

Review

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

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Review

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

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Abstract

In Latin America, coffee is cultivated in distinct coffee agroecosystems (CAS), ranging from traditional agroforestry systems (CAFS) to intensive unshaded 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 examines how different CAS in Latin America affect human and planetary health, applying the Planetary Boundaries framework and structuring results through the DPSEEA (Drivers, Pressures, State, Exposure, Effects, Actions) model to map the relationships between socio-environmental drivers, different CAS, 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, food insecurity, 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; farming; agroforestry; agroecology; planetary health; DPSEEA; planetary boundaries; sustainability; food systems; food security

1. Introduction

Coffee is among the world's most traded tropical commodities, with a global market valued at over US \$200 billion annually (ICO 2020). 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 (FAO 2024). 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 (Scott 2015). It accounts for 56% of global coffee production (USDA, 2023), concentrated in Latin America, East Africa, and the Arabian Peninsula (Myhrvold 2024). 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 (Jha et al. 2014; Pham et al. 2019). Its production is concentrated in Brazil and Vietnam (the world's two largest coffee producers), alongside Southeast Asia and West and Central Africa (Rafferty 2023).

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 (Perfecto et al. 2019b). 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 (Figure 1). A more detailed typology proposed by Moguel & Toledo (1999) further differentiates CAFS according to decreasing vegetation structural complexity, ranging from traditional “rustic” systems (rustic T-CAFS), in which coffee is planted within mature primary forests traditionally managed by indigenous communities; to traditional polycultures (T-CAFS), where coffee is intercropped with other plants for human use under primary forest canopy; to commercial polycultures, where forest cover is replaced by planted shade trees and a limited variety of commercial crops; and finally to shaded monocultures (M-CAFS), dominated by one or a few species of shade trees (Figure 2).

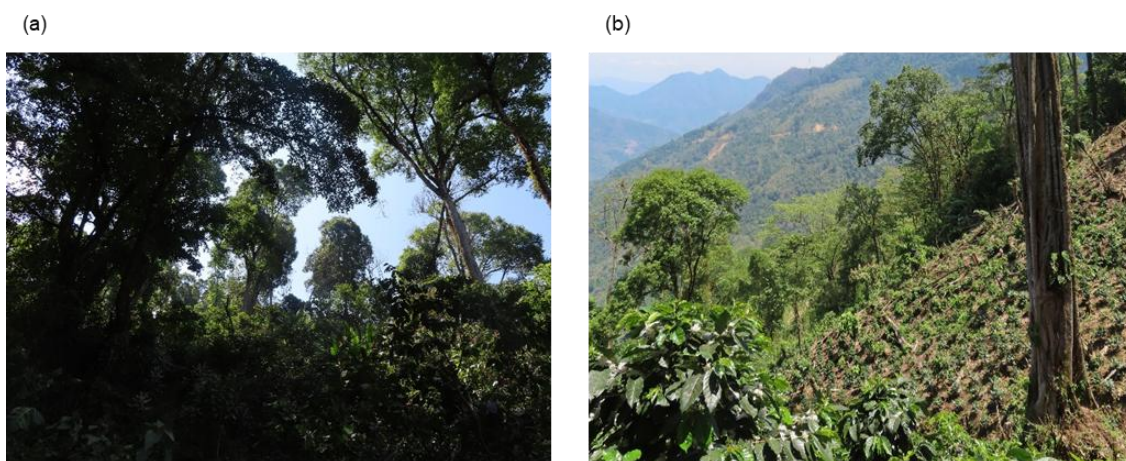


Figure 1. Examples of coffee agroecosystems in Latin America: (a) A traditional coffee agroforestry (“shaded”) system (T-CAFS); and (b) an unshaded (“sun”) coffee agroecosystem (UCAS). Photo credit: Emiliano Hersch González, 2020.

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. (2019b), 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.

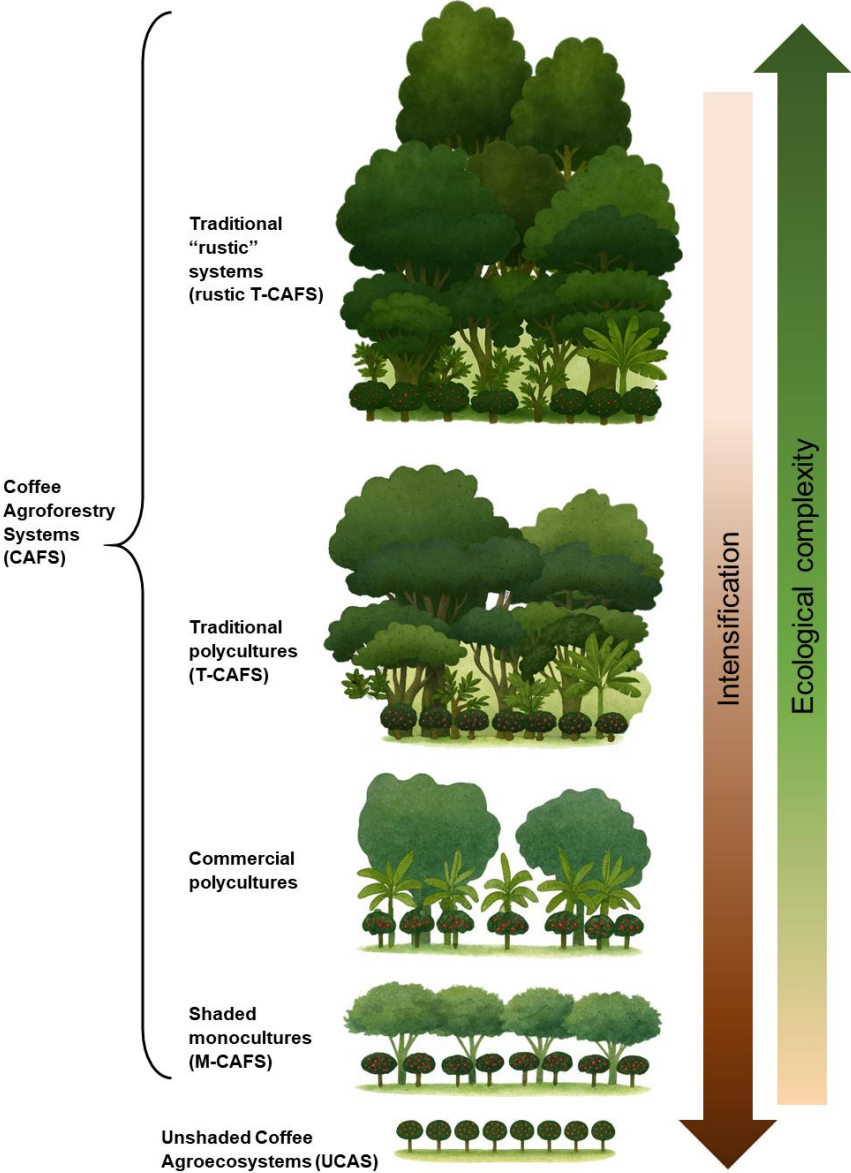


Figure 2. Five categories of CAS across the coffee intensification gradient used in this review. Modified from Moguel & Toledo, 1999.

In recent decades, a growing body of research has documented the positive impacts of multifunctional 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 (Davidson 2004; Toledo and Moguel 2012; Libert-Amico and Paz-Pellat 2018; Perfecto et al. 2019b). 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 (Fernandez and Méndez 2019; Anderzén et al. 2020), pesticide exposure (Conti et al. 2018; Hutter et al. 2018b), and mental health (Nieto-Betancurt et al. 2024).

However, since the 1960s, T-CAFS have undergone widespread intensification in Latin America. Between 1970 and 1990, roughly 50% of T-CAFS in the region were converted to monocultures, and by 2010 only 24% remained (Jha et al. 2014). This trend appears has accelerated in the last decade

¹ NCP: the positive and negative contributions of living nature (i.e., the biosphere) to people’s quality of life (IPBES 2017). The conceptual antecedent of the NCP framework is the *ecosystem services* framework.

(Valencia et al. 2018; Harvey et al. 2021). Despite growing interest, no prior study has synthesized the evidence linking coffee farming under different CAS, natural systems at local and planetary scales, and human health and wellbeing. To map the existing evidence, a literature review was conducted guided by the research question: *what are the impacts of different CAS in Latin America and their transformation on planetary health?* –defined here as the interdependent health of human populations in all its dimensions and the natural systems on which they rely (Whitmee et al. 2015). Different frameworks were integrated to address this question. First, the Planetary Boundaries (PB) framework was used to evaluate the differential impacts of various CAS in Latin America on local and global natural systems. The review then assessed how coffee farming influences human health and its determinants, and identified key leverage points and policy actions needed to support fairer, healthier, and more sustainable coffee systems. Finally, these relationships are integrated using the Drivers-Pressures-State-Exposure-Effect-Action (DPSEEA) framework, synthesizing the links between CAS and planetary health.

This review focuses on Latin America due to the region's shared historical, cultural, and socioeconomic trajectories in coffee cultivation; however, the findings are intended to inform discussions on global food systems and agroecological transitions, and contribute to the identification and promotion of coffee systems that offer co-benefits for planetary health in diverse contexts worldwide.

2. Methods

While not a systematic review, efforts were made to structure and systematize the literature search and screening process. To facilitate integration into DPSEEA, the review was conceptually divided into two complementary streams:

1. D-P-S review: a review of the *Drivers* of CAS management practices and their transformation (*Pressure*), and their impacts of these on the six PB deemed most relevant in coffee farming (*State*): biosphere integrity, land-system change, climate change, biogeochemical flows, novel entities, and freshwater use.
2. S-E-E review: a review of the impacts of the former on the ecosocial determinants of human health (*Exposure*) and health outcomes (*Effect*), particularly among coffee-growing communities and farmers.

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 (DPS review: n=553;1754. SEE review: n=1220;908), After removing 1443 duplicates, 2992 (DPS: 1592; SEE: 1400) 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 was conducted in 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 categorized by topic, study type, main findings reported in the abstract and strength of evidence. Then, in order to identify key literature for evidence mapping and integration within the DPSEEA model, they were sorted by relevance according to scope, thematic representativeness, strength of evidence, and alignment with the PB and DPSEEA frameworks. When multiple studies addressed overlapping topics, the most representative were prioritized, often systematic reviews or meta-analyses. Additional preference was given to studies covering under-researched areas or underrepresented regions. During this process 151 records were pre-selected as key literature. During full-text reading 40 further records were identified by snowballing and targeted thematic searches, and 146 were finally included in this review, including 120 original journal articles, 24 reviews and reports and 2 book chapters. (Figure 3). Evidence was charted and synthesized using the DPSEEA framework, and interpreted in light of the Planetary Health framework, with insights from complex systems and equity perspectives. Mexico, Brazil and Colombia contribute to half (51%) of the reviewed literature (Figure 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 (the SEE elements of DPSEEA).

Table 2. Selection criteria.

Inclusion criteria
1. Peer-reviewed research papers, reviews, and book chapters, and gray literature including reports, policy documents, conference papers, theses, and preprints. 2. Research on Latin American CAS. 3. 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 impacts on PB on the health of human populations and its determinants. 4. Studies that provide key insights in terms of thematic representativeness, strength of evidence, and alignment with the DPSEEA model. 5. Studies published in English or Spanish.
Exclusion criteria:
1. Studies dealing with or based on research carried outside Latin America. 2. Studies that describe ecological impacts of CAS that cannot be classified under at least one of the six PB chosen. 3. Studies that describe health determinants and outcomes of coffee farmers, farmworkers, or coffee-growing communities that cannot be attributed to CAS, their transformations, or the change in at least one of the six PB chosen.

