound wholesale price discount on leaf tea due to smaller leaf size from accelerated growth cycles that is less desirable for premium markets requiring intact large leaves, increased stem and twig content from more aggressive harvesting techniques, potential stress-induced off-flavors including bitterness and astringency that reduce cup quality, and market perception of over-harvested trees producing inferior product. The quality multiplier for F4 is calculated as the discounted price of $8.50 divided by the base oolong price of $9.00, yielding 0.944 or a 5.6% discount.

Labor requirements scale non-linearly with harvest frequency due to experience curve effects and diminishing marginal efficiency. The F1 scenario integrates with routine pruning at marginal labor cost near zero, with workers familiar with tree locations and access patterns and no additional scheduling complexity. The F2 scenario achieves 12% efficiency gain per flush from experience curve, still integrated with bi-annual pruning schedule with minimal coordination overhead. The F3 scenario achieves 8% efficiency gain per flush but requires dedicated harvest scheduling separate from pruning with moderate coordination complexity. The F4 scenario faces diminishing returns as most accessible leaves were already harvested in earlier flushes, with higher labor per flush due to tree height and difficult access to remaining leaves, plus increased supervision requirements for quality control.

Net revenue calculations demonstrate significant upside potential beyond the conservative base case. The F1 scenario generates gross leaf revenue of $47,648, with labor costs of $1,175 (calculated as 40 hours per hectare times 4.05 hectares times $7.25 per hour) and processing costs of $262, yielding net leaf revenue of $46,211. The F2 scenario generates gross leaf revenue of $95,296 (double F1), with labor costs of $2,495 (calculated as 85 hours per hectare times 4.05 hectares times $7.25 per hour) and processing costs of $524 (double F1), yielding net leaf revenue of $92,277. The F3 scenario generates gross leaf revenue of $142,944 (triple F1), with labor costs of $3,964 (calculated as 135 hours per hectare times 4.05 hectares times $7.25 per hour), processing costs of $786 (triple F1), and bean revenue penalty of $762 (calculated as $25,399 times 0.03), yielding net combined revenue of $137,432 and effective leaf contribution of $112,033 after subtracting the $25,399 bean baseline. The F4 scenario generates gross leaf revenue of $179,999 (calculated as $190,592 times the 0.944 quality discount), with labor costs of $5,578 (calculated as 190 hours per hectare times 4.05 hectares times $7.25 per hour), processing costs of $1,048 (quadruple F1), and bean revenue penalty of $2,032 (calculated as $25,399 times 0.08), yielding net combined revenue of $171,341 and effective leaf contribution of $147,974 after subtracting the $23,367 penalized bean revenue.

Assuming all other model parameters held constant, incremental annual net revenues for Years 1-10 under each flush scenario would generate different NPVs. Rough approximations not accounting for dynamic yield changes over 10 years indicate F1 base case achieves S4 NPV of $194,571 as the actual model result. The F2 estimate adds approximately $45,000 per year times 7.96 (the NPV factor at 3.57% over 10 years) to

yield approximately $552,771. The F3 estimate adds approximately $65,800 per year times 7.96 to yield approximately $718,339. The F4 estimate adds approximately $101,000 per year times 7.96 to yield approximately $998,531. However, these estimates do not account for bean yield penalties reducing base revenue in F3-F4, cumulative plant stress potentially increasing over years such that F4 may not be sustainable for 10 years, market saturation effects if all farms simultaneously increase leaf output two to four times, quality degradation in F4 potentially worsening over time, and labor availability constraints during peak periods.

The strategic recommendation for most farms follows a phased adoption trajectory. The F1 scenario represents conservative entry optimal for new adopters, risk-averse operators, and regions with uncertain markets, offering advantages of minimal operational change, proof-of-concept validation, and no bean trade-offs, with NPV of $194,571 representing 70-80% of theoretical optimum but highest adoption probability, and should be chosen during Phase 1 adoption when testing market demand and building buyer relationships. The F2 scenario represents standard operations optimal for established WTEM participants with moderate risk tolerance, offering advantages of balanced returns with manageability, no bean penalties, and double revenue, with estimated NPV of approximately $552,771, and should be chosen post-Phase 1 after successful one-flush validation with strong buyer relationships established and cooperative processing capacity confirmed. The F3 scenario represents intensive management optimal for high-capacity farms with strong market access and premium pricing, offering advantages of maximized leaf revenue at triple base with minimal 3% bean penalty, with estimated NPV of approximately $718,339, and should be chosen by

experienced operators with multiple buyer contracts in premium quality markets willing to pay for increased volume. The F4 scenario represents aggressive harvest that is not recommended, optimal only for desperation scenarios such as coffee market collapse or S5-type situations, with disadvantages of 8% bean penalty, quality discount, sustainability concerns, and diminishing returns, and estimated NPV of approximately $998,531 representing theoretical maximum that is likely unsustainable, and should be avoided in any scenario where coffee beans remain a viable market but may be considered when coffee price falls below $4 per pound (below production cost) and the farm is transitioning to a full biomass-only model.

