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Smallholder Coffee in the Global Economy—A Framework to Explore Transformation Alternatives of Traditional Agroforestry for Greater Economic, Ecological, and Livelihood Viability

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Sixty percent of global coffee is produced from farms of <5 ha. Studies show that returns from such farms do not generate a living income for producers or workers threatening supplies. Smallholders use agroforestry to reduce coffee production costs, diversify income and address livelihood needs. We undertook a three-phase analysis to test the following hypothesis. Current coffee agroforestry must shift from a low labor, low risk-stable return, slowly-changing matrix to more active management of species and stem turnover in system renovation cycles targeted to sustaining, reorienting and intensifying ecosystem-based benefits to coffee production, diversified income and household food. First, we conducted a document survey of current traditional tree diversity, research trends, and market drivers for more benefits-oriented agroforestry. Second, we proposed a framework for multiple benefits quantification converting tree use characteristics and density into five categories of benefits, each with sub-categories which we tested using previously collected data of stem density by species from coffee agroforestry in northern Nicaragua. Third, we modeled radiation in mixed canopy scenarios using the program SExI- FS based on modifications of species and density to target food and income diversification and tested our framework by quantifying benefits. We found that smallholder coffee faces farms decreasing coffee margins, labor scarcity, new pests and climate variability best addressed with targeted and adaptive shifts in coffee varieties and associated trees. Increasing data demands from certification and regulations provide a basis more data-driven coffee farm management. Our data bases of stem density by species of established agroforestry systems were sufficient to identify gaps in food and income benefits which were addressed in the scenarios thereby verifying the hypothesis. The benefits ranking both of current systems and three scenarios also provided insights into data collection specifications for a more rigorous academic test of the hypothesis and data-driven grower strategies for agroforestry transformation.

Keywords: coffee agroforestry, agroecology, agroecosystem design, ecological intensification, ecosystem services

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INTRODUCTION—CAN AGROFORESTRY TRANSFORMATION ENSURE SMALLHOLDER COFFEE PRODUCTION?

Smallholders with <5 hs supply 60% of the global coffee market (Panhuysen and Pierrot, 2020 referencing Enveritas, 2018) with farms between 5 and 50 ha producing another 19% of world supply (https://carto.com/blog/enveritas-coffee-poverty-visualization/). Coffee price increases in the past year appear to offer some respite, offset by increases in input and transport costs. However, numerous studies summarized by Muñoz-Rodríguez et al. (2019) and Sachs et al. (2019) suggest that over the past decade costs of production have been greater than prices received. The returns provided by smallholder coffee are below a living income both for producers and workers even without taking into account external environmental costs of increasing input use calculated by the True Price method (https://trueprice.org/monetisation-factors-for-true-pricing/). Unfavorable returns may become a threat to global supplies as growers shift to other crops and the sons and daughters of growers and workers seek more promising livelihoods (Giller et al., 2021). Of the estimated 12.5 million coffee-producing small farms, 44% earn below the poverty line (https://carto.com/blog/enveritas-coffee-poverty-visualization/), and a far greater percent do not earn a living income, an income which provides a nutritious diet, decent housing, adequate income to cover education, clothing, health and transport and a reserve for unexpected expenses (https://www.living-income.com/the-concept). A prosperous income level which provides opportunities to progress in life with future generations continuing to produce coffee was proposed by International Coffee Organization (2020) as a goal for the sector.

Fortunately for coffee consumers, smallholder coffee is characterized by inelastic supply (Sachs et al., 2019). Small coffee growers have sunk costs in plantation establishment and on-farm infrastructure. Alternative non-perishable agricultural enterprises are not abundant for remote hilly upper watershed lands and may offer even lower household income from small land areas. On the short term most smallholder coffee producers continue to produce coffee even when prices are low. However, the conditions behind the current inelastic supply may not be enough to ensure the next generation of smallholder coffee growers.

An additional factor favoring the inelastic supply is the diversified agroforestry production system developed by smallholder coffee growers throughout the tropics which harness trees and other associated crops to reduce costs and input needs for coffee and address multiple dimensions of the living income from within the coffee field—food, fuel, housing materials, secondary income, and emergency cash. We propose to focus on these benefits or ecosystem services with a concrete use value locally to smallholder coffee households. Diversified multi-strata coffee is a variant of a very common farmer-originated cropping strategy based on mixed species plantings with complementary plant architecture and crop cycles practiced with the beginnings of agriculture (Rindos, 1984). Moguel and Toledo (1999) proposed a typology of five types of coffee production systems applicable in Mexico which is now widely cited to illustrate coffee production system diversity worldwide. Three of the types are mixed species plantings—"rustic" with coffee planted into thinned forests, "traditional polyculture" with coffee and a diversity of other useful plants planted into thinned forest and "commercial polyculture" with coffee and a diversity of useful trees creating a multi-strata vegetation complex. The remaining two types have simplified tree species and structure with only one or two tree species or without trees to maximize coffee production *via* monoculture. The gradient has been generated by coffee growers seeking greater cash income in response to technological and development forces aimed to improve coffee yields through increasing monoculture.

The drawbacks of smallholder livelihood strategies dependent on coffee alone are highlighted for Central America and Mexico (Fernandez et al., 2013; Bacon et al., 2014; Anderzén et al., 2020) as a larger issue for food sovereignty and sustainable development in rural communities. Increasing seasonal food insecurity measured as "lean months" is associated with greater percentage of household land in coffee, declining on-farm production of annual food crops and low-income diversification (Morris et al., 2013). Pinoargote et al. (2017) in their comparison of three coffee production systems of increasing diversity found that coffee was the main income in all three systems. Total benefits were similar in financial equivalents across systems, but more diversified and with greater carbon accumulation for the systems with higher plant diversity. They sampled only fields with well-managed, productive coffee and emphasize in their conclusion that good coffee management, pruning and adequate inputs are key to achieving these system synergies, although they did not address household food security. In a coffee growing region of Ethiopia, Duguma et al. (2019) documented four production systems. The annual food crop systems were much less diverse in species and had fewer ecosystem services overall, although the provisioning function of food production increased. Three systems generated coffee income—two types of coffee agroforestry and home gardens which had both coffee and high species diversity, including some for food consumption (**Table 1**). Fernandez and Méndez (2019) also contrasted home gardens (primarily without coffee), annual food plots and coffee fields on 79 farms in Chiapas, Mexico. Household food security was linked to on-farm diversity. Although major dietary components came primarily from annual food plots and home gardens, they also identified leafy green vegetables which were collected from coffee fields, highlighting the potential to increase food security benefits from the coffee plots themselves.

In our own field work on coffee agroforestry in Central and South America, we documented tree species diversity and stem density, quantified tree and soil carbon and income mostly focusing on bananas in the system (Staver et al., 2010; Cerdán et al., 2012; Siles et al., 2012). However, we have not addressed the multiple benefits potential of traditional diversified agroforestry as a smallholder strategy with both profits from global coffee markets and food security, income diversification, on-farm inputs to production and other livelihood needs. In this paper, we build on our own field experience and a survey both of coffee sector documents and academic research to propose an

TABLE 1 | Selected parameters from studies of smallholder coffee multi-strata diversity in four continents (nr, not reported by authors).

Continent	Country/region	# trees /ha	# coffee plants/ha	# banana stems/ha	Tree Shannon diversity	Products from associated vegetation	References
Asia Indonesia	Lampung, Sumatra	200–350	1,200–1,550	None	Nr	Timber, firewood, legume, fruits, spices	Philpott et al., 2008
Asia Indonesia	Western Lampung	97–350	nr	nr	0.8–1.4	Timber, legume, firewood, fruits, spices	Evizal et al., 2016
Asia India	Western Ghats	273–377	nr	nr	2.68–2.71	Timber, legumes, firewood, native tree diversity	Ambinakudige and Sathish, 2009
Asia India	Kerala	nr	nr	None	Nr	Timber, firewood, native tree diversity, black pepper, ground spices	Kumar et al., 2019
East Africa Ethiopia	Southeastern: Harerge	nr	nr	None	Nr	Legume, timber, fruit, stimulant, grains, pulses	Teketay and Tegineh, 1991
East Africa Ethiopia	Southwestern: Yayo Coffee Forest Biosphere	nr	nr	Banana, Ensete	3.14	Timber, legume, firewood, fruits, tubers, fodder, vegetables	Duguma et al., 2019
		nr	nr	None	1.21	Timber, wild fruits, legume	
		nr	nr	None	2.09	Timber, wild fruits, legume	
East Africa Uganda	Mt Elgon	63–146	2,200	10–240	Nr	Timber, firewood, fodder, fruits	Rahn et al., 2018
East Africa Tanzania	Mt Kilimanjaro	100	nr	1,000	Nr	Timber, fruits, legume	Wagner et al., 2019
West Africa Togo	Atakora mountains	198–273	2,670	None	3.58–4.06	Timber, legume, fruits, cloth, food	Koda et al., 2019
West Africa Cameroon	Western Region Kekem, Haute-Nkam	133	nr	650–1,000	0.5–2.16	Oil, legume, timber, fruits, medicinal	Temgoua et al., 2020
C America	El Salvador, Honduras, Nicaragua	198–488	Nr	10–240	1.57–3.08	Legume, timber, fruits	Somarriba et al., 2004
C America Nicaragua	El Cua, Tuma-La Dalia, Rancho Grande	114	5,356	516	1.23	Legume, firewood,	Pinoargote et al., 2017
		197	5,691	208	1.69	Legume, firewood, timber	
		437	5,946	179	2.36	Legume, firewood, timber, fruits	
N America Mexico	Chiapas, Mexico	371	1,500	nr	Nr	Native trees, timber, legume, firewood, fruits, materials other uses	Soto-Pinto et al., 2001
Caribbean Dominican Republic	Mixed with varying proportions of fruits, service, timber, banana tubers	539	3,732	450	Nr	Avocado, citrus, tubers, firewood, banana	Tapia et al., 2021
		412	3,418	301		Citrus, timber, avocado, firewood	
		853	3,366	738		Banana, citrus, timber, firewood, tubers	
		534	3,731	417		Timber, other fruits, cocoa	

initial hypothesis and a multiple benefits scoring framework. We test the framework using data collected previously of species diversity, stem density and biomass in coffee agroforestry in Nicaragua. Our conceptual timeline based on three scenarios to increase benefits illustrates the tree species and stem turnover in response to numerous market and livelihood challenges.

We hypothesize that while current smallholder agroforestry substitutes for certain coffee production inputs and provides opportunistic livelihood benefits generating stable participation in an unstable global coffee market, a transformation is opportune to more active management of species and stem turnover in system renovation cycles targeted to generating greater and more diverse benefits to farm household income, livelihood needs and ecosystem services to coffee production.

The phases of our analysis were as follows with greater methods details in the respective sections:

1) survey of research and technical documents in response to three questions: Does traditional tree diversity translate to critical livelihood benefits? Are practical research results increasingly available to build strategies for more benefits-oriented diversity in coffee agroforestry? Are the drivers of global markets compatible with more benefits-rich smallholder coffee agroforestry?
2) design of multiple benefits scoring framework drawing on insights from the document survey and test using our previously collected data sets of tree species density in 140 coffee fields in Nicaragua to visualize how tree

use characteristics and density converts into market diversification, seasonal food needs, other household uses, coffee productivity maintenance and habitat;

3) feasibility testing of benefits intensification scenarios by grower typology to address recurrent gaps like food security and income diversification scored with the same preliminary system. The program SExI- FS which models light capture and penetration based on individual tree canopy dimensions and characteristics was used to target at least 50% light for high coffee productivity with different reconfigurations of the agroforestry components.

In the discussion we address gaps in current data on traditional agroforestry systems and highlight the need for simple methods to collect data on-farm of the current benefits of trees by species, tree specifications and density. Equally the benefits potential of alternatives needs to be data-based. Such data have relevance for academic hypothesis-testing and data-driven grower strategies for agroforestry transformation.

