Review

Not peer-reviewed version

The Planetary Health Impacts of Coffee Farming Systems in Latin America: A Review

Emiliano Hersch-González * and Horacio Riojas-Rodríguez

Posted Date: 17 November 2025

doi: 10.20944/preprints202509.2173.v2

Keywords: coffee agroecosystems; agroforestry; agroecology; planetary health; DPSEEA; planetary boundaries; food systems; food security; occupational health; coffee farmers

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 November 2025 doi:10.20944/preprints202509.2173.v2

Review

The Planetary Health Impacts of Coffee Farming Systems in Latin America: A Review

Hersch-González, Emiliano [1,*] and Riojas-Rodríguez, Horacio [1]

Department of Environmental Health, National Institute of Public Health, Cuernavaca, 62100, Mexico; ORCID Emiliano Hersch González: 0009-0006-2156-1749; ORCID Horacio Riojas Rodríguez: hriojas@insp.mx, 0000-0002-6734-0486
* Correspondence: emiliano.hersch@insp.edu.mx

Abstract

In Latin America, coffee is cultivated in distinct coffee agroecosystems (CAS), ranging from traditional agroforestry ("shade") systems (CAFS) to intensive, unshaded ("sun") monocultures (UCAS). While various socioenvironmental impacts of these systems have been studied, their implications have not yet been integrated within a Planetary Health perspective. This review of 146 studies applies the Planetary Boundaries and Nature's Contributions to People frameworks and the DPSEEA (Drivers, Pressures, State, Exposure, Effects, Actions) model to map the relationships between socio-environmental drivers of change, different CAS, the state of natural systems at local and global scales, and human health and well-being. The analysis shows that conventional intensification, driven by low revenues for producers, climate change, and disease outbreaks, has accelerated deforestation, biodiversity loss, greenhouse gas emissions, agrochemical use and leakage, and water pressures. These changes create health risks for coffee-growing communities, such as pesticide exposure and increased vulnerability to external shocks. Conversely, agroecological practices can mitigate environmental pressures while reducing exposure to health hazards and improving resilience, food security, and income stability. However, mainstreaming these practices requires addressing structural inequities in the global coffee value chain to ensure fairer revenue distribution, stronger institutional support, and the protection of coffee-growing communities.

Keywords: coffee agroecosystems; agroforestry; agroecology; planetary health; DPSEEA; planetary boundaries; food systems; food security; occupational health; coffee farmers

---

1. Introduction

Coffee is among the world's most traded tropical commodities, with a global market valued at over US $200 billion annually [1]. 80% of the world's coffee is produced by around 25 million smallholder families in the Global South, yet most of the consumption and revenues are concentrated in the northern hemisphere [2]. Two species dominate global coffee production. *Coffea arabica* is generally considered superior, but it is a delicate plant requiring specific temperature, humidity, and shade conditions usually found in tropical mountainous regions [3]. It accounts for 56% of global coffee production [4], concentrated in Latin America, East Africa, and the Arabian Peninsula [5]. Conversely, *Coffea canephora*, whose main variety is *Robusta*, is bitter, contains higher caffeine levels, and is both more productive and disease-resistant. Robusta thrives in warmer climates, often under direct sunlight and at lower altitudes [6,7]. Its production is concentrated in Brazil and Vietnam (the world's two largest coffee producers), alongside Southeast Asia and West and Central Africa [5].

The distinct ecological traits of *Arabica* and *Robusta* have interacted with diverse biocultural landscapes and historical processes to shape their geographic distribution and cultivation methods. In Brazil, for instance, coffee production is dominated by large-scale, intensively managed Robusta monocultures that depend heavily on wage labor, and similar patterns are found across Latin America in the so-called *finca* model [8]. Conversely, a significant share of coffee is cultivated by smallholder farmers in agroforestry systems (often traditional) where Arabica varieties are intercropped with a range of productive and non-productive plants. In this way, coffee cultivation emerges from a dynamic interplay between ecological configurations, sociopolitical structures, and cultural knowledge, resulting in distinct coffee agroecosystems (CAS).

In Latin America, differences between CAS have long been recognized by both producers and scholars. A broad, popular distinction recognizes “shaded coffee”, or coffee agroforestry systems (CAFS), and “sun coffee”, or unshaded coffee agroecosystems (UCAS), based on the presence or absence of shade trees (fig. 1). A more detailed typology proposed by Moguel & Toledo [9] further differentiates CAFS according to decreasing vegetation structural complexity, ranging from traditional “rustic” systems (rustic T-CAFS), to traditional polycultures (T-CAFS), to commercial polycultures, to shaded monocultures (M-CAFS) (fig. 2).

Figure 1. Examples of coffee agroecosystems in Latin America: (a) A traditional coffee agroforestry (“shaded”) system (T-CAFS); and (b) an unshaded (“sun”) coffee agroecosystem (UCAS). Photo credit: Emiliano Hersch González, 2020.

However, CAS differ in several dimensions beyond shade level and vegetation structure, including biodiversity, farm size, use of technology and agrochemicals, as well as land tenure and labor organization. These characteristics are captured in the “coffee intensification gradient” proposed by Perfecto et al. [8], which spans from traditional, low-intensity multifunctional systems to highly intensified monocultures. Low-intensity multifunctional CAS typically feature:

- Multistory agroforestry with diverse shade trees.
- High biodiversity and ecological complexity, supporting key ecosystem functions.
- Native Arabica varieties.
- Minimal external inputs such as agrochemicals.
- Small-scale farms (<10ha), often family-owned and operated.
- Integration with local or indigenous knowledge and labor systems.

Conversely, at the high-intensity end, CAS are marked by:

- High-density coffee monocultures, often with no or low-diversity canopy.
- Ecological simplification and reduced biodiversity.
- Use of *Robusta* or hybrid *Arabica* cultivars.
- Heavy reliance on agrochemicals.
- Large-scale operations (>10 ha), often corporate-owned.
- Seasonal wage labor under hierarchical management.

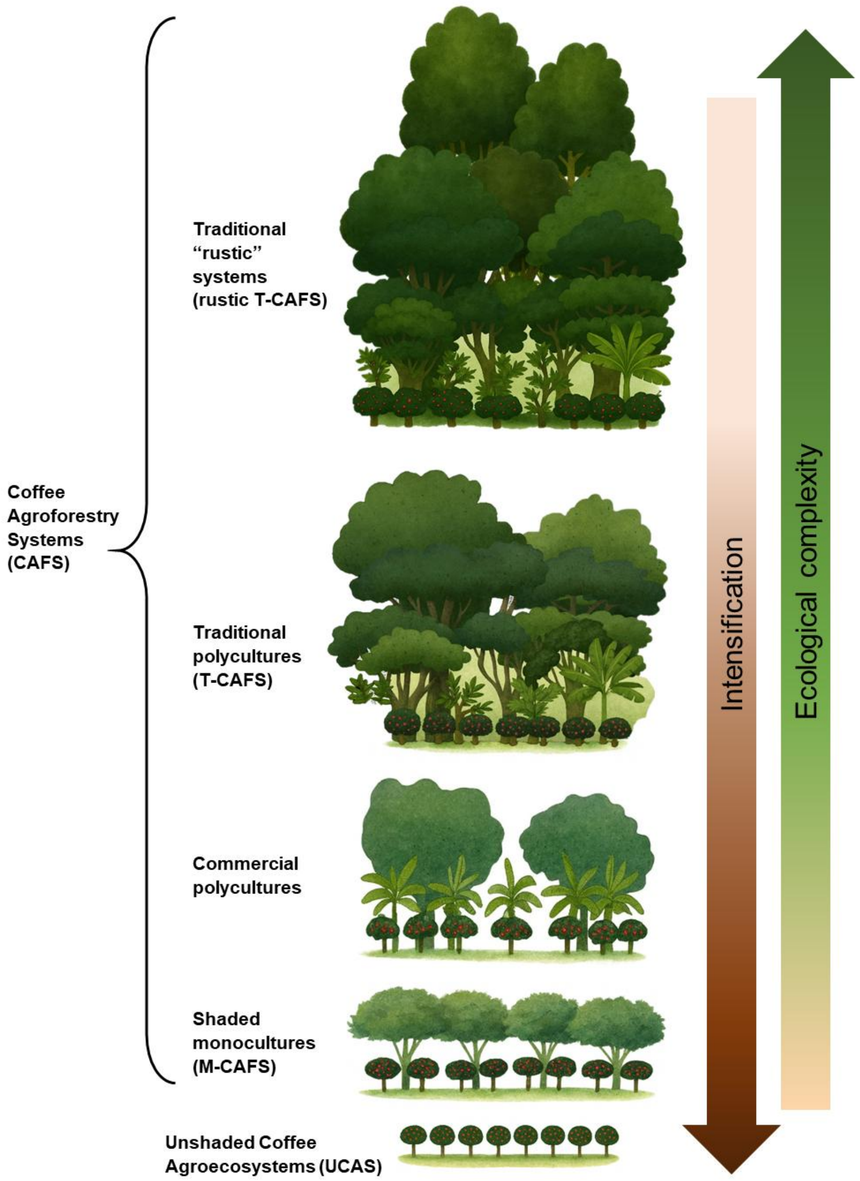

Figure 2. Five categories of CAS across the coffee intensification gradient used in this review. Modified from Moguel & Toledo, 1999.

A growing body of research has documented the positive impacts of CAFS on biodiversity conservation and on Nature's Contributions to People (NCP)[1] when compared to UCAS, including pollination, carbon (C) storage, soil formation and protection, and livelihood diversification [8,11–13]. In the past decade research has also extended beyond ecology to examine how varying agroecological configurations and management practices influence human health outcomes such as food security and nutrition [14,15], pesticide exposure [16,17], and mental health [18].

However, since the 1960s, T-CAFS have undergone widespread intensification in Latin America [6], a trend that appears to be accelerating [19,20]. Despite growing interest, no prior study has synthesized the evidence linking coffee farming under different CAS, natural systems, and human health and wellbeing within a Planetary Health perspective –defined here as *the interdependent health of human populations in all its dimensions and the natural systems on which they rely* [21]. To address this evidence gap, a literature review was conducted integrating different frameworks. The Planetary Boundaries (PB) framework was used to evaluate the drivers and impacts of various CAS in Latin

---

[1] NCP: the positive and negative contributions of living nature (i.e., the biosphere) to people's quality of life [10]. The conceptual antecedent of the NCP framework is the *ecosystem services* framework.

America on local and global natural systems, and their effects on human health and wellbeing were evaluated directly or through the NCP framework. These relationships were integrated in the Drivers-Pressures-State-Exposure-Effect-Action (DPSEEA) model, linking socioecological drivers, environmental change, and human health. While this review focuses on Latin America due to the region's shared historical, cultural, and socioeconomic trajectories in coffee cultivation, its results may be relevant for the identification and promotion of co-beneficial coffee-growing practices in other coffee producing regions.

2. Methods

While not a systematic review, efforts were made to structure and systematize the literature search and screening process. A combination of keywords (table 1) was used to conduct a database search on Pubmed and Scopus on June 27th, 2024. The detailed search query is available in the supplementary material (S1). Searches were conducted in English and Spanish, and no publication date filter was applied. In total, 4435 records were retrieved. After removing 1443 duplicates, 2992 unique records remained.

Table 1. Sample of keywords used in the database search (see S1 for full list).

Element	Keyword sample
CAS in Latin America	Coffee, system, growing, harvesting, farming, agroecosystem, agroforestry, farming, plantation, smallholder, shaded, sun, unshaded, monoculture, landscapes, etc.
Planetary Boundaries	Climate change, global warming, biodiversity, conservation, nitrogen, phosphorus, land use, land system, deforestation, pollution, freshwater, agrochemical, fertilizer, pesticide, etc.
Geographical delimitation	List of 18 Latin American countries
Human Health and its determinants	Health, exposure, infections, zoonosis, vector, food security, nutrition, income, poverty, migration, violence, mental, gender, intoxication, water security, extreme weather, bite, sting, etc.

Screening followed three stages according to the selection criteria outlined in table 2: (1) by title and abstract, (2) by sorting for relevance, and (3) by full-text reading. After screening by title and abstract, 438 studies were sorted by relevance according to scope, thematic representativeness, strength of evidence, and alignment with the PB and DPSEEA frameworks. Additional preference was given to systematic reviews and meta-analyses, as well as studies covering under-researched areas or underrepresented regions. Selected grey literature (e.g., policy briefs and institutional reports) that clearly reported their data sources and methodologies was also included when peer-reviewed evidence was scarce. During this process 151 records were pre-selected as key literature. During full-text reading 40 further sources were identified by snowballing and targeted thematic searches. 146 results were included in this review (fig. 3). Evidence was charted and synthesized using the DPSEEA framework. Mexico, Brazil and Colombia contribute 51% of the literature (fig. 4). Results are presented in three sections: section 3 presents the main drivers of coffee landscape transformations in Latin America (DP elements of DPSEEA); section 4 presents the main impacts of CAS on PB (PSE elements of DPSEEA); and section 5 presents the main pathways linking CAS, their trends of change and their impact on PB with human health (SEE elements of DPSEEA).

Table 2. Selection criteria.

Inclusion criteria
Peer-reviewed research papers, reviews, and book chapters, and gray literature including reports, policy documents, conference papers, theses, and preprints clearly reporting data sources and methodologies.
Studies reporting results related to coffee farming in Latin America.

Studies that describe the drivers of change in CAS and their impact on six of the PB (climate change, biosphere integrity, land system change, biogeochemical flows, freshwater use and novel entities) OR studies that describe the effects of CAS, their transformations, or their environmental impacts on the health of human populations and its determinants.
Studies that provide key insights in terms of thematic representativeness, strength of evidence, and alignment with the DPSEEA model.
Studies published in English or Spanish.
Exclusion criteria:
Studies whose results are not related to coffee farming in Latin America.
Studies describing ecological impacts of CAS that cannot be classified under at least one of the six PB chosen.
Studies describing health determinants and outcomes of coffee farmers, farmworkers, or coffee-growing communities that cannot be attributed to CAS, the drivers of their transformations, or the change in at least one of the six PB chosen.

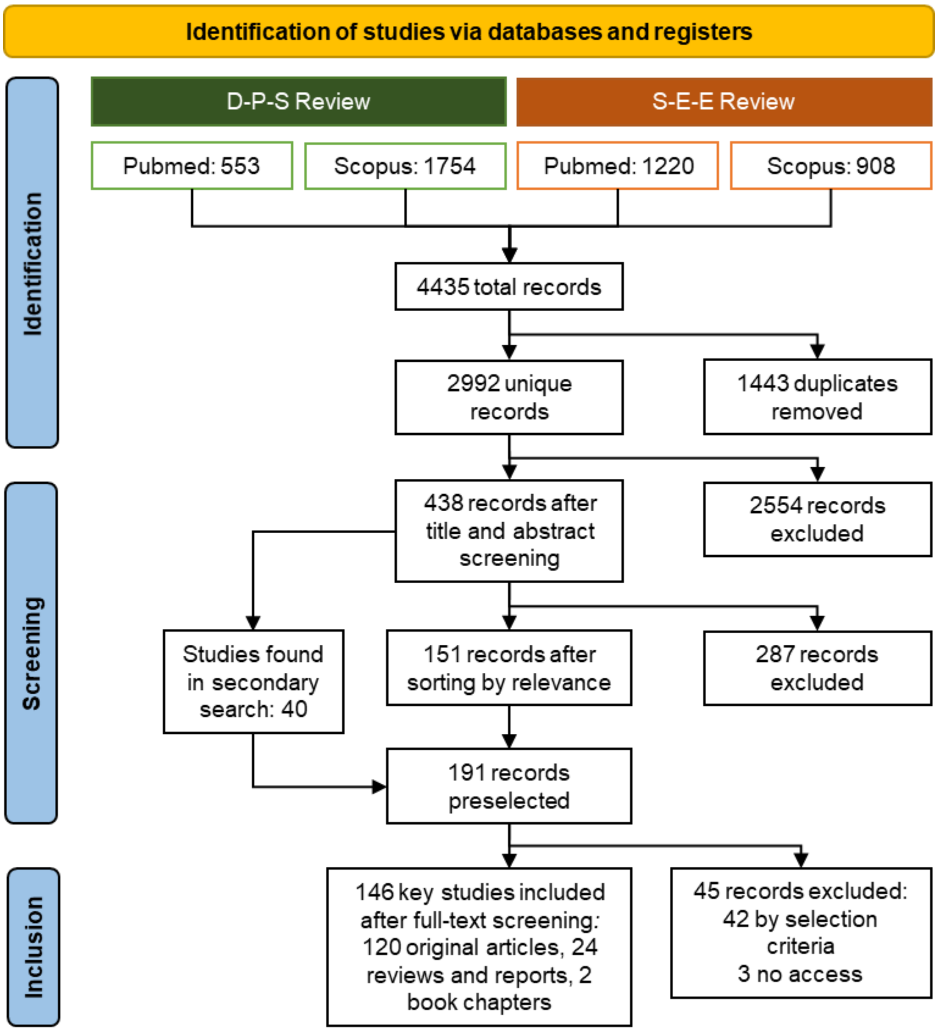

Figure 3. Outline summary of the review process.