The optimal strategy for most farms proceeds as follows: during Years 1-2, adopt F1 (one flush) for validation and market entry; during Years 3-5, scale to F2 (two flushes) after confirming demand and processing capacity; during Years 6-10, consider F3 (three flushes) only if leaf prices exceed $10 per pound average, buyer contracts secure volume, and no signs of plant stress emerge from F2 operations; and never adopt F4 unless coffee becomes economically unviable and the farm is pivoting to biomass-only production. The F2 scenario represents the optimal risk-adjusted strategy for mature WTEM operations, doubling leaf revenue without bean penalties while maintaining operational sustainability. The ultra-conservative F1 base case used throughout this analysis ensures model validity under minimal intensification, with F2-F3 scenarios representing upside potential for committed adopters.

Cascara Production Mass Balance

Cascara production derives from the coffee cherry processing mass balance, where green coffee beans represent only 20% of total fresh cherry weight. The remaining

80% consists of pulp and mucilage at 45% that becomes cascara when dried, parchment at 20% that is removed during dry milling and not typically valorized, silver skin at 4% that is removed as chaff during roasting by the buyer, and moisture and waste at 11% that is lost during processing.

For S3, S5, and S6 scenarios that monetize cascara, green bean production follows the S2 regenerative baseline with all penalties applied. Starting from the S1 baseline of 3,455 pounds, applying the 25% system penalty yields 2,591 pounds, then the 1% broca penalty yields 2,565 pounds, and the 1% rust penalty yields 2,539 pounds of net green beans. Reversing the mass balance to fresh cherries, 2,539 pounds of green beans divided by 0.20 yields 12,695 pounds of fresh cherries and multiplying by the 0.45 pulp fraction yields 5,713 pounds of fresh pulp.

However, cascara is calculated from actual cherry processing volume, which is based on pre-penalty bean production. Beginning with 3,455 pounds of beans processed (the S1 baseline before penalties), dividing by the 0.20 bean-to-cherry ratio yields 17,275 pounds of fresh cherries, multiplying by the 0.45 pulp fraction yields 7,774 pounds of fresh pulp, and multiplying by the 0.15 drying ratio (reflecting that fresh pulp contains 85-90% moisture and drying to 10-12% final moisture for storage stability and quality) yields 1,166 pounds of dried cascara.

Year 1 cascara revenue under natural process conditions is calculated as 1,166 pounds multiplied by $4.50 per pound, totaling $5,247 gross revenue. Processing costs at $0.05 per pound total $58, resulting in net cascara revenue of $5,189 per 10-acre farm or $1,281 per hectare. The alternative wet process option produces faster drying and lighter color at $4.00 per pound, generating gross revenue of $4,664 and net revenue of $4,606.

The natural process earns $583 more annually but requires longer drying time of 3-5 days versus 1-2 days, carries more weather risk as rain can damage partially dried cascara, and demands higher quality control as darker color hides defects less effectively.

Combined Biomass Revenue Summary

Year 1 combined biomass revenue is presented in Table 28. Green tea contributes 1,571 pounds at $10.00 per pound for $15,710 gross and $15,631 net after $79 processing; oolong tea contributes 2,618 pounds at $9.00 per pound for $23,562 gross and $23,431 net after $131 processing; black tea contributes 1,047 pounds at $8.00 per pound for $8,376 gross and $8,324 net after $52 processing; the leaf subtotal is 5,236 pounds at $9.10 weighted average for $47,648 gross and $47,386 net after $262 processing; cascara (natural process) contributes 1,166 pounds at $4.50 per pound for $5,247 gross and $5,189 net after $58 processing. Total biomass revenue is 6,402 pounds at $8.26 blended average for $52,895 gross and $52,575 net after $320 processing.

