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Indigenous Agricultural Practices for Environmental Conservation and Food Insecurity

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By

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To: Dean Michael R. Heithaus
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This thesis, written by Joseph Anthony Navarro and entitled "Indigenous Agricultural Practices for Environmental Conservation and Food Insecurity", having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this thesis and recommend that it be approved.

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DEDICATION

This thesis is dedicated to my wife for the sacrifices she has made on this journey, to my parents, extended family, and friends for their unwavering support in my endeavors, and to my two advisors who believed in me and aided in improving the Puerto Rican agroecological community.

SPECIAL DEDICATION

Dedico esta tesis a la memoria de Don Tato García, quien, con amor, salsa, y sabiduría, me permitió trabajar su tierra como se abre el alma: con generosidad profunda y sin medida. Su legado florece en cada semilla, renace en cada sueño que el suelo abriga, y vive, eterno, en la raíz del gran roble que aún se alza, firme, como usted, en la memoria fértil de nuestros corazones.

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ABSTRACT OF THE THESIS

INDIGENOUS AGRICULTURAL PRACTICES FOR ENVIRONMENTAL CONSERVATION AND FOOD INSECURITY

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Puerto Rico has been facing significant challenges in agriculture due to unsustainable practices and insufficient investment. This has led to problems like soil degradation, food insecurity, and the loss of small farm systems. In this study, I investigated the potential of Indigenous agroforestry systems, particularly the Taíno *conuco* method, to restore ecological balance and enhance agricultural resilience. The *conuco* system, which involves creating organic mounds, intercropping, and methods for moisture retention, was tested to see how it affects crop growth and soil nutrients. While the *conuco* treatment did not influence plant growth after five months, longer-term studies with this system are recommended. Around the world, Indigenous agroforestry practices have shown their effectiveness in boosting biodiversity, improving soil health, and enhancing climate resilience. A review of different case studies demonstrates how adaptable these practices can be across regions facing similar agricultural challenges. By combining traditional knowledge with modern agroecology, Puerto Rico and other tropical regions can create sustainable solutions for food production and ecosystem healing. This research highlights the importance of further investigating Indigenous farming systems as a viable path toward recovering both agriculture and the environment.

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Abstract

The complex plant species assemblages associated with Indigenous agroforestry systems were developed over millennia to adapt to an ever-changing environment, often mimicking the elevated levels of biodiversity and natural disturbances found in natural forest ecosystems. Previous research has demonstrated that multi-storied Indigenous gardening systems contribute significantly to biodiversity conservation, soil health, and heat mitigation. Accordingly, adopting these methods could help 21st-century agricultural resource managers enhance the resilience of food production systems in a rapidly changing climate, including increased periods of heat, drought, rainfall, and biodiversity loss. This review paper highlights the ecosystem services supported by Indigenous agroforestry practices, their historical roots, positive species interactions in ecosystem services, and their ability to sustain food production within their communities. By reviewing 82 global case studies, I documented and analyzed the contributions of Indigenous agroforestry systems to biodiversity conservation, soil conservation practices, and their ability to withstand climate extremes. Additionally, I compared the case studies to determine complementary adaptations across the regions in question. The paper underscores the importance of highlighting the contributions of ancient traditional ecological knowledge to 21st-century problems, while also advocating for collaborative efforts to ensure the conservation of Indigenous agroforestry systems.

Keywords: agroecology, Indigenous food systems, multi-storied home gardens, regenerative agriculture, soil ecology,

1.1 Introduction

Agriculture is at a critical turning point wherein conventional agricultural practices have struggled to address the demands of a growing population and an increasing number of environmental threats (Perfecto, et al. 2019). In the 20th century, modern agriculture reigned as the preferred mode of production, prioritizing cash crops produced in monoculture systems supported by chemical fertilizers, pesticides, and heavy equipment to till (Kremen, et al., 2012). Currently, approximately 44% of the Earth's land area is utilized for agricultural production, with industrial agriculture the driving force behind cropland usage on large pieces of land (Ritchie & Roser, 2024). Although industrial agriculture has created a temporary boost in our ability to produce food, it has also generated a significant amount of environmental and ecological degradation. Indeed, industrial agriculture's dependence on monocrops has led to reduced genetic diversity of commercial plant species and a strong reliance on external inputs (e.g., chemical fertilizer, herbicide, insecticide; Francis, 2019). The cumulative effect of these practices has been the destabilization of global food systems, with agricultural productivity becoming increasingly erratic and less sustainable over time (Khatri et. al. 2023).

Compounding the problem of unsustainable practices is the unpredictability in current global weather trends, including the frequency and severity of natural disasters (Ericksen, et al., 2011). Extreme weather events perpetuate major disruptions in our ability as a society to harvest, sustain, and distribute products within the agricultural infrastructure (Altieri, et al., 2015). These challenges are especially significant in the Earth's equatorial belt, where small-scale farmers are severely impacted by a lack of resources to combat and adapt to these changes (Raj, et al., 2022). In turn, food security consistently rises to the top of a list of concerns threatening United

Nations' Sustainable Development Goal #2 (to end global hunger by 2030; THE 17 GOALS | Sustainable Development (un.org), accessed 18 October 2024) and allowing less resource-rich communities down a path of hunger and malnutrition.

Accordingly, there is a growing need for global society to adopt alternative agricultural practices that that promote long-term productivity, sustainability, and resiliency in the face of climate change (Ahsan et al., 2021). Agroforestry, an agricultural system that incorporates trees, shrubs, and other flora into a production system that essentially is meant to mimic natural forest ecosystem settings, canopy structures, and enhance ecosystem services (Riyadh, 2021). Globally, Indigenous communities have played an essential role in keeping these sustainable agricultural management systems relevant in an increasingly mechanized society (Lelamo, 2021; Tewari, et al. 2022, Ntawuruhunga et al., 2023). Indigenous agroforestry methods are often sustained through generational teachings and the ability to identify sustainable natural resource uses and understand their local environments (Rossier & Lake, 2014).

Agricultural systems that enhance ecosystem function (e.g., soil microbial activity, leaf litter/nutrient cycling, mycorrhizal networks, and rhizobia nitrogen fixation; Rossier & Lake, 2014; Bilali et al., 2018; Pantera, 2019; Nair et al., 2021) play a pivotal role in soil health, carbon sequestration, water retention, and provision of habitat for beneficial faunal species (e.g., pollinators and predatory insects; Power, 2010; Udawatta et al., 2019). Agroforestry enhances ecosystem services through the implementation of woody perennial species and groundcover to prevent soil erosion (Fahad et al., 2022). Specific strategic measures like providing shade for minimizing heat and light stress, mulching through leaf litter and shredded residual material, and moisture-retaining plants can help aid in water retention and actively contribute positively to hydrological cycles. Water conservation is achieved by strategically using shade, mulching, and moisture-retaining plants, which minimize water loss, support natural hydrological cycles, and maintain microclimates that reduce the need for conventional irrigation systems (Norton, 2019).

Historically, the bulk of agroforestry literature has tended to focus on discrete categories (e.g., alley cropping, windbreaks, etc.; Atangana et al. 2014) of agroforestry production, as well as biophysical aspects of the discipline (e.g., soil fertility; Nair 1998). In contrast, emphasis on Indigenous management of tree-based systems, as well as categorical distinctions associated with Indigenous food production, has been less clear (Nair et al. 2017). While not traditionally viewed as a form of agroforestry, slash-and-burn (or swidden) agriculture, in which small patches of primary or secondary forest are razed for temporary crop cultivation, is one of the oldest forms of food production (Van Vliet et al. 2013, Maezumi et al. 2022). Indeed, since the late 20th century, modern practitioners of this method have often been cited for high rates of tropical forest loss and soil degradation due to repetitive cycles of the method (see Fujisaka et al. 1996, Tinker et al. 1996, Silva et al. 2021). Yet when practiced sustainably, this food production model can serve as a regenerative method that enriches soil fertility, controls pests, and fosters biodiversity (Padoch and Pinedo-Vasquez 2010, Bezerra et al. 2024). Indigenous communities carefully manage fallow periods, allowing forests to regenerate and restore soil nutrients before replanting, creating a cyclical balance that minimizes long-term degradation (Mukul et al., 2016). Unlike large-scale deforestation that is typically associated with industrial land clearing, traditional slash-and-burn agriculture operates on a rotational basis, ensuring that land is not overexploited while also supporting the next cycle of canopy-providing trees (e.g., Schmidt et al.

2021). This well-established approach highlights how intensive agriculture can unify with ecological stewardship, use modern technology to its advantage, and adapt it for climate-smart agricultural production.

Indigenous agroforestry practices can serve as an excellent point of reference for developing agroecosystems with the potential to adapt to climate change and thrive within a given microbiome (Imoro et al., 2021). This review explores global Indigenous agroforestry designs and methods as a blueprint for adapting to climate change and food security in the global south. The paper emphasizes traditional knowledge in agroforestry systems, demonstrating a positive impact on food security, climate resilience, carbon sequestration, and community health through socio-ecological resilience. This research's primary goal is to highlight the success stories of Indigenous societies that can sustainably produce enough food within their communities through reliance on local resources and minimal inputs (Martinez-Cruz & Rosado-May, 2022). Examining each unique bioregional system's ecological, socio-economic, and cultural aspects reveals how different geographical conditions correspond to adaptability and diverse agricultural issues.

1.2 *Research questions*

1. **Question 1:** Do Indigenous agroforestry systems reduce the vulnerability of food crops in extreme weather events and enhance their adaptive capacity?

   Hypothesis: Indigenous agroforestry systems reduce food crops' vulnerability to extreme weather events and enhance their adaptive capacity by improving landscape resilience and local resource availability.

2. **Question 2:** Do Indigenous agroforestry systems enhance local biodiversity?

   Hypothesis: Indigenous agroforestry systems enhance local biodiversity by creating habitat diversity and supporting species richness, in contrast to the monoculture of conventional agricultural systems.

3. **Question 3:** Do Indigenous agroforestry support soil conservation practices?

   Hypothesis: Indigenous agroforestry practices improve soil conservation by reducing erosion, enhancing soil fertility, and increasing organic matter through natural, continuous nutrient cycling.

4. **Question 4:** How do Indigenous practices compare across different regions?

   Hypothesis: Indigenous agroforestry practices across regions reveal common ecological principles, such as biodiversity integration and resource cycling, alongside unique adaptations tailored to specific environmental and cultural contexts, contributing to their long-term ecological success.

This research merges historical context, environmental data, and ethnographic insights to interpret the patterns in which Indigenous agroforestry projects promote food sovereignty across generations. The study's framework is rooted in socio-ecological resilience theory, highlighting links between communities and their environments (Fajardo Cavalcanti de Albuquerque, 2019). By examining these systems through the lens of climate resiliency, the study assesses the ability of Indigenous agroforestry systems to enhance adaptive capacities against natural disasters and to increase food security, offering valuable insights into practices that could contribute to 21st century food security and biodiversity conservation efforts.

1.3. Methods

The research used throughout the paper consists of a blend of primary and secondary sources, including ethnographic fieldwork, literature reviews, and some archival studies, to investigate the socio-cultural dynamics and effectiveness of implementing Indigenous agroforestry practices. Eighty-two articles were selected for comprehensive analysis through keyword searches, yielding scholarly work findings and informing further literary analysis. A few studies were excluded from the analysis because they did not fully align with the focus of Indigenous agroforestry. Many historical and anthropological studies were incorporated to explain the origins of these practices. The authors of the study (Branch et al., 2008), used Geographic Information Systems (GIS) mapping through the Floramap platform (FloraMap: a computer tool for predicting the distribution of plants and other organisms in the wild, CGIAR.org; accessed 30 October 2024) to assess land use patterns and biodiversity within these systems. In addition, soil fertility and crop yield data from existing studies and field observations were documented to evaluate the sustainability of the agroforestry practices. Key journals like Agroforestry Systems, Ecological Applications, and Global Good Security were examined for the review, with keywords used to retrieve relevant sources from platforms such as Google Scholar and JSTOR (See Tables 1.1 and 1.2 below).

To select articles for the review paper, I carried out keyword searches on academic platforms such as Google Scholar and JSTOR, specifically examining Indigenous agroforestry (See Table 1.2 below). A total of 82 articles were analyzed, focusing on both primary and secondary sources, which included ethnographic studies, historical and anthropological research, as well as scientific literature. Some studies were excluded if they did not closely align with the research objectives. Additionally, I examined key journals like Agroforestry Systems, Ecological Applications, and Global Food Security for relevant publications.