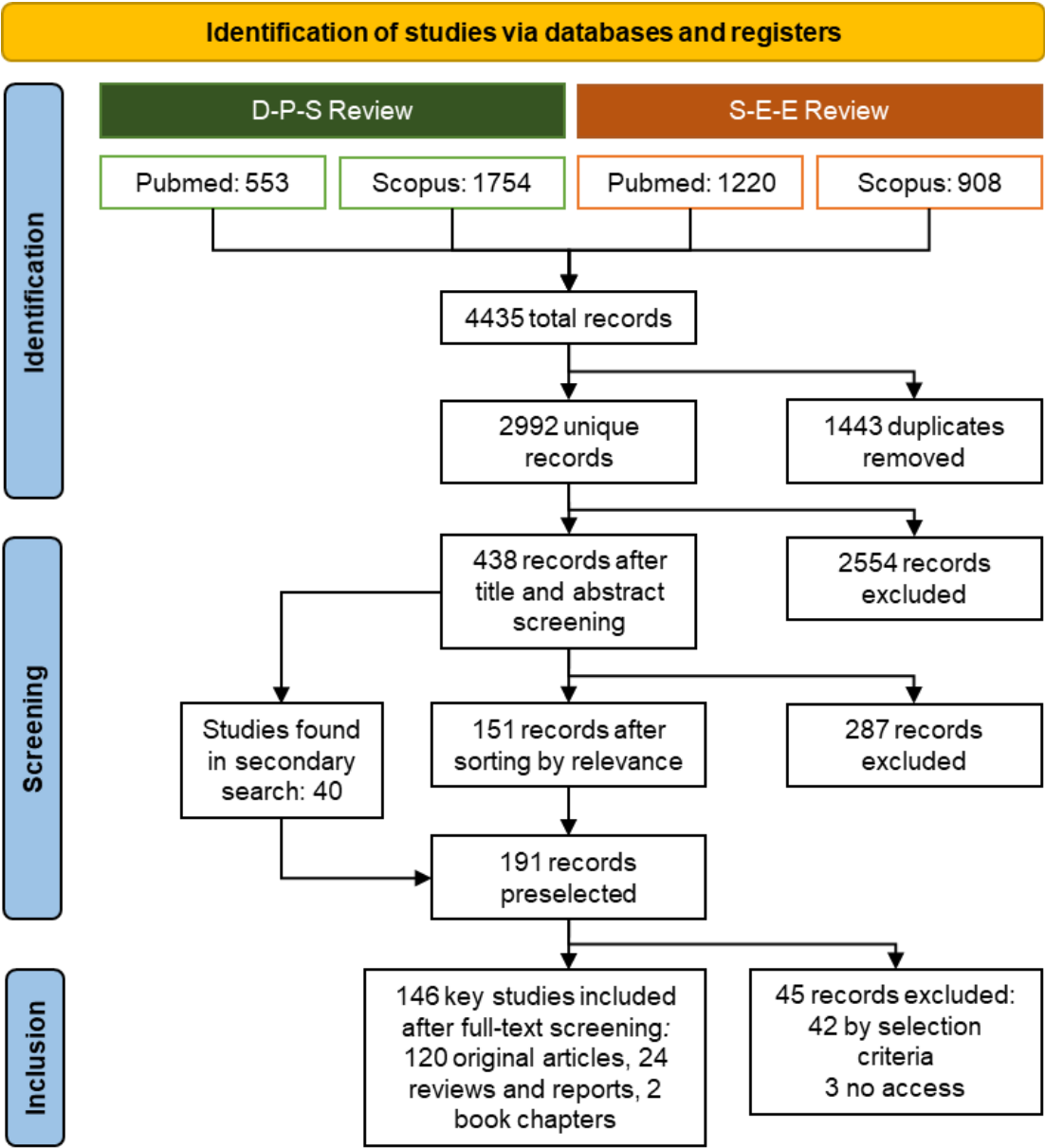


Figure 3. Outline summary of the review process.

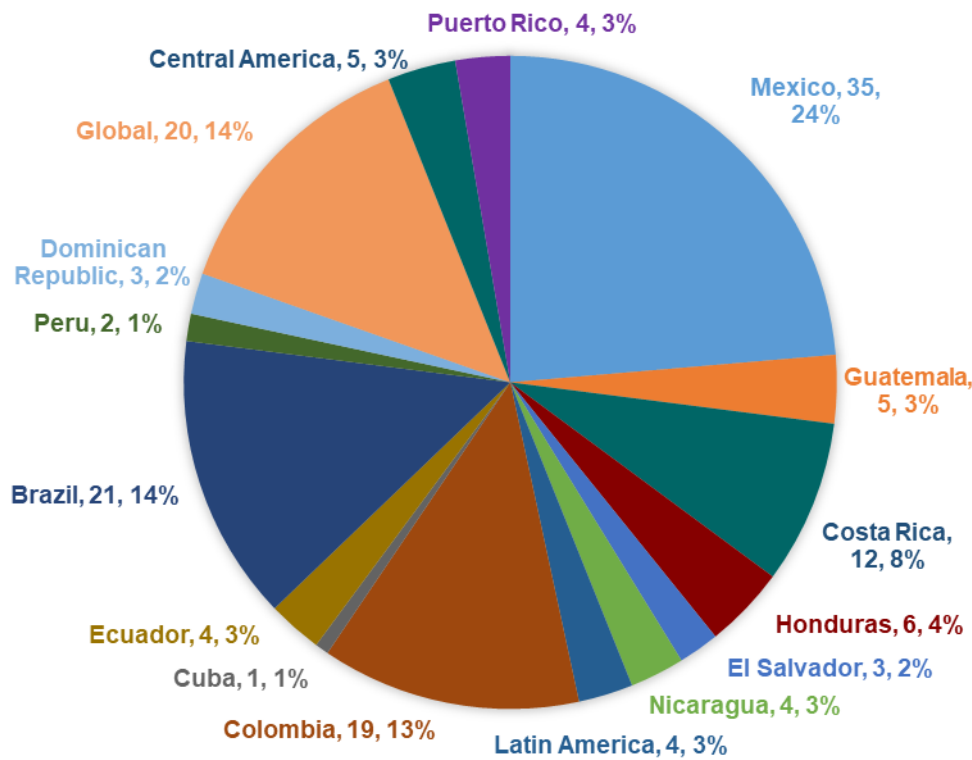


Figure 4. Included literature by country of origin.

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 (Harvey et al. 2021). 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 (Harvey et al. 2021; Escobar-Ocampo et al. 2023; Gabriel-Hernández and Barradas 2024). Other contributing factors include labor shortages and weakening institutional support (Renard 2011; Griffith et al. 2017; Gabriel-Hernández and Barradas 2024).

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 (Cordes et al., 2021; ICO, 2020), most producers in the Global South live below the poverty line, earning less than a living income (Cordes et al. 2021; Panhuysen and de Vries 2023). 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, leading to a decline in coffee prices paid to producers (Figure 5), a shift in market control toward corporations, the financialization of the coffee

trade, and a concentration of revenues within financial and commodity markets (Rettberg 2010; Renard 2011; Hausermann 2014; Utrilla-Catalan et al. 2022). 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%; today, producers earn roughly 10% of coffee’s final value (Rettberg 2010; Renard 2011; Devoney 2022). Monopolistic corporate consolidation has eroded producers’ bargaining power, often forcing them to sell below production costs (Braunschweig et al. 2019; Vázquez 2023; Lalani et al. 2024).

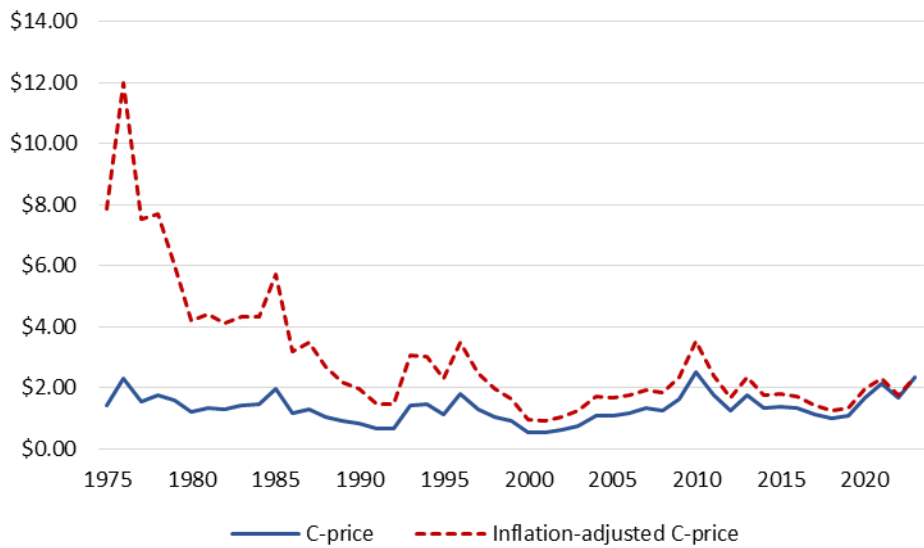


Figure 5. Yearly reference Arabica coffee price (C-price) in USD per pound, not adjusted for inflation (blue continuous line) and inflation-adjusted (red dotted line). Data from Macrotrends (C-Price) and the US Bureau of Labor Statistics (consumer price index).

Global coffee prices are largely determined in futures markets, where speculative trading has exploded since 1994 and now exceeds physical coffee production by a factor of ten (Hicks 2018; International Coffee Council 2019; European Coffee Federation 2022). Low prices are compounded by extreme volatility, driven by financial speculation and fluctuations in coffee supply and production costs (Barrios-Puente et al. 2022). This undermines farmers’ livelihoods, and has triggered widespread crises associated with food insecurity, school dropout, reduced healthcare spending, and increased migration, as happened during the 2000s coffee crisis in Central America (Gresser and Tickell 2002; Bacon 2010). Outmigration of coffee farmers, in turn, contributes to labor shortages and rising production costs (Griffith et al. 2017; Gabriel-Hernández and Barradas 2024).

Box 1. Human Rights violations in Coffee Farming.

In Brazil, large coffee farms have been found to violate human rights and labor laws, including withholding workers’ salaries, paying below minimum wages, denying mandatory benefits and neglecting safety standards for pesticide management. These violations were documented on farms supplying brands such as Nestlé, Starbucks, and ECOM, and certified by Rainforest Alliance, UTZ, and Fairtrade (Campos, 2016). Further investigations revealed slave labor –defined by forced labor, debt bondage, strenuous working hours and degrading conditions– on certified Brazilian coffee farms supplying major retailers, with over 700

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 (Jha et al. 2014; Perfecto et al. 2019b). Some authors point out that resulting overproduction has depressed prices further, justifying continued intensification (Renard 2011; Jha et al. 2014). 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 (Renard 2011).

3.2. Climate Change

The literature reviewed documents that rising temperatures, unpredictable precipitation patterns, and extreme weather events, such as droughts and hurricanes, are already affecting coffee production and reshaping coffee landscapes across Latin America (Harvey et al. 2021). For example, in Veracruz, Mexico, climate change is reported by farmers as the second most important stressor after low coffee prices, and yield models confirm significant losses attributable to shifting climatic conditions (Gabriel-Hernández and Barradas 2024). In Central America, a survey of 860 smallholder farmers across three countries found that 66% reported negative effects of rising temperatures, erratic rainfall, and extreme events on yields, pest and disease pressure, income, and food security, and 58.7% had changed their practices in response (Harvey et al. 2018). 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) (Fromm 2023; Escobar-Ocampo et al. 2023). 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 (Harvey et al. 2018, 2021).

Climate change is expected to become an increasingly determinant driver of change in coffee farming. A recent systematic review of 148 studies on the impacts of climate change on coffee farming found that 35 out of 42 studies project Arabica yield declines in Latin America of up to 70% over the coming decades due to rising temperatures and changing humidity, though some studies suggest partial mitigation from CO₂ 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. Combined with more extreme weather, these shifts will impact coffee farming distribution and management practices, as well as food and income security (Bilen et al. 2023).

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. Introduced to the Americas in the 1960s, CLR remained a minor concern until major epidemics emerged in 2008, devastating coffee cultivation across the region (Libert-Amico and Paz-Pellat 2018; Perfecto et al. 2019b). Between 2012 and 2014, CLR caused an estimated U.S.D. \$1 billion in damages across Latin America, affecting over two million people (Valencia et al. 2018). In Central America alone, coffee yields dropped by up to 55%, resulting in losses of U.S.D. \$515 million (Harvey et al. 2018). In Colombia, production fell by 31% during the 2008–2011 outbreak, and in southern Mexico, losses reached 95% in 2015–2016, leading many producers to abandon coffee altogether (Avelino et al. 2015; Libert-Amico and Paz-Pellat 2018; Valencia et al. 2018). 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 (Avelino et al. 2015), 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 coffee landscapes, leading to the crossing of a tipping point in CLR transmissibility (Perfecto et al. 2019b).