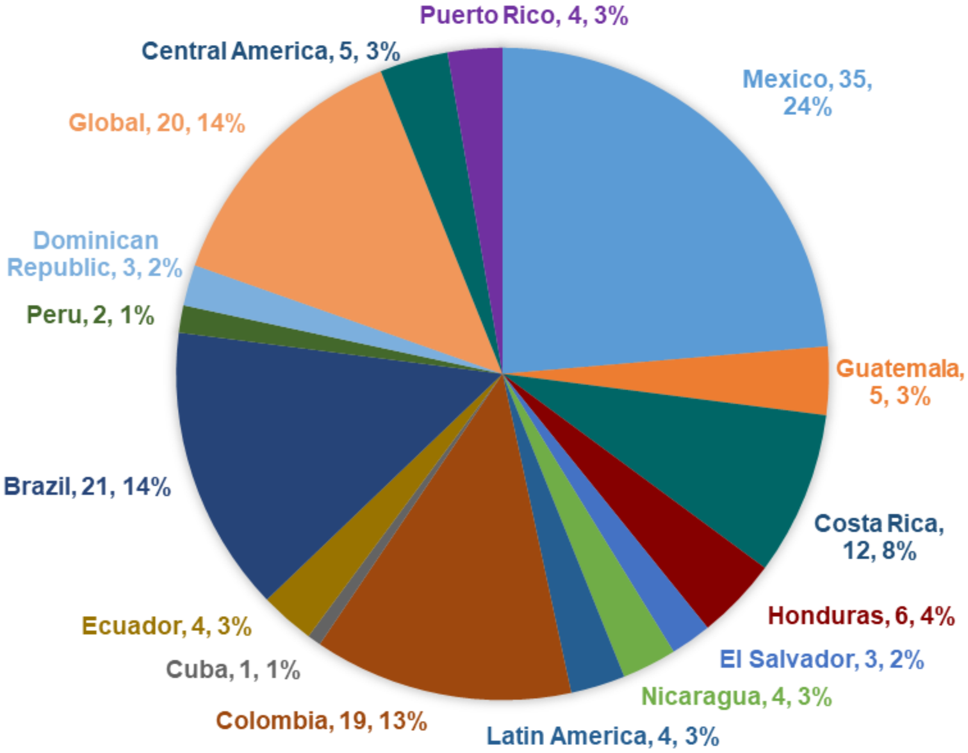

Figure 4. Included literature by country of origin.

3. Drivers of Transformation in Coffee Landscapes

The literature reviewed shows that coffee cultivation in Latin America is undergoing seven major trends of transformation the 21st century: (1) a shift to disease-resistant cultivars; (2) conventional intensification through reduced shade, higher planting densities, and increased agrochemical use; (3) the replacement of *Arabica* with *Robusta*; (4) the introduction of *Robusta* in previously uncultivated areas; (5) the conversion of CAS to other crops or pastureland; (6) the expansion of coffee cultivation into forests; and (7) the adoption of sustainability standards [19]. Most of these trends reflect the increasing management intensification and ecological simplification of CAS. The drivers of these transformations are multiple, but three stand out: declining net revenues and producer share in the coffee value chain (CVC), increasing impacts of climate change, and recurrent outbreaks of coffee leaf rust (CLR), a fungal disease affecting coffee [19,22,23]. Other contributing factors include labor shortages and weakening institutional support [23–25].

3.1. Decreasing and Volatile Revenues for Coffee Producers

The literature reviewed consistently points at decreasing and volatile revenues for coffee producers as a critical driver of coffee landscape transformations. Despite a market value exceeding USD $200 billion and steady demand growth of 2% annually over the past two decades [1,26], most producers in the Global South live below the poverty line, earning less than a living income [26,27]. The collapse of the International Coffee Agreement in 1989 and the dismantling of national coffee institutes during the 1980s amidst neoliberal reforms exacerbated these imbalances by heralding a decline in coffee prices paid to producers (fig. 5), a shift in market control toward corporations, the financialization of the coffee trade, and a concentration of revenues within financial and commodity markets [25,28–30]. For instance, Colombian producers' share of final coffee value fell from 20% to 13% between 1970 and 1989, while roasters' share rose from 53% to 78% [25,28]. Today, producers retain less than 10% of coffee's total value, less than the tax revenues it generates in the US alone [31]. In turn, the monopolistic corporate consolidation during this period has eroded producers' bargaining power, often forcing them to sell below production costs [32,33]. In Brazil, large coffee farms have been involved in human rights and labor law abuses, including child and slave labor. These violations were documented on farms supplying brands such as Nestlé, Starbucks, and ECOM, and certified by Rainforest Alliance, UTZ, and Fairtrade [34,35].

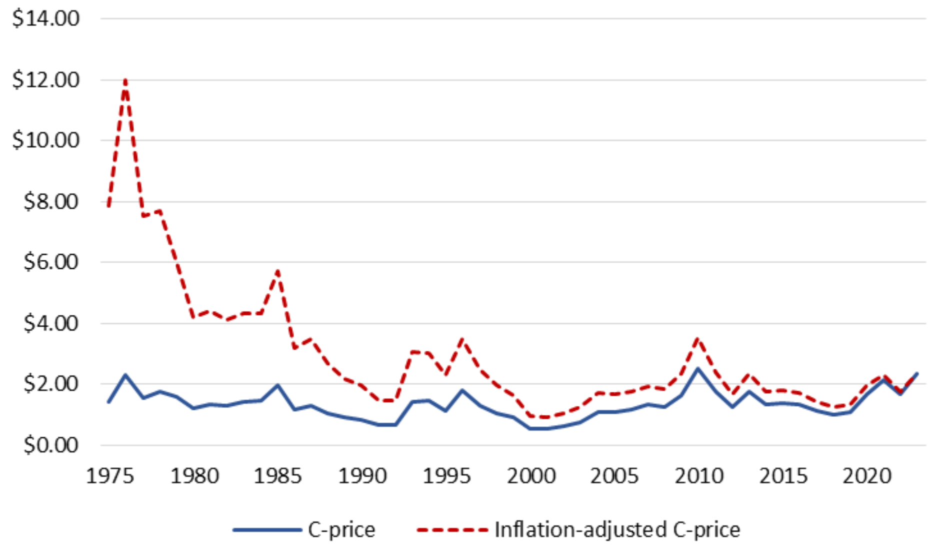

Figure 5. Yearly reference Arabica coffee price (C-price) in USD per pound, not adjusted for inflation (blue continuous line) and inflation-adjusted (red dotted line). Data from Macrotrends (C-Price) and the US Bureau of Labor Statistics (consumer price index).

On the other hand, global coffee prices are largely determined in futures markets, where a substantial rise in speculative trading, combined with fluctuations in coffee supply and production costs, has resulted in extreme price volatility [36,37]. This undermines farmers' livelihoods, and has triggered widespread crises associated with food insecurity, school dropout, and increased migration, as happened during the 2000s coffee crisis in Central America [38,39]. Outmigration of coffee farmers, in turn, contributes to labor shortages and rising production costs [23,24]. Facing these pressures, many producers have sought to sustain their incomes by increasing production through conventional intensification and expansion into natural areas. This has been encouraged institutionally through the promotion of Robusta cultivation, recommendations to reduce shade, and agrochemical subsidization [6,8]. Some authors point out that resulting overproduction has depressed prices further, justifying continued intensification [6,25]. For example, an aggressive promotion of Robusta cultivation in Vietnam –subsidized by the World Bank– led to an oversupply of cheap coffee that displaced higher-quality Arabica, contributing to lower coffee prices in Latin America [25].

3.2. Climate Change

The literature reviewed documents that climate change is already affecting coffee production and reshaping coffee landscapes across Latin America [19]. Climate change is reported by farmers in Veracruz, Mexico, as the second most important stressor after low coffee prices [23]. In Central America, 66% of smallholder farmers reported negative effects of rising temperatures, erratic rainfall, and extreme events on yields, income, and food security [40]. Extreme weather events are also altering coffee landscapes through forced migration and farm abandonment, as seen after hurricanes Mitch (1998), Stan (2005), and more recently Eta and Iota (2020) [22,41]. In response, producers are adapting in various ways, including forest encroachment, shifting from Arabica to Robusta, intensifying management, and, in some cases, increasing on-farm tree cover [19,40].

Climate change impacts on coffee are expected to become increasingly determinant. A recent systematic review found that most studies project Arabica yield declines in Latin America –as high as 70%– over the coming decades due to rising temperatures and changing humidity, though some

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 November 2025 doi:10.20944/preprints202509.2173.v2

studies suggest partial mitigation from CO_2 fertilization. The area suitable for growing Arabica will reduce by an estimate ~30% for Mesoamerica, 16–20% for the Andes, and 25% for Brazil by 2050–2070, with some estimates as high as 84% for Puerto Rico, 98% for Mexico, and 73–88% for overall Latin America. Coffee-growing zones will shift to cooler, higher altitudes and possibly the Amazon basin, threatening forests and protected areas. By contrast, Robusta may maintain or expand its suitability, possibly driving deforestation to meet demand. Pests and diseases are expected to spread faster and become more severe, while pollinator populations are projected to reduce [42].

3.3. CLR Outbreaks

Literature consistently reports that CLR, a fungal disease of coffee leaves, has become a significant driver of coffee transformations since the late 2000s [8,13]. Between 2012 and 2014, CLR caused an estimated U.S.D. $1 billion in damages across Latin America, affecting over two million people [20]. In Central America alone, coffee yields dropped by up to 55%, resulting in losses of U.S.D. $515 million [40]. In Colombia, production fell by 31% during the 2008–2011 outbreak, and in southern Mexico, losses reached 95% in 2015-2016 [13,20,43]. The exact drivers of this shift in CLR epidemic potential are debated. Hypotheses include the effects of climate change in shortening the latency period of CLR [43], reduced investment in farm management due to low coffee prices, and the erosion of natural control mechanisms as a result of the intensification and ecological simplification of CAS, crossing of a tipping point in CLR transmissibility [8]. Responses have focused on the introduction of high-yielding, CLR-resistant hybrid cultivars and increased fungicide use, which successfully helped reduce CLR incidence and recover production [19,43]. In Colombia, for example, CLR rates fell from 40% in 2009 to just 3% by 2013 [43]. However, they have also become a leading driver of conventional intensification, since resistant varieties typically require higher sunlight and agrochemical inputs. In parts of Chiapas, Mexico, organic CAFS largely gave way to intensified CAS after the outbreaks, with agrochemical use rising from 0% to 54% between 2012 and 2016 [20], and shade cover decreasing from 50% to 25-30% between 2005 and 2015 [22]. A recent modeling study found that CLR-affected municipalities in Chiapas experienced a 32% rise in deforestation, primarily at the expense of T-CAFS, resulting from policy-supported adoption of resistant varieties [44].

4. Coffee Farming’s Impacts on Planetary Boundaries

This section synthesizes 89 studies examining how CAS and their transformations influence six PB —land-system change, biosphere integrity, climate change, biogeochemical flows, freshwater use, and novel entities— and how these alterations in turn affect coffee farming.

4.1. Biosphere Integrity

Biosphere integrity includes both genetic diversity and functional integrity [45]. Compared with UCAS, CAFS support significantly higher biodiversity levels and key NCP such as soil health, hydrological services, regulation of extreme weather, pollination, and regulation of detrimental organisms (fig. 6).

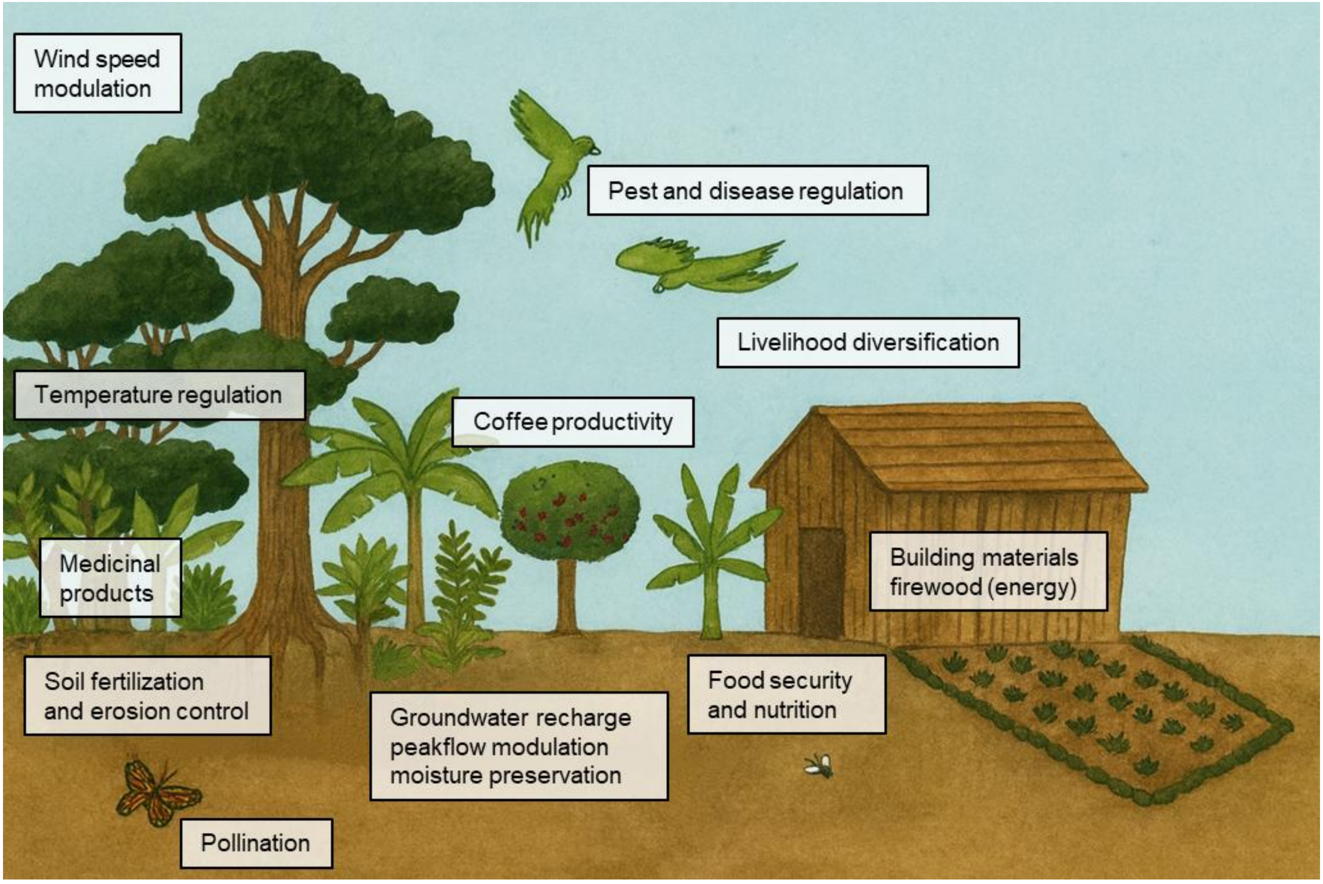

Figure 6. Key NCP supporting coffee farmers and coffee-growing communities.

4.1.1. Impacts of CAS on Biodiversity Conservation

Biodiversity and ecological complexity are better preserved in CAFS and decline with intensification. One meta-analysis showed that bird, ant, and tree biodiversity in Latin American CAS inversely correlates with management intensity [46]. Another meta-analysis found that the diversity and abundance of bird, mammal, epiphyte and insect species in Latin America is significantly higher in high-shade (>30%) CAFS versus low-shade (6–30%) CAFS or UCAS (<5%), controlling for agrochemical use [47]. Bee abundance and diversity are best predicted by tree species richness [48], and some pollinators apparently cannot survive in UCAS [49]. Amphibians also fare better in CAFS [9,50,51], and fungal diversity is higher in organic systems [52], while soil microbial communities shift with management intensity [53,54]. CAFS also enhance connectivity across forest fragments, supporting biodiversity even in intensively managed agricultural areas [8,47,55]. These results show that high shade levels, tree diversity, multistrata canopy structures and organic management support high ecological complexity and are critical for conserving biodiversity within CAS and across coffee landscapes. However, CAFS support less biodiversity than primary forests [46,47,56,57], emphasizing the need to avoid forest encroachment [47]; one study found that intensive, small-scale, land-sparing farms within a highly forested area may preserve higher landscape biodiversity than CAFS [58].

4.1.2. Impacts of CAS on NCP

Soil Health, Nutrient Cycling, and Erosion Control

Studies show that soil health declines with management intensification: CAFS consistently sustain richer microbial communities, lower denitrification rates, and higher bioavailable nutrients than UCAS.[59]. CAFS also benefit from the nitrifying activity of leguminous trees widely used for shading. Their pruning alone contributes 70-90kg of N/ha/year, comparable to one-third the synthetic nitrogen (N) input in UCAS [60]. Agroforestry and organic management independently protect soil health: CAFS show higher microbial diversity and nutrient retention and uptake than UCAS independently of agrochemical use [60–63], while conventional CAS have lower soil pH, bioavailable N, and food web diversity than organic CAS at equal shade levels [54,62,63]. Extensive root systems, litter, vegetation, and mulch in CAFS also reduce erosion, with nitrogen loss over three times higher in UCAS [62,64,65].