To assess the sustainability of these practices, we incorporated GIS mapping along with soil fertility and crop yield data obtained from phytolith analysis. This study particularly examines Indigenous agroforestry systems and their effects on soil fertility and crop yield. GIS enables us to explore land-use patterns, biodiversity, and microclimates in regions like Puerto Rico's Cordillera Central and the dry forests of Honduras, illustrating how Indigenous methods can reduce erosion and enhance climate resilience. Phytolith analysis provides valuable insights into the historical aspects of crop cultivation and soil management, revealing long-term nutrient cycling in agricultural systems such as the Quechua *milpa* and Taíno *conuco*. By combining GIS spatial data with evidence of historical agricultural practices derived from phytoliths, this research demonstrates the effectiveness of Indigenous techniques like intercropping and mulching as responses to current soil degradation issues. This interdisciplinary approach bridges traditional ecological knowledge with modern agroecology, offering policy recommendations for expanding these practices in areas at risk from climate change. While short-term studies may limit immediate conclusions, the integration of GIS and phytolith data highlights the enduring sustainability of Indigenous agroforestry.

Table 1.1 Categories of sources reviewed.

Category	Number of Journals
Peer-reviewed journals in agriculture, environment, and sustainability	22
Interdisciplinary and Socio-ecological Peer-reviewed Studies	12

Peer-reviewed journals forestry and agroforestry	9
Peer-reviewed journals in development and policy	14
Books	11
Reports and case studies	13

Table 1.2 Keywords

Indigenous agroecology
Indigenous agroforestry
Indigenous food production
Indigenous forest farming
Indigenous gardens
Indigenous multi-storied home gardens
Indigenous permaculture
Indigenous sustainable agriculture
Indigenous swidden agriculture

1.4 Results

1.4.1 Case Study Selection and Criteria

The selection of Indigenous agroforestry systems for analysis was intentionally limited to tropical regions with historical significance and a strong capacity for biodiversity conservation, as well as those that demonstrated resilience in addressing food security challenges across diverse ecological conditions (See Table 1.1 above). The focus was primarily on tropical agroforestry systems, as these regions are not only rich in biodiversity but also align closely with the central theme of the thesis, Taíno agroforestry systems. These systems, once prevalent across the Caribbean, were severely impacted by colonialism, resulting in a loss of cultural practices and agricultural knowledge (Clarke, 1983).

Table 1.3 Agroforestry methods evaluated (by region).

Geographical region, economic species of importance, & agroforestry systems implemented	Agroforestry method description	References
Andean region (Quechua *Milpa*) – Heirloom Potatoes, Maize, Quinoa	• This Andean agroforestry system was selected for its integration of terraced agriculture, intercropping techniques, and emphasis on seed/genetic conservation	Nair et al. 1999; Agrawal et al. 2001; Bendix, et al., 2013; Branch et al., 2008; Sarapura-Escobar & Hoddy, 2022; Chifamba & Nyanga, 2012; Duran-Diaz, 2023; Bruckmeier & Pires, 2018; Angelakis, et. al., 2020; Pimbert, 2022; Abidi, et. al., 2024; Figueroa et. al. 2018; Mazess. et. al. 1964
Guatemala (Mayan *Milpa*) –Maize, Beans, Squash	• The Mayan *Milpa* system was chosen for its practice of alley cropping the "Three Sisters" (corn, beans, squash) • Exemplifies sustainable land use through ecological independence and cultural heritage.	Fonteyne, et. al., 2023; Kapayou et. al., 2023; Riyadh et al., 2021; Pantera, 2019
Honduras (Lenca Quesungual) – Coffee, Beans, Maize	• Combines coffee production with fruit trees and annual crops like maize and beans. • System illustrates effective moisture retention, soil protection, and enhanced crop yields in dry tropical regions.	Barahona, 2017; Ordonez-Hellin, 2018; Schnetzer, 2018
Tanzania (Chagga Home Gardens) – Tropical Fruit Trees & Sustainable Livestock Management	• Selected for rich biodiversity and complex multi-layered structure on relatively condensed pieces of land.	Fernandes, et al., 1985; Hemp, 2006; Nair, 2021; Mbilinyi et al., 2016; Kingazi et al., 2024

	• Home gardens combine fruit trees, staple crops, and livestock in a harmonious system • Sustains households and promotes soil health in populated areas.	
New Zealand (Maori Mara Kai) – Sweet Potato, Taro, Gourd	• Incorporation of native trees like kanuka and manuka alongside food crops such as jumara and taro promote food security. • Mara Kai was included for its deep cultural and spiritual connections, demonstrating Indigenous stewardship and connection to land.	Smith & Hutchings, 2023; Webb Malone, 2023; Reid, Et al., 2024; Miller, 2007; Glassey et al., 2023
Northeast India (Khasi "Jhum") – Rice, Millet, & Maize	• Shifting cultivation, a unique agroforestry system known for its ability to maintain biodiversity and regenerate soil fertility. • The rotational system highlights sustainable land use, nutrient cycling, increased microbial activity, and cultural continuity.	Poffenberger, 2006; Sati & Lalmalsawmzauva, 2017; Kamruzzaman et al., 2019; Jeeva, 2014; Dkhar et al., 2012
Southeast Asia (Hawaiian Ancient Agriculture "ahupua'a"**) –** Taro, Sweet Potato, & Bananas	• Deeply rooted in complex systems with the use of taro and food forests, colloquially referred to as (alae). • Exemplify sustainable land use through the integration of native	Soroka, 1995; Anderson-Fung & Maly, 2002; Langston & Lincoln, 2018; Elevitch & Ragone, 2018; Perroy et al., 2016; Watson, 2006; Ka'onohi et al., 2023; Nakaoka, et al., 2019; Kurashima et al., 2019

	plants and water management practices. • Systems reflect deep cultural connections to the land and showcase biodiversity conservation and food security in rugged island-ecosystem terrain.	
Caribbean (Taíno Conuco/Monton) – Tubers, Soursop, and Maize	• Research follows the transition from slash-and-burn agriculture to the Spanish-documented conuco method • Use of mulch mounds and aerated, organic matter-based plotting methods. • Highlights ecological insights and social transformations that informed sustainable agricultural practices during the pre-colonial period.	Beckford & Campbell, 2013; Rouse, 1993; Ortiz Aguilu et. al., 1991; Pagan-Jimenez, 2011 Fernandez, 2021; Siegel, et. al., 2008; Las Casas, 1927; Moscoso, 1997; Watlington, 2019

1.4.2 Review of methods for agroforestry system assessment

The journal articles and other selected sources utilized quantitative and qualitative methods to analyze the ecological and social benefits of Indigenous agroforestry practices with data gathered using methods outlined in Table 1.4.

Table 1.4. Research Collection Methods

Ethnographic Interviews & Participant Observation	• Interviews with Indigenous farmers, community leaders, and agricultural experts • Field observations' assessment of agroforestry structures and the role of traditional knowledge • Spanish primary sources and archaeological soil analysis to determine historic land use in Puerto Rico
Soil and Crop Yield Analysis	• Secondary data on soil fertility, crop yields, and biodiversity drawn from local agricultural studies and FAO reports. • Datasets analysis to compare productivity and resilience across the selected case studies.
Cultural and Ecological Literature Reviews	• Archival research conducted to review historical context of each agroforestry system • Examination of the evolution of practices in response to colonialism, land-use change, and climate pressures.
GIS Mapping and Landscape Analysis	• Land use patterns, forest cover, and agricultural expansion were analyzed using GIS to measure the extent of agroforestry practices • Impact of agroforestry systems on biodiversity conservation and soil erosion also measured • Programs used, Floramap and Homalogue

1.4.3 Quechua *Milpa* Terraces

In many regions of the contemporary Andean region, socioeconomic influences are constantly reflected in an agrarian-centric point of view on agriculture as a comprehensive system (Sarapura-Escobar & Hoddy, 2022). This perspective, centers around utilizing land for soil and water resources, methods of cultivation for domesticated plants and sustainable livestock management, establishment of microclimatic framework (mini ecosystems), and techniques for conservation, storage, and the transportation of the produce to market for sale (Chifamba & Nyanga, 2012). These systems established by the Quechua people, deeply rooted in local customs and practices, differ significantly from mechanized industrial agriculture, often reflecting historical and contemporary relationships within ethnic groups and cultural symbolism (Sarapura-Escobar & Hoddy, 2022). Efforts have been made to integrate these local systems into territorial and national policies to enhance territorial sustainability. By linking urban and rural communities, these Indigenous land management initiatives aim to address various issues in resource use/management, food production, and environmental conservation (Duran-Diaz, 2023). A focus on the concept of socioecological resilience highlights the intimate connection between community culture and identity and provides an extra meaning to the importance of these resources to make meaningful impacts in sustainable agriculture and resource management (Bruckmeier & Pires, 2018).

One of the most important integrated methods evidenced in Quechua practices and adopted in Indigenous cultures worldwide for irrigation management is the presence of terraced agriculture, tracing back to the pre-Hispanic period (Angelakis et al., 2020). An archaeological study conducted by Branch et al. (2007) in the Chicha-Soras Valley of Peru extensively details distinct periods of occupation, settlement patterns of the valley's inhabitants, and notable changes in pottery construction – an important indicator in pre-colonial sociological and anthropological analyses for understanding societal functions of the period.

Per Branch et al.'s 2008 investigation, the phytolith analysis of two terrace profiles – Infiernillo and Tocotoccasa, abbreviated as INF and TOC, respectively – provides insight into the vegetation and agricultural practices of the Chicha-Soras Valley during the Middle Horizon (c. 600-1000 CE) and Late Intermediate Period (c. 1000-1470 CE). For the INF Terrace Profile, paleopedological and geochemical analyses revealed a well-defined soil horizon characteristic of a buried terrace soil profile, identified as a heavily weathered 2bBt horizon. This horizon aligns with an argillic horizon classification in modern soil taxonomy, indicating significant clay accumulation due to pedogenic processes. Radiocarbon dating of wood charcoal samples from 2aAt horizon further confirmed that terrace dates to the Middle Horizon, with additional verification provided by associated ceramic artifacts. Phytolith morphotype analysis indicated substantial maize (*Zea mays*) cultivation, underscoring its agricultural importance in the region. Although the sample size is limited, this methodology could serve as a valuable tool for paleobotanists in reconstructing native vegetation patterns of ancient landscapes. Similarly, the TOC Terrace Profile exhibited distinct soil horizons, including a 3bAh horizon representing the original sloping land surface and a 2bAh horizon indicative of a prior agricultural terrace. The presence of these horizons suggests long-term soil modification and management practices consistent with anthropogenic influence on landscape formation (Branch et al., 2008).

The Indigenous agroecosystems native to the Andean Mountain region tend to operate across many different ecological zones and regional biomes that each provide distinct characteristics and ecosystem services (Bendix et. al., 2013).

Despite challenges such as poor soil quality and erosion, Quechua communities prioritize and maintain natural resources through traditional practices of *Milpa* production. Specifically, from a socioecological perspective, women in Quechua communities play a significant role in seed selection, biodiversity management, and usage of agricultural products for traditional usage (Pimbert, 2022). This Agroforestry system utilizes an intercropping system of Botija olives (*Olea europea*), maize (*Zea mays*), potatoes (*Solanum tuberosum group andigenum),* beans (*Phaseolus vulgaris*), goosefoot (*Chenopodium*), barley (*Hordeum vulgare*) and quinoa (*Chenopodium quinoa*) combined with the planting of trees such as cinchona, cedar, and *Schinus molle* (Abidi et. al., 2024, Mazess et. al. 1964). The *Milpa* agricultural system consists of terraces on sharp slopes with stone retention walls and earthworks to prevent eroding soil along watercourses (Figueroa et. al. 2018).

1.4.4 Mayan *Milpa* "Three Sisters"

In Guatemala's fertile highlands, Indigenous Mayan communities developed the Mayan *milpa* agroforestry system, which has reflected much innovation regarding ecological dynamics while preserving their cultural identity and planting in a way that is distinct to the region's topography and unique climate (Fonteyne et al., 2023). Essential in the *milpa* system is the use of a synergistic intercropping technique hailed as the "Three Sisters": corn, squash, and beans. This combination exemplifies the historical conservation of these varieties and methods but also demonstrates crop diversity, sustainable practices, and an additional income source.