Responses have focused on the introduction of high-yielding, CLR-resistant hybrid cultivars and increased fungicide use, promoted by governments and multilateral agencies. These strategies helped reduce CLR incidence and recover production, often with higher yields and reduced fungicide use (Avelino et al. 2015; Harvey et al. 2021). In Colombia, for example, CLR rates fell from 40% in 2009 to just 3% by 2013 (Avelino et al. 2015). 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 epidemic, with agrochemical use rising from 0% to 54% between 2012 and 2016 (Valencia et al. 2018), and shade cover decreasing from 50% to 25-30% between 2005 and 2015 (Escobar-Ocampo et al. 2023). 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 (Chort and Öktem 2024).

4. Coffee Farming’s Impacts on Planetary Boundaries

This section synthesizes findings from 89 key 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 affect in turn coffee farming.

4.1. Biosphere Integrity

In the PB framework, biosphere integrity includes both genetic diversity and functional integrity, measured by extinction rates and the Human Appropriation of Net Primary Production (HANPP) (Richardson et al. 2023). This review adopts the integrity of NCP as a practical proxy to evaluate biosphere functionality at local scales, as these are key for natural system’s regulation and human livelihoods and wellbeing, linking biosphere integrity with human and planetary health (Figure 6).

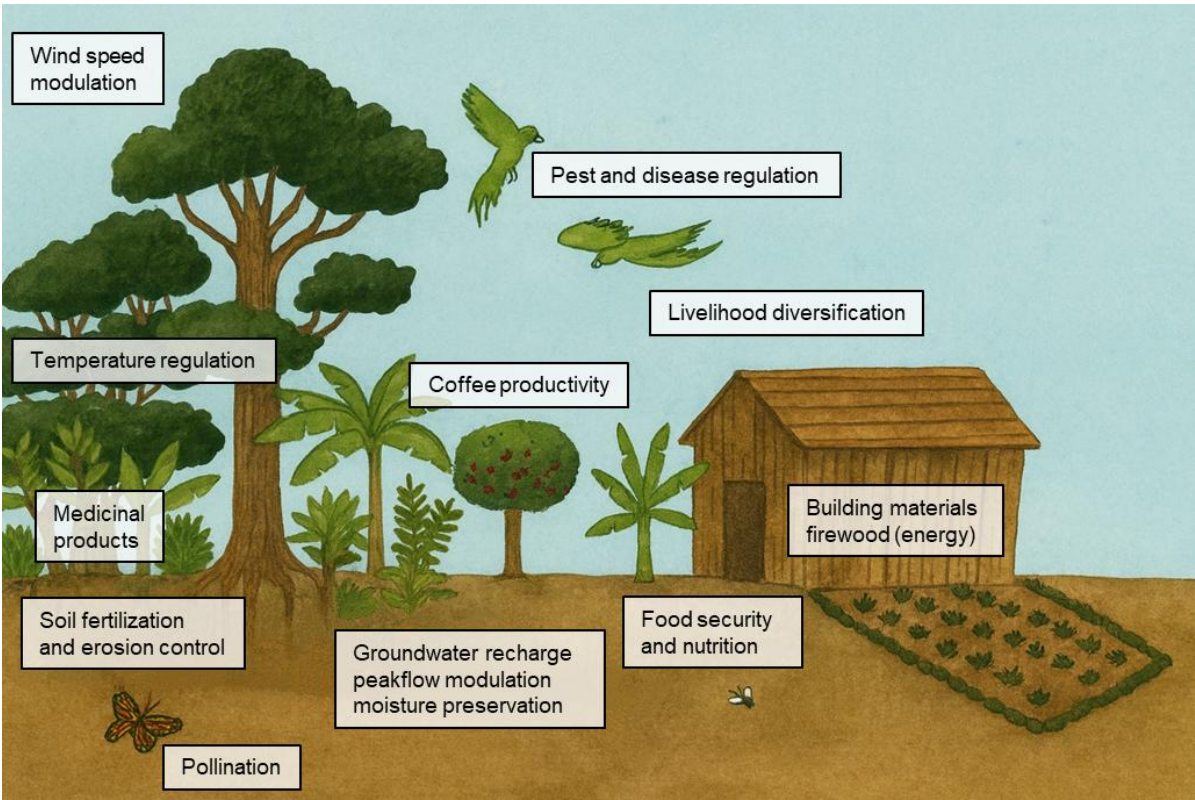


Figure 6. Key NCP supporting coffee farmers and coffee-growing communities.

4.1.1. Impacts of CAS on Biodiversity Conservation

Available literature consistently shows that biodiversity and ecological complexity decline with intensification. One meta-analysis showed that bird, ant, and tree biodiversity in Latin American CAS inversely correlates with management intensity, with UCAS exhibiting the lowest diversity and rustic T-CAFS the highest, sometimes comparable to primary forests (Philpott et al. 2008a). A broader global meta-analysis (Manson et al. 2024) 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. Bee diversity was higher in low-shade CAFS, possibly due to flower availability during bloom, while other pollinators (wasps, flies, butterflies) thrived in high-shade CAFS, probably due to their higher floristic diversity. Generalist species are the most benefited by high-shade CAFS, though sufficient ecological complexity also supports specialists. These systems also provide important stopover habitats for migratory birds (Manson et al. 2024). Other studies found that in Chiapas, Mexico, bee abundance and diversity were best predicted by tree species richness and the number of flowering trees (Jha and Vandermeer 2010), and that some pollinators like the Mexican stingless bee apparently cannot survive in UCAS (Vaidya et al. 2023). Lesser-studied taxa show similar trends. Amphibians fare better in CAFS than in UCAS (Moguel and Toledo 1999; Murrieta-Galindo et al. 2013; Ríos-Orjuela et al. 2024). Fungal diversity is higher in organic systems (Sternhagen et al. 2020), and soil microbial communities shift with management intensity (Caldwell et al. 2015; Carrasco-Espinosa et al. 2022). In addition to serving as wildlife habitats, CAFS enhance the quality of the landscape matrix, facilitating connectivity for fauna like birds, mammals and forest specialists through canopy bridges connecting forest fragments. This connectivity supports biodiversity maintenance and repopulation in even intensively managed agricultural areas (Perfecto et al. 2019b; Libert Amico et al. 2020; Manson et al. 2024). These results show 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, literature shows that CAFS in general support less biodiversity than primary forests, especially for specialist species (Philpott et al. 2008a; De Beenhouwer et al. 2013; Bedoya-Durán et al. 2023; Manson et al. 2024), emphasizing the need to avoid forest encroachment (Manson et al. 2024). Notably, it has been suggested that intensively managed UCAS, which generally achieve higher yields per area, may reduce pressure on forests by requiring less land. One study found that small-scale land-sparing coffee farms within a highly forested area preserved higher landscape biodiversity than CAFS (Chandler et al. 2013). This approach requires a strict protection of adjacent forests, which is often lacking. These results show that, in Latin America, biodiversity protection both within farms and across landscapes is best served by combining land-sharing and land-sparing strategies, preserving and increasing the shade levels and complexity within CAS while protecting the remaining native forests from further encroachment.

4.1.2. Impacts of CAS on NCP

Soil Health, Nutrient Cycling, and Erosion Control

Several studies show that soil health declines with management intensification. For example, rustic T-CAFS have been found to sustain the richest microbial communities, lowest denitrification rates, and highest levels of bioavailable phosphorus (P) and potassium (K) among five different CAS types in Mexico, whereas UCAS showed the poorest soil health (Molina-Monteleón et al. 2024). CAFS also benefit from the nitrifying activity of leguminous tree species widely used for shading, such as *Inga* and *Erythrina*. Their pruning alone contributes 70-90kg of N/ha/year, comparable to one-third the synthetic nitrogen (N) input in UCAS. Agroforestry also conserves soil moisture, limits erosion, and sustains biodiversity, reducing the need for external fertilizers (Tully et al. 2013).

Shade levels correlate with soil health independently of agrochemical use. Studies in Costa Rica and Brazil have found that CAFS show higher soil nutrient mineralization, microbial activity and

nutrient retention and uptake than UCAS (Souza et al. 2012; Tully et al. 2012, 2013), and that both organic and conventional CAS exhibit higher soil fauna diversity at higher shade levels (Sauvadet et al. 2019). Conversely, agrochemical use independently undermines soil health. At equal shade levels, organic CAS have higher soil pH, bioavailable N, and food web diversity than conventional CAS (Sauvadet et al. 2019), likely resulting from pesticide exposure, acidification, reduced N-fixing bacteria and higher nutrient loss (Tully et al. 2012; Sauvadet et al. 2019; Carrasco-Espinosa et al. 2022). N-fertilization can also suppress P mineralization increase its losses, leading to depletion and fertilizer dependency (Tully et al. 2013; Carrasco-Espinosa et al. 2022).

Agroforestry and organic management also reduce soil erosion and nutrient loss. Extensive root systems, litter, vegetation, and mulch in CAFS enhances water infiltration and reduces erosion. Nitrogen leaching decreases linearly with increasing shade trees, and can be over three times higher in UCAS than in CAFS (Babbar and Zak 1995; Tully et al. 2012; Cerretelli et al. 2023). Organic and conventional CAFS under similar shade levels show comparable nitrogen fluxes and nutrient concentrations at 1-meter depth, while a reference UCAS showed triple the nitrogen loss, indicating that trees may be the primary regulator of nutrient retention (Tully et al. 2012, 2013). Organic fertilizers also release nutrients more slowly than synthetic fertilizers, which mobilize and leach rapidly. At least 50% of N inputs in chemical fertilizers may be lost this way (Tully et al. 2013; Sauvadet et al. 2019).

Hydrological Services

Evidence suggests that hydrological services are better preserved in CAFS due to their root networks, litter, and improved soil structure and health. They can maintain hydraulic conductivities comparable to natural forests (Lozano-Baez et al. 2021), and show low surface runoff and high infiltration rates, helping to retain soil moisture, minimize erosion, and reduce the superficial transport of sediments (Gómez-Delgado et al. 2011; López-Ramírez et al. 2020; Noriega-Puglisevich and Eckhardt 2024). This also contributes to groundwater recharge and sustained soil moisture and aquifer reserves during dry periods (Gomez et al. 2020; Lozano-Baez et al. 2021). In Mexico, CAFS have been shown to sustain higher baseflows and improve the modulation of peak flows during storms relative to pastures, though not as effectively as native forests (López-Ramírez et al. 2020). One study in Peru suggests that CAFS may even outperform mature forests in reducing surface runoff and enhancing groundwater recharge (Noriega-Puglisevich and Eckhardt 2024). Additionally, CAFS exhibit lower soil evaporation and higher plant evapotranspiration than UCAS, suggesting a more efficient use of rainfall as a result of their microclimatic characteristics (Padovan et al. 2018).

Regulation of Microclimate and Extreme Weather

Studies show that shade in CAFS moderates microclimatic extremes by buffering temperature, radiation, humidity, and soil moisture fluctuations. Field data indicates maximum daily temperatures can be up to 5.4 °C lower in M-CAFS than in UCAS (Souza et al. 2012), while CAFS shaded by rubber trees report reductions of 1.4-2.5 °C (Zaro et al. 2022). Even minimal shading can lower wind speed and temperatures by 0.6°C on average, and increase humidity during dry periods (Coltri et al. 2019). Higher shade correlates with lower variability in temperature, solar radiation, and soil moisture, reducing evaporation (Lin 2007). This microclimatic regulation is increasingly valuable for protecting crops and farmworkers under climate change (Lin 2007; Souza et al. 2012; Zaro et al. 2022).

Some evidence suggest that agroforestry also enhances resilience and resistance to extreme weather events, likely due to root stabilization and wind buffering. A study in Chiapas found that higher vegetation complexity and lower management intensity within CAS was associated with reduced economic losses and roadside landslides at the landscape level after hurricane Stan (Philpott et al. 2008b). However, this benefit was not clear after hurricane Maria in Puerto Rico. While one study found that diverse CAFS suffered less damage and recovered faster (Mayorga et al. 2022), another didn't find an association between hurricane resistance and canopy cover (Perfecto et al.