Hydrological Services

CAFS better preserve hydrological services through deeper root networks, litter, and improved soil structure, achieving hydraulic conductivities comparable to natural forests, with low surface runoff, high infiltration rates, reduced sediment transport, and enhanced groundwater recharge and soil moisture storage during dry periods [66–70]. Compared with pastures and UCAS, CAFS show better modulation of peak flows during storms [68], and may even outperform mature forests in reducing surface runoff and enhancing groundwater recharge [69]. Additionally, CAFS exhibit lower soil evaporation and higher evapotranspiration, suggesting a more efficient use of rainfall through their microclimatic characteristics [71].

Regulation of Microclimate and Extreme Weather

Shade in CAFS moderates microclimatic extremes by lowering temperature (between 0.6°C and 5.4 °C in M-CAFS compared with UCAS), reducing wind speed, increasing humidity, and stabilizing soil moisture, thereby reducing evaporation and protecting crops and workers under climate change [61,72–74]. Evidence also suggests that agroforestry can enhance resilience to extreme weather events through root stabilization and wind buffering, with more complex, less intensive CAFS associated with reduced losses and landslides after hurricane Stan in Chiapas, Mexico [75]. However, results in Puerto Rico after hurricane Maria are mixed; one study found that diverse CAFS may have suffered less damage and recovered faster [76], while another didn't find an association between hurricane resistance and canopy cover [77]. Nonetheless, CAFS were found to support ecological resilience by providing a refuge for biodiversity recovery after the hurricane [78].

Pollination

A global meta-analysis indicates that greater pollinator richness in CAFS increases Arabica fruit set by around 18% and improves fruit size, weight, and cup quality, benefits associated with agroforestry and proximity to native forests [79]. Even UCAS close to forests report a 15% higher productivity, related to a 32% higher pollinator population [80], as well as improved yields and quality due to pollination [81].

Regulation of Detrimental Organisms

Ecological complexity in CAS improves pest and disease control by reducing pathogen dispersal and supporting natural biocontrol agents, including fungi, birds, reptiles, nematodes, spiders and insects [8,82–84]. Two key threats in Latin America revised here are the coffee berry borer (CBB, *Hypothenemus hampei*) and CLR [85]. CBB infests developing berries, causing global losses exceeding $500 million annually. CAFS with multiple ant and bird species can lower CBB populations by up to 50%, potentially preventing $75–310/ha/year in crop damage [82,84]. These benefits decline with intensification [84], and some evidence shows that CBB infestations are lower in organically-managed Robusta CAS [86]. The impact of management intensity in CLR is more controversial. While their high humidity may favor CLR development, CAFS also reduce aerial spore dispersal and foster natural *Hemileia* predators such as *Lecanicillium lecanii* and *Mycodiplosis hemeliae, and it has been suggested that* intensification may reduce CAS resilience and increase CLR outbreak severity [8,83,87]. The ecological interactions of biocontrol agents, microclimates, and host plants within CAS are complex and non-lineal, and further research is required to clarify these dynamics.

Coffee Productivity

Evidence on the relationship between shade and Arabica yields is nuanced. Shade removal is traditionally recommended based on experiments showing reduced photosynthesis and yields under shade [83]. However, field research report that moderately shaded Arabica CAFS can have similar or exceeding yields compared to UCAS, probably by balancing photosynthetic rates with NCP such as fertilization, pollination and pest control [33,79,88,89]. Robusta can also maintain similar yields under moderate (25%) shade from leguminous trees as under full sun [88]. CAFS shaded with nitrogen-fixing trees have the highest yields [33,88,89], while species such as *Eucalyptus* hinder growth [80]. The effect of agrochemical management is also nuanced. Studies have found that organic CAFS can be as productive as conventional ones [89], and that CAFS combining low to moderate agrochemical use with moderate shade levels typically achieve the highest yields [33] and a higher yield-to-nitrogen input ratio [90]. Studies on complementary NCP show that biocontrol and pollination by birds and bees can jointly contribute up to 25% of production [91], and farms maximizing NCP through shading, polyculture, and low pesticide use have lower yield and economic losses, even under high CLR prevalence [85]. Agroecologically managed CAFS have achieved competitive yields using less than a third of agrochemicals and half the labor than UCAS, while generating higher net incomes due to secondary products and reduced expenses [92]. In Puerto Rico, island-level analyses suggest that total planted area, not shade level, is the strongest predictor of yield, while shade cover correlates with greater food crop richness [76]. These findings show that tradeoffs between shade and organic management with productivity can be minimized by maximizing NCP.

4.2. Land-System Change

Forests are the control variable for land-system change in the PB framework [45], and CAS influence this boundary mainly through deforestation of native forests and loss of on-farm shade and structural complexity.

Between 1990 and 2010, intensification increased global coffee production by 36% despite a 9% fall in cultivation area [6]. In Latin America, coffee covers roughly 4.6 million hectares [19,93], often adjacent to high-conservation-value forests [6,9]. Cultivation area is contracting in countries such as Brazil and Colombia while expanding into forested zones in Ecuador, Peru, Mexico, and Central America, a pattern likely to increase under climate change [19,42]. Annual deforestation attributable to coffee cultivation globally is estimated at 130,000 hectares [27], with Latin American estimates by indirect land-balance models reaching at least 37,000 ha/yr between 2005 and 2017 (fig. 7) [94]. This amounts to 3.3% of the 1,108,800 ha lost to deforestation in Latin America in 2020 [95], or 0.004% of the regional tropical forest cover in 1995 [96]. Coffee-driven deforestation is highest in Honduras, Ecuador, and Peru, accounting for 17%, 10%, and 7% of total national forest loss between 2005 and 2013, respectively (supplementary material S4) [97].

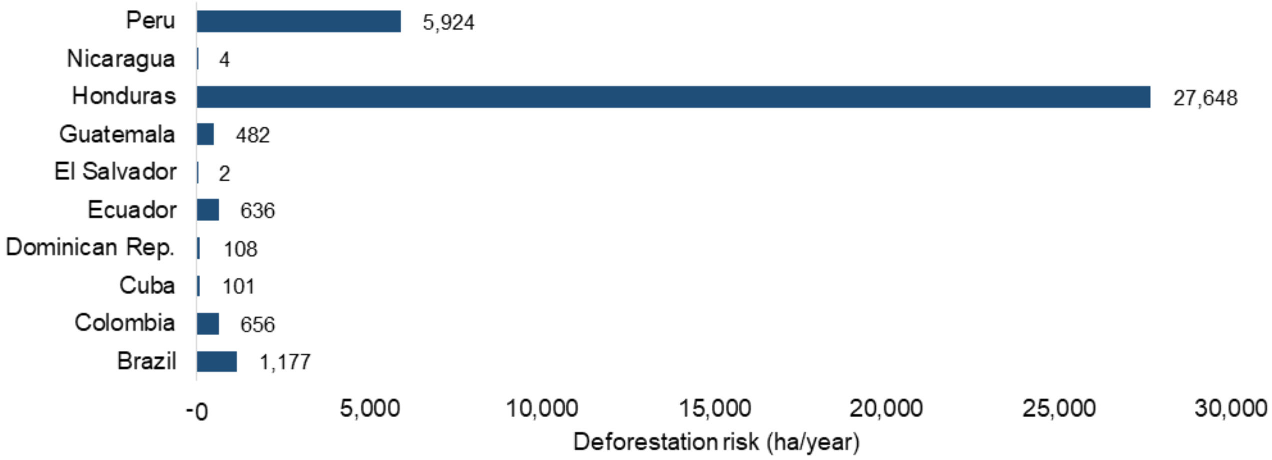

Figure 7. Deforestation risk attributable to coffee expansion among 10 Latin American countries. No data available for Bolivia, Costa Rica, Haiti, Mexico, Panama, and Venezuela. Data from Pendrill et al. 2019.

A substantial share of deforestation occurs within farms as shaded coffee systems are replaced by unshaded monocultures or other crops. In Chiapas, most of the deforestation during the CLR epidemic came from T-CAFS rather than native forests [44]. From 1970–1990, ~50% of CAFS in Latin

America shifted to low-shade or UCAS [98], with further declines in the 1990s–2010s, particularly in El Salvador (92 to 24%), Nicaragua (55 to 25%), Guatemala (45 to 40%), and Costa Rica (10 to 0%) [6]. Shade remained stable in Colombia (~30%) and rose in Honduras (15 to 35%) and Mexico (10 to 30%). By 2010, UCAS covered 41% of coffee area, M-CAFS 35%, and diverse CAFS just 24% [6]. This intra-farm simplification is critical because CAFS preserve many key functions of native forests, as discussed in sections 4.1 and 4.3.

Although less extensive, farm abandonment and agroforestry-driven reforestation also shape land-system change. Abandoned farms are often converted to crops or pastures, reducing tree cover, but in some cases regenerate into secondary forests [19]. Coffee expansion can also promote reforestation when shade levels and diversity increase. In Mexico's Sierra Norte de Puebla, over 60,000 ha were reforested between 1988 and 2003, two thirds through CAFS established on grasslands and cornfields [12], while CAFS drove a 17% tree cover rise in Honduras from 1954–1992 [99]. Growth in certified coffee (organic, fair trade) also supports agroforestry, with Latin America leading global production [19].

4.3. Climate Change

The coffee supply chain contributes approximately 1% of global food systems' carbon footprint, largely from cultivation and consumption [100]. In Brazil, coffee accounts for 5% of agricultural emissions and 1.14% of the country's total [101]. A land-balance model estimated deforestation emissions at over 12 million t CO_2/yr in Latin America [94]. On the other hand, a review of eight studies found that T-CAFS store over five times more C than UCAS (54.6 vs. 9.7 t/ha) [102], while converting T-CAFS to UCAS or other crops can release 133-192 t C/ha on average (table 3) [13]. Conversely, transitioning UCAS to CAFS could sequester about 1.3 t C/ha/year, potentially making CAS carbon-neutral or carbon-negative [102].

Table 3. Carbon stocks in selected CAS and land systems. Adapted from Libert-Amico & Paz-Pellat 2018.

Land system	Soil (t C ha)	Biomass (t C ha)	Total (t C ha)
T-CAFS	180	80	260
M-CAFS	130	43	173
UCAS	120	7	127
Cornfield	66	2	68
Grassland	80	8	88

Despite methodological differences, all studies reviewed show increasing carbon footprints with management intensity: in Central America between T-CAFS and UCAS (0.51 kg CO_2eq/kg vs. 0.64 kg CO_2eq/kg cherry coffee[2]) [102]; across five Latin American countries between polycultures and monocultures (6.2–7.3 vs. 9.0–10.8 kg CO_2eq/kg parchment coffee) [104]; in Colombia between CAFS and UCAS (3.1 vs. 5.8 kg CO_2eq/kg parchment coffee) [105]; near fivefold lower difference between organic and conventional CAS in Brazil (1.4 vs. 0.3 kg CO_2eq/kg green coffee) [106]; and the lowest reported in organic T-CAFS managed by an indigenous cooperative in Mexico (0.15 CO_2eq/kg green coffee, excluding transport) [107].

Fertilization emissions from manufacturing and soil N_2O volatilization is the largest contributor to GHG emissions in intensified CAS, accounting for 70–94% of total emissions, followed by C-stock loss [100,102,106]. A systematic review estimated N_2O emissions from coffee farms at 0.2-12.8 kg N/ha/year (94-5995 kg CO_2eq/ha/year), scaling directly with fertilizer use [108]. Moreover, increasing N inputs reduces efficiency due to saturation and losses. In Ecuador, optimal environmental and economic performance was observed at 70 kg N/ha/year, roughly half the national recommendation [90].

---

[2] To convert between different coffee forms, a ratio of 5.4 : 2 : 1.25 : 1 (fresh cherry coffee : dry cherry coffee : parchment coffee : green coffee) is suggested [102;103].

4.4. Biogeochemical Flows

Synthetic fertilization and shade loss are the main drivers of change in this PB through increased N and P inputs and nutrient runoff, fueling eutrophication, harmful algal blooms, and oxygen depletion in freshwater and marine ecosystems [45,109]. In 2017, coffee production used ~2.1 Mt of fertilizer (1.2% of global use) [93]. The exact synthetic N and P inputs from coffee farming are unknown, but given global N (190 Tg/yr)[3] and P (22.6 Tg/yr) flows [45] and coffee's share of fertilizer use, net N and P flows attributable to coffee cultivation can be estimated at about 2.28 Tg N and 0.27 Tg P annually –about 3.6% of the N boundary (62 Tg) and 2.4% of the P boundary (11 Tg). These estimates correlate with fertilization rates in conventional monocultures (66–400 kg N/ha/yr and 22–109 kg P/ha/yr) [90,108]. At global scale (10.3 Mha), this would equate to 0.7–4.1 Tg N/yr and 0.22–1.1 Tg P/yr, or 1–6% and 2–10% of the respective PB under low and high fertilization rates, respectively, highlighting the importance of keeping them near the lower range.

Life-cycle assessment generally show lower eutrophication impact in less intensive systems: in Colombia, CAFS were found to have lower less terrestrial, freshwater and marine eutrophication impact than UCAS [105], and in Brazil, organic coffee had a lower contribution to freshwater, marine and terrestrial ecotoxicity, but higher freshwater eutrophication potential associated to high-P organic fertilizers [106]. Field studies have measured eutrophication directly. In Veracruz, Mexico, streams from CAFS and forest had higher N pollution but lower eutrophication than pasture streams despite higher N loads, likely because shade limits eutrophication [110]; in Costa Rica, M-CAFS streams generally showed lower nutrient pollution and eutrophication than cattle highlands, and shade also correlated with lower eutrophication [111]. Wet coffee processing is another source of nutrient pollution, contributing ~80,000 t of biochemical oxygen demand (BOD) in Mexico in 2000 [112].

4.5. Freshwater Change

Coffee cultivation relies primarily on rainwater; its global green and blue water use (~108 km^3 and ~0.75 km^3 in 2017, respectively) is therefore significantly lower than for many other crops [93], representing ~0.019% of the 4000km^3 blue-water PB set in 2015 [113]. However, blue-water pressures are rising due to increasing irrigation in highly intensified systems (~1,104 m^3/t cherry) and wet processing (~7.5 m^3/t) [100,114,115]. In Latin America, irrigation is concentrated in Brazil, covering 5.9% of the coffee area [101,114], yet using 274 million m^3/year blue water, a third of coffee's global use [93], resulting in water scarcity impacts ten-fold higher than in Central America or Colombia (0.15–0.27 vs. 0.02 m^3/l coffee) [100]. Life-cycle assessments show that CAFS use ~53% less water than UCAS [105], and organic CAS up to ten times less water than conventional CAS (3 vs 33 m^3 eq./t green coffee) [106].

4.6. Novel Entities

The *Novel Entities* PB includes human-made or mobilized entities such as synthetic chemicals and genetically modified organisms, with a proposed boundary of zero release of untested synthetics [45]. In CAS, the main contribution to this PB is pesticide use, which closely follows the coffee intensification gradient, although evidence specific of CAs remains limited. Pesticides used in coffee cultivation across Latin America include many listed as highly hazardous and banned in several countries (table 4) [116,117]. Their use has expanded rapidly, with a 190% increase in Brazil in the last decade [83,116], where producing 1,000 kg of green coffee requires ~10 kg of pesticides [118], or ~38 million kg annually [83]. Documented environmental leakage includes 59 pesticides —over half highly toxic— in Brazil's Itapemirim River Basin [116], and elevated organophosphates and organochlorines, including banned pesticides such as dieldrin, heptachlor, and DDT, in surface waters of coffee areas in Quindío, Colombia [117], highlighting weak enforcement driven by easy access, limited testing, and regulatory gaps [116].

---

[3] 1 Tg = 1,000,000 tons.

Table 4. Highly hazardous pesticides used in coffee farming in Latin America.

Pesticide	Human Health Hazards	Environmental Hazards
Chlorpyrifos	Reproductive toxicant (GHS)	Highly toxic to bees (EPA)
Copper II Hydroxide	Fatal if inhaled (GHS)	Very toxic to aquatic organisms and very persistent in water, soil or sediment (EPA)
Cypermethrin		Highly toxic to bees (EPA)
Cyproconazole	Reproductive toxicant (GHS)	
Diazinon	Probable carcinogen (IARC)	Highly toxic to bees (EPA)
Disulfoton	Extremely high acute toxicity (WHO Ia)	
Diuron	Probable carcinogen (EPA)	
Endosulfan	Fatal if inhaled (GHS)	Persistent Organic Pollutant (Stockholm convention)
Epoxiconazole	Probable carcinogen (EPA, GHS), reproductive toxicant (GHS)	
Glyphosate	Probable carcinogen (IARC)	
Iprodione	Probable carcinogen (EPA)	
Malathion	Probable carcinogen (IARC)	Highly toxic to bees (EPA)
Mancozeb	Probable carcinogen (EPA, GHS), reproductive toxicant (GHS), endocrine disruptor (EU)	
Methyl Parathion	Extremely high acute toxicity (WHO Ia), fatal if inhaled (GHS)	Very toxic to aquatic organisms (EPA)
Methomyl	High acute toxicity (WHO 1b)	Highly toxic to bees (EPA)
Paraquat Dichloride	Fatal if inhaled (GHS)	
Pendimethalin		Very bioaccumulative, very persistent in water, soils or sediments (EPA)
Permethrin	Probable carcinogen (EPA)	Highly toxic to bees (EPA)
Simazine	Probable carcinogen (GHS), probable reproductive toxicant (GHS)	
Thiamethoxam		Highly toxic to bees (EPA)
Triadimenol	Reproductive toxicant (GHS)	
Triazophos	High acute toxicity (WHO 1b)	

Note: highly hazardous pesticides reportedly used in coffee cultivation in Latin America [83,116,117,119,120], classified as such by the World Health Organization (WHO), the U.S. Environmental Protection Agency (EPA), the Globally Harmonized System of Classification and Labelling of Chemicals (GHS), the International Agency for Research on Cancer (IARC) and the Stockholm convention, compiled in the PAN list of highly hazardous pesticides [121].

