Indigenous agroforestry systems for addressing climate change mitigation and food insecurity: A review of contributions to ecosystem services

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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 studies have 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, we documented and analyzed the contributions of Indigenous agroforestry systems to biodiversity conservation, soil conservation practices, and their ability to withstand climate extremes. Additionally, we compared case studies to determine complementary adaptations across the regions in question. This 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

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, the "Green Revolution" reigned as the preferred mode of production, prioritizing cash crops produced in monoculture systems supported by chemical fertilizers, pesticides, and heavy equipment to till, prioritizing quantity (production) over quality (Kremen et al., 2012). Currently, approximately 44% of the Earth's land area is utilized for agricultural production, with mechanized industrial agriculture being the driving force behind the use of cropland on large-scale land areas (Ritchie & Roser, 2024). Although this type of agricultural production has created a temporary boost in food production, it has also generated a significant amount of environmental and ecological degradation. Indeed, the idea of mechanized industrial agriculture following the pattern of the Green Revolution'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 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 mimics natural forest ecosystem settings, canopy structures, and enhances 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 uses of natural resources 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 groundcovers to prevent soil erosion (Fahad et al., 2022). Specific strategic measures like providing shade for reduced heat and sunlight exposure, 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). By 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).

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). The present review explores global Indigenous agroforestry designs and methods as a blueprint for adapting to climate change and food security in the global south. This 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. The primary goal of this research 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 extraneous 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.

Research questions

This review looks at how Indigenous agroforestry systems help communities adapt to climate change, protect biodiversity, and improve soil health in different ecological and cultural settings. It considers whether these systems make food crops less vulnerable during extreme weather, enhance biodiversity by providing diverse habitats and species, and support long-term soil health through natural nutrient cycling and erosion prevention. The review also compares Indigenous agroforestry practices from various regions to find common ecological ideas and unique adaptations influenced by local environment and culture.

Our research merges historical context, environmental data, and ethnographic insights to interpret the patterns in which Indigenous agroforestry projects promote food sovereignty across generations. The framework of the study 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.

Methods

The research used for this review 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, we 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, we 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 found from (Branch et al., 2008). This study particularly examines Indigenous agroforestry systems and their effects on soil fertility and crop yield. GIS allows to explore land-use patterns, biodiversity, and microclimates in regions like the Cordillera Central of Puerto Rico 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 intends to 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

Results

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 rich in biodiversity and closely align with the central theme of the thesis: Taino agroforestry systems. Once widespread throughout the Caribbean, Indigenous agroforestry systems were deeply impacted during the colonial period. European powers enforced forced labor systems that pushed Indigenous communities away from their traditional, subsistence farming methods towards growing crops for export and supporting Spanish, Dutch, French, and British colonizers. This shift led to a significant loss of traditional ecological knowledge and disrupted culturally rooted land management practices. (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. • Home gardens combine fruit trees, staple crops, and livestock in a harmonious system • Sustains households and promotes soil health in populated areas.	Fernandes, et al., 1985; Hemp, 2006; Nair, 2021; Mbilinyi et al., 2016; Kingazi et al., 2024
New Zealand (Māori 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 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.	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
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

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 and assessments 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. • Field data analysis to compare productivity and resilience across the selected case studies.
Cultural and Ecological Literature Reviews	• Archival research conducted to review the 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

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, which centers around utilizing land for soil and water resources, is a method of cultivation for domesticated plants and sustainable livestock management, establishment of microclimatic framework (mini ecosystems), 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.

According to Branch et al. (2008), 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 spp.*), 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).

Mayan *Milpa* "Three Sisters"

In the fertile highlands of Guatemala, 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). The role of corn 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 devotion to land stewardship of the Mayan people, 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).

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).

Chagga Home Gardens of Mt. Kilimanjaro

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 sustainable nature of the Chagga garden in Mt. Kilimanjaro makes it an ideal candidate as a model project for organic/regenerative operations as the ecosystem services provided by the dominant woody species limit the need for synthetic pesticide treatments and fertilizers. The reliance of the Chagga people 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* that 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).

Māori Mara Kai Agroforestry Gardens of New Zealand

The Mara Kai Māori Agroforestry Gardens from New Zealand, often referred to as "Māra Kai," is a large representation of the Māori 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 Māori'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 Māori 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).

Khasi Jhum Agroforestry of Northeastern India

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. Intercropping with native tree species enhances biodiversity and delivers vital ecosystem services. It supplies sustainable timber and promotes fruit production. Moreover, these systems improve soil health by boosting organic matter through leaf litter, helping to maintain environmental stability (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 can 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 forests' ecosystem services are crucial to producing 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, 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).

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)*, and *A. altillis*. 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 uses 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). The commitment of native Hawaiians 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).

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 amid 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 1.2 *Conuco* terrace in production intercropped with sweet potatoes, aji dulce peppers, soursop, lemon drop mangosteen, papaya, and guava in Utuado, Puerto Rico.

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, Māori 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 may offer 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 Māori 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, the involvement of women 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 consider 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.

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