2019a). Nonetheless, CAFS were found to support ecological resilience by providing a refuge for biodiversity recovery after the hurricane (Irizarry et al. 2021).

Pollination

Although coffee can self-pollinate, studies show that animal pollination significantly enhances quality and quantity. A global meta-analysis indicates that pollinator richness in CAFS increase Arabica fruit set by 18% on average, alongside improvements in fruit size, weight, and cup quality. Agroforestry and proximity to native forests patches boost Arabica production and quality by providing habitat for pollinators (Moreaux et al. 2022). Even UCAS close to forests can benefit from pollination, with studies reporting a 15% higher productivity, related to a 32% higher pollinator population (Latini et al. 2020), as well as improved yields and quality due to pollination (Pereira Machado et al. 2024). These findings show that land-sharing and land-sparing are both important to support pollinator services.

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, and particularly ants, flies and wasps (Karp et al. 2013; Perfecto et al. 2019b; Koutouleas et al. 2023; Moreno-Ramirez et al. 2024). Two key threats in Latin America are the coffee berry borer (CBB, *Hypothenemus hampei*) and CLR (Cerdeira et al., 2020).

CBB infests developing berries, causing global losses exceeding \$500 million annually. CAS with multiple predator ant species can lower CBB populations by up to 50% (Moreno-Ramirez et al. 2024), and birds from forest patches near to CAS in Costa Rica reduce CBB infestations by a similar margin, potentially preventing \$75–310/ha/year in crop damage (Karp et al. 2013). These benefits decline with increased agrochemical use and reduced shade (Moreno-Ramirez et al. 2024). While these studies are in Arabica plantations, evidence shows that CBB infestations in Robusta CAS also are higher under conventional than under organic management (Piato et al. 2021).

The impact of coffee management in CLR is complex and 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*. These organisms may help explain the relatively low CLR incidence in Puerto Rico (Hajian-Forooshani et al. 2016). The complex and non-linear interactions of biocontrol agents, microclimates, and host plants within CAS are difficult to capture in cross-sectional studies (Koutouleas et al. 2023), and while intensification may reduce CAS resilience and increase CLR outbreak severity (Perfecto et al. 2019b), further research on this area is required to clarify these dynamics.

Coffee Productivity

Evidence on the relationship between shade and Arabica yields is nuanced. Shade removal is a traditional recommendation based on controlled experiments showing that shade limits photosynthesis and reduces yields (Koutouleas et al. 2023). However, field research incorporating agroecological complexity has found that moderately shaded Arabica CAFS can have similar or exceeding yields compared to UCAS (Rossi et al. 2011; Piato et al. 2022; Moreaux et al. 2022; Lalani et al. 2024), probably by balancing photosynthetic rates with NCP such as fertilization, pollination and pest control. One study also found that Robusta can grow taller, with higher leaf N, and similar yields under moderate (25%) shade from leguminous trees as under full sun in Amazonian conditions (Piato et al. 2022). Shade-tree species matter. CAFS shaded with nitrogen-fixing trees like *Inga* and *Erythrina* have the highest yields (Rossi et al. 2011; Piato et al. 2022; Lalani et al. 2024), while species such as *Eucalyptus* hinder growth (Latini et al. 2020). The literature also shows nuances on the effect of agrochemical management on coffee yields. For example, one study found that organic CAFS can be as productive as conventional CAFS (Rossi et al. 2011), while another found that the highest yields

among various CAS types were typically achieved in CAFS combining low to moderate agrochemical use with moderate shade levels (Lalani et al., 2024). Additionally, low fertilization rates achieve a higher yield-to-nitrogen input ratio than high fertilization (Capa et al. 2015).

Some studies have evaluated the synergistic effect of complementary NCP on coffee yields. In Costa Rica, one study found that CBB control by birds and pollination by bees jointly contributed up to 25% of total production (Martínez-Salinas et al. 2022). Another study among 61 farms showed that those maximizing NCP through shading, polyculture, and low pesticide use had the lowest yield and economic losses, even in cases of high CLR prevalence (Cerdeira et al. 2020). In Brazil, a study found that agroecologically managed CAFS achieved competitive yields using less than a third of agrochemicals and half the labor than UCAS. Despite lower yields, these systems generated higher net incomes due to secondary products and reduced expenses (Pronti and Coccia 2020). In Puerto Rico, a study evaluating island-level data on coffee yields and shade management found that total planted area, not shade level, was the strongest predictor of yield, while shade cover correlated with greater food crop richness, suggesting that agroforestry can simultaneously support productivity, food security, and other NCP without obvious tradeoffs (Mayorga et al. 2022).

4.2. Land-System Change

Forests have a critical role in global biophysical regulation, and are the control variable for land-system change in the PB framework (Richardson et al. 2023). 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% while cultivation area fell 9% (Jha et al. 2014). In Latin America, coffee covers roughly 4.6 million hectares (Sporchia et al. 2021; Harvey et al. 2021), often adjacent to high-conservation-value forests (Moguel and Toledo 1999; Jha et al. 2014). Although overall area is stable, cultivation is contracting in countries such as Brazil and Colombia while expanding into forested zones in Ecuador, Peru, Mexico, and Central America. Pressure on forests is expected to increase as climate change shifts suitability areas (Harvey et al. 2021; Bilen et al. 2023). Annual deforestation attributable to coffee cultivation globally is estimated at 130,000 hectares (Panhuisen and de Vries 2023), with Latin American estimates by indirect land-balance models reaching at least 37,000 ha/yr between 2005 and 2017 (Figure 7; Pendrill et al. 2020). This amounts to 3.3% of the 1,108,800 ha lost to deforestation in Latin America in 2020 (ECLAC 2021), or 0.004% of the regional tropical forest cover in 1995 (FAO 1997). 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 (Pendrill et al. 2019, supplementary material S4).

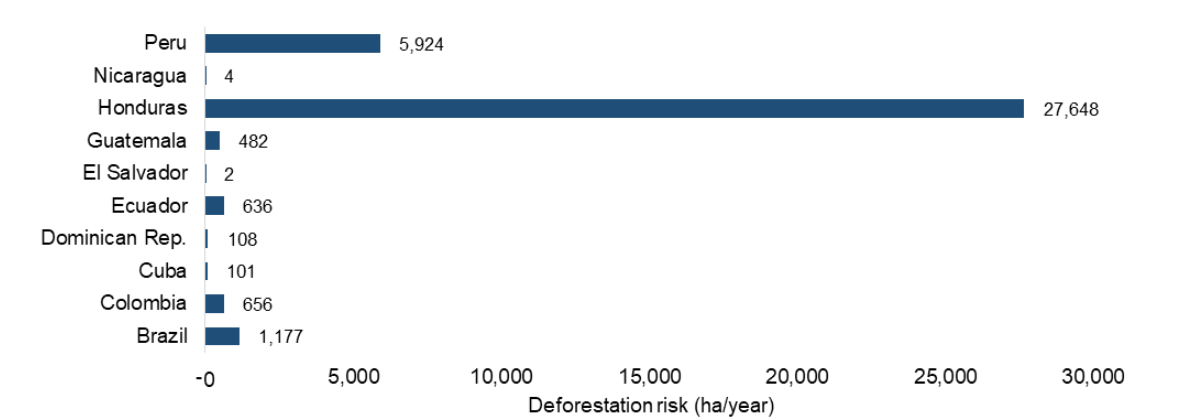


Figure 7. Deforestation risk attributable to coffee expansion among 10 Latin American countries. No data available for Bolivia, Costa Rica, Haiti, Mexico, Panama, and Venezuela. Data from Pendrill et al. 2019.

On the other hand, a big share of deforestation occurs within farms as shaded coffee systems are replaced by unshaded monocultures or other crops. For example, a study in Chiapas found that most of the deforestation during the CLR epidemic was not in native forests but within T-CAFS (Chort and Öktem 2024). From 1970–1990, ~50% of CAFS in Latin America shifted to low-shade or UCAS (Perfecto et al. 1996), 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%) (Jha et al. 2014). 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% (Jha et al. 2014).

Although less prominent than deforestation and farm simplification, coffee farm abandonment and agroforestry-driven reforestation also shape land-system change. Abandoned farms are often converted to crops or pastures such as sugarcane, reducing tree cover, but in some cases regenerate into secondary forests (Harvey et al. 2021). Coffee expansion can also promote reforestation when shade levels and diversity increase. For example, 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, exceeding deforestation losses (Toledo and Moguel 2012). Similarly, western Honduras saw a 17% rise in tree cover from 1954–1992 due to CAFS (Bass 2006). Growth in certified coffee (organic, fair trade) also supports agroforestry, with Latin America leading global production (Harvey et al. 2021).

4.3. Climate Change

The coffee supply chain contributes approximately 1% of global food systems’ carbon footprint, most of which comes from cultivation and consumption (Usva et al. 2020). In Brazil, coffee production’s carbon footprint is estimated at 5% of the agricultural emissions, and 1.14% of the country’s total (Martins et al. 2018).

Coffee intensification contributes to climate change through three mechanisms: deforestation-related emissions, release of in-farm soil and biomass C stocks, and direct greenhouse gases (GHG) emissions, including CO₂ emissions from agrochemical production, transport, and on-farm fuel and electricity use, N₂O emissions from fertilizer volatilization, and CH₄ from wet-processing, background soil emissions, and litter decomposition. While literature on coffee’s deforestation emissions is scarce, a land-balance model estimated them at over 12 million tCO₂/yr⁻¹ in Latin America (Pendrill et al. 2020). On the other hand, multiple studies have quantified carbon stocks in CAS along the intensification gradient. For example, a review of eight studies found that T-CAFS store over five times more C than UCAS in Central America, with C stocks decreasing from 54.6 to 9.7 t/ha with increasing intensification (Arellano and Hernández 2023), and a study from Chiapas found that converting T-CAFS to UCAS can release 133 t C/ha on average, and up to 192 t C/ha if replaced by maize or pasture (Table 3; Libert-Amico & Paz-Pellat 2018). Conversely, transitioning UCAS to CAFS could sequester about 1.3 t C/ha/year during tree growth, potentially making CAS carbon-neutral or carbon-negative (Arellano and Hernández 2023). These findings underscore both the emission risks of intensification and the climate mitigation potential of CAFS.

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

Land system	Soil (t C ha ⁻¹)	Biomass (t C ha ⁻¹)	Total (t C ha ⁻¹)
T-CAFS	180	80	260
M-CAFS	130	43	173
UCAS	120	7	127
Cornfield	66	2	68
Grassland	80	8	88

Direct GHG emissions from coffee cultivation vary widely with management. Litter decomposition emissions tend to be higher in CAFS, while emissions from fertilizer production, N₂O volatilization, wet processing, and deforestation are higher in UCAS (van Rikxoort et al. 2014). Reported carbon footprints differ greatly across studies due to variations in methodologies, emission sources considered, and product units (e.g. cherry, green, or parchment coffee). However, across all studies, management intensity consistently correlates with carbon footprints. The carbon footprint of CAS in Central America has been found to increase from 0.51 kg CO₂eq/kg cherry coffee² in T-CAFS to 0.64 kg CO₂eq/kg in UCAS (Arellano and Hernández 2023), while another study across five Latin American countries showed that polycultures have significantly lower carbon footprints (6.2–7.3 kg CO₂eq/kg parchment coffee) than monocultures (9.0–10.8 kg CO₂eq/kg) (van Rikxoort et al. 2014). Life-cycle analyses have found that carbon footprints are 47% lower in CAFS than UCAS in Colombia (3.1 vs. 5.8 kg CO₂eq/kg parchment coffee; Acosta-Alba et al. 2020), near fivefold lower in organic CAS than conventional CAS in Brazil (1.4 vs. 0.3 kg CO₂eq/kg green coffee; Coltro et al. 2024), and the lowest reported in organic T-CAFS managed by an indigenous cooperative in Mexico, after excluding transport (0.15 kg CO₂eq/kg green coffee; Calvillo-Arriola and Sotelo-Navarro 2024).