This cropping succession has been cultivated together over many centuries as an important agricultural tradition for the Mayan communities (Kapayou et al., 2023). Corn's role in the system is as a trellis support for the beans, which, as a vine, climb up the corn meristem as the beans (leguminous plant) fixate atmospheric nitrogen into the soil to increase fertility (Kapayou, et al., 2023). Squash provides a ground cover that helps retain moisture in the soil by shading it and keeping it from drying out while at the same time suppressing weed growth. This group of plants proximity to one another within the system plays a positive role in boosting crop health and embodies positive traditional wisdom which transcends conventional methods of production for these crops (Fonteyne et al., 2023). In addition to the Three Sisters, *milpa* agroforestry incorporates a diverse assortment of fruit trees, coffee, bananas, and plantains, but mainly spicy chili peppers (*Capsicum* spp.) within an integrated system (Xu, et al., 2020 - see Fig. 2.1, https://www.nal.usda.gov/collections/stories/three-sisters).

This integration of trees and perennial crops introduces a multi-layered approach to agriculture. Fruit trees provide a valuable source of sustenance and income for Mayan communities. Coffee has become an essential cash crop, contributing significantly to local economies. The shade offered by the fruit trees benefits the coffee plants, helps maintain soil moisture, and prevents erosion, ultimately fostering a more resilient and sustainable agroecosystem (Riyadh et al., 2021). The Mayan *milpa* system promotes significant cultural and ecological elements. This method calls attention to the Mayan people's devotion to their land stewardship within their environment, which showcases the adaptability of their ancient ancestral systems in modern-day society. This system's adoption of a holistic perspective underlines the inherent mutualism between us as humans and our surroundings. Amidst universal sentiment towards sustainable management practices, the *milpa* stands as a compelling model, demonstrating how traditional knowledge can provide culturally and ecologically viable solutions in the face of modern agricultural challenges (Pantera, 2019).

Figure 1.1 *Photo of "Three Sisters" Mayan Milpa agroforestry system* Zea mays, *Phaseolus vulgaris, Cucurbita pepo.*
(Photo credit – Secretaría de Desarrollo Sustentable, Gobierno del Estado de Yucatán via Flickr, 2019).

1.4.5. Honduras Lenca Agroforestry

Indigenous agroforestry can sustain a harmonious natural system and at the same time, yield numerous ancillary advantages. For example, within the *Lenca* community in Honduras, a woman's cooperative was created to provide an avenue to produce fair trade, organic coffee operations grown amidst the lower canopy with trees sectioned off for timber production as well as fruit trees, a way to bolster food security with heightened yields (Barahona, 2017). The practice's remarkable productivity holds clear advantages for the participating communities. The diverse coexistence of trees, shrubs, and annual plants amplifies yields through enriched soil fertility and moisture retention, while yielding an array of crops with varying timelines. For instance, as the Lenca people in Honduras await the ripening of their coffee beans in the arid forests of the region, they concurrently reap other harvests like plantains, or ice cream fruit (*Inga edulis*), which they can exchange at markets with communities that grow other staple products such as corn from other nearby communities practicing a similar form of agroforestry called *quesungual (*Barahona, 2017).

Mostly centered around subsistence consumption, *quesungual* uses techniques that combine coffee bushes with strategically pruned fruit trees (adequate sunlight exposure) that in turn, create cool, semi-shaded environments with moist, well-drained soils that help facilitate the cultivation of maize and beans specifically in tropical dry forests (Ordonez & Hellin, 2018). This system allows for a protective blanket covering the soil, eliminating the need for tilling and fostering soil structure preservation, erosion prevention, and reduced water loss. Fivefold increases in soil loss and 25% to 60% water runoff in slash and burn plots compared to *quesungual* with 54% increase in corn and 66% increase in bean yield (Schnetzer, 2018).

1.4.6. Chagga Home Gardens

The Chagga people over many generations have converted their homesteads into thriving biodiversity islands, producing both sustenance and boasting ecological services. Established initially by the Chagga tribe on the peaks of Mt. Kilimanjaro, Chagga gardens are typically small-scale subsistence silvopastoral systems meant to feed individual families or small villages (Fernandes, et al., 1985). Intricate mixes of vegetable/tuber crops, fruit trees, and livestock, are carefully selected to take on its own role in the homestead's ecosystem. Some of the Chagga main crops in production include bananas, coffee, beans, maize, and other fruits and vegetables of lesser economic value (Fernandes, et al., 1985). The Chagga design small multi-level forestry systems with taller trees providing shade and an upper canopy for lower canopy trees like coffee that need shade to grow. This in return also provides the soil with a steady supply of leaf litter and mulch from the residual materials, enhancing organic matter and soil microbial activity (Fernandes, et al., 1985).

Some of the main livestock used in these silvopastoral systems, including chickens, goats, and cows, graze and fertilize in the sites, and in return, produce meat (Hemp, 2006). The Chagga garden's sustainable nature makes it an ideal candidate as a model project for organic/regenerative operations as the ecosystem services provided by the forestry setting limit the need for synthetic pesticide treatments and fertilizers. Chagga's reliance on biological pest control through intercropping or decoy planting (trap cropping - this method is an agricultural technique that uses specific crops, known as decoys, to attract pests away from your main crops. By enticing pests to these designated plants, it safeguards your primary crops from damage and enhances the focus and efficiency of pest management concerning the decoy plants). for their crops of higher importance. These crops include coffee, beans, maize, and leafy vegetables , as well as other economic species like *Datura arborea* and *Rauolfia caffra*, which repel insects (Fernandes, et al.,1985). In addition to decoy planting, the Chagga also intercrop species of wildflower and nitrogen-fixing trees for optimizing pollination and fixating nitrogen (Nair, 2021). Rainwater harvesting is very popular in this region and is often incorporated as an efficient use of irrigation and conservation of drinking water (Mbilinyi et al., 2016). The high levels of species variability in the home gardens allow for minimal crop failure susceptibility to pests and diseases (Kingazi et al., 2024).

1.4.7. Maori Mara Kai Agroforestry Gardens

The Mara Kai Maori Agroforestry Gardens from New Zealand, often referred to as "Māra Kai," is a large representation of the Maori cultural identity and is especially becoming adopted as an urban forestry sustainable land management practice (Smith & Hutchinson, 2023). This system is based on the usage of both crops for consumption and native, non-fruit bearing trees within a single cultivation space. One standout of the Maori's planting technique is the incorporation of endemic shrubs and trees specifically *Kunzea ericoides* and *Leptospermum scoparium* intercropped alongside traditional food crops like *kūmara* (sweet potato), taro, and various greens (Webb Malone, 2023). The trees and shrubs are utilized in these systems as windbreaks, medicinal plants, and regenerative timber (Reid, et al., 2024). Generations of Indigenous knowledge and experience guide the careful selection and placement of plants within the Māra Kai system. Beyond its ecological benefits, Māra Kai holds profound cultural significance for the

Māori people and its preservation allows for the study of the technique and how it can be incorporate in other areas.

The Mara Kai Gardens demonstrate a deep connection between the land, the Maori and their ancestors, and their bridge to the spiritual realm. These practices connect to the land, ancestors, and the spiritual realm. Traditional Māori values like *kaitiakitanga* (guardianship), *whanaungatanga* (relationships), and *manaakitanga* (hospitality) are embodied in this practice (Miller, 2007). The mastery of Māra Kai is carried from generation to generation through oral storytelling and interactions within the communal network to promote the preservation of Mara Kai as a green alternative for sustainable farming. In recent years, there has been an uptick in research being conducted amongst the local universities of New Zealand where Māra Kai is being evaluated to potentially address contemporary challenges such as food security, environmental conservation, and cultural revitalization (Glassey et al., 2023).

1.4.8. Khasi Jhum Agroforestry

For centuries, the Khasi people of Northeastern India have been engaging in an ancient Indigenous agroforestry practice referred to colloquially as *jhum*, a subsistence method of production. The protocol for implementing the practice starts off as the farmers clearing out select vegetated areas to grow consumable crops, followed by a significant fallow period so as not to disturb the soil microbes (Poffenberger, 2006). Some of the main crops grown in these systems consist of rice, maize, millet, and vegetables. The ecological services provided based off the biodiversity from the intercropping with Indigenous tree species has fueled an increasing sustainable timber industry as well as aid in the production of fruit crops with a large organic matter retention rate from leaf litter (Sati & Lalmalsawmzauva, 2017). *Jhum* also facilitates the preservation of local plant genetic diversity, a seed collection can also take place in clearing areas post-harvest (Kamruzzaman et al., 2019).

By establishing pre-determined rotations in the shifting cultivation methods, the Khasi are able to overcome nutrient loss on the land, letting the regeneration process take place naturally as forests need time to replenish the ecosystem services. The cleared field, due to large amounts of organic matter from removing vegetation, allows for green mulch material to serve as a foundation with organic matter and micronutrients that promise high yields. When fallow, the cleared areas regenerate, and the adjacent forest supports the system via a diverse flora and fauna (Sati & Lalmalsawmzauva, 2017). Understanding how forest's ecosystem services are crucial for the production of crops is a key component of Khasi cultural consciousness (Jeeva, 2014). Efforts to support and promote Khasi agroforestry while respecting their cultural heritage and traditional knowledge are essential for preserving both the landscape and the unique way of life that has sustained the Khasi people for centuries. In a rapidly changing world, the Khasi's deep-rooted relationship with their environment serves as a reminder of the importance of harmonious coexistence between humans and nature (Dkhar et al., 2012).

1.3.9 Hawaiian Ancient Agriculture

The Hawaiian Islands have a unique agricultural history that intertwines Indigenous knowledge and local ecological systems. Native Hawaiian cultivation practices, passed down over centuries, represent a holistic relationship with the land and sea that evolved from the islands' geographical isolation and diverse ecosystems. Early Polynesian voyagers brought essential crops such as taro

(*Colocasia esculenta*), breadfruit (*Artocarpus altillis*), and coconut (*Cocos nucifera*), which flourished in the tropical environment and supported large communities in one of the most remotely inhabited places on Earth (Soroka, 1995). The Native Hawaiian agricultural systems, particularly the *ahupua'a* land management model, were intricately designed to meet ecological, social, and economic needs. These systems actively engage in sustainability by distributing land from the mountains to the sea, allowing communities to access a variety of resources across different ecosystems (Anderson-Fung & Maly, 2002). In the *ahupua'a*, farmers created irrigated terraces for taro (lo'i kalo) in wetter, low-lying areas and used drier lands to grow sweet potatoes (*Ipomoea batatas*), yam (*Dioscorea* alata spp.), and breadfruit. By incorporating layers of plants with different functions—with shade-providing breadfruit, medicinal plants serving as groundcover, this complex system is inherently resilient (Langston & Lincoln, 2018). The optimization of water use and prevention of soil erosion through planting deep rooting species allows for success, particularly in mountainous areas. These practices allow Native Hawaiians to meet their nutritional needs while conserving resources, underscoring a sustainable, symbiotic relationship with the land (Elevitch & Ragone, 2018).

The arrival of European explorers in the late 18th century altered Indigenous land management in Hawai'i. The ensuing plantation-style economy prioritized profit over sustainable practices, transforming swathes of fertile land into monocultures of sugarcane and pineapple. The shift in land ownership marginalized Native Hawaiians, depriving them of traditional food sources and effectively erasing their cultural practices (Perroy et al., 2016). Towards the end of the 19th century, Western economic structures further modified Native land management. Institutions like Kamehameha schools were established to benefit Native Hawaiians, but initial mandates emphasized financial gain over cultural preservation (Watson, 2006). It was not until recent decades that a renewed focus on Indigenous values, such as viewing land as *aina* (an elder or an entity), rather than as a commodity, began to reshape these management practices and shifted towards sustainability and cultural respect. Since the 1970s, there has been a growing movement within the Native Hawaiian community to revive traditional farming practices as part of a broader cultural renaissance (Ka'onohi et al., 2023). This resurgence aligns with the concept of preserving cultural identity and food security through the lens of these methods. Projects like Ho'okua'aina integrate farming with social services, 12

By leveraging Indigenous knowledge and reviving underutilized land, Hawai'i could significantly reduce its dependence on imported food and start to supply its own, which would be constituting 87% of its supply if incorporated correctly (Ohara, 2024). Implementing this ancient knowledge with the revival of land that is not currently in agricultural use, Hawai'i can begin to reduce its reliance on imported products, currently making up 87% of its actual consumption (Ohara, 2024). The ability to restore these systems could create a positive climate value added (CVA) by expanding ecological services from nearby forested areas that can aid in soil regeneration and be used as the baseline for Hawaiian agricultural policy reform. CVA helps us grasp how climate-related risks and opportunities can impact the finances of businesses and investment portfolios. It often employs Value-at-Risk (VaR) analysis to quantify this impact (Randers, 2012). Native Hawaiians' commitment to reinstating these traditional systems demonstrates a cultural resilience and respect for wisdom and community-based agriculture to thrive amidst a critical period of global economic and environmental challenges (Kurashima et al., 2019).