These figures reveal several key ratios: leaf represents 90.1% of gross biomass revenue ($47,648 divided by $52,895), cascara represents 9.9% of gross biomass revenue ($5,247 divided by $52,895), blended biomass price is $8.26 per pound ($52,895 divided by 6,402 pounds), and processing costs represent 0.6% of gross revenue ($320 divided by $52,895), a testament to cooperative efficiency. Comparing to bean revenue, S1 conventional bean revenue is $31,184 and S2 regenerative bean revenue is $25,399, while biomass revenue is $52,895. Biomass as a percentage of bean revenue is 169.6% versus S1 (biomass exceeds conventional beans by 70%) and 208.3% versus S2 (biomass exceeds regenerative beans by 108%).

Table 28. Year 1 biomass revenue breakdown.

Component	Volume (lb)	Price ($/lb)	Gross Revenue	Processing Cost	Net Revenue
Green tea	1,571	$10.00	$15,710	$79	$15,631
Oolong tea	2,618	$9.00	$23,562	$131	$23,431
Black tea	1,047	$8.00	$8,376	$52	$8,324
Leaf subtotal	5,236	$9.10 avg	$47,648	$262	$47,386
Cascara (natural)	1,166	$4.50	$5,247	$58	$5,189
Total Biomass	6,402	$8.26 avg	$52,895	$320	$52,575

These results carry several strategic implications. First, leaf is the primary value driver since 90% of biomass revenue comes from leaves, making the leaf-only S4 strategy viable. Second, cascara is supplementary since only 10% of biomass revenue is insufficient to justify standalone adoption, as S3 fails with negative NPV. Third, biomass dominates beans since combined biomass revenue exceeds even conventional bean revenue by 70%, fundamentally reframing coffee tree economics. Fourth, the value per pound hierarchy places green tea highest at $10.00 per pound, followed by oolong tea at $9.00 per pound, black tea at $8.00 per pound, cascara lowest at $4.50 per pound, and coffee beans at $10.00 per pound for premium specialty. Fifth, processing efficiency is critical since at $0.05 per pound cooperative processing cost margins remain healthy, but

at $0.20 per pound individual processing without cooperative, biomass revenues would be severely eroded: leaf processing cost would be $1,047 (5,236 times $0.20), reducing net revenue from $47,386 to $46,601 but still viable; cascara processing cost would be $233 (1,166 times $0.20), reducing net revenue from $5,189 to $5,014; and without cooperative, total biomass net revenue drops from $52,575 to $51,615, a 1.8% reduction.

Appendix 7

Operating Expenses, Capital Investments and Cooperative Efficiency.

This appendix documents the complete operating expense structure, capital investment requirements, and cooperative efficiency mechanisms as implemented in Model v30.4. All costs are expressed in 2024 US dollars for a 10-acre (4.05 hectare) reference farm.

Operating Expenses Analysis

Annual operating expenses vary by scenario based on management intensity and input requirements. The model tracks aggregate categories only, with detailed subcategory breakdowns not implemented in the current model structure. Table 29 presents the complete breakdown by category and scenario.

The conventional S1 scenario incurs field labor costs of $1,827 per hectare, chemical fertilizer costs of $3,509 per hectare, pest and disease management costs of $874 per hectare, energy costs of $2,400 per farm ($593 per hectare), water and waste treatment costs of $400 per farm ($99 per hectare), logistics and freight costs of $100 per farm ($25 per hectare), maintenance and repair costs of $500 per farm ($123 per hectare), and land lease costs of $1,200 per farm ($296 per hectare). Total S1 operating expenses amount to $7,346 per hectare or $29,752 per 10-acre farm.

The regenerative S2-S6 scenarios incur field labor costs of $2,010 per hectare reflecting 10% higher labor intensity in regenerative systems, regenerative input costs of $225 per hectare for compost and amendments replacing eliminated chemical fertilizers,

Table 29. Annual operating expenses by category and scenario.