In intensified CAS, conventional nitrogen fertilization is the largest contributor to GHG emissions, accounting for 70–94% of total emissions, followed by C-stock loss (Usva et al. 2020; Arellano and Hernández 2023; Coltro et al. 2024). Fertilization emissions arise from fertilizer manufacturing and from soil N₂O volatilization, a 298 times more potent GHG than CO₂. A systematic review estimated N₂O emissions from coffee farms at 0.2 to 12.8 kg N/ha/year –or 94 to 5995 kg CO₂eq/ha/year– scaling directly with fertilizer use (Quiñones-Huatangari et al. 2022). These results highlight the climate advantages of organic management, supported by NCP in CAFS. 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 (Capa et al. 2015).

4.4. Biogeochemical Flows

Synthetic N and P fertilizers are the main drivers of change in this PB, fueling eutrophication, harmful algal blooms, and oxygen depletion in freshwater and marine ecosystems (Rockström et al. 2009; Richardson et al. 2023). In coffee systems, conventional management increases N and P inputs while shade loss and agrochemical use enhance nutrient runoff.

In 2017, coffee production used ~2.1 Mt of fertilizer, or 1.2% of global use (Sporchia et al., 2021, supplementary material). 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 (Richardson et al. 2023) 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, equivalent to 3.6% of the N planetary boundary (62 Tg) and 2.4% of the P boundary (11 Tg), a significant use of Earth's resources for a non-nutritious crop. This estimates correlate with fertilization rates in conventional monocultures, ranging from 66–400 kg N/ha/yr and 22–109 kg P/ha/yr (Capa et al. 2015; Quiñones-Huatangari et al. 2022). 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. Therefore, keeping them near the lower range is critical.

A few life-cycle assessment studies have estimated the eutrophication impact of CAS. A study in Colombia found that CAFS had 44–48% less terrestrial and freshwater and 33% less marine eutrophication impact than UCAS (Acosta-Alba et al. 2020). Another study in Brazil found that, although organic coffee had a lower contribution to freshwater, marine and terrestrial ecotoxicity, it had higher freshwater eutrophication potential due to high-P organic fertilizers (3.33 vs 1.02 kg P-eq/kg green coffee; Coltro et al. 2024). Beyond nutrient input estimates, some studies have measured

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 (ICO 2011; Arellano and Hernández 2023).

³ 1 Tg = 1,000,000 tons.

eutrophication directly. In Veracruz, Mexico, streams from CAFS had the highest N pollution, followed by forest streams, both exceeding pasture streams; yet, both CAFS and forest had lower eutrophication than pasture streams, likely because high shade limits eutrophication despite higher nutrient load from leaf litter (Vázquez et al. 2011). In Costa Rica, M-CAFS streams generally showed low nutrient pollution and eutrophication during most of the year, and greater canopy cover also correlated with lower eutrophication. Water quality was higher than in cattle-dominated highlands but lower than in Veracruz, possibly due to higher management intensity (de Jesús Crespo et al. 2020). These studies show that factors like shade, erosion control, and nutrient uptake by trees strongly mediate nutrient leakage and eutrophication impacts from CAS.

Beyond fertilizer runoff, wet coffee processing is another source of nutrient and water pollution. In 2000, Mexico's wet mills discharged an estimated 1.5 m³/s of gray water —about 80,000 t of biochemical oxygen demand (BOD) —making coffee a major upstream nutrient source. In Veracruz alone, 22,160 t BOD/year flowed to the Gulf of Mexico, second only to sugarcane (900,000 t) (Olguín et al. 2004).

4.5. Freshwater Change

Coffee cultivation relies primarily on rainwater in most producer countries. As a result, its global green and blue water use (estimated at ~108 km³ and 0.75 km³ in 2017, respectively) are significantly lower than those of other crops (Sporchia et al. 2021). For reference, this amounts to approximately 0.019% of the 4000km³ PB for blue water use set in 2015 (Steffen et al. 2015).

Blue water depletion in production is mainly driven by irrigation (~1,104 m³/t cherry) and wet processing (~7.5 m³/t), both linked to intensive CAS (Chapagain and Hoekstra 2007; Usva et al. 2020). In Latin America, irrigation is concentrated in Brazil, covering 5.9% of the coffee area (Chapagain and Hoekstra 2007; Martins et al. 2018), yet using 274 million m³/year blue water, a third of coffee's global use (Sporchia et al. 2021). As a result, water scarcity impacts of coffee farming are ten-fold higher in Brazil (0.15–0.27 m³ water/l coffee) than in Central America or Colombia (0.02 m³/l coffee; Usva et al. 2020). On the other hand, wet processing is common in intermediate-intensity CAS across Latin America, as it reduces labor and produces higher-quality coffee than traditional sun-drying, while remaining far less expensive than newer ecological processing technologies (Leal-Echeverri and Tobón 2021; Calvillo-Arriola and Sotelo-Navarro 2024). Life-cycle assessments show that CAFS in Colombia have a 53% lower water use than UCAS (Acosta-Alba et al. 2020), and that organic CAS in Brazil use ten times less water than conventional CAS (3 vs 33 m³ eq./t green coffee; Coltro et al., 2024), confirm lower water impacts in less intensive systems.

4.6. Novel Entities

The *Novel Entities* PB includes synthetic chemicals, anthropogenically mobilized radioactive materials, genetically modified organisms, and other human-driven evolutionary interventions. As safe loading thresholds are unknown and substance-specific, the proposed boundary is zero release of untested synthetics (Richardson et al. 2023). In CAS, the main contribution to this PB is pesticide use. Despite growing research on pesticide impacts, literature specific to CAS is limited; here, five relevant studies on global and regional use, leakage, and ecological effects are reviewed. Impacts on human health are discussed on section 5.

Pesticides used in coffee cultivation across Latin America include many listed as highly hazardous and banned in several countries (Table 4; de Queiroz et al. 2018; García Ríos et al. 2020). Their use has expanded rapidly, with a 190% increase in Brazil in the last decade (de Queiroz et al. 2018; Koutouleas et al. 2023). There, producing 1,000 kg of green coffee requires ~10 kg of pesticides (Coltro et al. 2006), amounting to ~38 million kg annually (Koutouleas et al. 2023). Evidence shows environmental leakage. In Brazil's coffee-producing region in the Itapemirim River Basin, 59 pesticides were found in use —more than half considered highly toxic— with contamination risks estimated at 44.7% for surface water and 23.7% for groundwater (de Queiroz et al. 2018). In Quindío, Colombia, surface waters from coffee areas contain high levels of organophosphates and

organochlorines, including banned pesticides such as dieldrin, heptachlor, and DDT (García Ríos et al. 2020). Many of these are forbidden, yet enforcement remains weak, undermined by easy accessibility, limited testing, and regulatory gaps (de Queiroz et al. 2018).

Table 4. Higly 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 persistant 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 accute 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 accute 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 persistant 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 (Craves 2006; de Queiroz et al. 2018; Londoño et al. 2018; García Ríos et al. 2020; Merhi et al. 2022; Koutouleas et al. 2023), 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 (PAN International 2021). In total, 55 different pesticides used in coffee farming in Latin America were identified in this review: Aldicarb, Aldrin, Ametryn, Atrazine, Azoxystrobin, Beta-BHC, Boscalid, Carbendazim, Cartap, Chlordane, Chlorpyrifos, Copper II hydroxide, Cypermethrin, Cyproconazole, DDT, Delta-BHC, Dieldrin, Diazinon, Dinotefuran, Disulfoton, Diuron, Endosulfan, Endosulfan II, Endosulfan sulfate, Endrin, Endrin aldehyde, Endrin Ketone, Epoxiconazole, Etion, Flutriafol, Heptachlor, Heptachlor Epoxide, Iprodione,

Lindane, Malathion, Mancozeb, Methamidophos, Methoxychlor, Methyl parathion, Methomyl, Paraquat dichloride, Parathion, Pendimethalin, Permethrin, Picoxystrobin, Propiconazole, Simazine, Tebuconazole, Thiamethoxam, Thiophanate-methyl, Triadimefon, Triadimenol, Triazophos, Trifloxystrobin, 2,4-D and 4,4'-DDE (Craves 2006; de Queiroz et al. 2018; Londoño et al. 2018; García Ríos et al. 2020; Merhi et al. 2022; Koutouleas et al. 2023). A list of 117 different pesticides detected in raw coffee beans can be found in Reichert et al. (2018).

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

This review included 46 studies on the impacts of different CAS on human health, either through direct occupational exposure or mediated by ecosocial determinants of health.

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

Coffee farming is physically demanding and hazardous, and farmworkers are exposed to harsh weather, pesticides, animal stings, and heavy physical labor during harvests. Yet, access to protective equipment and healthcare are limited—for example, a survey in Cauca, Colombia, found that only 3% of coffee farmworkers had medical insurance (Palomino-García and Vargas-Vásquez 2023), while a study in Dominican Republic found that just 5% of pesticide handlers consistently used protective equipment (Hutter et al., 2018a). As a result, occupational exposures in coffee farming frequently result in serious health impacts.

Although evidence on pesticide exposure among coffee workers is limited, it indicates significant health risks. In the Dominican Republic, a set of studies found that conventional CAS farmworkers showed higher frequencies of cytotoxic and genotoxic biomarkers—such as micronucleated cells and karyolysis—than organic farmworkers, consistent with elevated cancer risk, as well as greater symptoms of acute intoxication and a possible reduction in male fertility linked to early-life exposure (Hutter et al., 2018a; Hutter et al., 2018b; Moshhammer et al., 2020). 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 (Bedoya et al., 2014; Londoño et al., 2018). A cytogenetic biomonitoring study further showed that farmers in regions with intensive use of glyphosate and other pesticides had significantly higher chromosomal damage than farmers in the predominantly organic coffee region of Sierra Nevada de Santa Marta (Bolognesi et al. 2009). Notably, some evidence suggest that pesticide use in coffee farming is not only hazardous for producers, but may also represent a risk for consumers. One Brazilian study identified 117 different pesticides in local raw beans (Reichert et al. 2018), and some, including DDT, have also been detected in roasted and grinded coffee beans (Merhi et al. 2022).

Coffee harvesting also exposes workers to repetitive movements, strained postures, heavy loads, and high physical effort, resulting in frequent musculoskeletal disorders. In Colombia, 18% of 72 surveyed farmworkers reported accidents, 50% chronic back pain, and 8% conditions such as osteoarthritis, carpal tunnel syndrome, or hernias (Palomino-García and Vargas-Vásquez 2023). Similarly, a survey conducted in a certified coffee farm in Honduras found that over 70% of 48 workers reported recurrent back, knee, and foot pain (Estrada-Muñoz et al. 2022).

Farmers also face risks from hazardous wildlife. Ethnographic research in Chiapas, Mexico, found farmworkers often prefer more intensively managed CAS to shaded CAFS, largely due to fear of snakes, ants, and spiders found in dense vegetation. These risks are exacerbated by the lack of proper footwear and protective equipment, as well as overseer-imposed penalties for leaving infested coffee bushes unharvested (Jimenez-Soto 2021). Similarly, an ecological study in Brazil found that snakebite incidence in Bahia was statistically associated with coffee and cocoa cultivation near the Atlantic Forest, but not with other more intensive crops, linking biodiversity-rich landscapes with higher snakebite incidence (Mise et al. 2016).

Cutaneous leishmaniasis has also been associated with multifunctional CAFS in Colombia and Venezuela since at least the 1980s. For example, a study in Tolima, Colombia, found that a township

with high leishmaniasis incidence had a greater forest cover, more shaded CAFS, and higher densities of *Lutzomyia* sandflies than a low-incidence township dominated by monocultures, consistent with the vector's transmission cycle dependent on dense vegetation (Ocampo et al. 2012). Another study found a Leishmanin skin test positivity among coffee farmers nearly twice as high in *traditional* (CAFS) than in *intensified* coffee farms (26.8% vs. 13.2%; Alexander et al. 2009). No studies linking CAS with other infectious diseases were found in this review.

5.2. Impacts on Ecosocial Determinants of Health

Beyond direct occupational hazards, CAS, their transformations, and the environmental changes they contribute to affect human health through ecosocial determinants. The literature reviewed documents impacts on income sufficiency, food security, migration, gender equity, violence, and mental 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. While intensification can increase coffee yields, it reduces these non-coffee contributions, leading to underestimation of productivity when measured solely in terms of coffee output (Rice 2008; Toledo and Moguel 2012). Literature highlights how this livelihood diversification supports income sufficiency and stability, food security and resilience to external shocks, as do other non-agroecological diversification strategies such as migration, staple crop cultivation, and livestock raising.