1.4.10. Caribbean Indigenous Methods

In the modern era, it has long been the consensus that food production in the Caribbean, much like other Indigenous cultures, relied heavily on swidden agriculture as the most prevalent technique dating back to De las Casas' and Columbus' first-hand accounts (Beckford & Campbell, 2013). Upon the arrival of the Spanish, the Taino were in the midst of an agricultural shift in method - *monton* or *conuco* in Taíno (Rouse, 1993). The emergence of the *conucos* as a standard practice during this period suggests that the nutritional needs of the Taíno population required a more systematic approach for constructing and maintaining healthy soil aggregates (Ortiz Aguilu et al., 2019). Based on palaeobotanical research, it is believed that the mosaic of Indigenous agroecosystems became integrated into the landscape just before Spanish ships touched down on Caribbean shores. Expansion likely occurred due to the growing population and restructuring of social organizations and hierarchy within the different Taíno communities (Rouse, 1982). This transition from small scale agriculture to a labor-intensive and highly organized system was likely driven by an increase in population density within the Taíno populations, which required higher yield production to meet demand and the evolution of localized land management practices (Rouse, 1982).

As far as proof of this agricultural transformation, terracing systems constructed with retaining stone walls closely resembling the Quechua *milpa* systems from the Andean highlands in the southern part of the *Cordillera Central* of Puerto Rico in the municipality of Cayey (Ortiz Aguilu et al., 1991). The preservation of this structure indicates the emphasis on permanent farming techniques as opposed to dispersed and non-permanent farming areas (Ortiz Aguilu et al., 1991). These terraces were discovered within close proximity of confirmed village sites with a combination of different ceramics, each with unique styles corresponding with different ancestral influences, which include Late Ostionoid, Capa, and Saladoid as well as a historic village “plaza” which contained stone drawings or “petroglyphs” (Siegel et al., 2008). Due to Puerto Rico’s colonial history, it has been notably difficult tracking the Indigenous lineage for Puerto Rican citizens. These historical findings leave a great model to follow and incorporate into present-day strategies for environmental protection, literal sustainability through stone retention terraces, and food security (Ortiz Aguilu et al., 1991).

The knowledge of pre-colonial agricultural practices in Puerto Rico and many other aspects of Taíno civilization have traditionally been based on Spanish explorer observations, including diaries and direct reports to Spanish royalty. Much of the knowledge of Taíno agricultural systems particularly as it pertains to Puerto Rico has largely been based on personal primary sources derived from Spanish colonizer accounts and official reports submitted to the Spanish crown. The Spanish sources over the years have ignited debates on the accountability and historical accuracy amongst researchers. However, our access to modern technology has allowed us to examine archaeological sites and soil sampling to determine the sophistication of this agrarian society contrary to previous notions of agricultural simplicity across Caribbean Taíno settlements. Soil sampling collected around the Laguna de Tortuguero on Puerto Rico’s northern karst coastal region exhibited human activity which dated back to between 4000-2500 B.C. as well as the evidenced presence of burned soil successions in preceding the Taínos (Pagan-Jimenez, 2011; Fernandez, 2021).

Further insights into Taíno agriculture in the 1500s come from the accounts of Spanish naturalists and chroniclers such as Pane, Friar Bartolome de Las Casas, and Fernandez de Oviedo. The descriptions provided highlight the complex processes involved in cultivation techniques, harvesting, and food preparation (i.e. *pan casabe*, *cojoba* nuts, ground *achiote* seeds). The most documented of the techniques gathered from the burned soil cycles is the use of slash-and-burn and raised *conucos* or *montones*. In some areas, natural methods of irrigation canals and terracing systems were also integrated (Las Casas, 1927). *Conucos*, are large mounds of soil, organic matter, and mulched debris sometimes reaching up to one meter in height with an aerated, permeable texture designed specifically to facilitate the distribution of rainwater efficiently, establish strong root systems to prevent erosion/soil loss, and to facilitate the growth of a wide array of crops in an integrated agroforestry system on mountainous terrain (see Fig. 2.5; https://www.iaacblog.com/programs/deliriums-colonized-people-agriculture-subject-political-condition-puerto-rico/, accessed December 2, 2020). Three of the most culturally important staple crops to the Taíno were the tropical/sub-tropical tubers cassava (*Manihot esculenta*), coontie (*Zamia integrifolia*), and yautia (*Xanthosoma sagittifolium*). Some other important crops included the cultivation of maize, sweet potato, beans as well as medicinal ceremonial, or artisanal serving plants such as tobacco (*Nicoteana tabacum*), cohoba (*Anadenanthera peregrina (L.) Speg),* agave (*Agave angustifolia*), and annatto (*Bixa orellana*). Important fruit species often found intercropped within these systems included guava (*Psidium guajava*), mamey (*Pouteria sapota*), soursop (*Anonna muricata*), caimito (*Chrysophyllum caimito*), and June plum (*Spondias dulcis*) (Fig. 2.6; Pagan-Jimenez, 2011; Fernandez, 2021). While these names correspond to contemporary classifications, the genetic makeup of these crops in pre-Columbian times may have differed due to centuries of cultivation, selection, and environmental adaptations.

The sophistication and success of Taíno agricultural methods challenge the simplistic and undeveloped image often presented of the Taíno people in modern representation in Puerto Rico. The division of labor associated with cassava production during the period reflects a complex social structure, comparable to that of other major pre-Columbian civilizations across the Americas. Following the Spanish colonization of Puerto Rico in 1512, the Taíno population dwindled, agricultural practices declined, and the introduction of livestock overpowered the presence of abandoned *conucos*. This species introduction, affecting both humans and animals, drastically altered the landscape, as free-ranging livestock contributed significantly to deforestation, hindering agricultural recovery until the mid-16th century (Moscoso, 1997; Fernandez, 2021). The Taíno agricultural system, rooted in a subsistence-based economy, was ultimately supplanted by the resource-extractive, exploitation-based economy of the Spanish colonial rule. This occupation not only disrupted the development of a sophisticated Taíno society but its eventual complete demise and ecological disruption (Watlington, 2019; Fernandez, 2021).

Figure 1.3 *Conuco* terrace in production intercropped with sweet potatoes, aji dulce peppers, soursop, lemon drop mangosteen, papaya, and guava in Utuado, Puerto Rico.

1.5. Discussion

In exploring the multifaceted tapestry of Indigenous agroforestry systems across diverse landscapes and cultures, this comprehensive review underscores their ecological significance and profound socio-economic and cultural implications. With a wealth of history and hundreds of years of proven track records of highly functioning agricultural systems throughout Indigenous communities around the globe (exemplified by the Quechua Milpa of the Andean highlands, the Mayan Milpa of the Guatemalan highlands, the Lenca and Quesungual systems of Honduras, Chagga home gardens of Tanzania, Maori Mara Kai from New Zealand, a Khasi *jhum*, in Northeast India, Hawaiian Ancient Agriculture, and Caribbean Taíno *conuco* systems), this study highlights a portal into traditional knowledge cemented in ecological balance and preservation of cultural heritage and resilience. From the promotion of subsistence agrarian living promoting organic inputs and celebrations of soil health and biological residence to the deep cultural and communal connections to the environments around them, Indigenous agroforestry serves a larger purpose as an integral framework for environmental policy, promotion of cultural conservation, and methods to combat food insecurity and biodiversity loss. An important caveat to the blending of traditional knowledge with modern practices is the concept of collaborative efforts for a common goal. Moreover, the preservation and recognition of traditional knowledge embedded in these practices stand as a testament to the importance of collaborative efforts.

Despite differing climates and cultural contexts, all systems reflect a deep understanding of crop interactions that improve resilience against erosion, pests, and climate variability. These practices emphasize that agroecological diversity is essential for long-term agricultural sustainability irrespective of the geographic region. Likewise, the Chagga home gardens of

Tanzania and the Taíno conduct system in the Caribbean illustrate the ecological benefits of multi-layered agroforestry systems through the incorporation of a mix of crops, trees, and animals to establish an ecosystem capable of sustaining itself. Unlike conventional monocropping, the Chagga and Taíno practices focus on regenerative production through natural pest control and soil enrichment (via recycled organic matter) in their food production systems. These complex systems underscore how traditional knowledge offers solutions to modern challenges such as soil degradation and a stark decline in general biodiversity.
Regardless of these shared principles, each system socially adjusts to its unique biome and context.

For example, the Quechua terraces in the Andes and the recently discovered stone Taíno retention walls in Cayey, Puerto Rico deliberately tackle the challenges of farming on steep slopes, creating microclimates that establish and stabilize mountainous soil aggregates and retain water/moisture. Conversely, the Mayan Milpa and Khasi "Jhum" systems in Guatemala and Northeast India utilize rotational planting and shifting agriculture to restore forests and sustain soil fertility. These differences emphasize the need to customize agroforestry practices to local conditions, essential for current initiatives to expand these systems worldwide. cultural significance is another aspect that contemporary agricultural policies must recognize. The Maori Mara Kai system in New Zealand represents more than just a food production method; it symbolizes a spiritual connection between the people and their land by integrating food crops and native trees. Likewise, women's involvement in seed selection and biodiversity management within the Quechua and Lenca communities underscores the essential principles of gender equity and community governance inherent in these communities' systems.

These insights underscore the importance of a multifaceted strategy that prioritizes ecological and cultural adaptation. For example, agroforestry techniques like the Mayan *milpa* or *quesungual* can be incorporated into modern farming. However, this integration should take into account local microclimates, crop varieties, and community needs. To effectively scale these systems, it is crucial to combine modern technologies with traditional methods. Using tools such as satellite monitoring, GIS imagery, and mobile advisory services can improve the management of agroforestry practices, especially in tropical regions facing extreme heat and water shortages (Abhilash et al., 2021). However, technological interventions must be grounded in practical realities and aligned with the principles of Indigenous agroecosystems to promote long-term sustainability and reduce adverse mechanical impacts on the existing ecology. Furthermore, policymakers, agricultural experts, and Indigenous communities need to collaborate to ensure that traditional knowledge is not only integrated into modern agricultural practices but is also adapted to the unique environmental and socio-economic conditions of different regions (Wheeler et al., 2020).

Indigenous agroforestry practices enhance resilience to extreme weather by integrating diverse, layered plant systems that stabilize soil, regulate microclimates, and improve water retention. Examples such as Chagga home gardens and Mayan *milpa* reduce erosion, buffer temperature fluctuations, and mitigate flooding or drought by optimizing canopy cover and root systems. Additionally, deep-rooted perennials in agroforestry systems access water during dry spells, while organic-rich soils improve infiltration and prevent runoff during heavy rainfall. The biodiversity inherent in these practices reduces the risk of total crop loss due to hurricanes, heatwaves, or prolonged droughts, ensuring food availability and ecosystem health. By maintaining soil fertility and fostering beneficial relationships between plants and soil microbes, Indigenous agroforestry sustains long-term productivity and enhances carbon sequestration, thereby lowering greenhouse gas emissions (Nair et al., 1998).

In today's evolving agricultural landscape and the increasing awareness of environmental issues, the legacy of Indigenous agroforestry highlights the importance of traditional ecological knowledge and commitment to sustainable practices. Indeed, they provide a comprehensive framework for addressing today's agricultural and environmental challenges. By recognizing the ecosystem service benefits provided by Indigenous methods, modern agriculture can adopt more sustainable and resilient practices that, to date, have eluded large-scale operations (e.g., Altieri and Nicholls 2012). Though highly variable across geographic regions, the Indigenous agroforestry systems documented in this review paper share overlapping methods for managing food production that harbor high levels of biodiversity, maintain soil health and protect food production systems from extreme climate fluctuations. Alternative models that are adaptable to different environmental conditions and inform a more holistic approach to food production are critical for addressing challenges posed by climate change and food insecurity. Upholding and respecting the Indigenous wisdom of these communities is vital for the perpetuation of these sustainable systems. Collaborative initiatives that combine traditional knowledge with modern scientific advancements can pave the way for innovative, context-specific approaches to global challenges.