DOCUMENT SURVEY: THE FUTURE FOR DIVERSE, BENEFITS-RICH SMALLHOLDER COFFEE AGROFORESTRY

Coffee agroforestry used by small growers has evolved and developed over the past 100 or more years in a context quite different from the forces at work currently. Our three-phrase document survey summarized in this section addresses first the benefits offered by smallholder coffee agroforestry reported in academic literature. Next, we profiled the contribution of coffee research to the challenges of future agroforestry systems, both component and system research. Finally, we surveyed academic work, sector strategy papers and advocacy proposals to characterize market, demand and regulatory pressures which might influence the transformation of coffee agroforestry.

In the following sections we provide substantiating detail contributing to our hypothesis. In summary, traditional low yield, multi-strata smallholder fields will need to undergo modification to become a viable livelihood for the next generation of smallholder growers and workers. An increasing demand for fine and bulk coffee ensures an available market. Agroforestry offers practical advantages for income and food diversification, and for input efficiency and reduced externalities.

However, on-going species and variety substitution to address climate change and market demand will be needed with altered species interactions to be addressed through ecological intensification as a pathway for more cost-effective coffee production. Driven by certification standards and national regulations, future smallholders of agroforestry coffee will need to address benefits such as habitat for native flora and fauna and clean water. Socio-economic, production and ecological research inputs will be needed to support updated multi-objective smallholder coffee agroforestry. Practical data collection and analysis tools can leverage the strengths of traditional agroforestry for data-driven transformative management for greater ecological intensification and economic efficiency.

An Overview of Local Benefits From Smallholder Coffee Production Systems

Studies worldwide inventorying the plant diversity in established coffee fields document farmer strategies to achieve cash income from coffee, while also addressing local benefits (**Table 1**). The cases selected by a search for studies with tree density and use illustrative of major continental coffee production regions present data from different plot sizes and different minimum tree diameters and calculate indices based on data sets with different samples—sometimes plots or multiple plots in a single community. Few studies quantified overhead shade and coffee productivity. We report the data as cited in the papers which provide an overview on farmer innovation in multi-strata coffee production in response to local biophysical, market and home consumption contexts. In all plots coffee is the key income source and a major plant component. Trees in the plots referenced from Asia, East and West Africa, Mexico, and Central America and the Caribbean, ranged in density from 50 to as many as 350–800 stems/ha. Wood products—timber and firewood—appear with greatest frequency followed by nitrogen-providing legumes and fruits. Shade, soil protection and habitat are not mentioned and are assumed, based on the presence of trees, to be services of all the plots listed. The lower tree diversity in certain zones in Asia provides these basic services, but little in terms of food and alternative income, while in higher diversity systems such as West and East Africa and some regions of Latin America the provision of food, income and other household materials is more common. Native tree and shrub species are an important component in India, Togo, Ethiopia, and Mexico. Zones in East Africa, Central America, and the Caribbean incorporate abundant banana mats as a major food and income crop in the agroforestry system. The presence of annual food crops is documented for cereal grains, pulses, tubers and vegetables in southeastern Ethiopia and tubers for coffee agroforestry plots in Dominican Republic.

On balance, the rich documentation of smallholder multi-strata coffee fields in **Table 1** suggests that the presence of trees generates certain services due to the nature of trees as a growth form—shade, soil protection, and wood products for fuel and local construction. Other benefits depend more on the composition of associated tree species—nitrogen enrichment, fruits, and spices. Staple foods are a relatively uncommon benefit in the studies cited. The range of stem density and species diversity reflected in **Table 1** is the source of abundant non-food local benefits compared to sun-grown coffee or with shade from a single tree species. The conversion of coffee agroforestry to annual food or income crops represent lower plant species diversity and a loss of associated services, although increased food (Duguma et al., 2019; Fernandez and Méndez, 2019). On the other hand, the expansion of coffee agroforestry at the expense of land for food production may result in losses in local food autonomy (studies already cited from Central America and Mexico), although accompanying gains in services like carbon, soil cover, water conservation, and habitat. This contrast of coffee agroforestry systems globally generates a question—how can traditional coffee plot tree diversity be oriented toward greater local benefits like food security and income diversification?

Trends in Research on Coffee Agroforestry Improvement

In this section we highlight advances in three major research lines—varietal development and pest and disease management, coffee agroforestry system description and improvement, including participatory research and economic efficiency analyses. We also identify gaps and opportunities for further research based on the other two sections of this document survey and our own experience.

Globally coffee research directs major efforts to diseases and pests, in particular coffee rust (Avelino et al., 2018) and coffee berry borer (Jaramillo et al., 2006) which generate both increased costs of production and often large losses for growers of all sizes. Complex food web interactions affecting losses to coffee pests and diseases have also been documented (Perfecto et al., 2014) in diverse agroforestry, although integrated management strategies incorporating these interactions are still under development. New coffee cultivars are in the pipeline to address disease losses, although primarily for lower shade and higher fertilizer inputs (Vossen et al., 2015). Varieties for agroforestry systems also incorporating climate change and coffee quality are the target of multi-partner breeding program (Bertrand et al., 2019). Such component research results on varieties for climate change and coffee cup quality under agroforestry and pest and disease management are essential to improving the viability of future smallholder coffee production enterprises.

The multiple objectives of smallholders in growing coffee with multi-strata trees are also a topic of research. Studies of existing diversity have already been summarized in the previous section. Staver et al. (2001) proposed an integrated system perspective to design pest suppressive multi-strata. Allinne et al. (2016) expanded on pest damage interaction with system characteristics as quantified in other ecosystem services. However, their study addressed highly contrasting production strategies with limited data on differences among agroforestry strategies. Tree canopy models have been developed to project light capture and penetration in mixed or single species tree plantings based on canopy dimensions, canopy openness, tree height and location with GPS coordinates (Harja and Vincént, 2008; Quesada et al., 2010). However, they have not been applied in highly diverse tree stands. More advanced models like Maespa are oriented to modeling ecophysiological processes including coffee in relatively simple agroforestry systems (Vezy et al., 2018). Research groups such as Rahn et al. (2014) have analyzed trade-offs and synergies of contrasting coffee agroforestry systems on-farm primarily from the perspective of carbon capture, climate change adaptation and mitigation and livelihoods. They use tree inventories of current systems to suggest best practices. The effects of climate change on tree species in coffee agroforestry were highlighted by de Sousa et al. (2019). They conclude that many current tree species in coffee agroforestry will not be adapted to higher temperatures and classify the ecological niches of 100 tree species in Mesoamerica to guide species substitution as climate continues to change.

Participatory research approaches have also addressed adaptation to climate change and improved food security with relatively little input from science and research (Shapiro-Garza et al., 2020), while others such as Cerdán et al. (2012) and Gram et al. (2018) have re-interpreted local knowledge in an ecosystem services framework. These approaches are deployed to facilitate farmers into action in a project framework with low potential to address the challenges of agroforestry redesign and management toward more targeted local benefits.

Economists have looked at the efficiency of coffee farms in different contexts (Binam et al., 2003; Perdomo and Mendieta, 2007; Ngango and Kim, 2019). The studies have primarily addressed technical efficiency of coffee production with results suggesting that coffee farms in Rwanda (82%) convert inputs into outputs more efficiently than farms in Cote d'Ivoire (47%) and Colombia (42%). The approach uses survey data from farms to generate production functions suggesting that the technology across farms in Rwanda is much more uniform than in Colombia. The study of coffee farms in Colombia expanded the analysis to contrast three farm sizes which addresses scale efficiency and allocative efficiency—the mix of land, labor and capital. The authors found that large farms deployed more optimum input levels, but that medium and small farms were lower cost producers. They also concluded that the coffee sector in general offered much scope for improvements in economic efficiency. The study in Cote d'Ivoire also identified significant scale efficiencies suggesting that farms could become more efficient by modifying the size of their operation. The authors identified both positive and negative socioeconomic factors linked to technical efficiency differences. For example, large family size may result in overuse of labor beyond efficient levels. None of these studies provide technical parameters on labor or input productivity, the role of tools, equipment or means of transport on-farm, tree species, age or pruning strategies, agroforestry composition, age of planting or renovation strategies, availability of off-farm services or resource endowment like clean water sources or road access. Ofori-Bah and Asafu-Adjaye (2011) focused on cocoa agroforestry to study efficiencies of scope, including intercropping and shade trees in their analysis, The efficiency of deployment of land, labor and capital in environmental sustainability has been measured (Grzelak et al., 2019) and environmental measures were incorporated into an analysis of cocoa in Indonesia by Tothmihaly et al. (2019), but no studies are available for coffee production. The long-term data base of farms in Europe from Grzelak et al. (2019) suggests that larger and more capital-intensive farms generate environmental value more efficiently. Practical calculations on the environmental costs of coffee production (https://trueprice.org/monetisation-factors-for-true-pricing/) conclude that the current price does not cover the environmental costs, but studies are yet to be done on farm to farm variability and the role of coffee agroforestry, worker skill sets and income levels, coffee processing technology, and other factors in coffee production eco-efficiency.

A large applied research challenge emerges from this brief analysis of technical, scale, allocative, scope, and eco-efficiencies which is largely economic in nature built from existing farm data. Production scientists, agroecologists and economists using farm and field data along with technical and ecological parameters could formulate and test alternative coffee agroforestry scenarios based on different factor endowments, farm sizes and production technologies and ecological processes. A potential product of such efforts would be practical data collection tools for smallholders to manage data-driven diversified agroforestry coffee from an enterprise perspective with accounting for externalities. Contreras-Medina et al. (2020) take a value chain stakeholder perspective to "roadmap" key technologies and capacities to a more sustainable future for the coffee sector in Chiapas, Mexico. They combine surveys of coffee farms and foresight analysis on emerging technologies and market demands to develop their conclusions which do not include coffee agroforestry. However, they highlight the need for a better understanding of small farm needs, the nature of emerging technologies and potential for the use of digital tools. In a major study on global coffee sustainability, Sachs et al. (2019) make no specific mention of agroforestry in their recommendations for national coffee sustainability plans. Similarly to Contreras-Medina et al. (2020) they take a commodity focus rather than a farm enterprise approach.

In summary, current research efforts are directed primarily to improved coffee varieties, including for agroforestry systems and climate change, and pest and disease management. Studies on coffee agroforestry as illustrated in **Table 1** document species diversity of current farmer strategies, while other studies not cited here quantify carbon storage which we considered a global and not a local benefit for climate change mitigation. While economic analyses are limited, they illustrate an important dimension to science inputs. We propose that research should be expanded to address the design and management of future smallholder coffee agroforestry fields and enterprises from the perspective of farm and value chain profitability, including worker wage livelihoods, sustainability, and resilience incorporating production technology, ecological intensification and technical, allocative, scale and eco-efficiencies.

Drivers of Future Coffee Production Systems and the Potential for Local Benefits

A summary of driving forces which will influence the viability of the next generation of smallholder coffee farms is a key input into strategizing agroforestry alternatives which update system benefits in evolving global and local contexts. While a more thorough foresight analysis of future smallholder coffee production systems would be opportune, here we summarize four areas of relevance from the market perspective—demand and pricing, enterprise competitiveness, certification and regulation requirements and climate change/pests and diseases which affect global supplies.