5. Coffee Farming's Impacts on Human Health and Its Ecosocial Determinants

This section examines 46 studies on how different CAS, their drivers of transformation, and coffee-driven environmental change affect human health through direct occupational exposure and ecosocial determinants such as coffee prices, CLR outbreaks, and climate change.

5.1. Occupational Health Hazards, Exposure to Dangerous Fauna, and Leishmaniasis

Coffee farmworkers are exposed to significant hazards with limited access to protective equipment and healthcare. A survey in Cauca, Colombia, found that only 3% of had medical insurance [122], and just 5% of pesticide handlers in Dominican Republic consistently used protective equipment [123]. The findings of this review show that, while farmworkers in intensified CAS are

doi:10.20944/preprints202509.2173.v2

more exposed to pesticides, those in CAFS are more exposed to dangerous fauna and leishmaniasis, a vector-borne disease.

In the Dominican Republic, conventional CAS farmworkers exposed to pesticides have shown higher cytotoxic and genotoxic biomarkers, greater symptoms of acute intoxication, and a possible reduction in male fertility linked to early-life exposure than organic farmworkers [17,123,124]. In Quindío, Colombia, residues of banned pesticides such as endosulfan and heptachlor were detected in 55% of coffee and banana farmworkers, and their presence in serum samples was associated to subclinical hypothyroidism in 6.7% of workers [119,125]. Cytogenetic biomonitoring also found higher chromosomal damage in farmers in regions with intensive pesticide use than in the predominantly organic coffee region of Sierra Nevada de Santa Marta [126]. Moreover, one Brazilian study identified 117 different pesticides in local raw beans [127], and some have been detected in roasted coffee beans [120], highlighting possible risks for consumers.

Coffee harvesting results in frequent musculoskeletal disorders: in Colombia, 18% of surveyed farmworkers reported accidents and 50% chronic back pain [122], while in Honduras over 70% reported recurrent musculoskeletal pain [128]. Farmers also face risks from hazardous wildlife. Some farmworkers in Chiapas reportedly prefer intensively managed CAS due to fear of snakes, ants, and spiders found in CAFS. These risks are exacerbated by the lack of proper footwear and protective equipment, and by penalties for leaving infested coffee bushes unharvested [129]. In Bahia, Brazil, an ecological study found higher snakebite incidence associated with coffee and cocoa cultivation near the Atlantic Forest compared with more intensive crops [130]. Cutaneous leishmaniasis has also been associated with multifunctional CAFS. In Tolima, Colombia, a high-incidence township had greater forest cover, more shaded CAFS, and higher densities of *Lutzomyia* sandflies than a low-incidence township dominated by monocultures [131], while Leishmanin skin test positivity among coffee farmers was nearly twice as high in T-CAFS than in *intensified* farms (26.8% vs. 13.2%) [132]. No studies linking CAS with other infectious diseases were found in this review.

5.2. Impacts on Ecosocial Determinants of Health

5.2.1. Livelihood Diversification and Income

Agrobiodiversity in CAFS –including shade trees, crops, beehives, and associated flora and fauna– supports livelihoods by providing a variety of commercial and non-commercial products. Intensification can increase coffee yields but reduces these contributions, leading to underestimation of productivity when measured solely as coffee output [12,133]. In Peru and Guatemala, woody products from CAFS –mainly firewood– have been found to account for 28.5% and 18.8% of smallholder coffee-holding value, with trees functioning as “stored capital” [133], while fruits contribute about ~10% of income, but up to 40% with appropriate market access [134]. In El Salvador and Nicaragua, CAFS supplied roughly half of household firewood–the primary energy source in rural Latin America–, valued at about 3-7% of household income, and 119 commonly used species of medicinal plants were recorded in CAFS, a significant therapeutic resource for households with little access to health services [135]. In Chiapas, beekeeping was associated with higher income sufficiency among coffee farmers (55.6% vs. 33.6%), while fruits and vegetables from CAFS supported household nutrition, fed seasonal workers, and facilitated barter [15].

A comparative modeling study in Guatemala and Costa Rica found that a 50% increase in coffee prices would be required for all farmers to achieve positive net cash incomes, although still below living income for most. Moderately shaded, high-investment CAFS had the highest probability of positive returns under most scenarios, whereas for farmers with limited investment capacity, highly shaded, diversified CAFS were the most economically viable option because diversification and lower costs buffer against price drops [33].

5.2.2. Food Security and Nutrition

Smallholders frequently experience seasonal food insecurity (*“thin months”) with reported* annual prevalences of 63% in Central America [135], 72% in Chiapas [15], 97% in El Salvador [136], and 52% in Guatemala [137], and average durations of 2.5-3 *thin months* in Chiapas and Nicaragua [15,138]. Proximate causes include income insufficiency, depleted staples, limited employment and land access, rising food and production costs, catastrophic health expenditures, and climatic variability [136,138]. Agricultural diversification both within and beyond coffee farms consistently supports food security and nutrition. The number of trees on CAFS [14,138], and its plant diversity [14] have been found to be significantly associated with fewer food-insecure months in Nicaragua and Chiapas. In Chiapas, more than 20 wild food species were identified within CAFS, including leafy greens, palm flowers, snails, and mushrooms, many shade-dependent and rich in micronutrients, and consumed by all surveyed households [14], while a different study recorded 108 different edible plant species linked to CAFS, *milpas* (traditional agroecological systems combining maize, beans, squash and other crops), and cacao systems, supporting dietary diversity [139]. Coffee farmers in Mesoamerica often maintain *milpas* to retain control over food supplies [14,15,136]. In a study in El Salvador, these staples supplied about half of household consumption [136]; in Guatemala, diversified households reported lower food insecurity than coffee-dependent ones [137]; and in Chiapas, staples provided 37% of coffee household food, and that both growing staples and beekeeping significantly increased food security [14,15]. Similarly, diversified coffee smallholders in Honduras experienced lower food insecurity than coffee-dependent ones during Covid-19 lockdowns, which reduced labor, coffee yields, and access to food and markets [140].

On the other hand, landscape transformations, shifting food cultures, and limited access to fresh foods are driving a transition toward industrialized diets and to obesity and micronutrient deficiencies. In Guatemala, households relying solely on coffee reported higher incomes, but also higher overweight, obesity, and reduced caloric access during *thin months* than diversified households[141], and a survey in 55 Colombian coffee-growing communities identified unhealthy diet (<5 daily servings of fruits/vegetables, 86.3%) as the most common risk factor for non-communicable diseases [142].

5.2.3. Migration

CLR outbreaks and low coffee prices have been linked to coffee farmer migration. A study among ten coffee-growing communities in Guatemala found that migration had almost doubled during an outbreak of CLR that caused a 71% loss in production [143], while a five-cent fall in coffee prices has been associated with a rise in about 160 migrants per 100,000 people in Honduras [144]. Similar migration surges have been reported following coffee price drops in Colombia and Mexico [28,145]. On the other hand, coffee smallholders rely on rainwater and are particularly vulnerable to climate change, especially in Central America’s “Dry Corridor” [146]. Recurrent droughts have devastated harvests, and in 2020 alone they threatened the food security of 2.2 million people. That same year, Hurricanes Eta and Iota displaced an estimated 7 million people across Central America, destroyed 80% of agricultural production, and severely disrupted infrastructure and logistics, greatly affecting coffee farmers [41]. While this review did not find studies directly quantifying climate’s contribution to coffee-farmer migration, rainfall variability has been statistically linked to higher apprehensions of Honduran family units at the U.S. border [147].

5.2.4. Peace and Security

Coffee prices have been linked with violence, particularly in Colombia’s Coffee Axis. Rates of homicides, kidnappings, and attacks were significantly associated with coffee prices during the 1990s-2000s, when the price collapse forced many farmers to abandon coffee and turn to coca and poppy and armed groups filled the vacuum [28]. A similar study found that the 68% drop in coffee prices between 1997–2003 coincided with 18-31% more guerrilla and paramilitary attacks, 22% more armed clashes, and 14% more war-related deaths in coffee-growing regions relative to non-coffee ones [148].On the other hand, qualitative research suggests that community-based agroecology projects can contribute not only to ecological practices but also to social cohesion, resilience, and collective action by building local institutions, mediating conflicts, promoting gender equity, preserving historical memory, defending territories, and expanding political participation and marketing channels in post-war Colombian coffee-growing communities [149].

5.2.5. Gender Equity

Public and institutional policy, certification programs, and producer cooperatives can be levers to narrow gendered asset gaps in land, credit, education, and representation. The increasing incorporation of women into the FNC in Colombia has expanded their productivity, income, and decision-making power [150]; in Oaxaca, Mexico, women's registration in Fairtrade-organic certification programs rose from 9% in the 1990s to 42% by 2013, and female cooperative members reported strong household decision-making and higher control over income [151], while members of a women-led Fairtrade cooperative in Nicaragua reported higher revenues, school attendance, and empowerment than women in a conventional cooperative [38]. However, women's increased participation in coffee farming adds to disproportionate domestic workload, and increases time poverty, with some authors pointing out the contradiction of market-based solutions that rely on continuous intensified labor and unpaid work to advance gender equity [150,151].

5.2.6. Identity, Quality of Life and Mental Health

Strong biocultural ties are evident in rustic T-CAFS managed by indigenous communities, such as Mixes and Zapotecs in Oaxaca [152,153], Tzeltales and Zoques in Chiapas [107,154] and Nahuas in Puebla [9]. The Kuojtakiloyan, for example, are agroecological landscapes carefully developed by the Nahuas, with up to 300 species spanning 13 of 19 recognized plant/fungal "life forms", each playing an ecological or subsistence role, and where biodiversity and traditional identities are preserved [12]. These relationships transcend ethnic distinctions. Smallholder coffee farmers in Colombia's Coffee Cultural Landscape describe their relationship with the landscape as central to their sense of place, identity, and well-being, citing emotional and cultural reasons for choosing to practice traditional coffee farming [155], while in Veracruz, most farmers reported keeping traditional CAFS despite economic losses due to cultural significance, emphasizing environmental, economic, and cultural value [29]. Many report acceptable quality of life thanks to family, community life, and contact with nature, particularly among cooperative members, despite minimal education, distrust of authorities, inadequate health care, seasonal food insecurity, and low coffee income (US$416–1,115 annually) [156].

On the other hand, the transformation of coffee landscapes can be distressful: an ethnographic study in Risaralda, Colombia, documented high depressive symptoms and suicide rates among older male coffee farmers, linked to market-driven transformations such as ecotourism and "feminine coffee" that commercialize particular narratives and demand performances of idealized relationships with nature and gender roles [18].

Few studies address mental health among seasonal farmworkers. In Minas Gerais, Brazil, seasonal workers reported significantly higher anxiety, depression, and sleep impairment than permanent workers, reflecting insecurity between harvests [157], while in Southeast Brazil, depressive symptoms in coffee farmers were associated with pesticide exposure, tobacco use, chronic disease, and poor self-perceived health [16], consistent with evidence linking pesticide exposure to anxiety and depression [158].

6. Discussion

6.1. Human and Planetary Health Impacts of Coffee Farming

The results of this review show that coffee farming in Latin America is undergoing a profound trend of intensification, characterized by shade removal, higher agrochemical use and planting densities, and the replacement of Arabica with Robusta, alongside the expansion of coffee into new or forested areas. While some counter-trends exist, such as certification programs, these remain marginal and insufficient to offset the structural drivers of intensification: declining and volatile coffee revenues for coffee producers, climate change, devastating CLR outbreaks, weak institutional support, and migration. Caught in this precarious context, smallholders are forced to intensify production as a short-term strategy to sustain their livelihoods, undermining the ecological foundations of production and of human health, with impacts on local communities, ecosystems, and ultimately on planetary health.

This review shows that coffee intensification is exerting widespread pressure on six of the nine PB (fig. 8). Approximately 3% of total deforestation in Latin America can be attributed to coffee farming, further aggravated by within-farm reductions on shade and ecological complexity, which, coupled with rising agrochemical use, result in a decline in biodiversity [47]. This in turn erodes key NCP for human and planetary health, such as soil fertilization and conservation, carbon sequestration, pollination, pest control, hydrological services, microclimate regulation, mitigation of extreme weather events, and livelihood diversification [57,66,74,79]. Nitrogen fertilization, shade removal and deforestation also drive climate change, accounting to about 1% of global food systems' GHG emissions [100,106,108]. Yet coffee itself is highly vulnerable to climate change, with Arabica yields and suitability projected to shrink drastically during next decades, which may accelerate Robusta-driven deforestation and intensification [42]. We estimate that global coffee cultivation currently accounts for approximately 3% of the PB for N and P biogeochemical flows, based on total cultivation area and fertilizer consumption estimates from Sporchia et al. [93], and average fertilization rates reported by Capa et al. [90]. At the upper end of the intensification gradient –if all coffee were produced in intensive systems using high fertilization rates– this contribution could rise to 6% and 10% of the N and P flow PB, respectively.

These figures indicate that a considerable share of the global C, N, and P budgets are being consumed by coffee production, a non-nutritious crop that has historically been grown at much lower environmental costs under multifunctional CAFS. Most of these environmental impacts result from two management practices: shade removal and agrochemical use. Thus, agroforestry and organic farming in multifunctional CAFS offer an alternative to mitigate coffee's environmental footprint by enhancing carbon sequestration, reducing fertilizer dependency, and fostering high levels of biodiversity, while simultaneously sustaining good coffee quality and productivity and supporting key NCP for human health, wellbeing, and resilience [8,13].

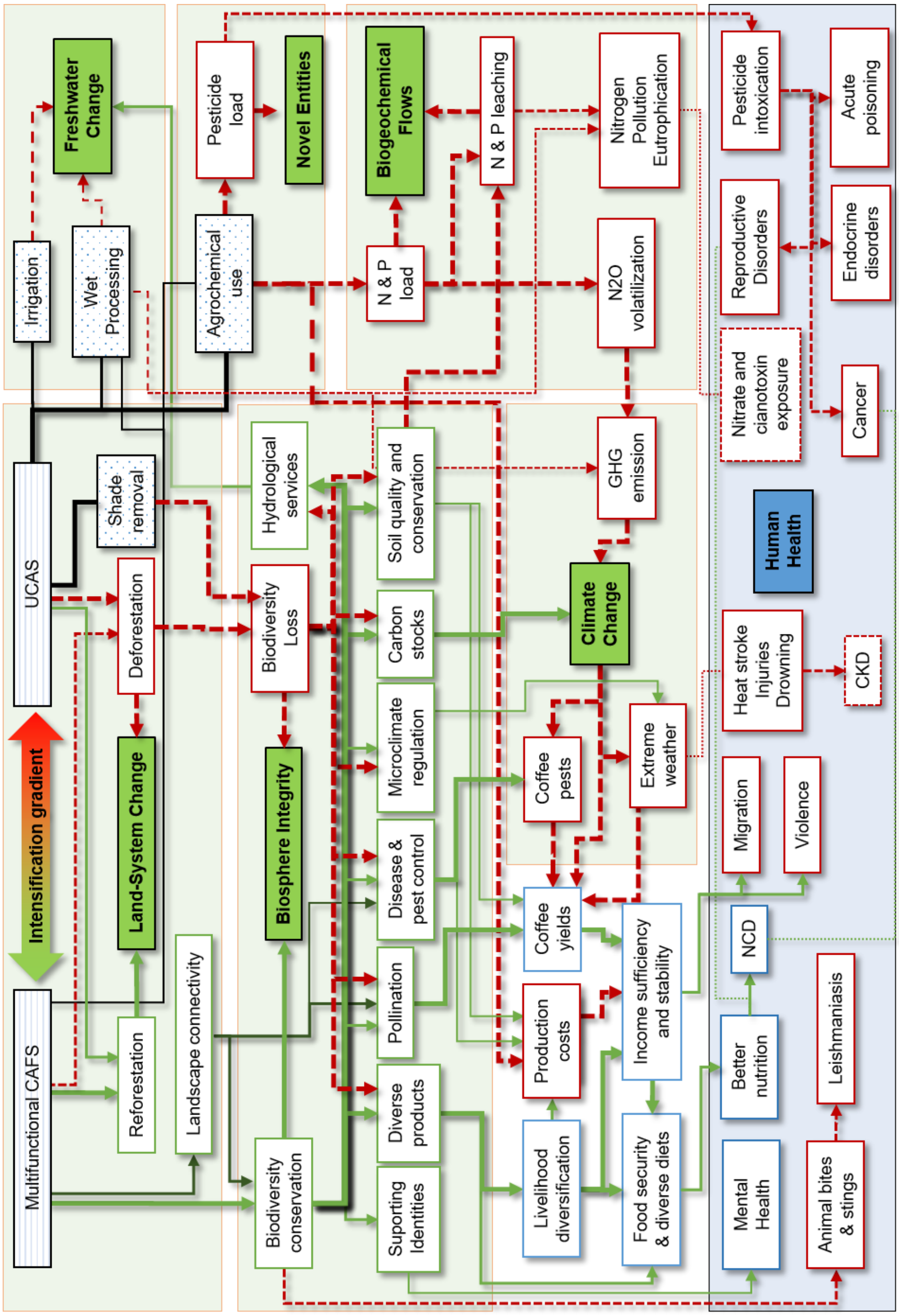

Figure 8. Main impacts of the coffee intensification gradient extremes on the Planetary Boundaries and Human Health (bold). Green continuous arrows: positive impacts; red dashed arrows: negative impacts; black continuous lines: management practices; dotted lines (green and red): theoretical links. The width of the arrow represents the strength of evidence and magnitude of the impact.