Cost Category	S1 (Conventional)	S2-S6 (Regenerative)	Variance	Driver of Difference
Field Labor	$1,827/ha	$2,010/ha	+10%	Higher labor intensity in regenerative systems
Fertilizers				
- Chemical fertilizers	$3,509/ha	$0/ha	-100%	Eliminated in regenerative
- Regenerative inputs	$0/ha	$225/ha	N/A	Compost and amendments
Fertilizer subtotal	$3,509/ha	$225/ha	-94%	Massive regenerative savings
Pest & disease management	$874/ha	$874/ha	0%	No differentiation implemented in model*
Energy	$2,400/farm	$2,400/farm	0%	Same processing regardless of yield
Water & Waste Treatment	$400/farm	$400/farm	0%	Same water needs

Cost Category	S1 (Conventional)	S2-S6 (Regenerative)	Variance	Driver of Difference
Logistics & Freight	$100/farm	$100/farm	0%	Distance unchanged
Maintenance & Repairs	$500/farm	$500/farm	0%	Equipment base unchanged
Land Lease	$1,200/farm	$1,200/farm	0%	Fixed lease payment

**Note: The model currently uses the same pest & disease management costs for both scenarios. If regenerative practices reduce pest pressure by 75% as anticipated in field research, this category should be reduced to approximately $218/ha for S2-S6.*

and identical costs to S1 for all other categories. Total S2-S6 operating expenses amount to $4,245 per hectare or $17,193 per 10-acre farm, representing annual savings of $12,560 per farm or a 42% reduction from conventional operations.

Regenerative agriculture achieves this substantial cost reduction primarily through elimination of expensive synthetic fertilizers. The savings arise from eliminating $3,509 per hectare in synthetic fertilizers while adding $183 per hectare in additional field labor (10% increase) and $225 per hectare in regenerative inputs, yielding net savings of $3,101 per hectare or $12,560 per farm annually. This permanent structural advantage compounds over the 10-year modeling horizon, contributing significantly to regenerative scenarios' NPV superiority over conventional operations even before considering biomass revenues.

The current model applies identical pest and disease management costs across all scenarios. If regenerative practices reduce pest pressure by 75% as anticipated in field research, this category should be reduced to approximately $218 per hectare for S2-S6 scenarios, adding approximately $656 per hectare in additional savings. The model tracks aggregate categories only and does not separately track the following subcategory breakdowns: field labor components including pruning, weeding, fertilization, and harvest supervision; fertilizer types including NPK, micronutrients, lime, and specific composts; pest management products including fungicides, insecticides, herbicides, and biologicals; energy uses including electricity, generator fuel, and dryer maintenance; and water uses for irrigation versus processing. The model also does not include a separate category for overhead costs including property taxes, insurance, certifications, and administrative expenses, which should be added in future model iterations at approximately $300-500 per farm depending on certification requirements.

The model separates Cost of Goods Sold (COGS) from Operating Expenses (OPEX). COGS includes harvesting labor at $6,254 per farm, processing, packaging, and quality control, totaling $8,842 per farm for S1 or $9,059 per farm for S2-S6. These are tracked separately from the OPEX figures described above.

Capital Expenditures Analysis

Capital investments occur primarily in Year 0 during the establishment phase, with minor maintenance and replacement in subsequent years. Cost-share subsidies at 50% from USDA programs apply only to the establishment phase. Table 30 presents the complete cooperative equipment cost breakdown.

Table 30. Cooperative biomass processing infrastructure (serving 75 farms)

Equipment	Total Cost	Per-Farm Allocation	Maintenance Reserve (30%)	Net Farmer Cost
Cascara Line				
Solar tunnel dryer (large capacity)	$4,700	$63	$19	$44
Mechanical backup dryer (propane)	$18,500	$247	$74	$173
De-hulling/cleaning equipment	$1,500	$20	$6	$14
Storage containers (food-grade)	$1,500	$20	$6	$14
Cascara subtotal	$26,200	$349	$105	$244
Leaf Processing Line				
Washing/sanitization system	$3,000	$40	$12	$28

Equipment	Total Cost	Per-Farm Allocation	Maintenance Reserve (30%)	Net Farmer Cost
Optical color sorter (automated)	$8,000	$107	$32	$75
Packaging equipment (heat sealer, scale)	$2,000	$27	$8	$19
Storage/curing racks (stainless steel)	$1,500	$20	$6	$14
Leaf subtotal	$14,500	$193	$58	$135
Total Processing Infrastructure	$40,700	$543	$163	$380

Key Observations: Cooperative model reduces farmer investment by 98.5%: Individual farmer purchasing all equipment independently would require $40,700 capital outlay. Cooperative allocation reduces this to $543 per farm ($380 after reserve).