In Peru and Guatemala, studies have found that woody products from CAFS –mainly firewood– account for 28.5% and 18.8% of smallholder coffee-holding value, and trees are often regarded as “stored capital” that can be felled when needed (Rice 2008). Fruits from CAFS, on the other hand, have considerable potential value (US\$95–270/ha), yet their contribution to household income averages only ~10% due to limited market access; however, with access, they may reach up to 40% (Rice 2011). Another study among smallholder coffee farmers in El Salvador and Nicaragua found that CAFS supplied roughly half of household firewood needs –the primary energy source in rural Latin America– valued at about US\$75 annually, or 3-7% of household income, and a wide range of foods (e.g., tomatoes, peppers, squash, cacao). Local seed diversity was also a valuable capital for Nicaraguan smallholders, most of which used their own seeds, while El Salvadoran households split between purchased and saved seeds. Farmer networks and cooperatives have been determinant in promoting traditional seed conservation and exchange. Moreover, 119 species of medicinal plants were recorded in CAFS, further supporting households with little access to health services (Méndez et al. 2010).

A study in Chiapas found that, while coffee contributed ~70% of coffee smallholders' income, livelihood diversification increased income sufficiency and food security. Beekeeping –introduced by a local cooperative and an NGO– was associated with higher income sufficiency (55.6% vs. 33.6%). Although fruits and vegetables from CAFS contributed little monetarily, they supported household nutrition, fed seasonal workers, and facilitated barter. Most households also engaged in other diversification strategies such as poultry raising, small businesses, off-farm labor, or payments for ecosystem services (Anderzén et al., 2020).

However, diversification and agroforestry alone cannot guarantee dignified livelihoods. 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 this would still not secure a living income for most farmers. Moderately shaded, high-investment CAFS had the highest probability of yielding positive returns under most coffee price and production costs scenarios, but for farmers with limited investment capacity, highly shaded, diversified CAFS were the most economically viable option, as diversification and lower costs buffer against price drops (Lalani et al. 2024).

5.2.2. Food Security and Nutrition

Despite coffee's economic value, smallholder farmers frequently experience seasonal food insecurity (or "*thin months*"), typically between June and September, when coffee revenues and grain stocks are depleted, staple food prices rise, and agrochemical costs peak. Its severity varies yearly and regionally, with different studies finding yearly prevalences of 63% in Central America (Méndez et al. 2010), 72% in Chiapas (Anderzén et al. 2020), 97% in El Salvador (Morris et al. 2013), and 52% in Guatemala (Lopez-Ridaura et al. 2019), with an average duration of 2.5-3 *thin months* in Chiapas and Nicaragua (Bacon et al. 2014; Anderzén et al. 2020). Proximate causes include income insufficiency, depleted staple crops, limited employment and land access, rising food and production costs, catastrophic health expenditures, and climatic variability (Morris et al. 2013; Bacon et al. 2014). Coffee is paid in one or two yearly lump-sums that are hard to predict due to price volatility, which, coupled with structural poverty, erodes producers adaptive capacity and exacerbates seasonal food insecurity (Morris et al. 2013). Coping strategies include livelihood diversification, borrowing, changing diets, selling livestock, and migration (Morris et al. 2013).

The literature reviewed shows that agricultural diversification –through staples, beekeeping, home gardens, and increased on-farm agrobiodiversity– consistently supports food security and nutrition of coffee smallholders. In Mesoamerica, farmers often combine coffee with *milpas* (traditional agroecological systems combining maize, beans, squash and other crops), even when unprofitable, due to its cultural significance and to retain control over food supplies (Morris et al. 2013; Fernandez and Méndez 2019; Anderzén et al. 2020). A study in El Salvador found that these staple food plots supplied about half of household consumption (Morris et al. 2013), and a study in Guatemala found that diversified households reported lower food insecurity than coffee-dependent ones (Lopez-Ridaura et al. 2019). In Chiapas, studies found that over 60% of coffee farmers grew staples, providing 37% of household food, and that both growing staples and beekeeping increased food security (Fernandez and Méndez 2019; Anderzén et al. 2020). These findings suggest that balancing cash (coffee, honey) and subsistence crops enhances food security more effectively than either strategy alone, though access to diversification opportunities remains unequal. On the other hand, a mixed-methods study in Honduras found that coffee smallholders with diversified livelihood experienced lower food security than coffee-dependent ones during the COVID-19 pandemic, when lockdowns reduced labor availability, coffee yields, and access to both imported and local foods and markets, showing the contribution of livelihood diversification to households' resilience in the face of external shocks (Rodriguez-Camayo et al. 2024).

Agrobiodiversity within CAS also contributes to food security and dietary diversity. A study in Nicaragua found that the number of trees on coffee farms correlated with fewer food-insecure months (Bacon et al. 2014). Another study among coffee cooperative members in Chiapas found that on-farm agrobiodiversity –measured by the number of trees and plant species– as well as staple crops reduced food-insecure months, highlighting the role of coffee agroforestry in food security. Moreover, more than 20 wild food species were identified within CAFS, including "*quelites*" (leafy greens), palm flowers, snails, and mushrooms, many shade-dependent and rich in micronutrients absent from typical regional diets. All surveyed households consumed *quelites*, underscoring their nutritional relevance (Fernandez and Méndez 2019). Similarly, another study in 17 communities in Chiapas recorded the use of 108 different edible plant species linked to CAFS, *milpa*, and cacao systems, and considered vital dietary complements (Soto-Pinto et al. 2022).

However, landscape transformations, shifting food cultures, and limited access to fresh foods are driving a transition toward industrialized diets, eroding traditional knowledge while contributing to obesity and micronutrient deficiencies. A study in Guatemala found that households relying solely on coffee reported higher incomes, but also higher rates of overweight and obesity than diversified households, while simultaneously experiencing reduced caloric access during the *thin months* (van Asselt and Useche, 2022). Similarly, a cross-sectional survey of adults 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, followed by hyperlipidemia (62.1%),

obesity (42.9%), sedentarism (31.2%), and smoking (21.1%), underscoring the ongoing nutritional transition linked to agricultural commercialization (González et al. 2013).

Literature shows that food security also correlates with income sufficiency, farm size, and coffee production volume, underscoring its broader socioeconomic determinants and the central role of coffee income (Anderzén et al. 2020). Other factors such as women's control over income, local market availability of nutritious foods, and price stability also shape food security outcomes, while gender inequality, domestic violence, and alcoholism divert coffee earnings away from food (Fernandez and Méndez 2019; Rodriguez-Camayo et al. 2024).

5.2.3. Migration

Coffee smallholders rely on rainwater and are particularly vulnerable to climate change, especially in Central America, where coffee production overlaps with the "Dry Corridor" (Reichman 2022). 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 (Fromm 2023). While this review did not identify studies that directly quantify the contribution of climate change to coffee farmer migration, rainfall variability has been statistically linked to higher apprehensions of Honduran family units at the U.S. border, underscoring the role of climate change as driver of farmer migration in the region (Bermeo and Leblang 2021).

CLR –linked to climate change and CAS management– and low coffee prices are also major push factors. 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 (Dupre et al. 2022), and it has been estimated that, in Honduras, a five-cent fall in the world coffee price generates about 160 additional migrants per 100,000 people (USAID 2021). Similar migration surges have been reported following coffee price drops in Colombia and Mexico (Rettberg 2010; Nava-Tablada 2012).

5.2.4. Peace and Security

Coffee prices have been linked with violence, particularly in Colombia's Coffee Axis. This region, once relatively shielded from Colombia's armed conflict, saw violence surge after the collapse of the International Coffee Agreement in 1989 and the shrinking of the National Coffee-grower Federation (FNC), which had regulated prices, purchased most national coffee, and funded cooperatives and social services. Between the 1990s and 2000s, coffee incomes fell, unemployment and substance abuse rose, and life expectancy and literacy declined. Falling incomes forced many farmers to abandon land or turn to coca and poppy. Armed groups filled the vacuum, and rates of homicides, kidnappings, and attacks rose in direct correlation with declining coffee prices (Rettberg 2010). An analysis of violent incidents in 1,950 Colombian municipalities shows that the 68% drop in coffee prices between 1997–2003 coincided with 18% more guerrilla attacks, 31% more paramilitary attacks, 22% more armed clashes, and 14% more war-related deaths in coffee-growing regions relative to non-coffee ones (Dube and Vargas 2013).

On the other hand, community-based agroecology has shown peacebuilding potential. A qualitative study of seven farmer-led "Agroecology Peasant Schools" in post-war coffee-growing communities in Colombia found that, beyond improving ecological practices and economic recovery, these organizations also strengthened 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. Such efforts enhance community capacity to organize, negotiate, and endure crises, contributing to sustainable peace (Chavez-Miguel et al. 2022).

5.2.5. Gender Equity

Women's contributions in coffee-growing communities extend well beyond household labor, encompassing crop cultivation, livestock care, accommodation for seasonal workers, harvesting, and processing. Despite this, they face a gendered asset gaps in land, credit, education, and representation, curtailing women's agency and economic independence. Literature shows that public and institutional policy, coffee certification programs, and producer cooperatives offer key leverage points to reduce these gaps.

In Nicaragua, the coffee association PRODECOP adopted a gender policy in 2008 requiring a 40% female leadership, and achieved a nearly tenfold increase within five years (Lyon et al., 2017). In Colombia, the FNC's coffee plant renovation program (2008–2014), though designed to combat CLR, inadvertently contributed to women's empowerment. Women were generally more interested in participating, and because land ownership was required for enrollment, many were granted land titles from spouses or relatives. Participation also granted them FNC membership, access to credit, subsidies, technical support, and voting rights. Many improved their productivity, income, and decision-making power. Yet, most women still remain outside the FNC (Pineda et al. 2019).

Participation in producer cooperatives and certification programs has also supported women's empowerment, though with limits. One study in Oaxaca, Mexico, found that women's registration as farm operators in Fairtrade-organic certification programs rose from 9% in the 1990s to 42% by 2013, and that female cooperative members reported strong household decision-making and higher control over income (Lyon et al. 2017). Similarly, an ethnographic study in Nicaragua found that members of a women-led Fairtrade cooperative reported higher revenues, school attendance, and empowerment than women in a conventional cooperative. However, this progress was not driven by certification alone, but by the convergence of broader processes including state-led land reforms that granted land titles to women, grassroots organizing, and support from NGOs. Formerly landless seasonal workers, the women who founded this cooperative gained land, training, and access to credit, enabling them to build their cooperative and expand operations (Bacon 2010). However, women's increased participation in coffee farming adds to disproportionate domestic workload creating time poverty. As a result, empowerment often comes at the cost of intensified labor and unpaid work, on which the CVC –including certified coffee– still relies (Lyon et al. 2017; Pineda et al. 2019).

5.2.6. Identity, Quality of Life and Mental Health

Mental health and quality of life remain notably under-researched topics among coffee-growing communities, but available literature highlights how they are shaped by traditional identities and farming practices, community life, relationship with nature, and the transformation of coffee landscapes.

One of the clearest expressions of the strong biocultural ties between people and coffee farming is found in the rustic T-CAFS managed by indigenous communities. Most cases found in this review are from Mexico, including those managed by Mixes and Zapotecs in Oaxaca (Juárez-López et al. 2017; Pascual-Mendoza et al. 2020), Tzeltals and Zoques in Chiapas (Soto-Pinto et al. 2001; Calvillo-Arriola and Sotelo-Navarro 2024) and Nahuas in Puebla (Moguel and Toledo 1999). The Kuojtakiloyan, for example, are complex agroecological landscapes developed over generations by the Nahuas, incorporating up to 300 species belonging to 13 of the 19 plant and fungal "life forms" recognized in Nahua knowledge, each playing a role in the structure of the agroforest and in the household's subsistence strategy, including staple foods, herbal medicines and species used for timber, firewood, construction, ornament and honey production. Thus, Kuojtakiloyan are spaces where biodiversity and traditional identities and knowledge co-evolve, are preserved, and reproduce through interdependent practices (Toledo and Moguel 2012).