Demand for coffee is growing, both specialty coffee and bulk coffee for coffee-based products (Panhuysen and Pierrot, 2014, 2018, 2020) which may have quite different structures of costs of production and marketing. Higher prices of export gourmet coffee may be more appealing, but the production of bulk coffee with lower production costs may offer lower risk income and greater flexibility for agroforestry systems. Production for national markets may offer production options to regions with limiting abiotic conditions for high quality coffee. Around a third of global coffee production is consumed in producing countries and future growth in coffee consumption will occur primarily in developing countries (Sachs et al., 2019). Coffee certified under different labels may also offer price incentives suitable for certain groups of growers with potential demand limitations on specific labels. For example, De Janvry et al. (2011) calculated that the price bonus in FairTrade coffee will result in overproduction and a loss of benefit to growers precisely because demand is limited, and coffee cooperatives are not able to place all their production with FairTrade buyers. While overall the future of coffee may appear promising, several studies (Earth Security Group, 2017; Sachs et al., 2019; Panhuysen and Pierrot, 2020) warn that the current coffee business model is not sustainable due to high environmental costs and low commodity prices which are unprofitable for smallholder producers who produce up from 60% of global production.

Small farms as enterprises must survive in an uncertain and evolving global coffee market. Numerous studies, summarized by Muñoz-Rodríguez et al. (2019), suggest that currently the costs of production of coffee are greater than prices paid and do not provide a living income. The True Price method (https://trueprice.org/monetisation-factors-for-true-pricing/) also includes externalities driving the actual cost of conventional coffee even higher. Barham and Weber (2012) found that yields rather than certification were more important to increasing net household returns from coffee production. They conclude that certification schemes should incentivize yield improvement addressing both grower wellbeing and compliance with certification norms. They highlighted the role of fertilization in yield improvement. Hernandez (2020) proposes a smallholder model primarily with family labor for Mexico with inputs to achieve yields of 800 kg/ha/year on 3 ha of coffee agroforestry. Pinoargote et al. (2017) also proposed that adequately fertilized and pruned coffee is a cornerstone to diversified multi-strata approaches. Their three grower groups reported yields from 500 to 850 kg/ha/year, above national averages in many countries. Coffee harvesting is a major cost component with a lower cost per volume harvested in higher yielding fields, illustrative of the importance of higher yields. Seasonal workers seek out farms with higher yields to contract their services paid by piece work and growers often complain of labor shortages. Fields with sparse and dispersed berries provide less income per day to workers than high yielding bushes. The labor challenges are illustrated vividly by Jimenez-Soto (2020) who documented the farm worker perspective in current coffee production and Cofre-Bravo et al. (2019) who identified farm workforce engagement in the innovation process as a key variable in the most dynamic enterprises. At the same time, the diversified livelihoods approach of smallholder coffee farms has been documented and has great relevance for an uncertain future (Anderzén et al., 2020). In their evaluation of the sustainability of the coffee sector, Earth Security Group (2017) identifies the need for "regenerative production systems which are commercially viable," although they do not mention food security or income diversification. Improved yields/ha, for example, a doubling of national yield averages, may benefit efficient growers, but would lead to general overall overproduction putting downward pressure on coffee prices (Waarts et al., 2019). Well-designed multi-strata agroforestry appears to offer a way forward based on well-yielding coffee with lower costs of production based on nutrient recycling and nitrogen enrichment, pest and disease suppression based on biotic and abiotic factors and labor efficiencies in harvesting and other practices. At the same time, drawing on lessons from traditional diverse multi-strata systems, well-selected and managed agroforestry system components could provide targeted complementary income diversification and production of staple foods ensuring enterprise resilience in the face of price fluctuations and climate and pest/disease variability.

Beyond enterprise issues, future smallholder coffee systems also face ever increasing requirements/opportunities from value chain certification frameworks through price incentives and national and local policies and regulations which orient food, worker and environmental safety through legal compliance mechanisms. Lambin et al. (2014) refer to the demand-driven voluntary certifications which enable access to certain markets and the command and control of national regulations. For coffee, Millard (2017) identifies three demand-driven initiatives—certification frameworks, company-driven standards and industry platforms. The certification frameworks in coffee are organic, FairTrade, Rainforest, and Smithsonian Bird-Friendly which have often entered into alliances with companies like Starbucks and Nespresso which have their own certification procedures. The 4-C certification platform originated from agreements among large food corporations to cover more basic environmental, social and economic issues. Specifications on multi-strata composition and structure are found primarily for bird-friendly coffee, while the other certifications have more general requirements around biodiversity, deforestation, soil and water management and social and labor criteria primarily to generate consumer confidence. A meta-analysis of studies on the contribution of voluntary certification on sustainability suggested that some evidence exists for positive impact primarily measured on environmental factors and price received, although not grower income (DeFries et al., 2017). Vellema et al. (2015) concluded that the extra costs to meet certification standards reduced income from other non-coffee activities resulting in no increase in overall household income from certified coffee production. Bianco (2020) examined corporate social responsibility strategies to address climate change in coffee and concluded that certification should be complemented by more direct action in development of alternative varieties for substitution and on-farm investment. The precise nature of certifications and standards and their approaches to both consumer and producer expectations is uncertain, but will certainly become more rigorous and directive in the next years. Future generations of smallholder multi-strata coffee producers and their organizations will need to be versatile, creative and data-driven managers of certification requirements to leverage them to guide small farm viability compatible with coffee agroforestry.

The command-and-control regulations by national governments for the environment, labor safety, use of pesticides, and food safety will also orient smallholder coffee production systems toward greater compliance with worker safety in such activities as tree pruning and pesticide use and more careful management of coffee wastes and increased infrastructure in coffee processing to reduce pollution. For multi-strata coffee, regulations on tree cutting will influence farmer willingness to manage their tree planting and cutting for timber and other benefits. Detlefsen and Scheelje (2012) concluded based on a comparison of regulations in the countries in Central America that legal procedures for tree cutting were very variable and only in few countries were simple and well-implemented to make on-farm planting for extraction attractive. Regulations on transparent and effective tree extraction and other core activities of coffee agroforestry may still be in the future in most coffee-growing regions. However, small coffee agroforestry enterprises and their associations will need to address the paperwork and investment from increasing labor, environmental, and business regulations.

Among biotic and abiotic factors threatening coffee returns and smallholder livelihoods are the resurgence of coffee rust and the breakdown of resistance in currently resistant varieties (McCook and Vandermeer, 2015), the possible spread of new diseases not yet present in certain regions like coffee berry disease and coffee wilt (Waller et al., 2007) and an increasing erratic climate linked to global warming (Morris et al., 2016; Pham et al., 2019). Abiotic and biotic threats may also threaten the associated plant diversity in the multi-strata system. For example, service trees currently used in multi-strata coffee may be less adapted to higher temperatures (de Sousa et al., 2019). These threats can be addressed with multi-strata production which offers micro-climate modification and increased beneficial flora and fauna. However, the traditional system based on a relatively static composition of certain cultivars and species will need to undergo dynamic evolution with change in coffee varieties and associated timber, service and fruit trees under the active management of growers backed by other grower experiences, technical assistance and scientific knowledge.

Salient characteristics of future smallholder coffee agroforestry emerge from this survey of drivers. "Regenerative production systems which are commercially viable" (Earth Security Group, 2017) will need to include moderately high yielding coffee and multi-strata agroforestry with components which are selected and managed to provide multiple and targeted benefits—reduced coffee production costs, diversified income and sustained support to household livelihood needs. In terms of grower management tools, data demands both for certification and national regulations should be leveraged to facilitate more dynamic grower adaptive management in terms of efficiency, resilience and profitability. This suggests that growers will move from the continuity and stability of traditional diverse agroforestry to more dynamic benefits-oriented use of diversity with species and stem turnover to optimize contributions to coffee productivity, income and household needs and to respond to shifting climatic and market conditions.

ADDRESSING BENEFITS GAPS IN COFFEE AGROFORESTRY: AN APPROACH AND PRELIMINARY TEST

Previous sections suggest that tree species diversity common in smallholder coffee agroforestry must be analyzed in terms of specific livelihood benefits. Documenting diversity alone is not sufficient. This step is fundamental toward proposing targeted modifications which address livelihood benefits gaps. In this section, we present our test using previously collected data to focus on the recurrent gaps in local benefits which are threatened by the shift to coffee monoculture or simplified agroforestry. The illustrative exercise tested our hypothesis and provided us insights and priorities for a research and development agenda addressing livelihoods benefits intensification in coffee agroforestry. In the following section we first describing a multiple benefits scoring framework. After providing details on our methods, we characterize our data sets from 140 coffee agroforestry fields and apply the multiple benefits scale to four typologies grouping smallholder coffee plots in the data sets. Finally, we analyze three scenarios for benefit enrichment compatible with improved coffee yields applied to examples from each typology.

A Method to Characterize Benefits Gaps in Smallholder Coffee Agroforestry

Multi-functionality is a characteristic of all ecosystems, although the measurement and comparison across functions may present challenges (Garland et al., 2021). Our concern here is to test whether ecosystem services generated by ecosystems functions result in livelihood benefits to coffee growing households and their communities. Our studies on the optimization of banana in coffee multi-strata agroforestry have provided insights into both multiple benefits and their distribution during the year (Staver et al., 2010). These benefits from banana include compatibility with mixed species systems, ease of establishment and management for shade and high biomass production for soil protection and improvement. Farm households are very clear in the importance of the monthly income resulting from the sale of bananas as a petty cash fund. Bananas are a food staple in a few coffee-growing regions and in other regions provide food for lean months and backyard animals. Leaves and stems are used in food preparation and as temporary shelter and packaging material. Banana flowers available in most months of the year depending on rainfall distribution attract a wide diversity of insects and ripening bunches of bananas left in the field attract mammals and birds. The banana example suggests certain dimensions important to screen alternatives to address gaps in local benefits. The reviews in the previous sections point to similar issues generated by the shift to less diverse coffee agroforestry and open sun monoculture described by Moguel and Toledo (1999). First, the "lean months" refer to both food and income shortfalls in specific months of the year. Second, dependence only on coffee income with volatile prices results in livelihoods vulnerability. Third, the reduction of ecological functions from agroforestry in support of higher yielding coffee production are not available from coffee monocultures or agroforestry with few species and need to be replaced with external inputs. Finally, biodiversity loss relating to the first three issues generates a loss of habitat functions.

Studies of species present in coffee agroforestry have quantified ecosystem services. Duguma et al. (2019) convened farmers in the Yayo Biosphere to rate four land use systems for 15 ecosystem services defined in the Millennium Ecosystem Assessment. This approach did not link tree species to the services which reduces its utility for multi-strata redesign. They looked at trends over decades, an important perspective, but did not capture within-year provision of benefits. Gram et al. (2018) convened farmer focus groups to document their classification of specific tree species in terms of regulating and provisioning services. The resulting information provides a rich basis to identify alternatives for increased services. They did not include income generation among the services and did not capture the within-year distribution of services which our experience with banana suggests is an important criteria for farm households. Cerdán et al. (2012) also documented farmer knowledge of tree species services focusing on services to coffee and soil productivity and habitat for biodiversity, missing food provision, income diversification and the within-year dimension.

We propose the framework described below to focus on recurrent gaps in livelihood benefits. We assume that soil and water conservation, leaf litter and micro-climate modification are general services from all species or are more related to number of individual trees, their size and layout. This assumption could be modified in later versions of the approach or for more location-specific analysis. To target the selection process on gaps, we rated each species according to five categories of benefits—coffee productivity, income, food, other household uses and habitat with sub-categories for each of the five types. We also rate species according to the strata they generally occupy into three categories—upper (trees), midstory (trees and bananas), understory (coffee, bushy, and herbaceous species) which contributes a useful filter to screening alternatives. We emphasize that our sub-categories are exploratory to illustrate the approach. The scales below are proposed to classify each species present in the coffee agroforestry plot:

- **Coffee productivity:** 0 – none; 1 - nitrogen fixation; 2 - temporary shade; 3 – phosphorus accumulation. The more general benefits of trees are not included in this rating. Leaf phenology might also be the basis to characterize differences in tree species, although in actively-managed mixed species multi-strata systems, some degree of shade will always be overhead. Another sub-category might be presence of nectaries (Rezende et al., 2014). This potential benefit could also be addressed through an additional category of service linked specifically to micro-environment effects and biocontrol of pests and diseases of coffee and other plant species in the multi-strata system.
- **Income:** 0 – none; 1 - monthly; 2 – seasonal for export; 3 – seasonal for national markets; 4 – seasonal for local sale and exchange; 5 – multi-year. Information on the season of production and the target market captured in these

sub-categories is an important input to income diversification. Rice (2011) provides useful insights about the characterization of fruit production in the household economy. Banana harvest, for example, although fluctuating throughout the year in response to abiotic conditions, still produces bunches in most months, even with rustic management.