Indigenous agroforestry systems offer scalable solutions for small-scale farmers facing challenges from climate change and limited budgets. For instance, the Quechua Milpa terraces and the Mayan Three Sisters intercropping method demonstrate how low-input, biodiversity-rich practices can enhance resilience without relying on costly external inputs. Smallholders can adopt these techniques by integrating multipurpose trees like nitrogen-fixing species, diversifying their crops, and applying organic mulch to improve soil health. These strategies help reduce vulnerability to market fluctuations and extreme weather while also ensuring consistent yields. To facilitate this transition, policymakers and NGOs should emphasize training programs, establish seed banks for native crops, and provide financial incentives. Moreover, prioritizing participatory research—where farmers collaborate in designing trials—ensures that techniques are adapted to local conditions, fostering ownership and encouraging long-term commitment.

CHAPTER 2

2. Adoption of a Taíno *conuco* garden method for modern crop production: Influence of environmental factors on the growth and survival of *aji dulce* (*Capsicum chinense*)

Abstract

Since Puerto Rico became a part of the United States in 1898, there has been a noticeable lack of investment in its agricultural sector, leading to persistent food insecurity and environmental damage, especially in the Cordillera Central Mountain range. Traditional farming techniques that prioritize commodity crops have contributed to soil nutrient depletion and marginalized local farmers. This situation highlights an urgent need for more sustainable and regenerative agricultural practices. This study explored the potential of Taíno *conuco* agroforestry systems, which feature raised beds enriched with mulch and planted with sweet potatoes (*Ipomoea batatas*), to improve crop yields and soil health. Focusing on *aji dulce* (*Capsicum chinense*), I compared the growth, survival rates, and soil nutrient levels between *conuco* and conventional control plots. While the differences in growth rates and survival outcomes between the two methods were insignificant, the *conuco* plots showed notable improvements in soil carbon, but significant deficiencies in phosphorus and potassium (graph only). This indicates there was an improvement in soil organic matter, but the significant decreases in phosphorus and potassium (graph) suggest altered nutrient dynamics likely influenced by plant uptake or the intercropping effect. These findings suggest that traditional Taíno farming techniques could offer important ecological benefits, meriting further long-term investigation. By embracing Indigenous knowledge within agroecological practices, Puerto Rico might restore resilient food systems rich in biodiversity and capable of withstanding the challenges of climate change and economic pressures.

Keywords: Ecosystem resilience, geological substrate, Indigenous agroforestry systems, New World ethnobotany, soil fertility, soil nutrient dynamics

2.1 Introduction

As climate change continues to pose severe challenges to food production, researchers and practitioners highlight the potential of agroecology and regenerative agriculture in addressing food insecurity and rejuvenating soil health (Moyer, 2020). For example, Indigenous agricultural systems typically incorporate a diverse mix of vegetables, tuber crops, and livestock alongside perennial woody plants, creating a rich, multi-layered home garden ecosystem (Olofson, 1983). By enhancing biodiversity, agroforestry systems support ecosystem services such as integrated pest management (IPM), which in turn enhances ecosystem resilience, an essential factor in combating climate change (Pantera, 2019).

Climate change is a serious threat to agriculture, food production, and food security around the world (Yadav, et al., 2019). This shift brings significant risks to both human settlements and ecosystems. Long droughts, severe flooding, heatwaves, and unpredictable rainfall are now the norm (Huber & Gulledge, 2011). Each of these factors disrupts traditional farming practices and reduces crop yields (Yadav et al., 2019). Research shows that for every degree Celsius increase in global temperature, staple crops like wheat, rice, and maize could see their yields drop by 3-7% (Cassman, et al., 2010). In some areas, the reductions could be as high as 25% by 2050 (Cassman et al., 2010). This issue hits hardest in equatorial regions, where farmers—often without the means to adapt—face the biggest challenges from rising temperatures and changing rainfall patterns (Rosenzweig & Hillel, 2008). On top of that, warmer temperatures can lead to more pests and plant diseases, further threatening the crops (Yadav, et al., 2019).

Incorporating Indigenous agricultural methods is essential to establishing soil health, increasing biodiversity, and managing crops using biocontrols (Ponge, 2011). Indigenous communities have amassed centuries of ecological insight through careful observation of their local ecosystems and a comprehensive approach to sustainable land management (Nelson & Shilling, 2018). Their farming methods—such as agroforestry, intercropping, controlled burns, and crop rotation—not only promote biodiversity but also improve soil fertility and fortify crop resilience, all while respecting the land (Fahad et al., 2022). Evidence demonstrates that Indigenous stewardship practices bolster ecosystem stability, restore soil health, and cultivate diverse food systems that can withstand the challenges of climate change (Keprate et al., 2024). A striking example of this is the Mayan *milpa* system in Central America, which combines maize, beans, and squash. This system has been remarkably effective at revitalizing soil nutrients and boosting overall crop yields, benefiting the environment as well as the nutrition of local communities (Drexler, 2020).

Healthy soil is essential for sustainable farming, and Indigenous practices play a key role in enhancing it. They prioritize the health of ecosystems over quick yields (Ponge, 2011). As we face increasing soil degradation from issues like monocropping, synthetic fertilizer use, and poor land management, Indigenous methods offer regenerative solutions that align well with modern ecological science (Baruah, 2024). Techniques such as natural composting, boosting biodiversity for pest management, and protecting native plant species help create healthier soils packed with organic matter and beneficial microorganisms (Duran et al., 2020). Furthermore, when we blend Indigenous practices with current scientific methods, we can develop strong, tailored agricultural strategies to tackle food security challenges in both urban and rural areas (Adefila, et al., 2024). Embracing Indigenous knowledge in the agricultural sector opens the door to management innovation, particularly for using bio-inputs (organic pesticides, fertilizers, or biological predator controls). Acknowledging and integrating Indigenous knowledge allows society to move toward a more cohesive and sustainable food system that respects traditional wisdom while solving present-day agricultural challenges (Adefila, et al., 2024).

With many small-scale farmers in the tropical Global South where so much of the world's agricultural operations take place, these people are the first to experience the negative effects of climate change as they happen (Roberts et al., 2017), potentially increasing interest in alternative methods. For instance, small-scale farmers in regions like Puerto Rico are increasingly reverting to ancestral techniques, such as the Taíno *conuco* system, which have been handed down through generations. The renewal of interest in these practices may prove to be a quintessential piece in reconstructing an environmentally based agricultural industry in Puerto Rico as more and more farmers spend thousands each year on chemical inputs (Aviles-Vazquez, 2014).

Archaeological evidence reveals that the Taíno people of Puerto Rico practiced agriculture on a need-based system, cultivating native flora such as tubers, legumes, and fruit trees without a market-driven value system (Rouse, 1992). Their techniques, including the use of mounded piles or organic matter (*conucos* or *montones*) were highly organized and ecologically sustainable. The Taíno transitioned from slash-and-burn (swidden agriculture) methods to more advanced agroforestry systems, creating *conucos* approximately three feet high and nine feet in circumference for ease of harvest and maintenance such as weeding (Rouse, 1992; Bargout et al., 2013). The *conucos* were strategically placed near dwellings for easy access. In the semi-arid southern highlands, particularly the Cayey/Salinas region, Taínos of that area developed innovative irrigation techniques using a wooden tool called *coa* – still used today – to dig trenches and terraces that directed rainwater runoff evenly across crops without disturbing the strong root systems.

Biophysical studies support the benefits of such agroforestry systems. For instance, Lorenz and Lal (2014) found that agroforestry systems significantly enhance soil organic carbon levels, improving soil fertility, water retention, and nutrient availability – crucial for sustainable crop growth in tropical regions. Additionally, integrating nitrogen-fixing (leguminous) trees and shrubs into these systems can help replace and create a steady source of soil nitrogen, reducing reliance on synthetic fertilizer (Jose, 2009). These systems can also improve biodiversity levels and establish natural pest regulation, as agroforestry supports beneficial insects, reducing the need for chemical pesticides (Altieri, 2015). Agroforestry systems also provide economic benefits by diversifying income sources through the production of timber, fruit, understory or lower canopy crops, and other non-timber forest products, making agroforestry a viable and perennial solution for commercial and home consumption crop growth.

For this study, I investigated the potential for a Taíno agricultural practices to enhance conventional farming methods in Puerto Rico. Specifically, I addressed questions on the relative growth rate and survival of *Capsicum chinense*, as well as soil health, to determine if this specific Taíno method increases agricultural productivity, thereby providing an alternative to conventional agricultural techniques in Puerto Rico.

2.2 *Research Questions*

Questions 1: Are relative growth rates (basal diameter and height) and survival of *C. chinense* higher in the *conuco* treatment plots (raised bed planted with mulch and local variety of sweet potato, *Ipomoea batatas*) than in the control plots (flat bed with no mulch and *I. batatas*)?

Hypothesis 1: The treatment (*conuco* method) will have a significant effect on the relative growth rate of basal diameter and height of *C. chinense*, as well as survival.

Question 2: Are soil macronutrients (total carbon, total nitrogen, phosphorus, and potassium) higher in the *conuco* treatment plots in comparison to the control plots?

Hypothesis 2: The treatment what treatment? describe will result in higher levels of total carbon, total nitrogen, phosphorus, and potassium in the soil.

2.3 Methods

2.3.1. Study site

The archipelago of Puerto Rico is situated in the middle of the Greater Antilles (18° 15" N, 66° 30" W) in the Caribbean Basin and comprises 660 small islands in addition to the main island (Cabrera, 2020). Due to its geographical location, Puerto Rico boasts an immense variety of soil types and microclimates, largely due in part to its variability in topography, geological substrates, and location in the tropics. The territory of Puerto Rico is estimated to be about 8,898 km^2 with a maximum elevation of 1,300 meters, which contributes significantly to Puerto Rico's unique microbiomes and soil properties (Balghin & Coleman, 1965).

Puerto Rico's soil is considerably heterogenous, containing nine of the twelve recognized soil orders which include: Entisols, Inceptisols, Mollisols, Ultisols, Vertisols, Oxisols, Alfisols, Aridisols and Histosols (USDA NRCS, 2006). The range of soil orders from underdeveloped in some of the coastal areas to severely weathered in the more humid and montane regions exhibit a large variance in weathering processes, accumulations of organic matter, and the quantity of minerals. Typically, in Puerto Rico, Oxisols and Ultisols are the abundant soil order throughout the island's *Cordillera Central*, possessing minimal amounts of nutrients available and significant weathering, whereas Puerto Rico's coastal valleys boast highly fertile Mollisols, which, in turn, are used to generate intensive agricultural operations (Munoz et al., 2017). A large part of Puerto Rico is considered to be tropical maritime with a clearly marked heavy rain period, and a period of less rain. Average temperatures for the island are between 21 to 29 degrees Celsius with little variation between seasons but large links to temperature gradients through the present elevation (Daly, et al., 2003). Rainfall throughout the island is extremely diverse and varying across the archipelago with annual precipitation encompassing between 800 mm in the southern side of Puerto Rico's semi-arid rain shadow and 4,000 mm in the Northeastern corridor of El Yunque (Larsen, 2000). The extensive range of precipitation, in conjunction with Puerto Rico's Tradewinds/orographic (rain shadow) effect, perpetuates regionally specific microbiomes forming extensive, niche ecosystems as well as regionally adaptable agricultural techniques (Hosannah et al., 2019).