The cooperative biomass processing infrastructure serves 75 member farms and consists of two processing lines. The cascara processing line includes a large-capacity solar tunnel dryer costing $4,700 total or $63 per farm allocation with $19 maintenance reserve yielding $44 net farmer cost, a mechanical backup dryer powered by propane costing $18,500 total or $247 per farm allocation with $74 maintenance reserve yielding $173 net farmer cost, de-hulling and cleaning equipment costing $1,500 total or $20 per

farm allocation with $6 maintenance reserve yielding $14 net farmer cost, and food-grade storage containers costing $1,500 total or $20 per farm allocation with $6 maintenance reserve yielding $14 net farmer cost, for a cascara line subtotal of $26,200 total or $349 per farm allocation with $105 maintenance reserve yielding $244 net farmer cost. The leaf processing line includes a washing and sanitization system costing $3,000 total or $40 per farm allocation with $12 maintenance reserve yielding $28 net farmer cost, an automated optical color sorter costing $8,000 total or $107 per farm allocation with $32 maintenance reserve yielding $75 net farmer cost, packaging equipment including heat sealer and scale costing $2,000 total or $27 per farm allocation with $8 maintenance reserve yielding $19 net farmer cost, and stainless steel storage and curing racks costing $1,500 total or $20 per farm allocation with $6 maintenance reserve yielding $14 net farmer cost, for a leaf line subtotal of $14,500 total or $193 per farm allocation with $58 maintenance reserve yielding $135 net farmer cost. Total processing infrastructure costs $40,700, with per-farm allocation of $543, maintenance reserve of $163, and net farmer cost of $380.

The cooperative model reduces farmer investment by 98.7%, from $40,700 for an individual farmer purchasing all equipment independently to $543 per farm allocation under cooperative membership ($380 after maintenance reserve). This massive capital efficiency is the primary mechanism enabling WTEM viability. Without cooperative infrastructure, individual farmers would face negative NPV even with strong biomass prices, as the $40,700 Year 0 investment would require decades to amortize at current production scales. Notably, cascara equipment is 1.8 times more capital-intensive than leaf processing at $26,200 versus $14,500, primarily due to the expensive mechanical

backup dryer needed for harvest-period capacity demands when solar drying may be insufficient.

Each farmer contributes the 30% maintenance reserve of $163 to the cooperative maintenance fund, ensuring long-term equipment functionality without requiring future capital calls. After 10 years, this reserve accumulates $122,250 across all 75 member farms (calculated as 75 farms times $163 times 10 years), sufficient to replace one or two major pieces of equipment. The economies of scale calculation shows individual processing cost per farm of $40,700, cooperative processing cost per farm of $543, savings per farm of $40,157, and efficiency of 98.7% (calculated as $40,700 minus $543 divided by $40,700).

Temporal Opportunity Cost Framework

Coffee cooperative processing infrastructure exhibits substantial capacity underutilization during off-harvest periods, creating fundamentally different cost structures for leaf versus cascara processing.

Coffee leaf harvesting occurs during routine pruning operations in February-March, May-June, and August-September, entirely outside the concentrated harvest window from November through January. Processing utilizes dryers, labor, and logistics during periods when these assets would otherwise sit idle. The economic implication is that marginal processing costs approach variable costs for energy, packaging, and incremental labor because fixed costs including equipment depreciation, permanent staff salaries, and facility maintenance are already sunk and paid regardless of biomass processing activity.

Cascara processing occurs during the concentrated harvest window from November through January when mills operate at maximum capacity processing coffee cherries. While the technical processing efficiency for drying, sorting, and packaging achieves the same cooperative advantage as leaf, cascara faces opportunity costs from several sources. Equipment competition arises because dryers allocated to cascara reduce parchment drying capacity, and wet parchment must be dried within 24-48 hours to prevent mold while cascara drying takes 3-5 days under natural process, creating processing queues, delays, and quality risks. Labor competition occurs because processing staff are diverted during peak bean operations when the harvest period already requires maximum workforce for pickers, processors, and quality control, and adding cascara processing increases labor demand by 15-20%, creating wage pressure in tight labor markets. Quality control bandwidth becomes stretched as inspection protocols during maximum-throughput periods must accommodate both careful bean sorting for defect removal, size grading, and density separation alongside cascara quality control for moisture testing, color sorting, and contamination removal, risking quality slippage in either product line. Working capital stress emerges because cascara inventory peaks when credit lines face seasonal maximum demand for picker wages requiring daily payment, input purchases, and equipment repairs, and cascara inventory ties up capital that could otherwise pay pickers or purchase inputs.