- **Food:** 0 – none; 1 - monthly; 2 – seasonal perishable; 3 – seasonal storable; 4 – emergency seasonal. The seasonality of food availability is highlighted in the studies on the lean months (Fernandez et al., 2013; Morris et al., 2013) suggesting that this benefit should have sub-categories by season. We also envisioned differences between perishable fruits and stored products like seeds and emergency foods which are sourced primarily in times of stress. We have seen that poorly filled out banana bunches can become food in years when lean months are severe.
- **Other household uses:** 0 – none; 1 - firewood; 2 – construction material; 3 – resins and medicinals; 4 - fibers and coverings. We debated whether this should be by season or by product and concluded that many of these are available year round with the exception of medicinals and resins which may be non-perishable. This last use is listed commonly in **Table 1** as well and merits more thorough data collection.
- **Habitat**: 0 – none; 1 – birds; 2 – bats; 3 – bees; 4 – small mammals. Peters et al. (2016) argue that tree species selection should be guided by type and season of feed resources provided to fauna. Narango et al. (2019) and Chain-Guadarrama et al. (2019) provide more specific information on insects as feed resource for birds and bees in pollination. We included this benefit based on types of fauna, but realize that both our own experience and the literature are limited to provide thorough information either by species or seasonality. Few tree species do not provide some habitat service, even just roosting or flowers and seeds. A scoring scale might recognize species with special habitat services either special habitat contributions for key fauna highly valued or broad general resources to multiple types of fauna and in multiple seasons.

Methods Used to Test the Benefits Gap Framework

To explore the potential of the scale proposed above to quantify local benefits, we re-analyzed three data sets from our previous work with smallholder coffee farmers in Nicaragua. The data set collected in 2009 from Monterrey (Jinotega department) and Yasica Sur (Matagalpa department) inventoried all stems > 5 cm in diameter in two subplots of 25 × 25 m in 30 coffee fields (Siles et al., 2012). The data set collected in 2011 from El Cua (Jinotega department) and Jalapa (Nueva Segovia department) inventoried all stems >3 cm in diameter in one 20 × 50 m plot in 40 coffee fields (Cerdán unpublished). The data set collected in 2016 from the Jinotega municipality (Jinotega department) inventoried all stems >2.5 cm in diameter in one 20 × 50 m plot in 70 coffee fields (Kichline, 2017). In each plot, all trees and saplings were identified and measured (DBH and height) for individuals above the minimum circumference at breast height (DBH taken at a height of 1.3 m). When buttresses and other irregularities were present at 1.3 m, the stem was measured 50 cm above the protuberances. For multi-stemmed individuals, DBH of all stems was measured as for the single individual. Tree species were identified by the authors in the field or with the help of dendrological keys (Gentry, 1993; Holdridge and Poveda, 1997; Zamora et al., 2000, 2003).

Our preliminary test using the scale in the previous section was carried out in three steps: (1) recombination of three data sets into typologies of agroforestry strategies based on stem densities and basal area by species; (2) local benefit quantification based on species stem density and use characteristics; and (3) analysis of three scenarios applied in one field from each of four typologies to address gaps through simulation with a spatial model and recalculation of summary statistics.

In the first step, the density of trees and saplings was determined by counting the number of individuals in the sampling plot, the stem basal area of each individual was calculated using the DBH and the plot basal area was the sum of all individual stems expressed per plot. Species richness per plot and Shannon diversity index were calculated using the BiodiversityR package in R, Version 3.2 (Kindt and Coe, 2005). Species accumulation curves (100 randomizations without replacement) were calculated using the Vegan package (Oksanen et al., 2007). To generate a typology from the three data sets together, we grouped species into three agroforestry components—*Musa*, *Inga* spp and other trees. Other groupings were tested, but did not generate as strongly differentiated typologies. An agglomerative hierarchical cluster analysis using the Ward-algorithm applied to a matrix of Euclidean distance coefficients between all plots using the Vegan package (Oksanen et al., 2007) was performed on the basal area, tree density and importance value index (IVI) grouped by *Musa*, *Inga*, and other trees. The IVI expresses the relative values of basal area and density by groups as follows: [relative basal area (%) + relative density (%)]/2; where the relative basal area is the basal area of each group divided by the total basal area in the plot and the relative density is the number of individuals per group divided by the total number of individuals present per plot (Galindo-Jaimes et al., 2002).

For step two, the three authors characterized the benefits provided by each one of the 122 tree species identified. We recognize that more precise and locally applicable characterization should combine both farmer and more broad-based scientific knowledge. Here we are motivated to illustrate a service gap-filling approach for further elaboration in later research. We visualized gaps in services by graphing plot by plot our five categories of services and the sub-categories in income and food. The level of each service was calculated by summing the number of individuals for each service across species present. These graphs for services were done both with and without banana. The graphs without banana reveal more clearly the profile of benefits provided by tree diversity.

In the final step we used spatial data of individual tree dimensions and distribution from four case studies of the nine plots measured (Kichline, 2017). Each of the plots was illustrative of one of the typologies (MIX, TD, ID and MD). We explored alternative multi-strata systems based on elimination

TABLE 2 | Characteristics of four typologies generated from the three data sets of composition of coffee multi-strata vegetation.

Description	Mix	MD	TD	ID
Musa density (ind 0.1 ha^{-1})	42.7 ± 2.3	43.4 ± 3.0	12.4 ± 3.8	6.4 ± 1.4
Inga density (ind 0.1 ha^{-1})	14.2 ± 1.0	4.2 ± 1.4	7.2 ± 0.6	11.5 ± 1.0
Diverse Trees (ind 0.1 ha^{-1})	15.1 ± 2.0	6.8 ± 0.7	22.4 ± 3.6	4.2 ± 1.0
Timber trees density (ind 0.1 ha^{-1})[a]	2.0 ± 0.6	0.6 ± 0.2	0.6 ± 0.2	0.2 ± 0.1
Fruit trees density (ind 0.1 ha^{-1})[b]	3.4 ± 0.9	1.7 ± 0.2	6.2 ± 1.7	1.5 ± 0.6
Rare2 trees density (ind 0.1 ha^{-1})[c]	2.8 ± 0.6	2.0 ± 0.4	4.1 ± 1.4	0.7 ± 0.3
Rare1 trees density (ind 0.1 ha^{-1})[d]	7.9 ± 1.3	2.6 ± 0.4	11.5 ± 2.5	1.8 ± 0.5
Basal area *Musa* (m^2 0.1 ha^{-1})	1.25 ± 0.08	1.22 ± 0.09	0.36 ± 0.11	0.16 ± 0.04
Basal area *Inga* (m^2 0.1 ha^{-1})	0.60 ± 0.05	0.17 ± 0.02	0.16 ± 0.03	0.48 ± 0.05
Basal area Diverse Tree (m^2 0.1 ha^{-1})	0.44 ± 0.06	0.28 ± 0.03	1.55 ± 0.32	0.27 ± 0.08
IVI *Musa* (%)	56.9 ± 1.7	73.3 ± 1.9	17.0 ± 4.0	20.0 ± 4.4
IVI *Inga* (%)	24.0 ± 1.5	9.8 ± 1.0	12.6 ± 2.8	59.7 ± 3.9
IVI Diverse Trees (%)	19.1 ± 1.8	16.9 ± 1.6	70.4 ± 4.5	20.3 ± 3.4
Species density (species 0.1 ha^{-1})	8.3 ± 0.5	5.7 ± 0.4	8.4 ± 1.6	4.8 ± 0.5
Shannon	1.25 ± 0.06	0.86 ± 0.06	1.18 ± 0.21	1.08 ± 0.11
% Shade	39 ± 19	41 ± 19	29 ± 19	41 ± 17

MIX, Inga, Musa and trees balanced; MD, Musa dominated; TD, other tree dominated; ID, Inga dominated.
[a] *Timber species found in >20 plots—Juglans olanchana, Cordia aliadora.*
[b] *Fruit trees found in >20 plots—Persea americana, Citrus spp, Mangifera indica, and Psidium guajava.*
[c] *Species found in 9–20 plots, including less common timber and native fruits.*
[d] *Species found in fewer than 9 plots, including less common timber and native fruits.*

and substitution of species with a different suite of services addressing specific gaps, while ensuring a minimum of 50% light to the understory coffee. The spatial model SExI-FS was used to complete simulations of light availability from alternative multi-strata (Harja and Vincént, 2008). The resulting stem densities by species were also scored by type of benefit as was done in step two.

Re-interpreting Coffee Agroforestry in Nicaragua in Terms of Local Benefits

Our three data sets from the northern Nicaragua coffee zone had a total of 140 tree species with 18 unidentified species (**Supplementary Table 1**). The species accumulation curves for each data set (**Supplementary Figure 1**) show minor differences which could be attributed to slight differences in sampling methods and territory covered. For example, the Monterrey/Yasica site not only covered two zones on different sides of the mountain, but also sampled two plots within each field generating a slightly higher species accumulation curve.

The typology resulting from the combined data set (**Table 2**) highlights how growers combine and recombine the suite of species common in coffee fields in the region. Three of the typologies represent fields with domination of either Musa (MD), *Inga* (ID), or other trees (TD), while the remaining typology has more equal proportions of all three groups (MIX). **Figure 1** highlights the separation of the four typologies based on the IVI scores for each plot. Each typology dominated by a single group is concentrated in a different corner of the triangle with MIX more centric representing more equal proportions of each group, although tending more toward the high Musa corner. MIX has the highest overall stem density with a higher species density

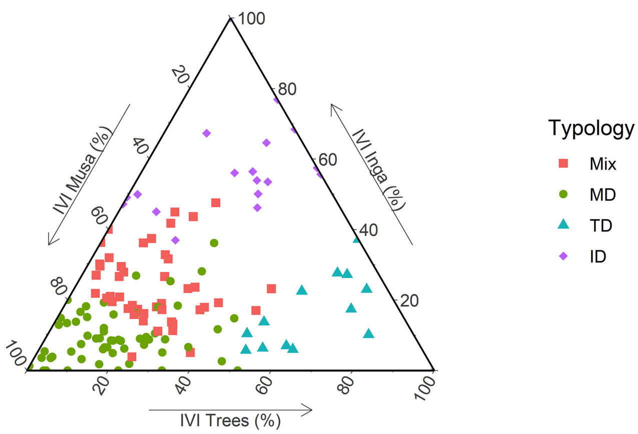

FIGURE 1 | Sampled coffee plots graphed by their importance value index of three categories of multi-strata vegetation—*Inga* (ID), banana or Musa (MD), and other trees (TD). The four typologies cluster in the triangular space based on the more dominant component with the typology MIX clustered more centrally.

and Shannon index. MD and ID had the lowest values both for species density and Shannon. The typology TD brings together higher tree density, diversity and basal area, although the group has lower timber species density than MIX. The typologies show stronger separation for Shannon index and species density than the three data sets (**Supplementary Figures 2**, **3**) which is also apparent in the species accumulation curves by typology. TD and MIX accumulate species at a faster rate and to a higher level, while MD and ID are lower on both dimensions. Average % shade of