Health impacts of coffee farming are also largely mediated by agrochemical use and agroforestry. Pesticide exposure in intensified CAS is associated with acute poisonings, depression, reduced fertility, endocrine disruption, and elevated cancer risk among coffee farmworkers [16,17,119,123,124]. Over a hundred pesticides are used in coffee farming in the region, many highly hazardous and with evidence of environmental leakage and impacts on population's health [116,120,125]. On the other hand, high biodiversity in CAFS increases contact with wildlife, resulting in stings, snakebites, and a higher incidence of Leishmaniasis [129,130,132]. More evidence is needed on other vector-borne diseases and zoonoses. Agroforestry also buffers coffee farmers from extreme heat and dehydration, potentially lowering risks for some non-communicable diseases. For example, chronic kidney disease of unknown origin (CKDu), widely reported among sugarcane and other agricultural workers, is often attributed to heat stress; notably, its incidence appears consistently lower among coffee-growing communities and farmworkers than among sugarcane workers or national averages [159–163]. While Arabica's higher altitude and cooler conditions likely reduce heat exposure, agroforestry may provide additional protection, particularly in warmer Robusta plantations. Further research on these potential protective effect is needed.

Agrobiodiversity in CAFS also reduces agrochemical dependence and losses to pests and diseases, buffers climate extremes, and diversifies livelihood by providing secondary products such as timber, food, firewood, medicinal plants, and honey [15,85,92,133], improving income stability, autonomy, food diversity and security and socioecological resilience, as shown during the Covid pandemic [14,138,140,141]. This resilience may also buffer the impacts of other shocks –such as coffee price drops and extreme weather– on mental health, migration, and violence, although evidence supporting this relationship is lacking. Finally, traditional coffee farming and contact with nature contribute positively to farmers' quality of life and mental health [18,155,156].

Yet these dynamics unfold within social determinants that constrain human and planetary health. Coffee-growing communities are typically remote, underserved, and characterized by limited healthcare access, entrenched patriarchal norms, and low educational attainment, and most smallholders in Latin America live in persistent poverty [27], and landless, seasonal workers that form the backbone of coffee harvest labor face precarious working conditions and occasional human rights violations [34,39]. These conditions are linked to structural inequities embedded within the CVC, manifested in the racialized labor regimes of *fincas*, the unpaid labor of women, the low prices set in speculative commodity markets, and externally imposed development agendas and epistemologies, facilitating the implementation of capitalistic solutions –including conventional intensification– ostensibly aimed at alleviating poverty but largely benefiting corporations and investors.

Although market-based solutions such as certification programs and corporate responsible sourcing have been promoted as ways to address poverty and environmental degradation, these schemes leave structural power asymmetries unaddressed, and sustainability niches remain small with market forces favoring cheap, high-volume production [136]. Jimenez-Soto (2021) likewise questions whether biodiversity conservation can truly benefit farmworkers where inequities persist, noting that the narrative of CAFS as spaces of wellbeing contrasts with workers' lived experience of frequent bites and stings, while most seasonal farmworkers can't afford rubber boots and other protective equipment [129]. Ensuring dignified livelihoods and safe working conditions is therefore paramount to mitigate health hazards and resolve the false dichotomy between conservation, farmer wellbeing and production.

6.2. Equity and Identity in the CVC

As some authors have pointed out, identity, ethnicity, culture, knowledge, and power structures are at play in CAS [8]. A remarkable difference lies in that, while conventional intensification requires financial capital, multifunctional CAFS (particularly T-CAFS) rely on "biocultural capital" –the ecological and cultural diversity accumulated over generations– and thus the planned increase in agrobiodiversity in T-CAFS represents "intensification without simplification" based on farmers' labor and knowledge, rather than technology [76,164]. By preserving agrobiodiversity, genetic resources, and traditional knowledge, multifunctional T-CAFS also foster identity, autonomy, food sovereignty, and resilience.

On the other hand, coffee intensification in Latin America is embedded in the context of colonial and neo-colonial legacies that impose hierarchies of peoples, knowledges, and modes of living and relating to nature, and which endure in the persisting devaluation of indigenous knowledge and the promotion of "modernization" agendas centered on farmers' specialization, agricultural commodification, and conventional intensification based on closed technologies[4]. These forces have eroded biocultural heritage and contributed to the broader "depeasantization" of coffee farmers. Such is the case, for example, of the Mame people in Chiapas, Mexico, whose language, culture, and traditional practices were largely lost during the 20th century under conditions of forced displacement, state persecution, and prolonged exploitation in *fincas* [165]. However, indigenous coffee producers have also found spaces to preserve and reinvent their identities and biocultural heritage, particularly in producer cooperatives, such as Tosepan Titataniske, which works to preserve Nahuat cultural heritage and agroecological knowledge in Mexico through educational projects, dictionaries, and the documentation of their taxonomic system [166].

6.3. Recommended Actions to Protect Planetary Health in Coffee Farming

This review highlights interventions to advance planetary health in coffee farming. While a detailed analysis falls beyond the scope of this review, two cross-cutting principles recur: agroecological management and equity.

Agroecological practices –such as diverse agroforestry, low-agrochemical or organic management, soil conservation, ecological or dry processing, minimal irrigation, and the intentional use of NCP to sustain productivity and diversify livelihoods– are consistently associated with benefits for human well-being and the environment [92,102,104,105], and should be supported to shift coffee production towards multifunctional CAFS. On the other hand, advancing equity in the coffee value chain requires addressing its distributional, procedural and recognitional dimensions [167]. Key measures may include:

- Strengthening national coffee institutions and sectoral development plans, including funding mechanisms to support producers during crises.
- Expanding farmer access to credit, land, CLR-resistant seed varieties, inputs, and technical assistance oriented to sustainable practices.
- Providing financial incentives for agroecological production in the form of direct subsidies, payments for ecosystem services, guaranteed minimum prices, and market premiums.
- Developing pricing schemes that internalize social and environmental costs, for instance through targeted taxation mechanisms.
- Incorporating social and environmental labeling.
- Promoting a rational and limited use of pesticides, banning highly hazardous pesticides, and enforcing restrictions.
- Promoting integrated pest management prioritizing complementary alternatives such as biological control, agroforestry, and emerging genomic tools.
- Establishing and enforcing minimum working conditions and safety standards, including provisions to ensure that all farmworkers have proper protective equipment.
- Integrating gender perspectives in sectoral programs, promoting female leadership and specifically addressing time poverty.
- Expanding healthcare, social security, and education services in coffee-growing regions, ensuring access for both resident and seasonal workers.
- Investing in infrastructure and local market access, including for secondary products.
- Establishing mechanisms for an open and equitable access to technological innovations, such as genomic tools for pest control.
- Shortening value chains by linking producers directly to urban consumers.
- Promoting horizontal knowledge exchange and recovery of traditional management practices, protecting biocultural heritage, native seed diversity, and cultural traditions.

Producer cooperatives and broader farmer movements, such as Via Campesina, are key actors for sustainable coffee farming and should be recognized as strategic partners. On the other hand, commodity, roasting and retailer corporations should strengthen sustainability and human rights standards, monitoring and enforcement, and establish fair price schemes. Governments in consuming

---

[4] Closed technologies include agrochemicals, farming machinery, genetically-modified seeds, software or other technologies impossible to manufacture, repair or modify by farmers themselves, thus increasing dependence.

countries can contribute by establishing and enforcing strict human rights, environmental and tax policies for multinational corporations based in their territories. Coffee-related taxes in consuming countries could be redirected to support producers and sustainable practices. Moreover, reaching an international agreement to control supply could restore coffee prices and limit the planetary health impacts of overproduction.

6.4. The DPSEEA Framework of Coffee Farming's Impacts on Planetary Health

The pathways through which coffee farming affects planetary health are synthesized in the DPSEEA model (fig. 9), together with recommended actions to mitigate health risks, protect ecosystems, and enhance the regenerative potential of coffee farming.

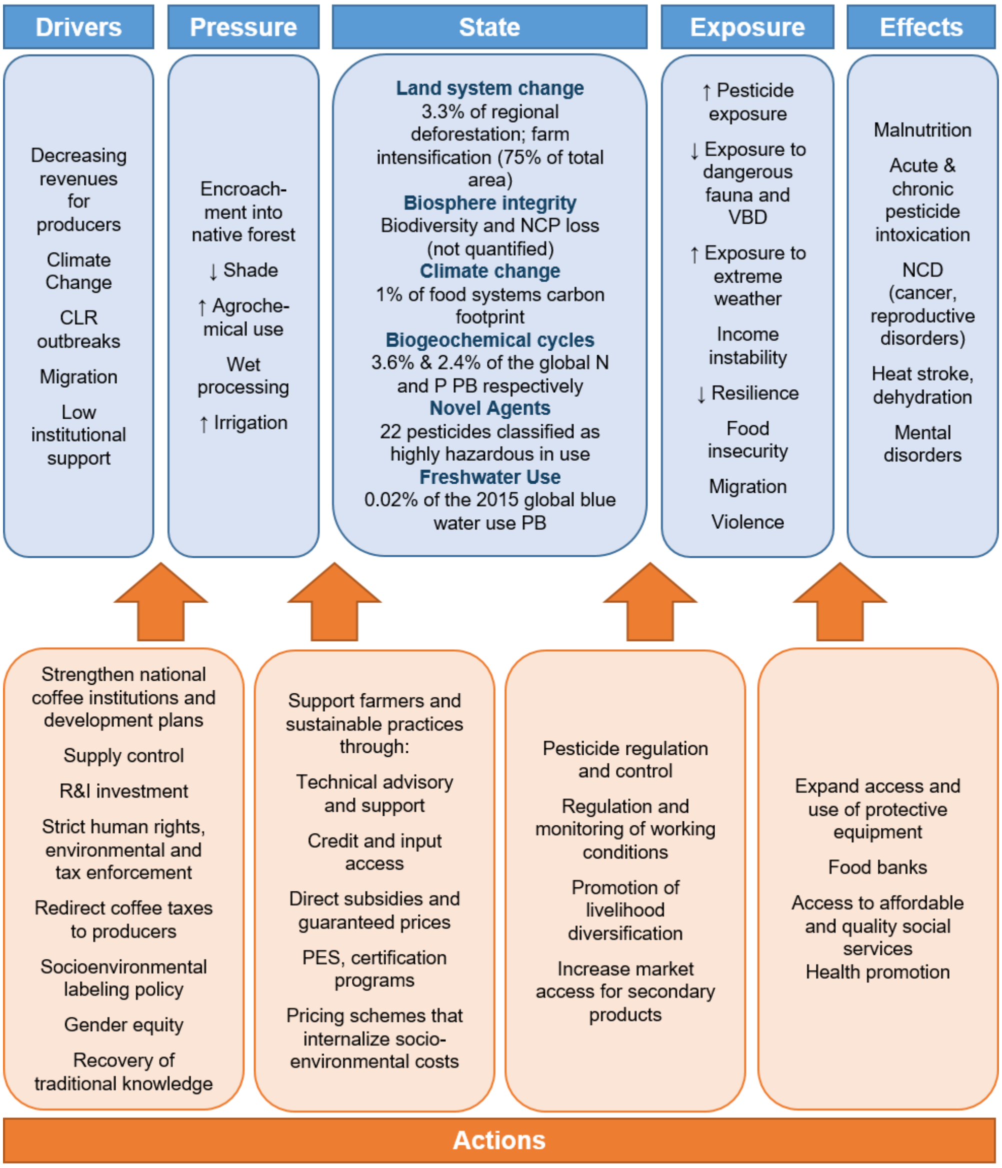

Figure 9. The DPSEEA model of coffee intensification and planetary health. More detailed relationships between the state, exposure and effect elements are shown on figure 8.

6.5. Strengths, Limitations, and Research Gaps

This review has several strengths. Its novel integration of analytical frameworks such as Planetary Boundaries, Nature's Contributions to People and DPSEEA provides a comprehensive lens to assess the Planetary Health impacts of coffee farming. It draws on a wide range of disciplines, linking ecological, agronomic, epidemiological, and socioeconomic perspectives, contributing to bridging fragmented fields of research to provide the first broad-scope review on the topic. Finally, while focused on Latin America, the study provides relevant insights for coffee farming around the world.

However, this review has multiple limitations. This study did not follow a formalized protocol for exhaustive literature retrieval, selection, and analysis. The search was limited to Pubmed and Scopus, excluding relevant literature found in other databases. Results were subjectively sorted and screened by relevance, excluding almost 300 papers. No formal quality appraisal was conducted, and the reliance on narrative synthesis limits the assessment of evidence across themes. Additionally, results in Portuguese were excluded, a significant limitation given that Brazil is the largest coffee producer. Although efforts were made to include a broad disciplinary scope, social sciences are likely under-represented in the selected databases. The inferences linking drivers, CAS and environmental changes with key determinants of health such as migration, gender equity, violence, and mental health were based on limited available evidence. Finally, causal relationships between coffee management, ecological processes, and health outcomes remain difficult to establish, as most studies are correlational and potentially influenced by confounding factors.

This review highlights key research gaps. These include updated measurements of coffee-driven deforestation and the extent of shade-coffee systems; the genetic diversity and resilience of native coffee seeds; sustainable cultivation methods for Robusta; epidemiological research on coffee-growing communities, particularly regarding mental health, substance use, violence, gender-based violence, migration, suicide, infectious and vector-borne diseases, food security, and nutrition; and the potential role of coffee agroecology in modifying these risks. Finally, more research is needed on indigenous knowledge and practices, ecological pest control mechanisms, the impact of coffee-oriented public policies on planetary health outcomes, and field studies to assess strategies to support sustainable coffee production.

7. Conclusions

This review shows that while conventional intensification may support higher yields in the short-term, it does so at significant costs to human and planetary health. While multifunctional agroforestry coffee farming can reconcile production with environmental sustainability and human well-being, persisting structural inequities in the global CVC must be addressed. Smallholder farmers and farmworkers, many from historically marginalized groups, bear the greatest risks while capturing the smallest share of value. These inequities drive ecological simplification, cultural erosion, and health vulnerabilities, limiting the adoption (and preservation) of sustainable practices. Without addressing these systemic imbalances, the potential benefits of these agroecological strategies remain marginal. Therefore, a planetary health approach to coffee farming calls for policies and institutions that incentivize and strengthen agroecological management, secure equitable livelihoods, and recognize the biocultural heritage of coffee landscapes.

Coffee farming offers an interesting case study on the interconnections between agrifood systems and planetary health in the Anthropocene, as the tensions observed between intensification and sustainability, well-being and global trade, equity and profit are characteristic of broader challenges across tropical agriculture. Multifunctional coffee farming demonstrates that coffee production and farmer well-being are possible within planetary boundaries –but only within a socioeconomic framework that ensures fair prices, empowers historically marginalized producers, protects livelihoods, and recognizes the biocultural foundations of sustainable coffee landscapes.

Finally, this review proposes the integration of the Planetary Boundaries, Nature's Contributions to People, and DPSEEA frameworks for the interdisciplinary analysis of socioeconomic, environmental, and human health factors within coffee farming, an approach that may be useful to other Planetary Health challenges beyond the coffee sector.

Supplementary Materials: Supplementary material is provided: table S1: search queries used; table S2: list of included studies; table S3: data for figure 5; table S4: data for figure 7.

Author Contributions: EHG: conceptualization, methodology, literature search, investigation, data curation, writing – original draft preparation, visualization. HRR: writing – review and editing.

Funding: No funding was received for conducting this study.

Ethics Approval: Not applicable.

Consent for Publication: All authors consent to the publication of this work.

Acknowledgments: During the preparation of this manuscript, ChatGTP-5 was used for stylistic enhancement of figures 2 and 6, originally produced by the graphic artist Tamara Davila for this publication. The authors verified the results and take full responsibility for the content. The authors would like to thank MSc. Samana Shreedhar for kindly reviewing the manuscript and providing feedback, as well as the coffee-growing communities of Chiapas, Mexico, that first brought the dynamics discussed in this paper to their attention, and in particular to Isel, Floricelda, and Limner Roblero.

Conflicts of Interest: The authors declare no relevant financial or non-financial interests to disclose.