Puerto Rico has a complex geological composition that has consisted of intense tectonic and volcanic activities spanning millions of years (Kaye, 1957). Understanding these geological features is crucial for analyzing erosion patterns and for creating effective land management and conservation strategies on the island. Puerto Rico comprises volcanic rocks which were created through the subduction processes of the North American plate pushing up under the Caribbean plate, showcasing basaltic and andesitic rocks mainly in the central and eastern regions (Kaye, 1957). These volcanic formations give rise to the rugged mountain landscapes found in the interior. In contrast, sedimentary rocks, predominantly limestone, define the karst topography in the northern and western parts of the island (Kaye, 1957), resulting in various caves and sinkholes (Kaye, 1957). Additionally, igneous rocks associated with plutons and magma intrusions can be found throughout the island's central, eastern, and western areas and are mainly granitic in composition (Hynek et al., 2017). In the tranquil northwest region of Puerto Rico, Aguadilla is situated on dense limestone and chalk deposits influenced by karst features, which present complex hydrological behaviors with low nutrient levels (Ghasemizadeh et al., 2012). Utuado, located in the central section of the Cordillera Central, lies within an alluvial valley known for its porous and permeable soil characteristics (Weaver, 1958). On areas with significant slopes, the rock type can be identified as granodiorite and volcanic - igneous rocks, which is physically very different from the alluvium in the valley (Weaver, 1958). Both types are lithified in nature and tend to be weathering with frequent rainfall, providing a nutrient-dense soil ecology (Weaver, 1958). Overall, my sites in Aguadilla and Utuado, given their dispersed geographic locations, confirm that the geological makeup is the result of a complex interplay of tectonic, volcanic, and sedimentary processes, which have shaped the island's unique landscape over the millions of years of its evolution (Weaver, 1958).

The analysis of rock substrate and geological composition is significant in assessing the impact of erosion in Puerto Rico (Pike et al., 2010). The island highlights diverse rock types and formations, such as volcanic, sedimentary, and igneous rocks (Pike et al., 2010). The central and eastern regions of Puerto Rico have primarily volcanic rocks, particularly basalt and andesite, contributing to the island's rugged, mountainous landscape (Porter et al., 2015). In the northern and western areas, sedimentary rocks like limestone dominate the coastal areas, creating karst topography with numerous caves and sinkholes (Monroe, 1976). On the other hand, igneous rocks containing granitic compositions are mostly abundant in the central and western parts of the island. Aguadilla, located in the northwest of the island, is built on a dense foundation of limestone and chalk, featuring unique karst formations that exhibit complex hydrological behavior with low nutrient levels (Monroe, 1976). Meanwhile, Utuado is located in a valley mainly composed of porous, permeable alluvium (Porder et al., 2015).

Taíno history in Puerto Rico

Before the Spanish arrived, the Taíno people of Puerto Rico were already skilled in agroforestry, using advanced techniques that reflected the diverse bioregions of the island. They practiced a method known as *conuco* (*monton*), which involved creating raised mounds to produce abundant, dependable food while also maintaining soil health, controlling erosion, and conserving water (Williams, 2019). This thorough strategy combined various perennial and annual crops, enhancing forest biomass and fostering sustainable yields through a layered planting system (Pagan-Jimenez et al., 2020). Puerto Rico's unique tropical location and varied topography create beneficial and challenging agricultural conditions. While it is true that abundant moisture provides a healthy foundation for plant growth, periods of uncharacteristic drought and severe storm systems can wreak havoc on both conventional intensive agriculture and agroecological or traditional practices. *Conuco* systems can withstand these challenges, as their design facilitates water retention during dry periods and promotes drainage and soil aggregate strength during storm seasons (Ortiz Aguilu et al., 1991).

The diverse ecosystems of Puerto Rico influenced the agricultural practices of the Taíno people. They cultivated drought-resistant, sun-loving crops such as cassava, maize, and yams in coastal lowlands. In contrast, the upland forests and karst regions emphasized fruit-bearing plants like guava, soursop, and mamey within multi-layered agroforests that allowed for the coexistence of tree crops, vines, tubers, and herbs (Rouse, 1982). Montane forests were ideal for growing root vegetables like sweet potatoes (*Ipomoea batatas*) and yautia (*Xanthosoma sagittifolium*), along with shade-tolerant crops like cacao (*Theobroma cacao*; Heindel, 2012). Initially, these landscapes were managed through swidden, or "slash and burn" agriculture, a traditional Indigenous technique where vegetation was cleared to plant crops (Madramootoo, 2000).

However, as agricultural yields began to decrease, the Taínos extended fallow periods to 5-10 years in fertile areas and 10-20 years in less fertile regions, supporting ecosystem recovery and the incorporation of organic material (Sauer, 1966). Puerto Rico's soil varies greatly, from fertile alluvial deposits in river valleys to shallow limestone-derived soils in the northern karst region (Munoz et al., 2017). The volcanic soils of the Cordillera Central provided a strong agricultural foundation, although they required careful management to prevent erosion on steep slopes (Munoz et al., 2017). The Taínos enhanced soil fertility and aeration by adding organic matter, employing charred wood residues and decomposed plant materials to create nutrient-rich substrates similar to the terra preta soils found in the Amazon (Rouse, 1982). This method, along with fruit tree alley cropping between each *conuco*, ensured sustained productivity for decades (Rouse, 1982).

Modern agriculture in Puerto Rico

While Puerto Rico has the potential to reduce the impacts of climate change, its complex colonial history and established agricultural methods, influenced by the post-World War II Green Revolution, have contributed to a decline in agricultural output (Lorek, 2022). Since the early 20th century, the agricultural sector's importance on the island has been on the decline (Carro-Figueroa, 2002). In 1935, there were 52,790 farms, but by 2012, this number had dropped dramatically to 13,159 (USDA, PRDA). Over several decades, agriculture as an industry in Puerto Rico has experienced a 25.1% reduction, which has negatively affected the nation's gross domestic product (GDP), decreasing from 25.6% in 1950 to just 0.5% by 2008. Additionally, the agricultural workforce saw its employment rate fall from 36.2% in 1950 to only 1.2% by 2008 (Alvarez Febles & Felix, 2020). As of

2025, Puerto Rico’s agricultural industry is heavily dependent on subsidies, particularly for coffee, plantains, and livestock. These subsidies primarily support traditional high-input agricultural practices and monocultures, often at the expense of soil health and sustainability. With increasing development and growing concerns over food security, there has been a slight rise in hydroponic greenhouse horticulture focused on intensive vegetable production, along with a burgeoning seed bank industry employing more biotechnological methods. Unfortunately, conventional agricultural methods continue to dominate some of Puerto Rico's most arable lands, particularly in the southeastern region, which features dry conditions, fertile soil, flat terrain, and accessible underground aquifers, all factors conducive to intensive agricultural production (Alvarez Febles & Felix, 2020).

2.3.2. Experimental design

Figure 2.1 participating farms in Aguadilla and Utuado (Google Earth, 2024).

I conducted research at two separate locations (see Fig. 2.1), each containing six distinct plots, for a total of 12 plots. Each site included four *conuco* beds measuring 0.9144 meters by 7.62 meters, spaced 2.1336 meters apart, along with one control plot. These *conuco* beds were carefully constructed into individual mounds using soil enriched with plant residues such as branches, leaves, and mulch (see Fig. 2.2). This method aimed to improve water drainage, enhance aeration, minimize erosion, and support healthy tuber crop growth. Traditionally, these mounds are complemented by intercropping with perennial species, which further enhances soil health by creating a communal root system (beneficial biological mutualism) to increase soil fertility. The three control plots each contained only *C. chinense* plants without any additional treatment. The layout featured three *conuco* beds intercropped with seven *C. chinense* and eight *I. batatas* plants per bed, with pathways designed to resemble an alley cropping system using

“New World” fruit trees. Selected fruit species for the study included soursop (*Annona muricata*), dwarf June plum (*Spondias dulcis*), anon (*Annona squamosa*), corazon (*Annona reticulata*), papaya (*Carica papaya*), guava (*Psidium guajava*), mamey (*Pouteria sapota*), sapodilla (*Manilkara zapota*), ice cream fruit (*Inga edulis*), star apple (*Chrysophyllum caimito*), and mameyito (*Garcinia intermedia*). Although four sites were initially chosen in the municipalities of Cayey and Santa Isabel, those sites were excluded from the study due to severe erosion and soil degradation. The general flora distribution of both sites is available in Table 2.1 below.

Table 2.1 Site descriptions and corresponding flora inventory estimations.

Region & Microclimate	**Flora Inventory & Distribution***
Aguadilla - considered hot, windy, and rainy due to its coastal proximity. Classified as Rugged, Humid Coastal Plains	- *Cocos nucifera* - *Coccoloba uvifera* - *Rhizosphora mangle, Avicennia germinans, Languncularia racemosa* - *Hibiscus rosa-sinensis* - *Delonix regia* - *Spathodea campanulata*
Utuado - mild, windy, tropical, extremely humid, and rainy year-round	- *Chrysophyllum caimito* - *Thespesia grandiflora* - *Cecropia schreberiana* - *Manilkara bidentata* - *Trema micrantha* - *Erythrina poeppigiana* - *Micropholis garciniifolia*

* USDA Plant Database (http://plants.usda.gov/home)

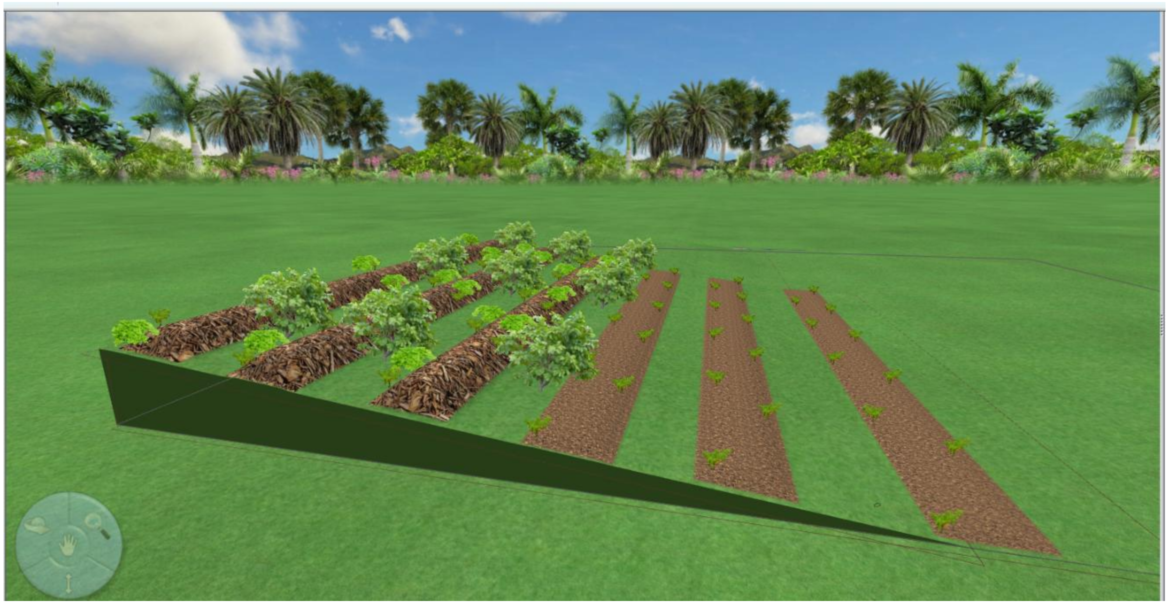

Figure 2.2 *Conuco* intercrop and alley crop growing method (Realtime Landscaping Pro, 2024).

2.3.3. Study species

Capsicum chinense

Aji dulce peppers, also known as *aji cachucha* or *aji gustoso*, play a vital role in Caribbean cuisine, especially in Puerto Rico. While their name suggests a Chinese origin (*Capsicum chinense*), these peppers are native to the Amazon Basin in South America. Indigenous Arawak ancestors from the Orinoco Valley likely introduced them to the Caribbean through trade and migration routes connecting Northern South America with the Antilles. The Taíno people adopted and cultivated *C. chinense*, incorporating it into their agricultural practices and culinary traditions. Over time, this pepper became an integral part of the region's cuisine, evolving into various local varieties. Although *C. chinense* is closely related to the *habañero*, it has been selectively bred for its mild, sweet flavor and delicate fruity undertones. This unique flavor profile made it a popular choice for the Taíno, who used it to enhance the taste of meats, fish, and stews (Rouse, 1992). The introduction of *C. chinense* into the Caribbean ecosystem has significantly enriched the region's agricultural diversity. It has become deeply woven into Puerto Rico's cultural fabric and culinary traditions, showcasing its Indigenous heritage (Moscoso, 2003). *Capsicum chinense* represents Puerto Rican cultural heritage. It is often grown in home gardens, symbolizing a strong connection to the land and a tradition of self-sufficiency. This practice is especially important in rural areas, where small-scale farming supports families. The pepper's presence in local markets and its incorporation into traditional recipes reflect its enduring significance in Puerto Rican culture, linking the past with the present.