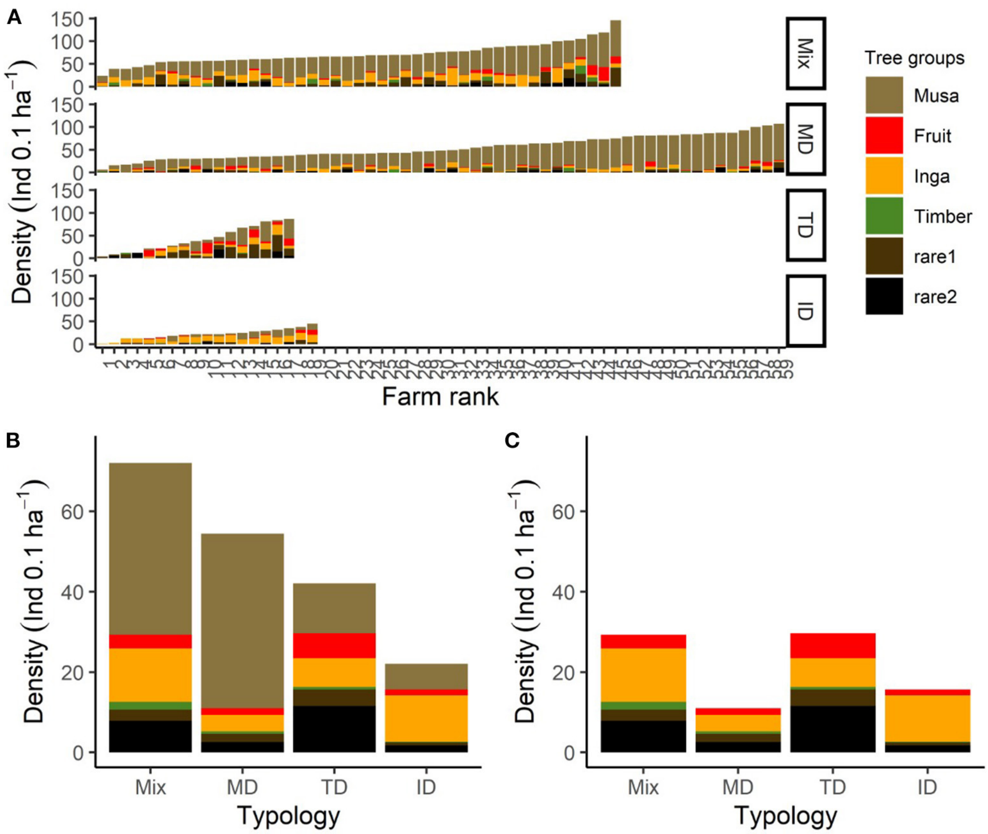

FIGURE 2 | (A) Tree composition for each of 140 plots by typology MD, ID, TD, MIX. (Fruit = fruit trees found in >20 plots—*Persea americana*, *Citrus* spp, *Mangifera indica*, *Psidium guajava*, Timber = timber species found in >20 plots—*Juglans olanchana*, *Cordia aliadora*, rare1 = species found in 9–20 plots, including less common timber and native fruits, rare2 = species found in fewer than 9 plots, including less common timber and native fruits). **(B)** Average density and composition for each typology including Musa. **(C)** Average density and composition for each typology without Musa.

40% was similar for three of the four typologies, while TD had lower shade levels at 29% with a similar standard deviation of 19% (**Table 2**). Two of the original data sets had average shade levels of 45–47% with standard deviation of 16–18%, while the data set for Jinotega had only 24% average shade. On average the typologies or data sets had sufficient light for productive coffee, but variability was also high indicating that some growers had 60% or more overhead shade in their plots, above the 50% threshold for more productive coffee (Franck and Vaast, 2009).

Plot by plot composition of individual trees by species groups for each typology highlights that within clusters there is a broad range of stem densities as seen in the overall height of each column (**Figure 2A**) from densities near zero to 100 stems or more per 1,000 m^2. Average density varies by typology (**Figure 2B**). Bananas are an important component in plots of both MIX and MD, grown primarily for markets nationally in Nicaragua or in the region in El Salvador. **Figure 2C** showing typology averages without Musa highlights more clearly contrasting proportions of the woody tree components. MIX and TD have higher tree density with greater stem density for three of the four components.

The potential local benefits available from each species found in the inventory as classified by the authors are documented in the **Supplementary Table 1**. Only seven species provide more than three of the five benefits. A common combination of four benefits, primarily leguminous shade trees, covers coffee productivity, food, firewood and habitat, while certain fruit trees generate income, food, firewood, and habitat. Only bananas provide all five benefits. The benefits provided by the fewest species were food, coffee productivity enhancement and income, while habitat and other household uses were the most common benefits. On a plot-by-plot basis, the overall range of total benefits in each typology is high from relatively few per plot to over 400 (**Figure 3**). If a plot has few individuals, quite obviously the benefits provided will be limited. Typology ID with limited banana has fewer benefits, while plots with abundant bananas have much higher benefit levels. In our simplified method to quantify benefits at plot level, a single individual may provide more than one benefit. While stem densities in **Figure 2** reach 100–150, the count for benefits reach 400 highlighting that certain stems by species offer multiple benefits. Since bananas are providers of five benefits and are also quite abundant in smallholder coffee plots in Nicaragua, they mask the benefit contribution of the remaining tree diversity. **Figure 4** contrasts average benefits by category for each typology with (4a) and without banana (4b). Without banana, total benefits

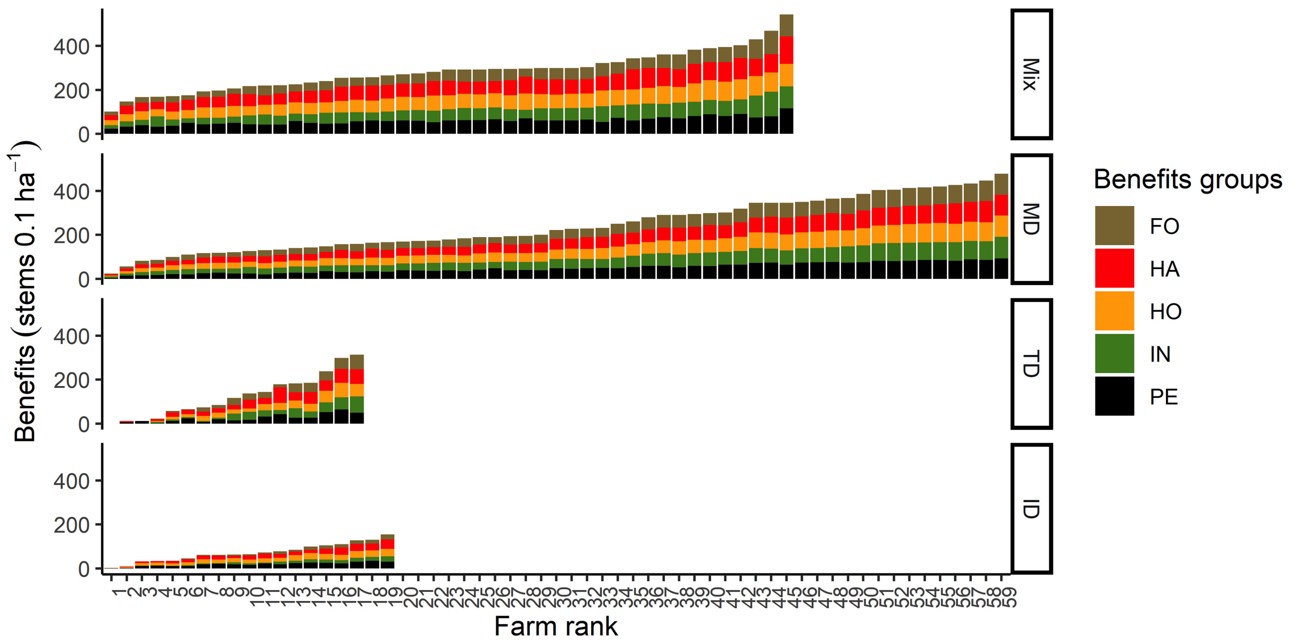

FIGURE 3 | Benefits composition from the agroforestry system in 140 plots displayed by typology. FO, Food; HA, Habitat; HO, Other household use; IN, Income; PE, Productivity enhancement coffee.

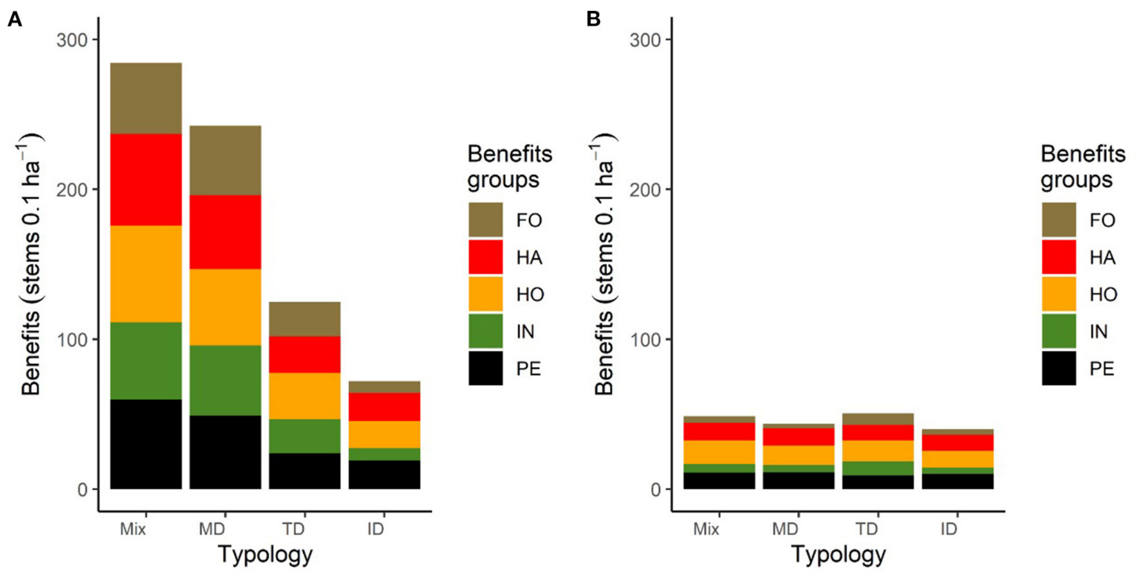

FIGURE 4 | Average benefits from the agroforestry system types, including **(A)** and excluding **(B)** banana stems. FO, Food; HA, Habitat; HO, Other household use; IN, Income; PE, Productivity enhancement coffee.

drop drastically and food and income benefits shrink as a proportion of the total. Other household uses, habitat and coffee productivity enhancement are present in all four typologies. A visual inspection of **Figure 3** highlights that the species richness of multi-strata coffee does not translate into many benefits linked to income and food. As a consequence Nicaraguan coffee agroforestry, except for banana intercropping, has only a limited contribution in addressing the lean months and income diversification highlighted earlier.