References

1. International Coffee Organization (ICO). The Value of Coffee. Sustainability, Inclusiveness, and Resilience of the Coffee Global Value Chain. 2020.
2. FAO Markets and Trade: Coffee. Available online: https://www.fao.org/markets-and-trade/commodities-overview/beverages/coffee/en.
3. Scott, M. Climate & Coffee. Available online: http://www.climate.gov/news-features/climate-and/climate-coffee (accessed on 20 April 2024).
4. United States Department of Agriculture (USDA). Coffee: World Markets and Trade Available online: https://fas.usda.gov/data/coffee-world-markets-and-trade (accessed on 20 April 2024).
5. Myhrvold, N. Coffee. *Encyclopaedia Britannica;* 2024.
6. Jha, S.; Bacon, C.; Philpott, S.; Méndez, E.; Läderach, P.; Rice, R. Shade Coffee: Update on a Disappearing Refuge for Biodiversity. *Bioscience* **2014**, *64*, 416–428, doi:10.1093/biosci/biu038.
7. Pham, Y.; Reardon-Smith, K.; Mushtaq, S.; Cockfield, G. The Impact of Climate Change and Variability on Coffee Production: A Systematic Review. *Climatic Change* **2019**, *156*, 609–630, doi:10.1007/s10584-019-02538-y.
8. Perfecto, I.; Jiménez-Soto, M.E.; Vandermeer, J. Coffee Landscapes Shaping the Anthropocene: Forced Simplification on a Complex Agroecological Landscape. *Current Anthropology* **2019**, *60*, S236–S250, doi:10.1086/703413.
9. Moguel, P.; Toledo, V.M. Biodiversity Conservation in Traditional Coffee Systems of Mexico. *Conserv. Biol.* **1999**, *13*, 11–21, doi:10.1046/j.1523-1739.1999.97153.x.
10. IPBES Update on the Classification of Nature’s Contributions to People by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services 2017.
11. Davidson, S. Shade Coffee Agro-Ecosystems in Mexico: A Synopsis of the Environmental Services and Socio-Economic Considerations. *Journal of Sustainable Forestry* **2004**, *21*, 81–95, doi:10.1300/J091v21n01_05.
12. Toledo, V.M.; Moguel, P. Coffee and Sustainability : The Multiple Values of Traditional Shaded Coffee. **2012**, *0046*, doi:10.1080/10440046.2011.583719.
13. Libert-Amico, A.; Paz-Pellat, F. Del papel a la acción en la mitigación y adaptación al cambio climático: la roya del cafeto en Chiapas. *Madera y Bosques* **2018**, *24*, doi:10.21829/myb.2018.2401914.
14. Fernandez, M.; Méndez, V.E. Subsistence under the Canopy: Agrobiodiversity’s Contributions to Food and Nutrition Security amongst Coffee Communities in Chiapas, Mexico. *Agroecology and Sustainable Food Systems* **2019**, *43*, 579–601, doi:10.1080/21683565.2018.1530326.
15. Anderzén, J.; Guzmán Luna, A.; Luna-González, D.V.; Merrill, S.C.; Caswell, M.; Méndez, V.E.; Hernández Jonapá, R.; Mier y Terán Giménez Cacho, M. Effects of On-Farm Diversification Strategies on Smallholder Coffee Farmer Food Security and Income Sufficiency in Chiapas, Mexico. *Journal of Rural Studies* **2020**, *77*, 33–46, doi:10.1016/j.jrurstud.2020.04.001.
16. Conti, C.L.; Barbosa, W.M.; Simão, J.B.P.; Álvares-da-Silva, A.M. Pesticide Exposure, Tobacco Use, Poor Self-Perceived Health and Presence of Chronic Disease Are Determinants of Depressive Symptoms among

Coffee Growers from Southeast Brazil. *Psychiatry Res* **2018**, *260*, 187–192, doi:10.1016/j.psychres.2017.11.063.

17. Hutter, H.-P.; Kundi, M.; Lemmerer, K.; Poteser, M.; Weitensfelder, L.; Wallner, P.; Moshammer, H. Subjective Symptoms of Male Workers Linked to Occupational Pesticide Exposure on Coffee Plantations in the Jarabacoa Region, Dominican Republic. *Int J Environ Res Public Health* **2018**, *15*, 2099, doi:10.3390/ijerph15102099.
18. Nieto-Betancurt, L.; Mosquera-Becerra, J.; Fandiño-Losada, A.; Guava, L.A.S. Suicide and Medical Practices: Assessing the Way of Life among Colombian Coffee-Growing Rural Men in Mental Health Care. *Salud Colect* **2024**, *20*, e4663, doi:10.18294/sc.2024.4663.
19. Harvey, C.A.; Pritts, A.A.; Zwetsloot, M.J.; Jansen, K.; Pulleman, M.M.; Armbrecht, I.; Avelino, J.; Barrera, J.F.; Bunn, C.; García, J.H.; et al. Transformation of Coffee-Growing Landscapes across Latin America. A Review. *Agron. Sustain. Dev.* **2021**, *41*, 62, doi:10.1007/s13593-021-00712-0.
20. Valencia, V.; García-Barrios, L.; Sterling, E.J.; West, P.; Meza-Jiménez, A.; Naeem, S. Smallholder Response to Environmental Change: Impacts of Coffee Leaf Rust in a Forest Frontier in Mexico. *Land Use Policy* **2018**, *79*, 463–474, doi:10.1016/j.landusepol.2018.08.020.
21. Whitmee, S.; Haines, A.; Beyrer, C.; Boltz, F.; Capon, A.G.; Dias, B.F. de S.; Ezeh, A.; Frumkin, H.; Gong, P.; Head, P.; et al. Safeguarding Human Health in the Anthropocene Epoch: Report of The Rockefeller Foundation–Lancet Commission on Planetary Health. *The Lancet* **2015**, *386*, 1973–2028, doi:10.1016/S0140-6736(15)60901-1.
22. Escobar-Ocampo, M.C.; Castillo-Santiago, M.Á.; Ochoa-Gaona, S.; Enríquez, P.L.; Mondragón-Vázquez, E.; Espinosa-Jiménez, F.R.; Sibelet, N. Drivers of Land-Use Change in Agroforestry Landscapes of Southern Mexico. *Hum Ecol* **2023**, *51*, 409–422, doi:10.1007/s10745-023-00417-w.
23. Gabriel-Hernández, L.; Barradas, V.L. Panorama of Coffee Cultivation in the Central Zone of Veracruz State, Mexico: Identification of Main Stressors and Challenges to Face. *Sustainability* **2024**, *16*, doi:10.3390/su16020802.
24. Griffith, D.; Zamudio Grave, P.; Cortés Viveros, R.; Cabrera Cabrera, J. Losing Labor: Coffee, Migration, and Economic Change in Veracruz, Mexico. *Cult. Agric. Food Environ.* **2017**, *39*, 35–42, doi:10.1111/cuag.12086.
25. Renard, M.C. Chapter 5: Free Trade of Coffee, Exodus of Coffee Workers: The Case of the Southern Mexican Border Region of the State of Chiapas. *Res. Rural Sociol.Dev.* **2011**, *17*, 147–165, doi:10.1108/S1057-1922(2011)0000017008.
26. Cordes, K.Y.; Sagan, M.; Kennedy, S. Responsible Coffee Sourcing: Towards a Living Income for Producers. *Columbia Center on Sustainable Investment* **2021**, doi:10.2139/ssrn.3894124.
27. Panhuysen, S.; de Vries, F. Coffee Barometer 2023. Conservation International and Solidaridad; 2023.
28. Rettberg, A. Global Markets, Local Conflict: Violence in the Colombian Coffee Region after the Breakdown of the International Coffee Agreement. *Lat. Am. Perspect.* **2010**, *37*, 111–132, doi:10.1177/0094582X09356961.
29. Hausermann, H. Maintaining the Coffee Canopy: Understanding Change and Continuity in Central Veracruz. *Hum. Ecol.* **2014**, *42*, 381–394, doi:10.1007/s10745-014-9644-x.
30. Utrilla-Catalan, R.; Rodríguez-Rivero, R.; Narvaez, V.; Díaz-Barcos, V.; Blanco, M.; Galeano, J. Growing Inequality in the Coffee Global Value Chain: A Complex Network Assessment. *Sustainability* **2022**, *14*, 672, doi:10.3390/su14020672.
31. Samper, L.; Giovannucci, D.; Vieira, L. *The Powerful Role of Intangibles in the Coffee Value Chain*; Economic Research Working Paper; 2017.
32. Braunschweig, T.; Kohli, A.; Lang, S. Agricultural Commodity Traders in Switzerland: Benefitting from Misery. *Public Eye Report* **2019**.
33. Lalani, B.; Lanza, G.; Leiva, B.; Mercado, L.; Haggar, J. Shade versus Intensification: Trade-off or Synergy for Profitability in Coffee Agroforestry Systems? *Agric. Syst.* **2024**, *214*, doi:10.1016/j.agsy.2023.103814.
34. Campos, A. *Certified Coffee, Rightless Workers*; Gomes, M., Ed.; Monitor; Repórter Brasil - RPBR, 2016; ISBN 978-85-61252-28-1.
35. Dallabrida, P.; Campos, A. *Certified Coffee, Rightless Workers 2*; Gomes, M., Ed.; Repórter Brasil - RPBR: Sao Paolo, 2021.

36. Barrios-Puente, G.; Galván-Manuel, O.; Pérez-Soto, F.; Sangerman-Jarquín, D.M.; García-Sánchez, R.C.; Barrios-Puente, G.; Galván-Manuel, O.; Pérez-Soto, F.; Sangerman-Jarquín, D.M.; García-Sánchez, R.C. Price Hedging for Coffee, Using the Futures Market. *Revista mexicana de ciencias agrícolas* **2022**, *13*, 1147–1154, doi:10.29312/remexca.v13i6.3313.
37. International Coffee Council. Futures Markets: The Role of Non-Commercial Traders. 2019.
38. Bacon, C.M. A Spot of Coffee in Crisis: Nicaraguan Smallholder Cooperatives, Fair Trade Networks, and Gendered Empowerment. *Lat. Am. Perspect.* **2010**, *37*, 50–71, doi:10.1177/0094582X09356958.
39. Gresser, C.; Tickell, S. *Mugged: Poverty in Your Coffee Cup*; Oxfam International, 2002;
40. Harvey, C.A.; Saborio-Rodríguez, M.; Martinez-Rodríguez, M.R.; Viguera, B.; Chain-Guadarrama, A.; Vignola, R.; Alpizar, F. Climate Change Impacts and Adaptation among Smallholder Farmers in Central America. *Agric. Food Secur.* **2018**, *7*, doi:10.1186/s40066-018-0209-x.
41. Fromm, I. Climate Change Impacts, Food Insecurity and Migration: An Analysis of the Current Crisis in Honduras. *Migr. and Diasporas: Struggl. Between Incl. and Exclusion* **2023**, 137–149, doi:10.1108/978-1-83797-146-620231009.
42. Bilen, C.; El Chami, D.; Mereu, V.; Trabucco, A.; Marras, S.; Spano, D. A Systematic Review on the Impacts of Climate Change on Coffee Agrosystems. *Plants* **2023**, *12*, doi:10.3390/plants12010102.
43. Avelino, J.; Cristancho, M.; Georgiou, S.; Imbach, P.; Aguilar, L.; Bornemann, G.; Läderach, P.; Anzueto, F.; Hruska, A.J.; Morales, C. The Coffee Rust Crises in Colombia and Central America (2008–2013): Impacts, Plausible Causes and Proposed Solutions. *Food Sec.* **2015**, *7*, 303–321, doi:10.1007/s12571-015-0446-9.
44. Chort, I.; Öktem, B. Agricultural Shocks, Coping Policies and Deforestation: Evidence from the Coffee Leaf Rust Epidemic in Mexico. *Am. J. Agric. Econ.* **2024**, *106*, 1020–1057, doi:10.1111/ajae.12441.
45. Richardson, K.; Steffen, W.; Lucht, W.; Bendtsen, J.; Cornell, S.E.; Donges, J.F.; Drüke, M.; Fetzer, I.; Bala, G.; von Bloh, W.; et al. Earth beyond Six of Nine Planetary Boundaries. *Science Advances* **2023**, *9*, eadh2458, doi:10.1126/sciadv.adh2458.
46. Philpott, S.M.; Arendt, W.J.; Armbrecht, I.; Bichier, P.; Diestch, T.V.; Gordon, C.; Greenberg, R.; Perfecto, I.; Reynoso-Santos, R.; Soto-Pinto, L.; et al. Biodiversity Loss in Latin American Coffee Landscapes: Review of the Evidence on Ants, Birds, and Trees. *Conserv. Biol.* **2008**, *22*, 1093–1105, doi:10.1111/j.1523-1739.2008.01029.x.
47. Manson, S.; Nekaris, K.A.I.; Nijman, V.; Campera, M. Effect of Shade on Biodiversity within Coffee Farms: A Meta-Analysis. *Sci. Total Environ.* **2024**, *914*, doi:10.1016/j.scitotenv.2024.169882.
48. Jha, S.; Vandermeer, J.H. Impacts of Coffee Agroforestry Management on Tropical Bee Communities. *Biol. Conserv.* **2010**, *143*, 1423–1431, doi:10.1016/j.biocon.2010.03.017.
49. Vaidya, C.; Fitch, G.; Martinez, G.H.D.; Oana, A.M.; Vandermeer, J. Management Practices and Seasonality Affect Stingless Bee Colony Growth, Foraging Activity, and Pollen Diet in Coffee Agroecosystems. *Agric. Ecosyst. Environ.* **2023**, *353*, doi:10.1016/j.agee.2023.108552.
50. Murrieta-Galindo, R.; González-Romero, A.; López-Barrera, F.; Parra-Olea, G. Coffee Agrosystems: An Important Refuge for Amphibians in Central Veracruz, Mexico. *Agrofor. Syst.* **2013**, *87*, 767–779, doi:10.1007/s10457-013-9595-z.
51. Ríos-Orjuela, J.C.; Falcón-Espitia, N.; Arias-Escobar, A.; Plazas-Cardona, D. Conserving Biodiversity in Coffee Agroecosystems: Insights from a Herpetofauna Study in the Colombian Andes with Sustainable Management Proposal. *Perspect. Ecol. Conserv.* **2024**, *22*, 196–204, doi:10.1016/j.pecon.2024.04.001.
52. Sternhagen, E.C.; Black, K.L.; Hartmann, E.D.L.; Shivega, W.G.; Johnson, P.G.; McGlynn, R.D.; Schmaltz, L.C.; Asheim Keller, R.J.; Vink, S.N.; Aldrich-Wolfe, L. Contrasting Patterns of Functional Diversity in Coffee Root Fungal Communities Associated with Organic and Conventionally Managed Fields. *Appl Environ Microbiol* **2020**, *86*, doi:10.1128/AEM.00052-20.
53. Caldwell, A.C.; Silva, L.C.F.; Da Silva, C.C.; Ouverney, C.C. Prokaryotic Diversity in the Rhizosphere of Organic, Intensive, and Transitional Coffee Farms in Brazil. *PLoS ONE* **2015**, *10*, doi:10.1371/journal.pone.0106355.
54. Carrasco-Espinosa, K.; Avitia, M.; Barrón-Sandoval, A.; Abbruzzini, T.F.; Salazar Cabrera, U.I.; Arroyo-Lambaer, D.; Uscanga, A.; Campo, J.; Benítez, M.; Wegier, A.; et al. Land-Use Change and Management

Intensification Is Associated with Shifts in Composition of Soil Microbial Communities and Their Functional Diversity in Coffee Agroecosystems. *Microorg.* **2022**, *10*, doi:10.3390/microorganisms10091763.