These connections transcend ethnic distinctions. In a study in Colombia's Coffee Cultural Landscape, a UNESCO World Heritage Site, smallholder coffee farmers described their relationship with the landscape as central to their sense of place, identity, and well-being, and cited emotional and

cultural reasons for practicing traditional coffee farming significantly more than semi-industrial farmers (Murillo-López et al. 2022). Another study in Veracruz, Mexico, found that many coffee farmers reported acceptable quality of life despite minimal education, distrust of authorities, inadequate health care, seasonal food insecurity, and low coffee income (US\$416–1,115 annually). Family, community life, and the contact with nature were highly valued as determinants of their quality of life. Cooperative members in particular described greater satisfaction, linked to stronger identity, participation, bargaining power, food security, and autonomy, though not necessarily higher income (Gasperín-García et al. 2023).

Given the relevance of traditional coffee farming for identities and wellbeing, it is not surprising that its transformation is a source of distress among coffee-growing communities. In Veracruz, a study found that most farmers chose to preserve their traditional CAFS during the 1990s-2000s coffee crisis despite economic losses due to their cultural significance. Some farmers expressed sadness on the idea of converting their farms, and many underscored their environmental, economic and cultural importance (Hausermann 2014). Similarly, an ethnographic study in Risaralda, Colombia, documented a high prevalence of depressive symptoms and high suicide rates among older male coffee farmers, linked to market-driven transformations such as ecotourism and “feminine coffee”, which commercialized particular narratives about their lives, and demanded producer families to perform expected dynamics and values, such as idealized relationships with nature and specific gender roles. Hegemonic masculinity limited emotional expression and access to care, leaving symptoms underreported and often expressed as suicide and alcohol abuse (Nieto-Betancurt et al. 2024).

Fewer studies address the mental health and well-being of seasonal coffee farmworkers. In a survey in Minas Gerais, Brazil, seasonal workers reported significantly higher anxiety, depression, and sleep impairment than permanent workers, reflecting insecurity between harvests (Lima et al. 2010). In a study among 220 coffee farmers in Southeast Brazil, depressive symptoms were associated with pesticide exposure, tobacco use, chronic disease, and poor self-perceived health (Conti et al. 2018), consistent with evidence linking long-term pesticide exposure to anxiety and depression (Salvi et al. 2003).

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 (Figure 8). Approximately 3% of total deforestation in Latin America can be attributed to coffee farming. However, within-farm intensification may have larger impacts on biodiversity and climate change. Evidence shows that rising agrochemical use and the reduction in shade and ecological complexity result in a decline in biodiversity (Manson et al. 2024). This 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 diversified produce that supports human livelihoods and resilience (Lin 2007; De Beenhouwer et al. 2013; Lozano-Baez et al. 2021; Moreaux et al. 2022). Nitrogen fertilization, shade removal and

deforestation are also the main contributors of coffee farming to climate change, accounting to about 1% of global food systems' GHG emissions (Usva et al. 2020; Quiñones-Huatangari et al. 2022; Coltro et al. 2024). Yet coffee itself is highly vulnerable to climate change, with Arabica yields and suitability projected to shrink drastically during the next decades, which may accelerate Robusta-driven deforestation and intensification (Bilen et al. 2023). Similarly, we estimate that 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. (2021), and average fertilization rates reported by Capa et al. (2015). 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 is 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 related to intensive CAS: shade removal and agrochemical use. Evidence shows that 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 (Libert-Amico and Paz-Pellat 2018; Perfecto et al. 2019b).

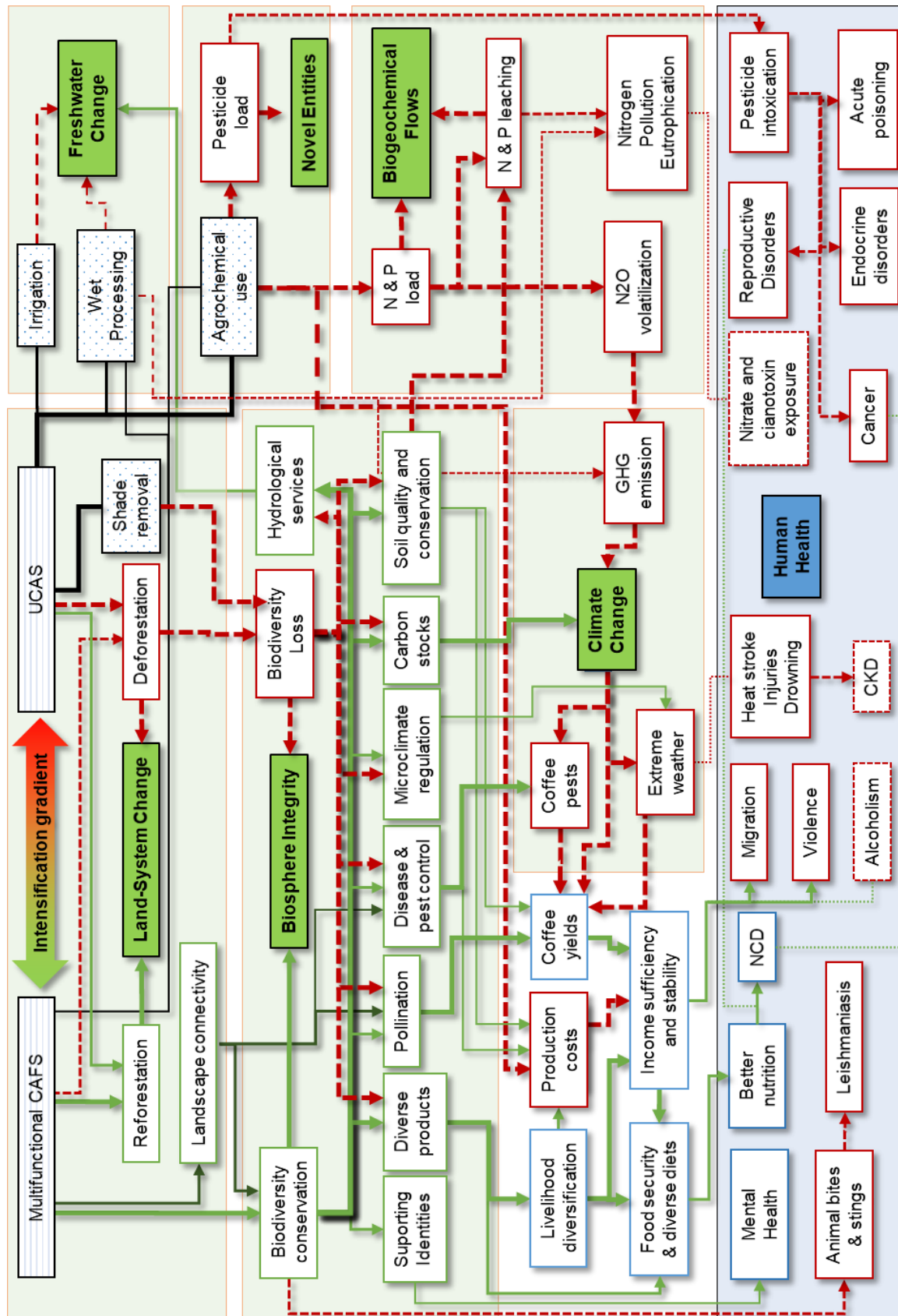


Figure 8. Main impacts of the coffee intensification gradient extremes on the Planetary Boundaries and Human Health. Green continuous arrows: positive impacts; red dashed arrows: negative impacts; black continuous lines: management practices; dotted lines (green and red): theoretical links. The width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

On the other hand, different CAS have both direct and indirect impacts on human health. As with environmental impacts, outcomes are mediated largely by **agrochemical use** and **agroforestry**, which modulate occupational exposures and NCP. Pesticide exposure in intensified CAS poses the most severe risk, with studies linking conventional management to acute poisonings, depression, reduced fertility, endocrine disruption, and elevated cancer risk among farmworkers (Conti et al. 2018; Hutter et al. 2018a, b; Londoño et al. 2018; Moshhammer et al. 2020). Over a hundred pesticides are regularly used in coffee farming in the region, many highly hazardous and persistent after roasting and grinding, with evidence of environmental leakage and impacts on ecosystem and population's health in affected areas (Bedoya P. et al. 2014; de Queiroz et al. 2018; Merhi et al. 2022). The high biodiversity fostered by CAFS, on the other hand, increases contact with wildlife, resulting in stings, snakebites, and a higher incidence of Leishmaniasis (Alexander et al. 2009; Mise et al. 2016; Jimenez-Soto 2021). More evidence is needed to evaluate if the risk of other vector-borne diseases and zoonoses is also increased by CAFS.

Agroforestry also buffers coffee farmers from extreme heat and dehydration, potentially lowering risks for several non-communicable diseases. A major regional concern is chronic kidney disease of unknown origin (CKDu), or "Mesoamerican nephropathy", widely reported among sugarcane workers. While its causes remain debated—including pesticide exposure, heavy metals, and particulate matter—most individual-level studies identify heat stress and dehydration during heavy labor as central risk factors. Importantly, CKDu incidence appears consistently lower among coffee-growing communities and farmworkers than among sugarcane workers or national averages (Laux et al., 2012; Peraza et al., 2012; VanDervort et al., 2014; Schaeffer et al., 2020; Hansson et al., 2021). For instance, one study in a Nicaraguan coffee community above 1000 m found a CKD prevalence of just 0.75%, the lowest recorded nationally (Laux et al., 2012). Arabica cultivation at higher elevations likely offers significant protection from heat stress, while agroforestry and organic management may provide additional safeguards against CKDu and other chronic conditions. Further research is needed to clarify these potential protective effects.

Agroforestry reduces exposure to extreme heat and dehydration among coffee farmers, potentially reducing the incidence of multiple non-communicable diseases. A regional concern is chronic kidney disease of unknown origin (CKDu), or "Mesoamerican nephropathy," widely reported among sugarcane workers. While causes remain debated—including exposure to pesticides and heavy metals—most studies identify heat stress and dehydration during heavy labor as key risk factors. Notably, incidence of CKDu appears consistently lower among coffee-growing communities and farmworkers than among sugarcane workers or national averages (Laux et al. 2012; Peraza et al. 2012; VanDervort et al. 2014; Schaeffer et al. 2020; Hansson et al. 2021). For instance, one study in a Nicaraguan coffee community above 1000 m found a CKD prevalence of just 0.75%, the lowest recorded nationally (Laux et al. 2012). Arabica cultivation usually occurs at higher altitudes and lower temperatures, greatly protecting farmworkers from extreme heat. Further research is needed to clarify the extent to which agroforestry and organic management protect workers' renal function and overall health in CAFS.

Indirect impacts on human health are mediated by broader ecosocial determinants. This review shows that NCP contribute to these determinants in a variety of ways. Higher agrobiodiversity in CAFS reduces agrochemical dependence, buffers climate extremes, reduces losses to pests and diseases, and diversifies livelihood by providing secondary products such as timber, food, firewood, medicinal plants, and honey (Rice 2008; Cerda et al. 2020; Pronti and Coccia 2020; Anderzén et al. 2020). These contributions improve income stability, autonomy, and socioecological resilience. Higher agrobiodiversity in CAFS correlates with better food security and more diverse diets, while specialization in coffee income is linked to both overweight and seasonal caloric insufficiency (Bacon et al. 2014; Fernandez and Méndez 2019; van Asselt and Useche 2022). Livelihood diversification also improved food resilience in Honduran coffee-growing communities during the COVID-19 pandemic. While no specific studies directly address this, it is likewise plausible that this contribution to resilience buffers the documented impacts of other external shocks—such as coffee price drops and

extreme weather– on mental health, migration, and violence. Traditional coffee farming and contact with nature have also been shown to contribute positively to farmers’ quality of life and mental health (Murillo-López et al. 2022; Gasperín-García et al. 2023; Nieto-Betancurt et al. 2024). Traditional coffee farming and contact with nature have also been shown to contribute positively to farmers’ quality of life and mental health (Murillo-López et al. 2022; Gasperín-García et al. 2023; Nieto-Betancurt et al. 2024).