The composition of benefits by subcategory for income and food provides additional insight into the contribution of specific benefits based on seasonality and other characteristics. **Figure 5A**

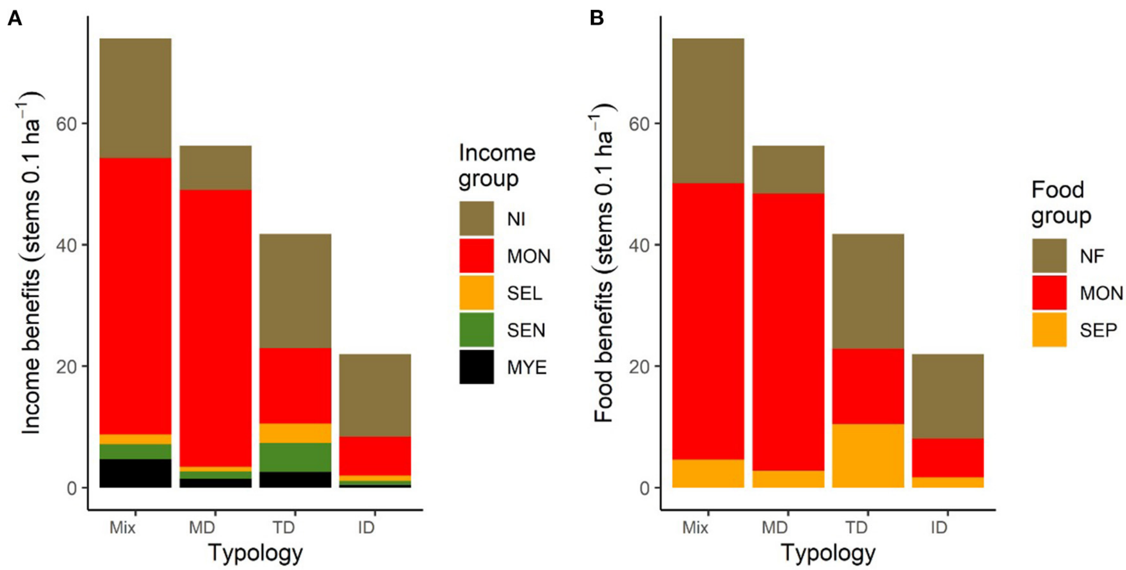

FIGURE 5 | Average income **(A)** and food types **(B)** from the agroforestry system types. Income (NI, no income; MON, monthly; SEL, seasonal local; SEN, seasonal national; MYE, Multiyear) and Food (NF, no food; MON, monthly; SEP, seasonal perishable). Categories absent from the graph are seasonable storable food and emergency or famine foods.

on income highlights that beyond the income from coffee to export markets, the monthly income from banana (MON) dominates followed by low levels of fruit (seasonal for local and national markets -SEL and SEN-) in certain typologies. Rice (2011) concluded that much of the fruit from coffee fields is wasted—not profitable for the market and too much for local and home consumption. Few benefits in **Figure 5A** result from timber, the only tree species with multi-year income potential (MYE). The timber income appears to be largely potential rather than realized income, since regulations and permissions limit tree harvest. The low density of timber trees also increases the cost of commercial extraction.

The benefits for food highlight a similar point—few species for food in only small numbers in the plots beyond banana (MON - monthly) and fruit (SEP—seasonal perishable) (**Figure 5B**). Several of our subcategories for food are not found in any plots. Seasonally produced food which can be stored such as maize or beans or even nuts and seeds is restricted to plots with a few cocoa plants. Although *J. olanchana* is somewhat common, the nuts are not consumed. No sources of emergency or famine foods were recorded, although we included it as a potential benefit from multi-strata coffee based on informal field observations during the coffee rust epidemic of 2013 when we were in the field.

Upon reflection we realized that the absence of data for seasonal stored and emergency food categories represent a methods weakness in many multi-strata tree inventories, including our own studies. Studies focus almost exclusively on the trees in intact and long standing coffee fields. In addition, most studies leave out the herbaceous component and field borders. A species like *Colocasia esculenta* is often found growing spontaneously in coffee fields with potential use only in times of dire need. The study by Fernandez and Méndez (2019) provides insight to food uses such as edible leaves from intact fields. The study of intact fields also misses the dynamic nature of coffee fields. Growers may cut down shade trees and cut back or uproot coffee during periods of low price, severe disease outbreaks or both. They may also seek to change coffee varieties or renovate shade trees. Such fields are often intercropped with annual food or cash crops providing seasonal storable food and potentially income, although data on fields in renovation or conversion do not appear in many data sets. The data set from Jinotega has 4 of 70 fields with no biomass in coffee plants suggesting recent renovation, but the other two studies missed systematic data collection on field renovation intervals and strategies both in interviews or field sampling.

In summary, the analysis of local benefits from the agroforestry component for smallholder coffee fields in Nicaragua show that beyond interplanted bananas, few other species provide food and income for the lean months or income diversification. The quantification of these benefits by subcategories provides a structure to capture distribution during the year and also differentiate between export, national and local markets. Certain authors have documented pilot programs to generate a more diversified mix of activities at the farm scale through food plots and beekeeping (Anderzén et al., 2020). In our exercise in the next section to screen alternatives for their contribution to the improvement of benefits, we direct our analysis at the scale of the coffee field, valid even if the farm is primarily planted to coffee.

TABLE 3 | Effects of scenarios on multi-strata characteristics for four cases representing MIX, MD, TD, and ID.

Descriptor	TD				MIX				ID				MD			
	Cur	Sc1	Sc2	Sc3	Cur	Sc1	Sc2	Sc3	Cur	Sc1	Sc2	Sc3	Cur	Sc1	Sc2	Sc3
Musa density	85	52	40	20	26	21	34	14	7	7	34	14	32	28	36	16
Inga density	5	2	2	0	1	1	1	1	8	6	6	0	9	6	6	0
Diverse Trees density	14	12	12	5	27	17	17	10	7	7	3	3	4	6	6	3
Timber trees density[a]	1	4	4	3	5	6	6	4	0	3	3	3	0	3	3	3
Understory density[b]	-	-	105	105 (155)	-	-	105	105 (155)	-	-	105	105 (155)	-	-	105	105 (155)
Species density	13	17	20	12	12	12	15	15	8	12	10	10	6	11	12	10
Shannon Index	0.9	1.3	1.9	1.3	1.7	1.7	1.9	1.4	0.9	1.3	1.7	1.6	1.8	2.2	1.8	1.6
Canopy openness (%)	40	44	40	78	39	49	43	76	50	54	49	77	49	51	47	78
Within-plot shade variability[c]	17	17	18	20	16	15	17	14	18	17	18	20	23	21	17	11
IN Total	91	59	152	180	54	41	159	180	7	10	142	172	32	31	144	174
FO Total	94	56	149	176	50	35	153	176	9	8	141	169	42	28	141	171

Cur, current situation; Sc1, timber with habitat; Sc2, agroforestry for zero-grazed ruminants; Sc3, rotational gap for system renewal.
[a] Timber trees included Cedrela, Juglans, Bombacopsis, Nectrandra, Platymiscium, and Dalbergia.
[b] In parenthesis total including annual crops accounted at units of 10 m^2.
[c] Standard deviation of shade values simulated on a 2 × 2 m grid in each simulation plot.

Testing the Potential of Diversity-Based Options to Address Recurrent Gaps in Local Services

In this section, we strategize modifications which maintain at least 50% light penetration to the coffee understory, while also generating increased benefits. Achieving improved coffee yields will require numerous additional inputs and management practices, but a base condition is adequate solar radiation for vigorous coffee plant growth. We propose this only as a preliminary step requiring numerous filters and follow-up studies involving biological, economic, and practical issues to reach field implementation. We propose that the step described here offers a concrete visualization to stimulate thinking about future smallholder coffee agroforestry with a focus on local benefits under dynamic and changing conditions. The current composition and benefits generated for income (IN) and food (FO) in each plot can be found in the columns labeled "Cur" in **Table 3**. The four cases have a broad range of shade from 50 to 60% with three cases close to the overall average of 40% with contrasting total stem densities from 220 to 1,050/ha. High banana density is found in one case. Tree density ranges from 40 to 320/ha, while *Inga* density ranges from 10 to 90. In the first step (Sc1 in **Table 3**), 50 trees/ha of five species with both timber and habitat potential or habitat potential alone with very open canopy are added or substituted depending on plot conditions. In the second step (Sc2 in **Table 3**), plots are further modified to diversify and increase monthly income and food availability. Bananas and hedges of leguminous fodder shrubs and cut and carry fodder are added to provide an adequate diet for a cow producing both milk for sale and consumption and manure to accelerate nutrient cycles. In the third step (Sc3 in **Table 3**), we simulate renovation in which coffee, service trees and some fruit trees and banana mats are cut down or severely pruned leaving only long cycle fruit and timber trees intact. We quantify whether available light is sufficient for food grain production during coffee and tree replanting using thresholds from studies on the quezungual system (Hellin et al., 1999) and field experience among the authors. For each of the steps and case studies we present data on density, species richness, Shannon diversity and canopy openness and the total score for income and food (**Table 3**). **Figure 6** illustrates the changes in canopy coverage and distribution through the different scenarios for the one case, while the other cases are available in **Supplementary Figures 4–6**.

Income With Habitat (Sc1)

In this first scenario we explored the contribution of increasing upper story timber trees or trees with high habitat contribution and very little light interception. The scenario is proposed given the paucity of timber trees in the great majority of the plots. Even when they are present, densities are low. At the scale of a hectare, the target was 50 additional individuals from five different species. In the typologies with low overall density and more available light the individuals can be added filling in areas with low shade level without generating excess shade, while for higher density plots, trees with lower timber potential or with lower habitat benefits or bananas were substituted. At the scale of 1,000 m^2, one individual of each species (15 year old tree for timber species and 10 year old tree for *Cecropia* which indicate the dimensions of the individual) of the following species was added or substituted into the spatial model:

- *Nectandra* spp represents several native species with well-recognized timber potential. Both flowers and edible fruits contribute to food sources for wildlife. The species have recalcitrant seed which represents a challenge to broader use which could be addressed through local and informal seed systems managed by growers who identify superior trees and notify neighbors and other contacts in moments of seed availability.

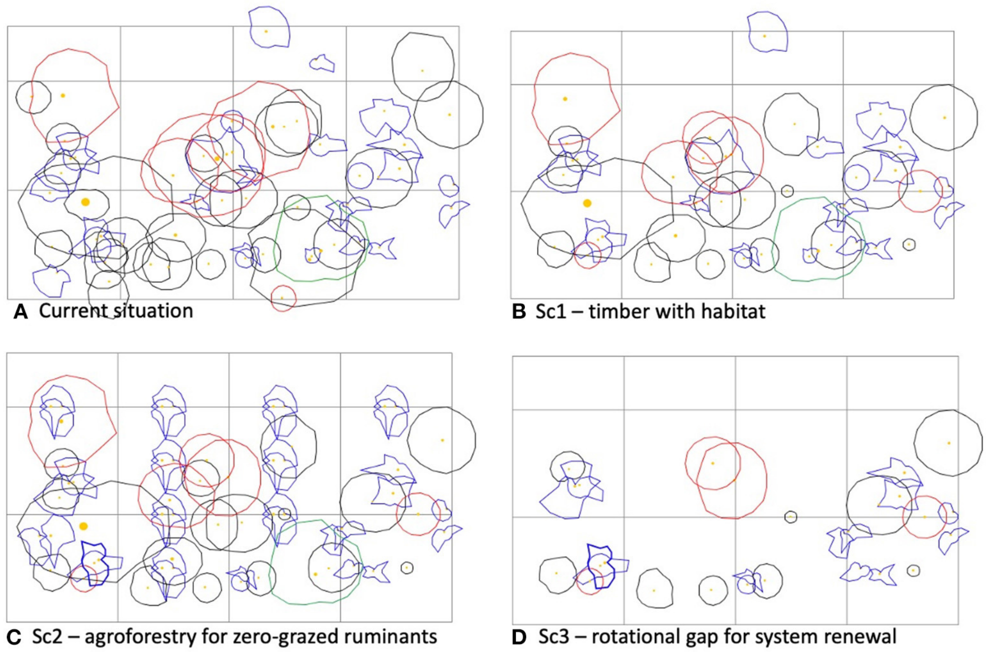

FIGURE 6 | Changes in canopy coverage and distribution for the current plot and three different scenarios for the MIX plot case. Four canopy components are graphed—banana (blue), *Inga* (green), timber trees (red), and other trees (black). **(A)** Current situation. **(B)** Sc1—timber with habitat. **(C)** Sc2—agroforestry for zero-grazed ruminants. **(D)** Sc3—rotational gap for system renewal.