55. Libert Amico, A.; Ituarte-Lima, C.; Elmqvist, T. Learning from Social–Ecological Crisis for Legal Resilience Building: Multi-Scale Dynamics in the Coffee Rust Epidemic. *Sustainability Science* **2020**, *15*, 485–501, doi:10.1007/s11625-019-00703-x.
56. Bedoya-Durán, M.J.; Jones, H.H.; Malone, K.M.; Branch, L.C. Continuous Forest at Higher Elevation Plays a Key Role in Maintaining Bird and Mammal Diversity across an Andean Coffee-Growing Landscape. *Anim. Conserv.* **2023**, *26*, 714–728, doi:10.1111/acv.12857.
57. De Beenhouwer, M.; Aerts, R.; Honnay, O. A Global Meta-Analysis of the Biodiversity and Ecosystem Service Benefits of Coffee and Cacao Agroforestry. *Agric. Ecosyst. Environ.* **2013**, *175*, 1–7, doi:10.1016/j.agee.2013.05.003.
58. Chandler, R.B.; King, D.I.; Raudales, R.; Trubey, R.; Chandler, C.; Arce Chávez, V.J. A Small-Scale Land-Sparing Approach to Conserving Biological Diversity in Tropical Agricultural Landscapes. *Conserv. Biol.* **2013**, *27*, 785–795, doi:10.1111/cobi.12046.
59. Molina-Monteleón, C.M.; Mauricio-Gutiérrez, A.; Castelán-Vega, R.; Tamariz-Flores, J.V. Importance of Soil Health for Coffea Spp. Cultivation from a Cooperative Society in Puebla, Mexico. *Land* **2024**, *13*, doi:10.3390/land13040541.
60. Tully, K.L.; Wood, S.A.; Lawrence, D. Fertilizer Type and Species Composition Affect Leachate Nutrient Concentrations in Coffee Agroecosystems. *Agroforestry Systems* **2013**, *87*, 1083–1100, doi:10.1007/s10457-013-9622-0.
61. Souza, H.N.D.; de Goede, R.G.M.; Brussaard, L.; Cardoso, I.M.; Duarte, E.M.G.; Fernandes, R.B.A.; Gomes, L.C.; Pulleman, M.M. Protective Shade, Tree Diversity and Soil Properties in Coffee Agroforestry Systems in the Atlantic Rainforest Biome. *Agric. Ecosyst. Environ.* **2012**, *146*, 179–196, doi:10.1016/j.agee.2011.11.007.
62. Tully, K.L.; Lawrence, D.; Scanlon, T.M. More Trees Less Loss: Nitrogen Leaching Losses Decrease with Increasing Biomass in Coffee Agroforests. *Agric. Ecosyst. Environ.* **2012**, *161*, 137–144, doi:10.1016/j.agee.2012.08.002.
63. Sauvadet, M.; den Meersche, K.V.; Allinne, C.; Gay, F.; de Melo Virginio Filho, E.; Chauvat, M.; Becquer, T.; Tixier, P.; Harmand, J.-M. Shade Trees Have Higher Impact on Soil Nutrient Availability and Food Web in Organic than Conventional Coffee Agroforestry. *Sci. Total Environ.* **2019**, *649*, 1065–1074, doi:10.1016/j.scitotenv.2018.08.291.
64. Babbar, L.I.; Zak, D.R. Nitrogen Loss from Coffee Agroecosystems in Costa Rica: Leaching and Denitrification in the Presence and Absence of Shade Trees. *J. ENVIRON. QUAL.* **1995**, *24*, 227–233, doi:10.2134/jeq1995.00472425002400020003x.
65. Cerretelli, S.; Castellanos, E.; González-Mollinedo, S.; Lopez, E.; Ospina, A.; Haggar, J. A Scenario Modelling Approach to Assess Management Impacts on Soil Erosion in Coffee Systems in Central America. *Catena* **2023**, *228*, doi:10.1016/j.catena.2023.107182.
66. Lozano-Baez, S.E.; Domínguez-Haydar, Y.; Di Prima, S.; Cooper, M.; Castellini, M. Shade-Grown Coffee in Colombia Benefits Soil Hydraulic Conductivity. *Sustainability* **2021**, *13*, doi:10.3390/su13147768.
67. Gómez-Delgado, F.; Roupsard, O.; Le Maire, G.; Taugourdeau, S.; Pérez, A.; Van Oijen, M.; Vaast, P.; Rapidel, B.; Harmand, J.M.; Voltz, M.; et al. Modelling the Hydrological Behaviour of a Coffee Agroforestry Basin in Costa Rica. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 369–392, doi:10.5194/hess-15-369-2011.
68. López-Ramírez, S.M.; Sáenz, L.; Mayer, A.; Muñoz-Villers, L.E.; Asbjornsen, H.; Berry, Z.C.; Looker, N.; Manson, R.; Gómez-Aguilar, L.R. Land Use Change Effects on Catchment Streamflow Response in a Humid Tropical Montane Cloud Forest Region, Central Veracruz, Mexico. *Hydrol. Processes* **2020**, *34*, 3555–3570, doi:10.1002/hyp.13800.
69. Noriega-Puglisevich, J.A.; Eckhardt, K.I. Hydrological Effects of the Conversion of Tropical Montane Forest to Agricultural Land in the Central Andes of Peru. *Environ. Qual. Manage.* **2024**, doi:10.1002/tqem.22221.
70. Gomez, J.; Alburqueque, G.; Ramos, E.; Raymundo, C. An Order Fulfillment Model Based on Lean Supply Chain: Coffee's Case Study in Cusco, Peru. *Adv. Intell. Sys. Comput.* **2020**, *1026*, 922–928, doi:10.1007/978-3-030-27928-8_138.

71. Padovan, M.P.; Brook, R.M.; Barrios, M.; Cruz-Castillo, J.B.; Vilchez-Mendoza, S.J.; Costa, A.N.; Rapidel, B. Water Loss by Transpiration and Soil Evaporation in Coffee Shaded by Tabebuia Rosea Bertol. and Simarouba Glauca Dc. Compared to Unshaded Coffee in Sub-Optimal Environmental Conditions. *Agric. For. Meterol.* **2018**, *248*, 1–14, doi:10.1016/j.agrformet.2017.08.036.
72. Zaro, G.C.; Caramori, P.H.; Wrege, M.S.; Caldana, N.F.D.S.; Filho, J.S.D.V.; Morais, H.; Junior, G.M.Y.; Caramori, D.C. Coffee Crops Adaptation to Climate Change in Agroforestry Systems with Rubber Trees in Southern Brazil. *Sci. Agric.* **2022**, *80*, doi:10.1590/1678-992X-2021-0142.
73. Coltri, P.P.; Pinto, H.S.; Gonçalves, R.R.D.V.; Zullo Junior, J.; Dubreuil, V. Low Levels of Shade and Climate Change Adaptation of Arabica Coffee in Southeastern Brazil. *Heliyon* **2019**, *5*, doi:10.1016/j.heliyon.2019.e01263.
74. Lin, B.B. Agroforestry Management as an Adaptive Strategy against Potential Microclimate Extremes in Coffee Agriculture. *Agric. For. Meterol.* **2007**, *144*, 85–94, doi:10.1016/j.agrformet.2006.12.009.
75. Philpott, S.M.; Lin, B.B.; Jha, S.; Brines, S.J. A Multi-Scale Assessment of Hurricane Impacts on Agricultural Landscapes Based on Land Use and Topographic Features. *Agric. Ecosyst. Environ.* **2008**, *128*, 12–20, doi:10.1016/j.agee.2008.04.016.
76. Mayorga, I.; Vargas de Mendonça, J.L.; Hajian-Forooshani, Z.; Lugo-Perez, J.; Perfecto, I. Tradeoffs and Synergies among Ecosystem Services, Biodiversity Conservation, and Food Production in Coffee Agroforestry. *Front. For. Glob. Change* **2022**, *5*, doi:10.3389/ffgc.2022.690164.
77. Perfecto, I.; Hajian-Forooshani, Z.; Iverson, A.; Irizarry, A.D.; Lugo-Perez, J.; Medina, N.; Vaidya, C.; White, A.; Vandermeer, J. Response of Coffee Farms to Hurricane Maria: Resistance and Resilience from an Extreme Climatic Event. *Sci. Rep.* **2019**, *9*, 15668, doi:10.1038/s41598-019-51416-1.
78. Irizarry, A.D.; Collazo, J.A.; Vandermeer, J.; Perfecto, I. Coffee Plantations, Hurricanes and Avian Resiliency: Insights from Occupancy, and Local Colonization and Extinction Rates in Puerto Rico. *Glob. Ecol. Conserv.* **2021**, *27*, doi:10.1016/j.gecco.2021.e01579.
79. Moreaux, C.; Meireles, D.A.L.; Sonne, J.; Badano, E.I.; Classen, A.; González-Chaves, A.; Hipólito, J.; Klein, A.-M.; Maruyama, P.K.; Metzger, J.P.; et al. The Value of Biotic Pollination and Dense Forest for Fruit Set of *Arabica* Coffee: A Global Assessment. *Agriculture, Ecosystems & Environment* **2022**, *323*, 107680, doi:10.1016/j.agee.2021.107680.
80. Latini, A.O.; Silva, D.P.; Souza, F.M.L.; Ferreira, M.C.; Moura, M.S.D.; Suarez, N.F. Reconciling Coffee Productivity and Natural Vegetation Conservation in an Agroecosystem Landscape in Brazil. *J. Nat. Conserv.* **2020**, *57*, doi:10.1016/j.jnc.2020.125902.
81. Pereira Machado, A.C.; Baronio, G.J.; Soares Novaes, C.; Ollerton, J.; Wolowski Torres, M.; Natalina Silva Lopes, D.; Rech, A.R. Optimizing Coffee Production: Increased Floral Visitation and Bean Quality at Plantation Edges with Wild Pollinators and Natural Vegetation. *J. Appl. Ecol.* **2024**, *61*, 465–475, doi:10.1111/1365-2664.14591.
82. Karp, D.S.; Mendenhall, C.D.; Sandí, R.F.; Chaumont, N.; Ehrlich, P.R.; Hadly, E.A.; Daily, G.C. Forest Bolsters Bird Abundance, Pest Control and Coffee Yield. *Ecol. Lett.* **2013**, *16*, 1339–1347, doi:10.1111/ele.12173.
83. Koutouleas, A.; Collinge, D.B.; Ræbild, A. Alternative Plant Protection Strategies for Tomorrow's Coffee. *Plant Pathology* **2023**, *72*, 409–429, doi:10.1111/ppa.13676.
84. Moreno-Ramirez, N.; Bianchi, F.J.J.A.; Manzano, M.R.; Dicke, M. Ecology and Management of the Coffee Berry Borer (Hypothenemus Hampei): The Potential of Biological Control. *BioControl* **2024**, *69*, 199–214, doi:10.1007/s10526-024-10253-6.
85. Cerda, R.; Avelino, J.; Harvey, C.A.; Gary, C.; Tixier, P.; Allinne, C. Coffee Agroforestry Systems Capable of Reducing Disease-Induced Yield and Economic Losses While Providing Multiple Ecosystem Services. *Crop Prot.* **2020**, *134*, doi:10.1016/j.cropro.2020.105149.
86. Piato, K.; Subía, C.; Pico, J.; Calderón, D.; Norgrove, L.; Lefort, F. Organic Farming Practices and Shade Trees Reduce Pest Infestations in Robusta Coffee Systems in Amazonia. *Life (Basel)* **2021**, *11*, doi:10.3390/life11050413.

87. Hajian-Forooshani, Z.; Salinas, I.S.R.; Jiménez-Soto, E.; Perfecto, I.; Vandermeer, J. Impact of Regionally Distinct Agroecosystem Communities on the Potential for Autonomous Control of the Coffee Leaf Rust. *Environ. Entomol.* **2016**, *45*, 1521–1526, doi:10.1093/ee/nvw125.
88. Piato, K.; Subía, C.; Lefort, F.; Pico, J.; Calderón, D.; Norgrove, L. No Reduction in Yield of Young Robusta Coffee When Grown under Shade Trees in Ecuadorian Amazonia. *Life (Basel)* **2022**, *12*, doi:10.3390/life12060807.
89. Rossi, E.; Montagnini, F.; de Melo Virginio Filho, E. Effects of Management Practices on Coffee Productivity and Herbaceous Species Diversity in Agroforestry Systems in Costa Rica. In *Agroforestry as a Tool for Landscape Restoration*; Nova Science Publishers, Inc., 2011; pp. 113–132 ISBN 978-161728940-8.
90. Capa, D.; Pérez-Esteban, J.; Masaguer, A. Unsustainability of Recommended Fertilization Rates for Coffee Monoculture Due to High N2O Emissions. *Agron. Sustainable Dev.* **2015**, *35*, 1551–1559, doi:10.1007/s13593-015-0316-z.
91. Martínez-Salinas, A.; Chain-Guadarrama, A.; Aristizábal, N.; Vilchez-Mendoza, S.; Cerda, R.; Ricketts, T.H. Interacting Pest Control and Pollination Services in Coffee Systems. *Proc Natl Acad Sci U S A* **2022**, *119*, e2119959119, doi:10.1073/pnas.2119959119.
92. Pronti, A.; Coccia, M. Agroecological and Conventional Agricultural Systems: Comparative Analysis of Coffee Farms in Brazil for Sustainable Development. *Int. J. Sustainable Dev.* **2020**, *23*, 223–248, doi:10.1504/IJSD.2020.115223.
93. Sporchia, F.; Taherzadeh, O.; Caro, D. Stimulating Environmental Degradation: A Global Study of Resource Use in Cocoa, Coffee, Tea and Tobacco Supply Chains. *Curr. Res. Environ. Sustain.* **2021**, *3*, doi:10.1016/j.crsust.2021.100029.
94. Pendrill, F.; Persson, U.M.; Kastner, T. Deforestation Risk Embodied in Production and Consumption of Agricultural and Forestry Commodities 2005-2017 2020.
95. Economic Commission for Latin America and the Caribbean (ECLAC). *Forest Loss in Latin America and the Caribbean from 1990 to 2020: The Statistical Evidence.*; ECLAC Statistical Briefings; 2021.
96. FAO. *State of the World's Forests, 1997*; Words and Publications: Oxford, UK, 1997; ISBN 92-5-103977-1.
97. Pendrill, F.; Persson, U.M.; Godar, J.; Kastner, T. Deforestation Displaced: Trade in Forest-Risk Commodities and the Prospects for a Global Forest Transition. *Environ. Res. Lett.* **2019**, *14*, 055003, doi:10.1088/1748-9326/ab0d41.
98. Perfecto, I.; Rice, R.A.; Greenberg, R.; Van der Voort, M.E. Shade Coffee: A Disappearing Refuge for Biodiversity: Shade Coffee Plantations Can Contain as Much Biodiversity as Forest Habitats. *BioScience* **1996**, *46*, 598–608, doi:10.2307/1312989.
99. Bass, J.O.J. Forty Years and More Trees: Land Cover Change and Coffee Production in Honduras. *Southeast. Geogr.* **2006**, *46*, 51–65, doi:10.1353/sgo.2006.0002.
100. Usva, K.; Sinkko, T.; Silvenius, F.; Riipi, I.; Heusala, H. Carbon and Water Footprint of Coffee Consumed in Finland—Life Cycle Assessment. *Int. J. Life Cycle Assess.* **2020**, *25*, 1976–1990, doi:10.1007/s11367-020-01799-5.
101. Martins, L.D.; Eugenio, F.C.; Rodrigues, W.N.; Tomaz, M.A.; dos Santos, A.R.; Ramalho, J.C. Carbon and Water Footprints in Brazilian Coffee Plantations - the Spatial and Temporal Distribution. *Emirates J. Food Agric.* **2018**, *30*, 482–487, doi:10.9755/ejfa.2018.v30.i6.1718.
102. Arellano, C.; Hernández, C. Carbon Footprint and Carbon Storing Capacity of Arabica Coffee Plantations of Central America: A Review. *Coffee Sci.* **2023**, *18*, doi:10.25186/.v18i.2072.
103. International Coffee Organization (ICO). *Rules on Statistics Statistical Reports.* 2011.
104. van Rikxoort, H.; Schroth, G.; Läderach, P.; Rodríguez-Sánchez, B. Carbon Footprints and Carbon Stocks Reveal Climate-Friendly Coffee Production. *Agron. Sustain. Dev.* **2014**, *34*, 887–897, doi:10.1007/s13593-014-0223-8.
105. Acosta-Alba, I.; Boissy, J.; Chia, E.; Andrieu, N. Integrating Diversity of Smallholder Coffee Cropping Systems in Environmental Analysis. *Int. J. Life Cycle Assess.* **2020**, *25*, 252–266, doi:10.1007/s11367-019-01689-5.
106. Coltro, L.; Tavares, M.P.; Sturaro, K.B.F.S. Life Cycle Assessment of Conventional and Organic Arabica Coffees: From Farm to Pack. *Int. J. Life Cycle Assess.* **2024**, *29*, 1672–1687, doi:10.1007/s11367-024-02317-7.