A newly attractive cash crop in Puerto Rico and a key species in lower canopies for agroforestry systems in Puerto Rico, *C. chinense* presents itself as a unique cash crop alternative that can be utilized in agroforestry system due to its shade tolerance, minimal input requirements and its high market value demand but domestically in Puerto Rico and abroad (Hernandez-Zerega, 2017). Average prices range between $4.00 and $5.00 per pound, making it particularly attractive to small-scale farmers seeking practical options to incorporate into their farms that will not require copious amounts of space (Lim, 2012). *C. chinense* thrives in Puerto Rico's warm climate and is less demanding in terms of water and care than other cash crops on the island. Its ability to grow year-round and quick fruiting cycles enables farmers to enjoy the benefits of multiple harvests over a year. In the growing agro/ecotourism sector in Puerto Rico, farms that grow *C. Chinense* can offer engaging tours, firsthand forestry or horticultural workshops, and unique culinary experiences that appeal to those eager to engage in Puerto Rico's strong agricultural identity actively. *C chinense* can open new opportunities for farmers, chefs, hobbyist gardeners, and tourists to explore new markets and generate extra income by creating value-added products such as sauces, spice blends, and fermented foods (Hernandez-Zerega, 2017).

Ipomoea batatas

The sweet potato holds deep significance in the cultural and traditional life of Puerto Rico and the broader Caribbean. Thought to have its roots in South America, particularly in what is now Peru and Ecuador, this beloved vegetable, known as *Ipomoea batatas*, was first domesticated around 5,000 years ago (Cutler, 2022). It crossed the Americas via pre-Columbian trade routes, reaching the Caribbean long before Europeans arrived. The Taíno people grew sweet potatoes using sustainable farming methods (Rouse, 1992). They called it "*batata*," a name the Spanish later adopted. Thanks to its resilience in tropical climates and rich nutritional profile, the sweet potato was a cornerstone of Taíno agriculture, helping to ensure food security and preserving cultural heritage (Chaparro-Martinez et al., 2019). In Taíno culture, *I.batatas* plants are an essential food source and a significant cultural symbol. People enjoyed them prepared in a variety of ways—including roasting in ashes, boiling, or mashing—and they often complemented other native crops like cassava (*Manihot esculenta*) and maize (*Zea mays*). Their inherent sweetness lends versatility, allowing for use in fermented beverages. (Chaparro-Martinez et al., 2019).

Recent studies have revealed that sweet potatoes contain beneficial bacteria in their aerial parts that can fix nitrogen (Marques, et al., 2019). This means these endophytic bacteria live within the plant’s tissues and are able to convert nitrogen from the air into a form that the sweet potato can use for its growth, reducing reliance on synthetic fertilizers. The N (15) dilution method, which uses stable nitrogen isotope ratio differences, has been employed to assess nitrogen fixation in sweet potatoes grown in the field. Results show that nitrogen fixation by these endophytes can account for 55-77% of the plant’s total nitrogen requirements by 90 days after transplanting. This process begins to increase around 47 days post-transplanting, aligning with the rapid growth of leaves and the development of tuberous roots (Yonebayashi et al., 2014). This new development in ongoing research has promising potential for groundcover, cover cropping, or intercropping, particularly in systems like the *conuco,* in which soil health and fertility are managed through natural methods. *Ipomoea batatas*, commonly known as sweet potatoes, can thrive even in low-nitrogen soils thanks to their collaboration with nitrogen-fixing endophytes. This natural partnership reduces the need for external fertilizers and boosts the sustainability of agroecosystems (Yonebayashi et al., 2014). Because of this capability, *I. batatas* is an excellent choice for organic farming and restoring degraded soils (Yonebayashi et al., 2014).

Besides nitrogen-endophytic nitrogen fixation, *I. batatas* aids in mitigation against soil erosion, soil microbial balancing, and the establishment of their fast, growing, incredibly strong root systems aiding in adherence as soil aggregate. This use of *I. batatas* provides additional value for a low-cost, easy-to-propagate, and harvestable product, as the most significant problem currently in Puerto Rico is the amount of erosion in the mountains. Moreover, the vines and leaves of sweet potatoes contribute to soil vitality by adding organic matter that can be used as mulch or green manure. This organic material helps improve soil structure, boosts water retention, and encourages the activity of beneficial microorganisms.

2.3.4. Soil samples

The soil samples were collected at a depth of 30.48 centimeters deep using a core sampling auger. The sampling was divided into three sections per plot with the sample ID corresponding to a specific Plot and a letter (e.g., 1, 1A, 1B, etc.) A total of 36 total samples were collected and shipped overnight via USPS to Louisiana State University Plant Soil Analysis Lab (https://www.lsuagcenter.com/portals/our_offices/departments/spess/servicelabs/soil_testing_lab) . The tests were conducted for continuous? measurements through routine soil tests consisting of calcium, magnesium, sodium, sulfur, copper, zinc, manganese, iron, potassium, and phosphorus using Mehlich 3 ICP analysis (Mehlich, 1984). Soil acidity (pH) was also measured using a water extractant and analyzed through pH meter and electrode (McLean, 1982). Optional soil tests conducted included Organic Matter with an Acid-dichromate oxidation extractant using a Dip-Prove colorimeter and Total Nitrogen and Carbon using a LECO CN Analyzer and Dumas Dry-Combustion (Nelson & Sommer, 1982). The project used USDA-NRCS Soil Classifications and Rock Substrate Database to understand site composition. Physical attributes and rock data were included. As we mimic Taíno *conuco* systems, manual irrigation will be omitted. Rainfall data from nearby USGS stations tracked meteorological changes.

2.3.5. Statistical analysis

Relative growth rate of height and basal diameter of C. chinense seedlings

An analysis of variance model (ANOVA) was conducted to test effects of two independent categorical fixed factors (treatment [*conuco*, control], site) on relative growth rate (RGR) of height. A non-parametric Mann-Whitney test was employed to test the influence of treatment on RGR of basal diameter.

Relative growth rate was calculated using the following formula:

$$RGR= (\ln G5-\ln G0)/ (t5-t0)$$

wherein G is the plant height or diameter at time *t*. Growth rates were calculated using growth measurements from initial (0 months since planting) and final (5 months) censuses. Individual plants were treated as replicates in the model.

Seedling survival

A regular logistic regression was used to model binary outcome variables (yes/no) to compare the rate of survival of *C. chinense* individuals between treatment and control plots. I employed a logistic regression with two independent fixed factors (treatment, site) and a random factor (site location) were included in the model.

Soil macronutrients

An ANOVA was used to evaluate effects of the *conuco* treatment on macronutrient (TN, TC, P, K) levels in the soil, with site and treatment as the independent variables.

All analyses were conducted using R 4.4.2 (Download R-4.4.2 for Windows. The R-project for statistical computing.; accessed 12 February 2025). Relative growth rate (height) and soil conformed to assumptions of normality and homoscedasticity. Relative growth rate (basal diameter) residuals were found to follow a non-normal distribution, in which case, a non-parametric analysis was observed. Results were considered statistically significant at $P \leq 0.05$.

3.1 Data Analysis/Results

3.2 Relative growth rate of height and basal diameter using ANOVA and Mann-Whitney analysis of *C. chinense* seedlings

Seedling Height

Table 2.2 Results from ANOVA testing relative growth rate of height (cm) as a function of treatment and site.

Factors	**npar**	**df**	***F***	***P***
Site	0.48	1	0.274	0.604
Treatment	1.25	1	0.704	0.406
Residuals	74.47	42		

The assessment of relative growth rates for seedling height indicates that neither the site nor the treatment had statistically significant effects on the growth rate of C. *chinense* (see figure 2.5 below). The F-value for the site factor was 0.274, with a p-value of 0.604. The F-value for the treatment was 0.704, accompanied by a p-value of 0.406 (see Table 2.2). The higher p-values suggest that growth patterns for height were unrelated to treatment or site.

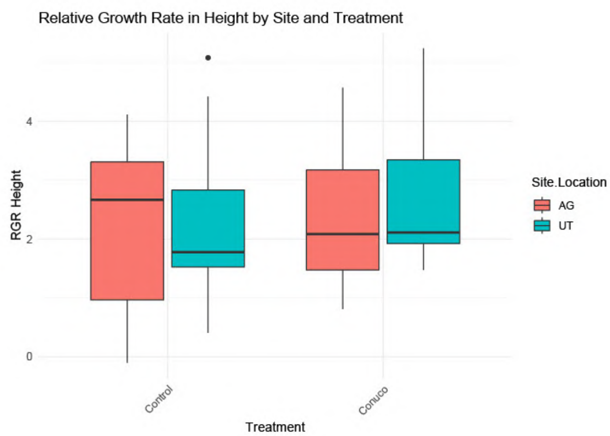

Figure 2.3 Relative growth rate of height (cm) as a function of treatment and site.

Basal Diameter

Table 2.3. Results from Mann-Whitney analysis testing relative growth rate (cm) of basal diameter.

Factors	**npar**	**df**	***F***	***P***
Site	0.0000152	1	0.841	0.3644
Treatment	0.0000010	1	0.056	0.8147
Residuals	0.0007605	42		

The analysis of basal diameter showed no significant effect from site or treatment on the relative growth rate. The F-value for the site factor was 0.841, with a p-value of 0.3644, while the treatment's F-value was lower at 0.056, accompanied by a p-value of 0.8147 (see Table 2.3). Similar to height, neither treatment nor site exhibited a notable impact. Growth in *C. chinense* remained consistent over the five-month period, unaffected by intercropping/raised mound conditions or the various ecosystems at the sites (see Figure 2.4).

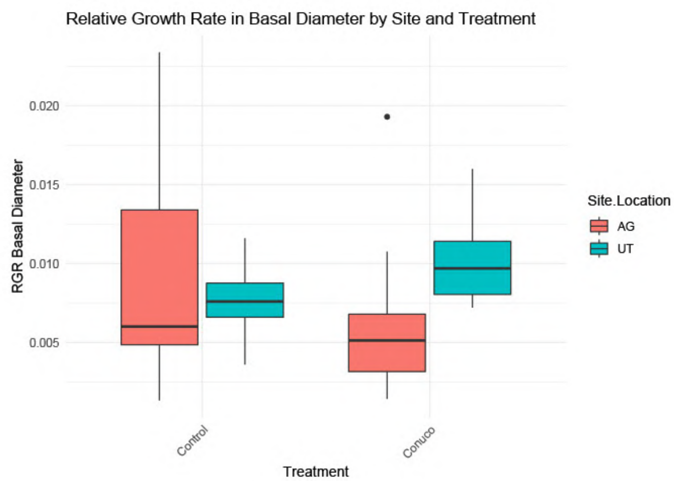

Figure 2.4 Influence of treatment and site on basal diameter relative growth rate (cm).

3.3 Seedling survival

Table 2.4. Results of logistic regression on seedling survival as a function of treatment and site.

Factors	**npar**	**df**	***F***	***P***
Site	0.0000152	1	0.841	0.3644
Treatment	0.0000010	1	0.056	0.8147
Residuals	0.0007605	42		

The survival analysis results indicate that treatment, rainfall, and site (see Figure 2.5) had no significant impact on the survival rate of *C. chinense*. Consistent with other measurements taken, survival rates remained stable across both sites despite their geological and ecological variations (F-value = 0.841, p = 0.3644 for site; F = 0.056, p = 0.8147 for treatment; see Table 2.4). These findings suggest that independent environmental and treatment factors had little to no effect on the survival of *C. chinense*.

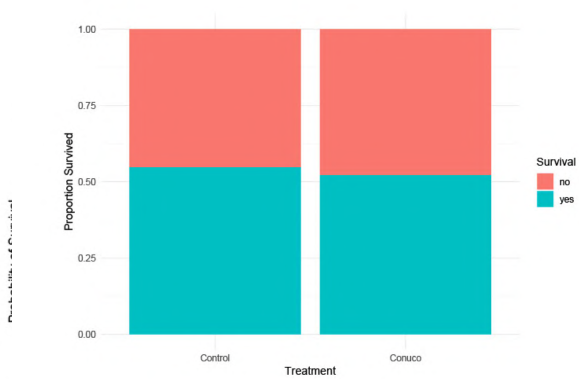

Figure 2.5 Proportion of *C. chinense* seedlings that survived for the duration of the experiment, as a function of treatment and site.