- *Platymiscium parviflorum* is a legume with storable seed which is available to a limited extent through seed services. The habitat contribution is primarily during flowering.
- *Dalbergia retusa* has a very prized timber and is currently found slightly outside current coffee zone at lower altitudes and drier conditions. Climate change over the next decades suggests that growers may anticipate increasing temperatures and more erratic rainfall by planting species adapted to future conditions. The habitat contribution of *Dalbergia*, a legume, is primarily flowers for bees.
- *Cecropia* spp are highlighted for their habitat potential by Peters et al. (2016). Four species are reported for Nicaragua - *obtusifolia* from 0 to 900 m, *peltata* from 0 to 1,200 m, *silvicola* at higher elevations in a more restricted zone from 1,200 to 1,400 m and *insignis* in wetter conditions from 0 to 1,000 m. Natural regeneration of *Cecropia* may provide sufficient plants to achieve 10–20 plants/ha. Young plants would require protection from eradication during weed control practices and minimal pruning when trees are young. The high and very open canopy of *Cecropia* has little impact on light availability, while providing flowers, leaf sprouts and fruits to birds, bats and mammals throughout the year.

The addition of five individuals representing timber and habitat potential in the 1,000 m^2 plot increases timber tree density and Shannon diversity in three of four cases. Diverse tree density declines in three cases (**Table 3**). For these cases smaller or clumped trees were eliminated, often species with only one individual. The canopy openness is shifted or kept close to 50% and variability within plot is slightly improved. The benefit contribution for Income (IN) from multi-year income (MYE) increases but declines overall due to reduction in banana stem density. Habitat benefits (not shown) increased based on *Cecropia* density. The top view profile (**Figure 6**) illustrates reduced canopy overlap in the upper story which timber and habitat trees occupy.

Monthly Food and Income (Sc2)

The noticeable gap for monthly income and household consumption from current coffee agroforestry spurred us to review shade tolerant alternatives to banana. Among spices and essential oil crops, some like cardamom are currently understory associated crops, although not with monthly income potential. We concluded that leguminous fodder production might provide a basis for zero-grazing milk production in coffee zones. Rather than mid-story legume trees like *Erythrina* for fodder we propose hedge row legumes and cut-and-carry grass on field boundaries, primarily for greater labor efficiency in daily fodder harvest. Reject bananas of market cultivars or highly productive cultivars with low market potential make up the third component of the proposed diet:

- Legume hedges composed of *Leucaena* and *Calliandra* on 1 m spacings with a potential of bimonthly harvests of 2 kg/plant.
- Cut-and-carry fodder in hedges with *Pennisetum purpureum* or *Tripsacum andersonii* on 1 m spacings with a potential of bimonthly harvests of 3 kg.

- Banana at 5–6 m associated with coffee. Each mat produces 1.5 bunches per year of 20 kg. At a density of 250–350 mats per hectare managed with 1–2 tall stems/mat, banana generates around 25% shade. An estimated 100–150 mats would be needed to provide 10–15 kg of banana/day for animal consumption, but this daily ration could also be met with bunches not achieving top grade with buyers. The additional mats per hectare up to 300 may provide monthly income from banana fruit sales. Banana cultivar diversity could also be deployed for bananas as staple human diet component in substitution for potatoes, rice, cassava or even wheat flour, common staple foods purchased by coffee growing households. This diversification of cultivars either for fodder or for staple diet contribution may also allow growers more flexibility to maintain the monthly income and food function of banana even with certain disease problems of market bananas such as *Fusarium* wilt. Data in **Table 3** are reported in stems/plot rather than mats with an average of 1.25 stems per mat.

This scenario has relatively small impacts on the overhead shade for coffee fields which already had higher banana densities. Adjustments were made both to stem density/mat and mat location within the plots (**Figure 6C**). Twenty banana mats or 27 stems per plot were added in one case and banana stem density was reduced in one case from 85 to 40. Legume and grass hedges as understory may need to be oriented to more open sun locations on field boundaries, although they could also substitute for a row of coffee. Farm level biosecurity to address the spread of new diseases and food safety to limit access to specific zones of the farm may also be addressed with multi-use fodder hedges. A single milk cow fed from bananas and hedge row legume shrubs and grass could be projected to produce up to 9–10 L of milk/day and a ton of manure on dry weight basis annually. The integration of these contributions into **Table 3** highlights a major methodological challenge to the comparison of benefits in alternative scenarios and the optimization of diverse services with different units of measurement which was also highlighted by Garland et al. (2021). In the calculations in the previous section, we used individuals as a common unit to calculate total benefits, since this information was available in our data bases. In this case, the population of fodder hedges could be deployed or a factor for the conversion to milk. To partially accommodate this problem, we added understory density into **Table 3** which at the scale of the 0.1 ha plot results in an increased density of hedge row legume shrubs and clumps of grass fodder. Overall Shannon diversity and species density are also increased in three of four cases. The benefits totals for income and food are increased based on the population of fodder plants, but we could have also used milk production itself, for example days of milk production in both monthly food and income. The manure production could be mapped into coffee productivity enhancement, although our sub-categories do not currently accommodate this type of benefit. Further studies to address quantification of multiple benefits are needed.

Rotational Gap for System Rejuvenation and Reorientation (Sc3)

The brief review of the drivers of the future for smallholder multi-strata coffee production suggested that dynamic and productive coffee management with frequent pruning and replanting will be essential to respond to changing climates and diseases and availability of new varieties. Regular renovation or rapid turnover of N-fixing trees like *Inga* increases potential for biomass production and nitrogen fixation which is greater for younger trees (Nygren et al., 2012). This suggested to us that periods of high light availability or a rotational gap when coffee and service trees are uprooted or cut back should be recognized as part of the coffee agroforestry system.

Schematically for testing a rotational gap in SExI- FS, we determined the effect on light availability generated by the elimination or heavy pruning of leguminous shade trees and other trees and uprooting or thinning of banana along with uprooting or renovation pruning of coffee. We did not attempt to propose a re-oriented species composition for the new field or capture the initial phases of replanted multi-strata. Trees not eliminated are primarily timber trees which remain standing and continue to grow in the upper story of the newly planted or renovated coffee, service trees, and bananas. Fruit trees may also be conserved or renovated depending on the availability of improved germplasm and changing markets. Studies from quezungual suggest that maize should have largely open sun conditions. Isolated high canopies trees are possible with maize (farmer interviews conducted by Siles). Beans may be more appropriate in shade up to 25% shade. For the parameters in **Table 3**, the elimination of unproductive or less useful trees and the harvest of large diameter timber trees results in a decline of tree density and overall plot species which could be compensated by the additional diversity of annual crop production. **Figure 6D** shows the resulting tree canopies. Trees may also be cut back as done in quezungual. Canopy openness increases in all plots to above 75% which is enough light available for maize or beans or other annual cash crops of 3–8 months duration. If growers renovate only smaller areas of their farms in a rotational plan every year, they will continue to have income from coffee as well as annual food or income crops. Their farms will consist of multi-strata plots in different stages of development—a relatively stable component of timber trees and fruit trees with service trees kept at optimum age for N fixation or foliage or other benefits and coffee plants with high production potential. To quantify the benefit provided in terms of food, we scored multiples of 10 m^2 of planted area in annual food or income crops. In our 0.1 ha plots, only 50% is calculated as plantable with a score of 50 points of understory plants and seasonal food which can be stored (**Table 3**).

The preliminary spatial analysis of scenarios with the light capture model and system descriptors and indices of diversity and benefits provides key insights to hypothesize a conceptualized timeline that captures in greater detail a more active coffee agroforestry management approach with more targeted benefits-oriented species and stem turnover to increase system viability (**Figure 7**). The three coffee renovation cycles

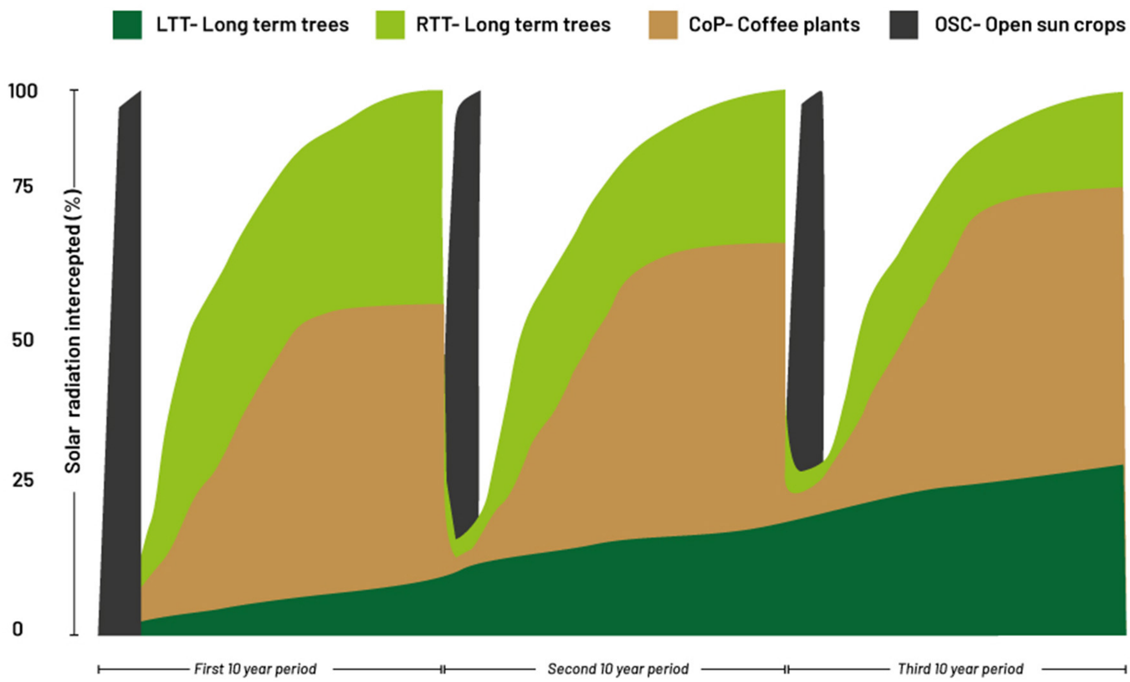

FIGURE 7 | Hypothetical dynamic shifts during three coffee renovation cycles.

shown in the timeline are punctuated by more open sun-gaps with abundant light for temporary short-term food or cash crops (Scenario 3) and a pivot point to shift coffee varieties, replant rapid turnover service trees and shift species or varieties of other associated trees, including banana (Scenario 2) while also maintaining long-term upper canopy trees (Scenario 1). Staggering the renovation cycles in different plots in the farm would distribute labor, inputs and capital demands and provide diversified income and food security across years. The timeline depicts zero biomass as a starting point and certain components return to zero at the beginning of each renovation cycle, neither of which may be the case in specific on-farm cases and would also contribute to carry-over benefits from one renovation cycle to the next beyond the long-term trees. In the discussion section that follows, we identify gaps in the literature and areas for improved data collection and analysis which address alternative pathways for more benefits-rich smallholder agroforestry.

DISCUSSION

Our summary of the current composition and diversity of coffee agroforestry fields on different continents clearly confirms the potential of high species diversity and associated local benefits in many different climatic and cultural situations to provide an enduring low-risk, resource-efficient production strategy for smallholder rural communities. The multi-strata system is recognized for conservation of soil potential, the biotic resources for complex food web relationships generating biocontrol and biodiversity habitat. Numerous studies have also shown that coffee agroforestry has useful carbon sequestration potential (e.g., Soto-Pinto et al., 2010; Pinoargote et al., 2017), although this ecosystem service may not generate much local value in and of itself. Studies which take a farm rather than a field perspective have highlighted the need to understand seasonal household wellbeing, particularly since income from coffee which is the main cash crop is highly seasonal and dependent on global factors. However, few current coffee agroforestry fields (**Table 1** and **Figure 3**) provide staple food. Income diversification appears more often to be potential rather than realized. Banana in coffee agroforestry is the exception generating both food and income throughout the year.