107. Calvillo-Arriola, A.E.; Sotelo-Navarro, P.X. A Step towards Sustainability: Life Cycle Assessment of Coffee Produced in the Indigenous Community of Ocotepec, Chiapas, Mexico. *Discov Sustain* **2024**, *5*, doi:10.1007/s43621-024-00194-6.
108. Quiñones-Huatangari, L.; Fernandez-Zarate, F.H.; Huaccha-Castillo, A.E. Nitrous Oxide Emissions Generated in Coffee Cultivation: A Systematic Review. *Nat. Environ. Pollut. Technol.* **2022**, *21*, 1697–1703, doi:10.46488/NEPT.2022.v21i04.023.
109. Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F.S.; Lambin, E.F.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. A Safe Operating Space for Humanity. *Nature* **2009**, *461*, 472–475, doi:10.1038/461472a.
110. Vázquez, G.; Aké-Castillo, J.A.; Favila, M.E. Algal Assemblages and Their Relationship with Water Quality in Tropical Mexican Streams with Different Land Uses. *Hydrobiologia* **2011**, *667*, 173–189, doi:10.1007/s10750-011-0633-4.
111. de Jesús Crespo, R.; Douthat, T.; Pringle, C. Stream Friendly Coffee: Evaluating the Impact of Coffee Farming on High-Elevation Streams of the Tarrazú Coffee Region of Costa Rica. *Hydrobiologia* **2020**, *847*, 1903–1923, doi:10.1007/s10750-020-04221-1.
112. Olguín, E.J.; Sánchez, G.; Mercado, G. Cleaner Production and Environmentally Sound Biotechnology for the Prevention of Upstream Nutrient Pollution in the Mexican Coast of the Gulf of México. *Ocean Coast. Manage.* **2004**, *47*, 641–670, doi:10.1016/j.ocecoaman.2004.12.006.
113. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; De Vries, W.; De Wit, C.A.; et al. Planetary Boundaries: Guiding Human Development on a Changing Planet. *Science* **2015**, *347*, 1259855, doi:10.1126/science.1259855.
114. Chapagain, A.K.; Hoekstra, A.Y. The Water Footprint of Coffee and Tea Consumption in the Netherlands. *Ecol. Econ.* **2007**, *64*, 109–118, doi:10.1016/j.ecolecon.2007.02.022.
115. Leal-Echeverri, J.C.; Tobón, C. The Water Footprint of Coffee Production in Colombia. *Rev. Fac. Nac. Agron. Medellín* **2021**, *74*, 9685–9697, doi:10.15446/rfnam.v74n3.91461.
116. de Queiroz, V.T.; Azevedo, M.M.; da Silva Quadros, I.P.; Costa, A.V.; do Amaral, A.A.; dos Santos, G.M.A.D.A.; Juvanhol, R.S.; de Almeida Telles, L.A.; dos Santos, A.R. Environmental Risk Assessment for Sustainable Pesticide Use in Coffee Production. *J. Contam. Hydrol.* **2018**, 18–27, doi:10.1016/j.jconhyd.2018.08.008.
117. García Ríos, A.; Martínez, A.S.; Londoño, Á.L.; Restrepo, B.; Landázuri, P. Determination of Organochlorine and Organophosphorus Residues in Surface Waters from the Coffee Zone in Quindío, Colombia. *J. Environ. Sci. Health Part B Pestic. Food Contamin. Agric. Wastes* **2020**, *55*, 968–973, doi:10.1080/03601234.2020.1802185.
118. Coltro, L.; Mourad, A.L.; Oliveira, P.A.P.L.V.; Baddini, J.P.O.A.; Kletecke, R.M. Environmental Profile of Brazilian Green Coffee. *Int. J. Life Cycle Assess.* **2006**, *11*, 16–21, doi:10.1065/lca2006.01.230.
119. Londoño, Á.L.; Restrepo, B.; Sánchez, J.F.; García-Ríos, A.; Bayona, A.; Landázuri, P. Pesticides and Hypothyroidism in Farmers of Plantain and Coffee Growing Areas in Quindío, Colombia. *Rev. Salud Publica* **2018**, *20*, 215–220, doi:10.15446/rsap.v20n2.57694.
120. Merhi, A.; Kordahi, R.; Hassan, H.F. A Review on the Pesticides in Coffee: Usage, Health Effects, Detection, and Mitigation. *Front Public Health* **2022**, *10*, 1004570, doi:10.3389/fpubh.2022.1004570.
121. PAN International. PAN International List of Highly Hazardous Pesticides; 2021.
122. Palomino-García, L.R.; Vargas-Vásquez, M.L. Identification of Hazards and Assessment of Risks Associated with the Harvesting of Coffee. *Puerto Rico Health Sci. J.* **2023**, *42*, 43–49.
123. Hutter, H.-P.; Khan, A.W.; Lemmerer, K.; Wallner, P.; Kundi, M.; Moshammer, H. Cytotoxic and Genotoxic Effects of Pesticide Exposure in Male Coffee Farmworkers of the Jarabacoa Region, Dominican Republic. *Int. J. Environ. Res. Public Health* **2018**, *15*, doi:10.3390/ijerph15081641.
124. Moshammer, H.; Poteser, M.; Hutter, H.-P. More Pesticides—Less Children? *Wien. Klin. Wochenschr.* **2020**, *132*, 197–204, doi:10.1007/s00508-019-01566-z.
125. Bedoya P., S.; García R., A.; Londoño F., A.L.; Restrepo C., B. Determination of Organochlorine Pesticide Residues In Serum of Coffee and Banana Growers in the Departament of Quindío by Gc-Mecd. *Rev. Colomb. Quim.* **2014**, *43*, 11–16, doi:10.15446/rev.colomb.quim.v43n3.53588.

126. Bolognesi, C.; Carrasquilla, G.; Volpi, S.; Solomon, K.R.; Marshall, E.J.P. Biomonitoring of Genotoxic Risk in Agricultural Workers from Five Colombian Regions: Association to Occupational Exposure to Glyphosate. *J. Toxicol. Environ. Health Part A Curr. Iss.* **2009**, *72*, 986–997, doi:10.1080/15287390902929741.
127. Reichert, B.; de Kok, A.; Pizzutti, I.R.; Scholten, J.; Cardoso, C.D.; Spanjer, M. Simultaneous Determination of 117 Pesticides and 30 Mycotoxins in Raw Coffee, without Clean-up, by LC-ESI-MS/MS Analysis. *Anal Chim Acta* **2018**, *1004*, 40–50, doi:10.1016/j.aca.2017.11.077.
128. Estrada-Muñoz, C.; Madrid-Casaca, H.; Salazar-Sepúlveda, G.; Contreras-Barraza, N.; Iturra-González, J.; Vega-Muñoz, A. Musculoskeletal Symptoms and Assessment of Ergonomic Risk Factors on a Coffee Farm. *Appl. Sci.* **2022**, *12*, doi:10.3390/app12157703.
129. Jimenez-Soto, E. The Political Ecology of Shaded Coffee Plantations: Conservation Narratives and the Everyday-Lived-Experience of Farmworkers. *The Journal of Peasant Studies* **2021**, *48*, 1284–1303, doi:10.1080/03066150.2020.1713109.
130. Mise, Y.F.; Lira-da-Silva, R.M.; Carvalho, F.M. Agriculture and Snakebite in Bahia, Brazil – An Ecological Study. *Ann. Agric. Environ. Med.* **2016**, *23*, 416–419, doi:10.5604/12321966.1219179.
131. Ocampo, C.B.; Ferro, M.C.; Cadena, H.; Gongora, R.; Pérez, M.; Valderrama-Ardila, C.H.; Quinnell, R.J.; Alexander, N. Environmental Factors Associated with American Cutaneous Leishmaniasis in a New Andean Focus in Colombia. *Trop. Med. Int. Health* **2012**, *17*, 1309–1317, doi:10.1111/j.1365-3156.2012.03065.x.
132. Alexander, B.; Agudelo, L.A.; Navarro, J.F.; Ruiz, J.F.; Molina, J.; Aguilera, G.; Klein, A.; Quiñones, M.L. Relationship between Coffee Cultivation Practices in Colombia and Exposure to Infection with Leishmania. *Trans. R. Soc. Trop. Med. Hyg.* **2009**, *103*, 1263–1268, doi:10.1016/j.trstmh.2009.04.018.
133. Rice, R.A. Agricultural Intensification within Agroforestry: The Case of Coffee and Wood Products. *Agric. Ecosyst. Environ.* **2008**, *128*, 212–218, doi:10.1016/j.agee.2008.06.007.
134. Rice, R.A. Fruits from Shade Trees in Coffee: How Important Are They? *Agrofor. Syst.* **2011**, *83*, 41–49, doi:10.1007/s10457-011-9385-4.
135. Méndez, V.E.; Bacon, C.M.; Olson, M.; Morris, K.S.; Shattuck, A. Agrobiodiversity and Shade Coffee Smallholder Livelihoods: A Review and Synthesis of Ten Years of Research in Central America. *The Professional Geographer* **2010**, *62*, 357–376, doi:10.1080/00330124.2010.483638.
136. Morris, K.S.; Mendez, V.E.; Olson, M.B. “Los Meses Flacos”: Seasonal Food Insecurity in a Salvadoran Organic Coffee Cooperative. *J. Peasant Stud.* **2013**, *40*, 423–446, doi:10.1080/03066150.2013.777708.
137. Lopez-Ridaura, S.; Barba-Escoto, L.; Reyna, C.; Hellin, J.; Gerard, B.; van Wijk, M. Food Security and Agriculture in the Western Highlands of Guatemala. *Food Secur.* **2019**, *11*, 817–833, doi:10.1007/s12571-019-00940-z.
138. Bacon, C.M.; Sundstrom, W.A.; Flores Gómez, M.E.; Ernesto Méndez, V.; Santos, R.; Goldoftas, B.; Dougherty, I. Explaining the “Hungry Farmer Paradox”: Smallholders and Fair Trade Cooperatives Navigate Seasonality and Change in Nicaragua’s Corn and Coffee Markets. *Global Environ. Change* **2014**, *25*, 133–149, doi:10.1016/j.gloenvcha.2014.02.005.
139. Soto-Pinto, L.; Colmenares, S.E.; Kanter, M.B.; Cruz, A.L.; Lugo, E.E.; Hernández, B.H.; Jiménez-Soto, E. Contributions of Agroforestry Systems to Food Provisioning of Peasant Households: Conflicts and Synergies in Chiapas, Mexico. *Front. Sustain. Food Syst.* **2022**, *5*, doi:10.3389/fsufs.2021.756611.
140. Rodriguez-Camayo, F.; Lundy, M.; Borgemeister, C.; Ramirez-Villegas, J.; Beuchelt, T. Local Food System and Household Responses to External Shocks: The Case of Sustainable Coffee Farmers and Their Cooperatives in Western Honduras during COVID-19. *Front. Sustain. food Syst.* **2024**, *8*, doi:10.3389/fsufs.2024.1304484.
141. van Asselt, J.; Useche, P. Agricultural Commercialization and Nutrition; Evidence from Smallholder Coffee Farmers. *World Dev.* **2022**, *159*, doi:10.1016/j.worlddev.2022.106021.
142. González, M.A.; Dennis, R.J.; Devia, J.H.; Echeverri, D.; Briceño, G.D.; Gil, F.; Jurado, A.; Mora, M. Risk Factors for Cardiovascular and Chronic Diseases in a Coffee-Growing Population. *Rev. Salud Publica* **2013**, *14*, 390–401.
143. Dupre, S.I.; Harvey, C.A.; Holland, M.B. The Impact of Coffee Leaf Rust on Migration by Smallholder Coffee Farmers in Guatemala. *World Dev.* **2022**, *156*, doi:10.1016/j.worlddev.2022.105918.

144. USAID. Monitoring & Evaluation Support for Collaborative Learning and Adapting - Climate Change, Food Security, and Migration Briefer. 2021.
145. Nava-Tablada, M.E. International Migration and Coffee Production in Veracruz, Mexico. *Migraciones Int.* **2012**, *6*, 139–171.
146. Reichman, D.R. Putting Climate-Induced Migration in Context: The Case of Honduran Migration to the USA. *Reg Environ Change* **2022**, *22*, 91, doi:10.1007/s10113-022-01946-8.
147. Bermeo, S.; Leblang, D. Honduras Migration: Climate Change, Violence, & Assistance. Policy Brief. *Duke Univ. Cent. Int. Dev* **2021**.
148. Dube, O.; Vargas, J.F. Commodity Price Shocks and Civil Conflict: Evidence from Colombia. *Rev. Econ. Stud.* **2013**, *80*, 1384–1421, doi:10.1093/restud/rdt009.
149. Chavez-Miguel, G.; Bonatti, M.; Ácevedo-Osorio, Á.; Sieber, S.; Löhr, K. Agroecology as a Grassroots Approach for Environmental Peacebuilding Strengthening Social Cohesion and Resilience in Post-Conflict Settings with Community-Based Natural Resource Management. *GAIA - Ecological Perspectives for Science and Society* **2022**, *31*, 36–45, doi:10.14512/GAIA.31.1.9.
150. Pineda, J.A.; Piniero, M.; Ramírez, A. Coffee Production and Women's Empowerment in Colombia. *Hum. Organ.* **2019**, *78*, 64–74, doi:10.17730/0018-7259.78.1.64.
151. Lyon, S.; Mutersbaugh, T.; Worthen, H. The Triple Burden: The Impact of Time Poverty on Women's Participation in Coffee Producer Organizational Governance in Mexico. *Agric. Hum. Values* **2017**, *34*, 317–331, doi:10.1007/s10460-016-9716-1.
152. Juárez-López, B.M.; Velázquez-Rosas, N.; López-Binnqüist, C. Tree Diversity and Uses in Coffee Plantations of a Mixe Community in Oaxaca, Mexico. *J. Ethnobiology* **2017**, *37*, 765–778, doi:10.2993/0278-0771-37.4.765.
153. Pascual-Mendoza, S.; Manzanero-Medina, G.I.; Saynes-Vásquez, A.; Vásquez-Dávila, M.A. Agroforestry Systems of a Zapotec Community in the Northern Sierra of Oaxaca, Mexico. *Bot. Sci.* **2020**, *98*, 128–144, doi:10.17129/BOTSCI.2423.
154. Soto-Pinto, L.; Romero-Alvarado, Y.; Caballero-Nieto, J.; Warnholtz, G.S. Woody Plant Diversity and Structure of Shade-Grown-Coffee Plantations in Northern Chiapas, Mexico. *Rev. Biol. Trop.* **2001**, *49*, 977–987.
155. Murillo-López, B.E.; Castro, A.J.; Feijoo-Martínez, A. Nature's Contributions to People Shape Sense of Place in the Coffee Cultural Landscape of Colombia. *Agric.* **2022**, *12*, doi:10.3390/agriculture12040457.
156. Gasperín-García, E.M.; Platas-Rosado, D.E.; Zetina-Córdoba, P.; Vilaboa-Arroniz, J.; Dávila, F.M. Quality of Life of Coffee Growers in the High Mountains of Veracruz, Mexico. *Agron. Mesoam.* **2023**, *34*, doi:10.15517/am.v34i1.50163.
157. Lima, J.; Rossini, S.; Reimão, R. Sleep Disorders and Quality of Life of Harvesters Rural Labourers. *Arq Neuropsiquiatr* **2010**, *68*, 372–376, doi:10.1590/s0004-282x2010000300008.
158. Salvi, R.M.; Lara, D.R.; Ghisolfi, E.S.; Portela, L.V.; Dias, R.D.; Souza, D.O. Neuropsychiatric Evaluation in Subjects Chronically Exposed to Organophosphate Pesticides. *Toxicol Sci* **2003**, *72*, 267–271, doi:10.1093/toxsci/kfg034.
159. Hansson, E.; Mansourian, A.; Farnaghi, M.; Petzold, M.; Jakobsson, K. An Ecological Study of Chronic Kidney Disease in Five Mesoamerican Countries: Associations with Crop and Heat. *BMC Public Health* **2021**, *21*, 840, doi:10.1186/s12889-021-10822-9.
160. Laux, T.S.; Bert, P.J.; Ruiz, G.M.B.; González, M.; Unruh, M.; Aragon, A.; Lacourt, C.T. Nicaragua Revisited: Evidence of Lower Prevalence of Chronic Kidney Disease in a High-Altitude, Coffee-Growing Village. *J. Nephrol.* **2012**, *25*, 533–540, doi:10.5301/jn.5000028.
161. Peraza, S.; Wesseling, C.; Aragon, A.; Leiva, R.; García-Trabanino, R.A.; Torres, C.; Jakobsson, K.; Elinder, C.G.; Hogstedt, C. Decreased Kidney Function among Agricultural Workers in El Salvador. *Am. J. Kidney Dis.* **2012**, *59*, 531–540, doi:10.1053/j.ajkd.2011.11.039.
162. Schaeffer, J.W.; Adgate, J.L.; Reynolds, S.J.; Butler-Dawson, J.; Krisher, L.; Dally, M.; Johnson, R.J.; James, K.A.; Jaramillo, D.; Newman, L.S. A Pilot Study to Assess Inhalation Exposures among Sugarcane Workers in Guatemala: Implications for Chronic Kidney Disease of Unknown Origin. *International Journal of Environmental Research and Public Health* **2020**, *17*, 5708, doi:10.3390/ijerph17165708.

163. VanDervort, D.R.; López, D.L.; Orantes, C.M.; Rodríguez, D.S. Spatial Distribution of Unspecified Chronic Kidney Disease in El Salvador by Crop Area Cultivated and Ambient Temperature. *MEDICC Rev.* **2014**, *16*, 31–38, doi:10.37757/mr2014.v16.n2.6.
164. McCune, N.; Luna, Y.; Vandermeer, J.; Perfect, I. Cuestiones Agrarias y Transformaciones Agroecológicas. In *Agroecología y Sistemas Complejos: Planteamientos epistémicos, casos de estudio y enfoques metodológicos*; Benítez, M., Rivera-Núñez, T., García-Barrios, L., Eds.; CopIt ArXives: México CDMX, 2021; pp. 27–50 ISBN 978-1-938128-24-0.
165. Hernandez-Castillo, R.A. Histories and Stories from Chiapas: Border Identities in Southern Mexico.; 1st ed.; University of Texas Press, 2001;
166. González Álvarez, A. La Comunidad Maseual En La Tosepan y La Revitalización de Las Lenguas Originarias; El Proyecto de La Maseualpedia. *La Jornada del campo* 2017.
167. Bremer, L.; al. Chapter 5 - Nature-Based Solutions, Sustainable Development, and Equity. In *Matthews, John H., Cassin, Jan, Lopez-Gunn, Elena, editors. Nature-based Solutions and Water Security*; Elsevier: Amsterdam, Netherlands ; Oxford, England ; Cambridge, Massachusetts, 2021; pp. 81–105 ISBN 978-0-12-819871-1.