Yet these dynamics unfold within social determinants that fundamentally constrain human and planetary health. Coffee-growing communities are typically remote, underserved, and characterized by limited healthcare access, entrenched patriarchal norms, and lower educational attainment. Most smallholders in Latin America earn below a living income and live in persistent poverty (Panhuisen and de Vries 2023). Landless, seasonal workers that form the backbone of coffee harvest labor face precarious working conditions and occasional violations to their human rights (Gresser and Tickell 2002; Campos 2016). These conditions are not only the result of local and regional trajectories of poverty and inequality, but also of structural inequities embedded within the CVC, manifested in the racialized labor regimes of *fincas*, the unpaid labor of women, the low prices paid to producers –and determined in highly speculative foreign commodity markets–, and the imposition of external development agendas and epistemologies. The state of perpetual vulnerability among coffee smallholders facilitates the imposition of capitalistic solutions –including conventional intensification–, which are ostensibly aimed at alleviating poverty but in practice primarily benefit corporations and investors. Such reliance on crises to justify neoliberal restructuring exemplifies what Klein (2008) described as the “shock doctrine”.

6.2. Equity and Identity in the CVC

The coffee intensification gradient is not only one of management, but also of identity, ethnicity, culture, knowledge, and power structures, as shown by the stark contrast between rustic T-CAFS managed by indigenous communities and the *finca* model. A remarkable difference lies in that, while conventional intensification relies on financial capital, multifunctional agroforestry systems sustain “biocultural capital” –the intertwined ecological and cultural diversity accumulated over generations. The planned increase in agrobiodiversity in T-CAFS is a form of “intensification without simplification” based on farmers’ labor and knowledge, rather than technology (McCune et al. 2021; Mayorga et al. 2022). By preserving agrobiodiversity, genetic resources, and traditional knowledge, multifunctional T-CAFS also foster identity, autonomy, food sovereignty, and resilience. Thus, CAFS are also a source of epistemic resources for transforming global food systems.

On the other hand, coffee intensification in Latin America can only be understood within the context of colonial and neo-colonial subordination of the region, which have imposed persisting hierarchies of peoples, knowledges, and modes of living and relating to nature. These endure in developmental discourses that continue to devalue indigenous knowledge and promote “modernization” agendas centered on farmers’ specialization, agricultural commodification, and conventional intensification based on closed technologies⁴. 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* (Hernandez-Castillo 2001). However, indigenous coffee producers have also found spaces for the preservation, reproduction and reinvention of their identities and biocultural heritage, particularly in producer cooperatives. An example of such is Tosepan Titataniske, which has actively worked to preserve Nahuatl cultural heritage and agroecological knowledge in Mexico through educational projects, the publication of dictionaries, and the documentation of their taxonomic system (González Álvarez 2017).

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.

On the other hand, while low coffee prices have been used to justify intensification, market-based solutions such as certification programs and corporate responsible sourcing have been promoted as ways to address poverty without challenging the underlying structural power asymmetries. Yet the persistence of seasonal hunger among certified producers calls into question the efficacy of these market-based solutions (Morris et al. 2013). Sustainability niches remain small, while the market forces continue to favor cheap, high-volume, environmentally harmful production. Jimenez-Soto (2021) questions if biodiversity conservation can truly benefit farmworkers where structural inequities persist, noting that the narrative of CAFS as spaces of wellbeing contrasts with workers' lived experience of frequent bites and stings from animals like the tropical fire ant. Most seasonal farmworkers can't afford rubber boots and other protective equipment, and prefer to work in UCAS, trading painful stings for pesticide exposure (Jimenez-Soto 2021). The solution lies not in cutting trees and exterminating dangerous fauna, but in ensuring safe working conditions and protective gear, which would mitigate most of the health hazards faced by farmworkers. The fact that most cannot afford them is perhaps the starkest display of the inequities embedded in a global market valued at over US \$200 billion annually (ICO, 2020).

Real equity requires moving beyond market-driven adjustments toward systemic change. Multifunctional coffee farming demonstrates that coffee production and farmer well-being are possible within planetary boundaries –but only within an economic framework that ensures fair prices, empowers historically marginalized producers, protects livelihoods, and recognizes the biocultural foundations of sustainable coffee landscapes.

6.3. Recommended Actions to Protect Planetary Health in Coffee Farming

This review identifies a range of interventions discussed in the literature as potentially relevant for advancing planetary health in coffee farming. While a detailed analysis falls beyond the scope of this review, two cross-cutting principles frequently emerge: agroecological management and equity.

Agroecological practices –such as diverse agroforestry, low-agrochemical or organic management, biofertilizer use, soil conservation, ecological or dry processing instead of wet processing, minimal irrigation, and the intentional use of NCP to sustain productivity and diversify livelihoods– are consistently associated with benefits for both human well-being and the environment (van Rikxoort et al. 2014; Acosta-Alba et al. 2020; Pronti and Coccia 2020; Arellano and Hernández 2023). These practices should be supported and promoted to shift coffee production towards multifunctional CAFS, along with strategies to diversify livelihoods. On the other hand, advancing equity in the coffee value chain requires addressing its three dimensions (Bremer and al. 2021): 1) distributional equity, ensuring a fair share of revenues, rights, and burdens for different actors in the CVC; 2) procedural equity, enabling inclusive, horizontal participation in decision-making processes; and 3) recognition equity, respecting diverse knowledge systems, cultural identities, and values embedded in coffee landscapes.

Governments, farmer organizations, NGOs, commodity corporations, retailers, and consumers can participate in these changes in a variety of ways. Indeed, a system-wide combination of public policies, government and private-led programs, and market incentives is required, as part of a larger food-system transformation. 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.
- Including information on the social and environmental impacts of production in product labeling.

- Promoting a more 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 standard, 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 farmers 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. They promote agroecology, facilitate knowledge exchange, protect biocultural heritage, and improve market and credit access. 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 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 also be redirected to support producers and sustainable practices. Moreover, reaching a new international agreement to control coffee prices could greatly restore producers' and limit the planetary health impacts of overproduction.

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

This review has identified multiple pathways through which coffee farming affects planetary health. These are summarized in the DPSEEA framework (Figure 9), along with recommended actions to reduce health risks, protect ecosystems, and enhance the regenerative potential of coffee farming. These recommendations build on findings from this review and draw from complementary frameworks, including sustainable livelihoods, agroecology, equity, and post-growth.

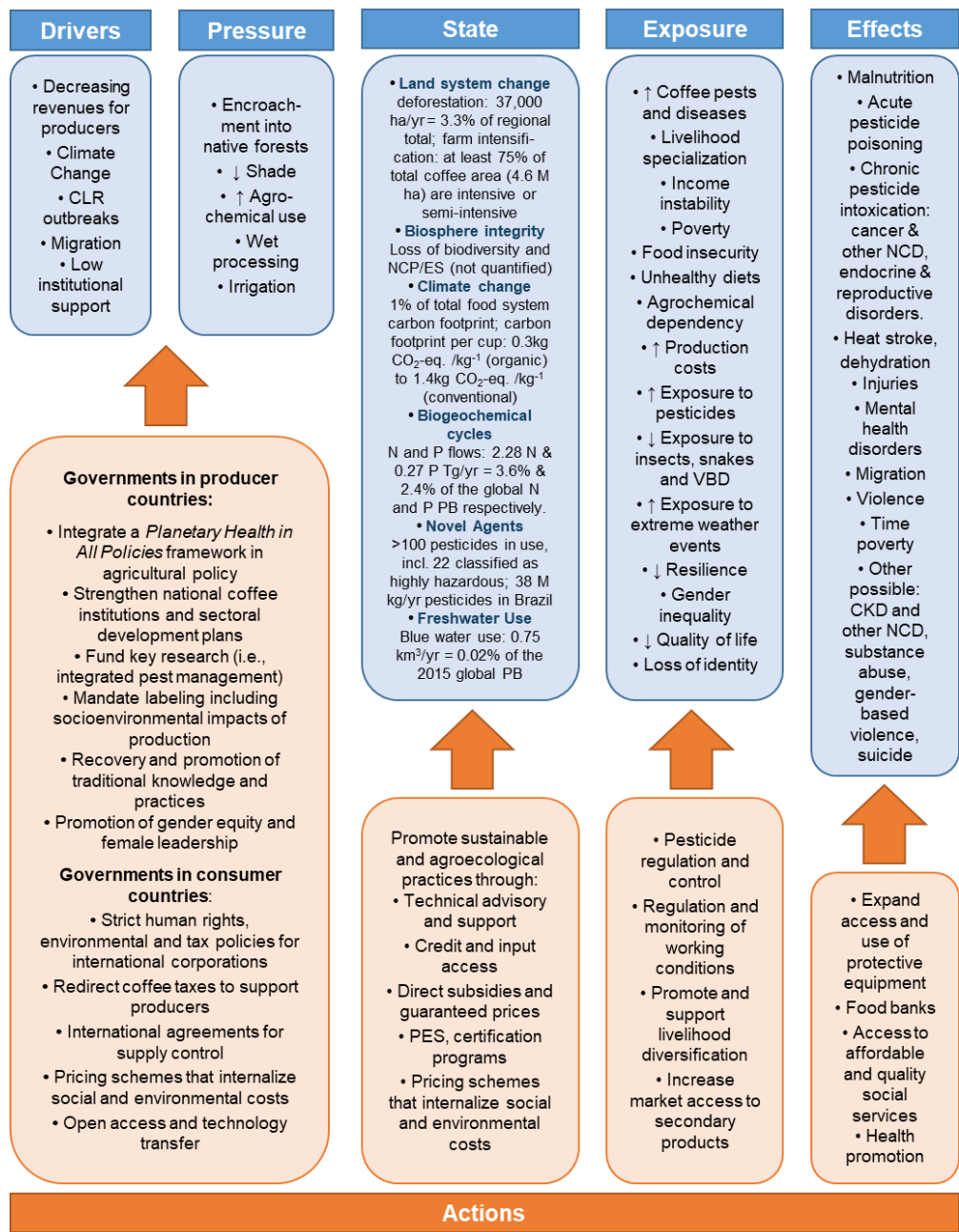


Figure 9. The DPSEEA model of coffee intensification and planetary health. More detailed relationships between the state, exposure and effect elements are shown on Figure 8.

6.5. Strengths, Limitations, and Research Gaps

This review has several strengths. It advances a novel synthesis by integrating analytical frameworks such as Planetary Boundaries, Nature’s Contributions to People and DPSEEA, providing a comprehensive lens to assess coffee farming in relation to Planetary Health. It draws on a wide range of disciplines, linking ecological, agronomic, epidemiological, and socio-political perspectives, contributing to bridging fragmented fields of research. Finally, while focused on Latin America, the study provides insights for global debates on sustainable food systems.

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 results that may have been found in other databases. Results were sorted and screened by relevance, a subjective method that excluded almost 300 papers, many of which may have included relevant data. No formal study quality appraisal was conducted, and the reliance on narrative synthesis limits the assessment of the weight of evidence across themes. Additionally,

results in Portuguese were excluded, a significant limitation given that Brazil is the main coffee producer in the region, particularly in intensified CAS. Although efforts were made to include a broad disciplinary scope, social sciences are likely under-represented in the used databases. 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 several key research gaps. Critical environmental gaps include updated measurements of deforestation linked to coffee, the current extent of shade-coffee systems, the genetic diversity and resilience of native coffee seeds, and sustainable cultivation methods for Robusta. Data on the health status of coffee-growing communities is also scarce, particularly regarding mental health, substance use, violence, gender-based violence, migration, suicide, infectious and vector-borne diseases, food security, and nutrition. The role of coffee agroecology in modifying these and other risks remains critically underexplored. Finally, more research is needed on indigenous knowledge and practices, ecological pest control mechanisms (especially for CLR), the impact of public policies on planetary health-related outcomes in coffee landscapes, and the development of pilot projects to assess strategies for supporting 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. In contrast, multifunctional agroforestry coffee farming demonstrates the potential to reconcile production with environmental sustainability and human well-being, while offering pathways for resilience and cultural continuity. However, persisting structural inequities in the global CVC remain a central barrier. 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.

Finally, coffee farming also offers a case study for understanding the interconnections between livelihoods, ecosystems, and health in the Anthropocene. The tensions observed in coffee between intensification and sustainability, well-being and global trade, equity and profit are not unique, but characteristic of broader challenges across tropical agriculture. As such, the lessons drawn from coffee landscapes may inform pathways toward more sustainable, healthy and equitable food systems.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org. 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.

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