The conceptualized timeline in **Figure 7** maintains coffee as central to smallholder livelihoods. Not all future small growers can double or triple yields even of their current area without flooding global markets. More cost-effectives coffee productivity in a dynamic benefits-rich multi-strata may be more viable for smallholders than increased coffee productivity in monoculture. Our schematic three-step analysis (typology formation, benefits quantification using species and plot inventory, testing through spatial modeling of stem/species rearrangements testing for increased, and more targeted benefits) brought to our attention gaps in field studies and challenges in improving data collection and analysis using the local benefits framework from agroforestry as an entry point. Addressing these gaps and challenges is needed to test our hypothesis in greater detail and adjust **Figure 7** to field realities.

Among the gaps we identified:

- The focus on the tree component of standing multi-strata coffee fields should be complemented with a more complete documentation of other species diversity including herbaceous groundcover layer and fence and hedge rows and vegetation dynamics during periods of coffee renovation when coffee agroforestry is disassembled and reassembled or converted to another use.

- A quantitative, seasonal perspective of local benefits, particularly of income, food, and habitat, is needed to orient species selection and renovation during the different phases of the multi-strata useful life. A particular challenge is the units of measure to evaluate a broad range of non-monetary benefits from wildlife and biocontrol habitat to nitrogen and recycled biomass from leguminous service trees. The units to measure food for home consumption and non-coffee income are clearly monetary, but actual measurement requires data collection methods not often deployed. We used stem density which was available in our data bases which indicates potential rather than actual benefits. The challenges of measuring non-monetary services and optimization of multiple objectives have been highlighted by other authors (Rapidel et al., 2015; Dendoncker et al., 2018).
- The multiple and changing pressures on smallholder enterprises to respond to national regulations and export market certification requirements, while also effectively combining their scare labor and capital with ecological processes, merit integrated and multi-year analysis. One-time studies do not capture the on-going strategies of smallholder farm enterprises to achieve household wellbeing with coffee production as a key activity. De Leijster et al. (2021) used time from conversion to agroforestry from 1 to 40 years in a latitudinal study of ecosystem service trajectories. While useful for environmental indicators which may link to services which increase from time of tree establishment, the data collection did not identify differing life spans for coffee, banana, service trees and timber trees, an important element in our hypothesis about the dynamic and purposeful approach needed for transformed agroforestry systems. Documentation for certification offers a potential large data base only infrequently tapped (see example—Barham and Weber, 2012) for broader analyses. However, certification requirements do not cover income diversification, food security or ecosystem services for pest control, among others, and are somewhat incipient for habitat, often using biodiversity as a general indicator.
- Studies of resource use efficiency and competitiveness of smallholder coffee have been piloted. However, the expanding tools for the study of efficiencies documented in the overview of research have not been applied to coffee agroforestry plots or farms/enterprises. Such studies can be envisioned to provide a platform for more applied indicators and tools for more forward-looking smallholders and their associations, but remain an important gap to complement the numerous studies of agroforestry diversity.

Challenges to data collection and analysis using a local benefits framework are:

- A unified analysis of very diverse benefits based on inventories of individuals and species in multi-strata systems drew our attention to the challenges in the units of measure. We used number of individuals and a simple scoring system, although clearly not all individuals have the same weight nor is the benefit linear in response to stem density. Other derived benefits such as manure did not link as easily to individual stem number. The study by Rice (2011) which contrasted fruit production and sale in two coffee zones illustrates the importance to measure actual benefits. He found that much of the fruit produced in coffee fields never reached the market and was not consumed locally.
- The seasonal breakdown of benefits contributing to household wellbeing opened a new window on understanding current systems and led us to identify potential alternatives such as zero grazing and the full sun short term crops. The seasonal breakdown is also an important perspective on species contribution to habitat. **Figure 7** was not prepared to capture the within-year seasonal dimension of coffee agroforestry, but does indicate moments for species substitution or supplementation with a seasonal filter.
- The identification and testing of scenarios guided by multiple objectives highlights the role of knowledge and measurement of responses as a basis for improved grower agroforestry management. In the scenarios applied to each plot, the initial review of the current tree by tree inventories raised many questions about each tree's contribution and possible additions and substitutions and the potential contributions of alternative species. The costs and returns of alternative multi-strata approaches can only be addressed directly based on grower experience using multi-year data. Big data analysis of coffee fields and small coffee farm enterprises could be a powerful source of recommendations on production and economic efficiency. Our data base of 140 coffee fields was useful to understand the diversity of farmer strategies, but is insufficient for expanded studies to guide management shifts.
- The spatial model to visualize alternatives does not integrate the diverse measures of efficiencies documented in an earlier section, although it did generate specific contexts to screen very different alternatives. Much more thorough characterizations of smallholder coffee agroforestry plots and farms/enterprises are needed first to move beyond just coffee production efficiency to integrate agroforestry, but also to link plot level data with household level food security, income diversification and such issues as availability, skills, and living wages of hired labor. Ho et al. (2017) in their comparison of coffee monoculture, coffee intercrops and coffee-rice found lower efficiencies in coffee-rice, but recognized possible farm household preference for reduced food security risk from coffee-rice.

These gaps and challenges on transformation alternatives of traditional coffee agroforestry lead us to visualize three future directions for a science and research agenda in support of farmer management tools:

- First, more extensive data bases are needed of small farms with coffee agroforestry as enterprises which are managing land, labor and capital to address household, market and biotic/abiotic demands. Certification data bases may provide some data, but are incomplete. Studies of coffee agroforestry species diversity like our data bases from Nicaragua are useful, but focus only on a single moment, are missing coffee data and do not address enterprise or livelihood issues. Studies of scale, technical and allocative efficiencies cited earlier have a coffee focus and miss the contributions of the agroforestry component addressed by economies of scope. They address primarily economic cost-benefit and input-output relations. Bringing together economists with specialists on coffee and coffee agroforestry agronomy and pest management is needed to design data collection and address the different efficiencies of farms, territories and value chains. The studies on food security cited in the introduction highlight an important component of farm data collection to build a better understanding of current strategies of the households of coffee farm owners and their permanent and seasonal workers. The potential of smallholders to harness ecological intensification as an additional component of efficiencies calls for expanded indicators, some of which may are not yet well-understood like tree contribution of nitrogen and trees as habitat for beneficial organisms. The potential of coffee with agroforestry to contribute to living and prosperous incomes needs to be dimensioned by farm size, availability of markets and off-farm services and natural resource base. Waarts et al. (2019) highlight the challenges for different sub-groups of farms based on income and land size to improve livelihoods through commodity production and the vulnerabilities of very smallholders and workers. The importance of data-driven analysis is key to more effective research and policy agendas.

- The second area for science with potential to guide management tools is the knowledge base of functions of individual tree, shrub and herbaceous species and their interactions to generate regenerative potential in the coffee ecosystem. Areas needing further attention are the role of tree species and their management in coffee system nutrient cycling and microenvironment, foodweb interactions and seasonal habitat potential for different classes of fauna. The development of this knowledge base for practical application may be facilitated by defining ecosystem services bundles which are co-occurring and linked to similar management practices (Raudsepp-Hearne et al., 2010; De Leijster et al., 2021). The use of vegetation species diversity also depends on a better understanding of tree and shrub seed phenology and availability and seedling establishment parameters.
- Finally, the interface between data for certification, the demand for which is growing, and data-driven multi-strata enterprise management merits attention. We propose that relevant indicators of key system variables and simple data capture building on both ecological and enterprise understanding as well as certification demands will provide a basis for management tools. We visualize that more systematic, widespread and routine deployment of data collection linked to data storage and analysis will have local and global benefits to individual growers, their organizations, certifiers, national regulators and consumers.

CONCLUSION

Our hypothesis highlighting the opportunities for transformation alternatives for coffee agroforestry builds on the multiple benefits possible from multi-strata diversity as a production system. Smallholders have leveraged lower coffee production costs and products for household needs and diversified income from agroforestry rich with farmer knowledge and experience to participate in the highly unstable global coffee commodity market. However, challenges are multiplying—decreasing coffee margins, increasing input and labor costs, new pests and diseases, climate variability and change and increasing data demands from supply chain certification and national laws and regulations. We hypothesize that coffee agroforestry must shift from a low labor, low risk-stable return, slowly changing matrix to more active management of species and stem turnover in system renovation cycles targeted to sustaining, reorienting and intensifying ecosystem-based benefits.

The multiple benefits framework, the test using stem density by species in smallholder coffee agroforestry in Nicaragua, and the scenario building based on light availability, although primarily illustrative with many aspects to be improved, confirmed the utility of categorizing benefits in food, income, other household use, coffee productivity and habitat. Sub-categories by season, type of market and development phase of the plot (including the gap phase during system renovation) provided insights into the potential for increasing benefits with more targeted species and stem management and turnover.

The multi-cycle framework proposed in the conceptual timeline in **Figure 7** addresses the fluctuation of system components on different periods of return. Species and stem turnover generate these cycles based on the active assessment and learning by the farm household, grower association and rural community. Cultivar changes to address climate change and emerging pests, cultivars and species with greater market value, shifts to species with greater integrative functions, for example income, household food, soil building and habitat to promote biocontrol, are location- and even time-specific.

Our data bases of stem density by species of established agroforestry systems were sufficient to identify gaps in several categories of food and income benefits for coffee-growing households in northern Nicaragua which were addressed in the scenarios thereby verifying the hypothesis. The benefits ranking both of current systems and three scenarios also provided insights into data collection specifications for a more rigorous test of the hypothesis and as the basis for farm enterprise management tools. Increasing data recording by small coffee farms is currently driven largely by the demands of certification and national labor, health and environmental laws. More systematic documentation of costs and the income and food provided by agroforestry components as well as coffee follows already available farm management procedures. The methods for the quantification of agroforestry contribution to ecological processes based on species and tree size are still incipient primarily for academic use and not applied to farm management. The diverse efficiency analyses used by economists provide a starting point for more exhaustive hypothesis testing on agroforestry benefits by farm size, proportions of labor, inputs and land, degree of diversity and response capacity to extreme market and climatic events. Integration of ecological processes into the efficiency analysis is essential requiring collaboration among farm management economists, agronomists, IPM specialists and ecologists. In our vision these more academic studies can and should lead to more useful applied farm management tools and data-driven alternatives for greater ecological, economic and livelihood viability for farm households and grower associations.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

CC identified the call for article and proposed a article using existing data sets. CS proposed a article on hypothesis and theory to explore the larger context of coffee agroforestry, developed initial arguments from the literature, developed the scoring system, and contributed to the interpretation of the results. PS and CC carried out the field data collection. PS did statistical analysis. CC and CS took the lead in writing the manuscript. All authors provided critical feedback, helped shape the research, analysis, and manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.808207/full#supplementary-material

Supplementary Table 1 | Species by attributed local benefits provided. PE, Coffee productivity enhancement; IN, Income; FO, Food; HO, other household use; HA, Habitat for biodiversity.

Supplementary Figure 1 | Species accumulation curves for three data sets and four typologies.

Supplementary Figure 2 | Shannon index distribution for 140 plots in three data sets and four typologies.

Supplementary Figure 3 | Species density distribution for 140 plots in three data sets and four typologies.

Supplementary Figure 4 | Changes in canopy coverage and distribution for the original plot and three different scenarios for a Musa-dominated plot (MD). Four canopy components are graphed—banana (blue), Inga (green), timber trees (red), and other trees (black).

Supplementary Figure 5 | Changes in canopy coverage and distribution for the original plot and three different scenarios for an *Inga*-dominated plot (ID). Four canopy components are graphed—banana (blue), Inga (green), timber trees (red), and other trees (black).

Supplementary Figure 6 | Changes in canopy coverage and distribution for the original plot and three different scenarios for a plot dominated by other trees (TD). Four canopy components are graphed—banana (blue), Inga (green), timber trees (red), and other trees (black).

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