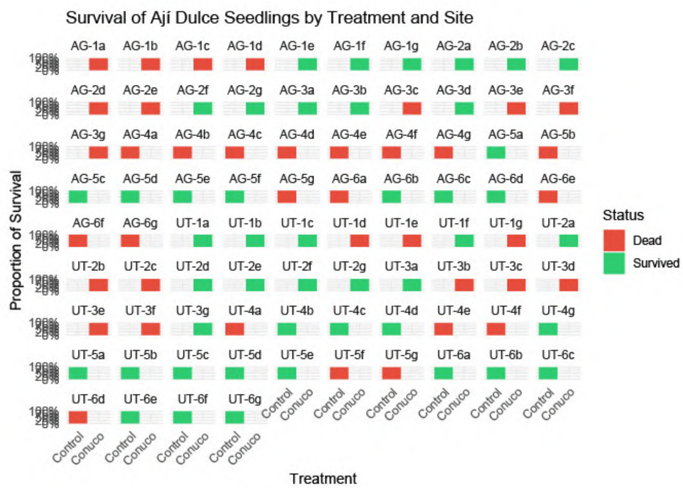

Figure 2.6 Survival of *C. chinense* seedlings by treatment and site.

3.4 Soil macronutrients

The examination of soil macronutrients by site and treatment revealed varying levels of significance. Both site and treatment influenced total phosphorus, statistically significant (F-value = 4.724, p-value = 0.01646 for treatment; F = 7.721, p-value = 0.00933 for site). Total nitrogen was also insignificant. Carbon levels in the soil proved to be positively significant (F-value = 3.321, p-value = 0.0498 for treatment; F-value = 0.241, p-value = 0.06269 for site, and 3.797 F-value and 0.0339 P-value for interaction between Site and Treatment). Potassium (F-value = 1.636, p-value = 0.212 for treatment; F-value = 28.016, p-value = 1.02e-05 for site, F-value = 2.457, P-value = 0.103 for interaction between Site and Treatment). These results imply that nutrient availability in the soil may remain relatively constant and stable across different sites and treatments, highlighting the need for ongoing monitoring to accurately evaluate ecosystem health through soil sampling.

Table 2.5 Results from ANOVA testing Carbon content parts per million (ppm) in soil as a function of treatment and site.

Factors	**Sum Sq**	**df**	***F***	***P***
Treatment	0.0994	2	3.321	0.0498
Site	0.036	1	0.241	0.6269
Site*Treatment	1.137	2	3.797	0.0339
Residuals	4.491	30		

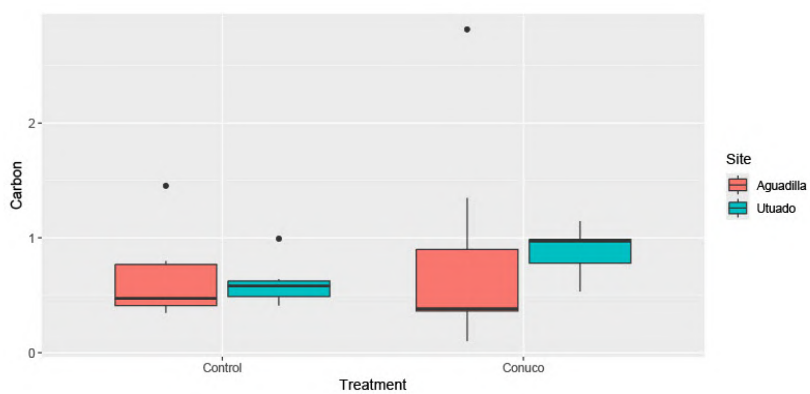

Figure 2.7 Carbon content in soil as a function of treatment and site.

Table 2.6 Results from ANOVA testing Total Nitrogen content (ppm in soil as a function of treatment and site).

Factors	**Sum Sq**	**df**	***F***	***P***
Treatment	0.001477	2	0.947	0.399
Site	0.002225	1	2.852	0.102
Site*Treatment	0.002523	2	1.617	0.215
Residuals	8.50-304	30		

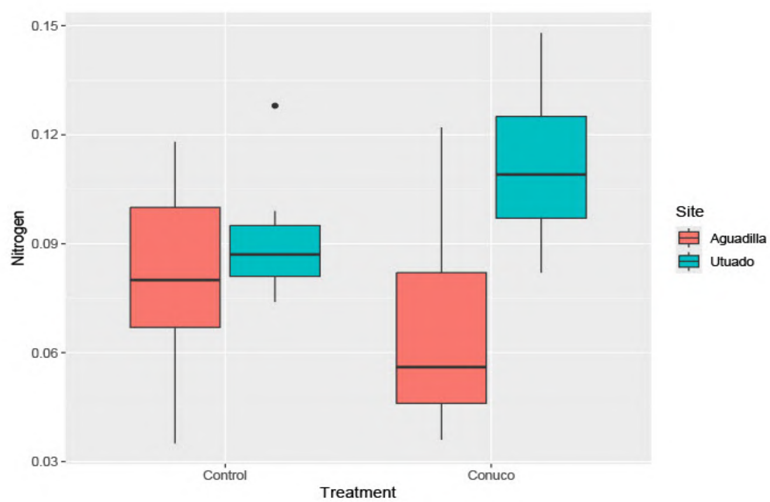

Figure 2.8 Total Nitrogen content in soil as a function of treatment and site.

Table 2.7 Results from ANOVA testing Total Phosphorus content (ppm) in soil as a function of treatment and site.

Factors	Sum Sq	df	*F*	*P*
Treatment	4338	2	4.724	0.01646
Site	3545	1	7.721	0.00933
Site : Treatment	1676	2	1.825	0.17866
Residuals	0.02500	30		

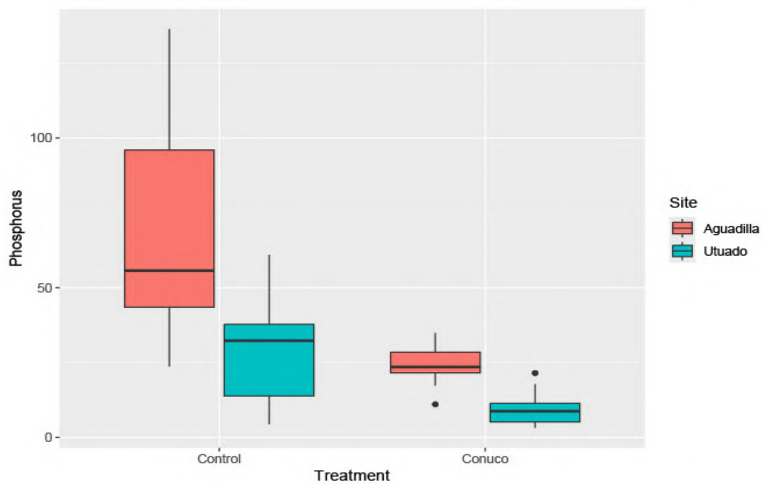

Figure 2.9 Total Phosphorus content in soil as a function of treatment and site.

Table 2.9 Results from ANOVA testing Potassium content (ppm) in soil as a function of treatment and site.

Factors	Sum Sq	df	*F*	*P*
Treatment	0.00490	2	1.636	0.212
Site	0.00020	1	28.016	1.02e-05
Site*Treatment	4684	2	2.457	0.103
Residuals	0.00145	2		

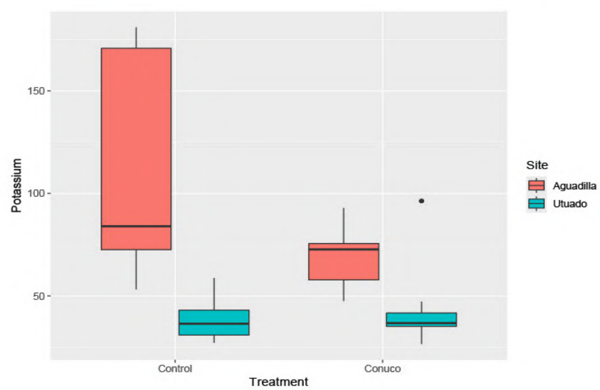

Figure 2.10 Potassium content in soil as a function of treatment and site.

4. Discussion

4.1 Seedling performance

Seedling survival and growth showed no significant differences across the various sites or treatments, indicating that the *conuco* treatment had no effect on survival or growth during the five-month study. This lack of significant effects may be due to the study's short duration, as a more extended period might be necessary to detect delayed treatment effects. Furthermore, several factors that were not measured could be included in a similar project, such as soil microbial communities, pest pressures, and variations in microclimates. Adding canopy measurements, elevation gradients, and light penetration metrics could also enhance our understanding of plant-ecosystem interactions. Incorporating additional environmental variables in future studies might reveal this species' ability to adapt to diverse conditions across sites, including drought and extreme heat, or to respond to specific local microclimates or pest presence (for example, specific losses might occur due to wild chickens disturbing organic mulch, leaves, and residues in Aguadilla). Therefore, long-term observations are recommended for future studies exploring this Indigenous agroecosystem.

Although the *conuco* treatment did not significantly affect seedling growth or survival, the choice to exclude steep slopes (such as those in Cayey and Santa Isabel) due to severe erosion underscores the importance of topography for system viability. On slopes exceeding 15 degrees, erosion and inadequate organic matter retention likely negate any benefits provided by raised mounds. However, in more moderate or terraced areas, such as the mountainous regions of Haiti, *conuco* systems can still be effective, particularly when paired with erosion control techniques like contour trenches or vetiver grass hedges. Future research should investigate the adaptability of *conuco* systems across varying slopes and incorporate methods like terracing or agroforestry windbreaks to help stabilize the soil. Given that Haiti experiences higher rainfall and has a cultural history of mound-based farming, these systems may perform better there; however, it is crucial to conduct specific trials tailored to the local conditions.

4.2. Soil macronutrients

In analyzing soil macronutrients, we found that total carbon, phosphorus, and potassium (See Table 2.9 and Figure 2.10) vary significantly from site to site due to the unique geological and ecological conditions in Aguadilla and Utuado. For example, the organic mounds created by the *conuco* treatment improved carbon retention, thanks to the decomposed mulch (Zhang et al., 2022). The availability of phosphorus also differed; Aguadilla, with its limestone substrate, has less phosphorus compared to Utuado, where the volcanic-alluvial soils offer more (Kim & Park, 2008). As for potassium, its significance at certain sites might be attributed to how parent materials weather, with volcanic rocks in Utuado releasing higher amounts of potassium (Cardozo et al., 2024). In the *conuco* plots, phosphorus levels dropped significantly, likely because of the rapid growth of the sweet potato intercropping were absorbing nutrients or due to leaching during the early stages of succession. Conversely, carbon levels in these plots increased, but this rise was significant only in Utuado, indicating a specific interaction at that site. Meanwhile, potassium levels were found to be higher in Aguadilla regardless of the treatment, suggesting that the differences might stem from inherent soil characteristics rather than the treatment's effects. However, it's important to note that the short duration of the study and the limited number of samples could have restricted our ability to detect treatment effects. This highlights the need for long-term monitoring to understand nutrient dynamics in these ecosystems fully.

4.3 Conclusion

Indigenous agroforestry methods offer excellent strategies for addressing climate change and food insecurity. Yet, integrating these practices into modern agriculture comes with its own set of challenges. This study has revealed important findings about soil macronutrients, especially total carbon, phosphorus, and potassium (site only), in plots treated with the *conuco* method. The results indicate that *conuco*, in long-term studies, could positively impact soil health and could aid in long-term ecosystem restoration. Although there were not statistically significant differences in the growth rates and survival of *C. chinense* seedlings, the increase in soil nutrients highlights the ecological advantages of Taíno agroforestry methods for Total Carbon but not for Phosphorus – reduced in the case of the treatment plots most probably attributed to the intercropping. These findings emphasize the necessity for more extensive field trials and detailed environmental monitoring, particularly regarding soil conditions and microclimate dynamics. This research supports the growing acknowledgment that Indigenous agroecological systems protect cultural traditions while providing effective, scientifically supported solutions for fostering resilient and biodiverse agricultural environments. Moving forward, it is vital to strengthen partnerships with Indigenous communities and focus on long-term, interdisciplinary studies to validate these regenerative systems' effectiveness further.

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