These opportunity costs reflect adoption barriers including harvest-period risk aversion and coordination complexity rather than inherent processing inefficiency. Once cooperatives commit to cascara processing and adjust systems accordingly, the mechanistic similarity to leaf processing enables equivalent efficiency gains from shared

infrastructure, bulk purchasing, and consolidated logistics. The model's identical $0.05 per pound processing cost for both leaf and cascara assumes cooperatives have successfully resolved harvest-period coordination challenges, achieving technical efficiency parity between the two product streams. In practice, early-stage cascara adoption may face higher effective costs until systems mature.

Cooperative Efficiency Mechanisms

Both biomass streams achieve 75% cost reduction relative to individual farmer processing through six structural advantages, as detailed in Table 31. Shared equipment amortization distributes capital costs across 60-90 member farms (approximately 75 on average), reducing individual investment from $40,700 to $543 for 98.7% savings. Bulk purchasing achieves 10-15% packaging material discounts at cooperative scale with orders of 500-1,000 kilograms compared to 10-20 kilogram individual orders. Consolidated logistics achieves 20-30% freight reduction through batch shipping by converting less-than-truckload shipments to full-truckload, reducing per-pound costs from $0.15 to $0.10 for 33% savings. Unified quality control provides centralized testing infrastructure with trained staff, eliminating individual equipment purchases of $2,000 moisture meters and $8,000 color sorters. Volume discounts on sales arise because buyers prefer consolidated shipments with lower transaction costs and consistent quality, paying 5-10% price premiums for container loads versus partial shipments. Labor specialization develops because full-time processing staff develop expertise compared to part-time farmer self-processing, achieving 15-20% faster processing with lower defect rates.

Table 31. Sources of cooperative processing efficiency.

Efficiency Source	Mechanism	Cost Reduction	Applies to Leaf?	Applies to Cascara?
Shared equipment amortization	Capital costs distributed across 60-90 member farms (~75 average)	$40,700 individual to $543 cooperative = 98.7% savings	Yes	Yes
Bulk purchasing	10-15% packaging material discounts at cooperative scale (500-1000kg orders vs 10-20kg individual)	10-15% packaging cost reduction	Yes	Yes
Consolidated logistics	20-30% freight reduction through batch shipping (LTL → FTL)	$0.15/lb individual to $0.10/lb cooperative = 33% savings	Yes	Yes
Unified quality control	Centralized testing infrastructure with trained staff	Eliminates individual equipment purchase ($2,000 moisture meter, $8,000 color sorter)	Yes	Yes

Efficiency Source	Mechanism	Cost Reduction	Applies to Leaf?	Applies to Cascara?
Volume discounts (sales)	Buyers prefer consolidated shipments (lower transaction costs, consistent quality)	5-10% price premium for container loads vs partial shipments	Yes	Yes
Labor specializatio n	Full-time processing staff develop expertise vs. part-time farmer self-processing	15-20% faster processing, lower defect rates	Yes	Yes

Individual farmer processing without cooperative membership would incur costs of $0.08 per pound for labor reflecting slower processing, learning curve, and errors, $0.04 per pound for energy from less efficient small equipment, $0.05 per pound for packaging at retail prices without bulk discount, $0.02 per pound for quality control as amortized equipment or skipped entirely, and $0.01 per pound for overhead covering administrative costs, certification, and marketing, totaling $0.20 per pound. Cooperative processing incurs costs of $0.02 per pound for specialized staff with efficient workflow, $0.01 per pound for energy from large-scale equipment efficiency, $0.01 per pound for packaging with bulk purchasing discounts, $0.005 per pound for quality control with shared equipment across 75 farms, and $0.005 per pound for overhead with distributed administrative costs, totaling $0.05 per pound. The cooperative efficiency calculation

yields 75% based on one minus the ratio of cooperative cost to individual cost ($0.05 divided by $0.20).

This 75% base case is conservative given that capital savings alone at 98.7% reduction could justify even higher efficiency estimates. However, the 75% figure accounts for cooperative management overhead not included in the individual calculation, transportation costs to and from the cooperative facility versus on-farm processing, coordination costs for scheduling, communication, and dispute resolution, and quality standardization requirements where some farmers may produce higher quality individually. Sensitivity analysis testing cooperative efficiency across a range from 50% to 80% demonstrates that institutional capacity is as critical as agronomic productivity in yields or market access in prices for WTEM viability. Policy interventions must address all three dimensions simultaneously to enable successful adoption.

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