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Brewing sustainability: Quantifying agricultural R&D investment gaps in the Global coffee sector

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ABSTRACT

The global coffee sector faces heightened risk, with production concentrated in a few countries, yields stagnating or declining, and climate change projected to shrink suitable growing areas. Using data from 41 major coffee-producing countries in the Global South, we develop scenario-based projections of demand growth, climate impacts, and shifts in market shares, and apply an economic model linking yield growth to research and development (R&D) investments to estimate the investment gap. Current coffee R&D spending—about $140 million annually (2020 USD)—is well below the level suggested by coffee's share in agricultural output. Across six demand–climate scenarios and two supply diversity assumptions, we estimate that an additional $10–$225 million per year would be needed if production becomes more concentrated, and $126–$405 million to maintain current diversity. Most new investment would be required in historically underfunded regions—Asia (excluding Vietnam), Africa, and Latin America and the Caribbean (excluding Brazil and Colombia)—where productivity gains are costlier but vital for sustaining supply. Closing this gap is both affordable and urgent: in a $200 billion industry, the cost is negligible for consumers yet critical for safeguarding diverse origins, protecting smallholder incomes, and averting deforestation. Achieving it will require coordinated financing—through producer/import levies, public–private partnerships, and regional research consortia—targeted to underfunded regions. Without such action, the future of coffee will be less diverse, less resilient, and more vulnerable to climate shocks.

1. Introduction

Coffee is the world's most favored beverage, generating an estimated total annual revenue of $200–250 billion [1,2]. The main ingredient, coffee beans, is harvested from >12 million hectares globally [3], with about 60 % produced on farms smaller than five hectares ([4], as cited in [5]). Coffee provides income for millions of smallholder farmers living close to the poverty line, generates employment in their communities, and delivers significant export revenues for predominantly low-income producing countries [4,6–9]. These attributes make coffee strategically important for achieving several Sustainable Development Goals (SDGs), particularly SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 8 (Decent Work and Economic Growth), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

Over the past three decades, coffee production has become increasingly concentrated in three major producers: Brazil, Vietnam, and Colombia (the "Big 3″) [5,10]. These countries have consistently outperformed the rest of the coffee-producing world ("ROW") in productivity growth, supported by relatively strong agricultural research and development (R&D) systems, better access to improved varieties and agronomic practices, and in some cases favorable policy and institutional environments [11]. Colombia's productivity performance, for example, has strengthened in recent years as the country emerged from internal conflict, benefiting from a producer-supported research and extension system [12,13].

In most ROW countries, however, productivity has stagnated or declined [14,15]. The increasing concentration of production in the Big 3 is related to a reduction in origin diversity[1]([16]; Ngure & Watanabe, 2024), narrowing the range of flavors and market options while increasing systemic risks to supply stability. Recurrent low farmgate prices and unequal value-chain distribution further strain the livelihoods of producers already confronting poverty and food insecurity [17,18]. Climate change compounds these pressures by reducing land suitability, increasing pest and disease pressures, lowering yields and

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[1] Throughout this paper, diversity in the context of coffee refers to geographic origin diversity.

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quality, and driving potential deforestation as production shifts to new areas [2,10,19–26].

The increase in global coffee demand adds to these pressures. Consumption has grown by 2.0–2.5 % annually and is expected to continue rising throughout the 21st century [27], driven by demographic change, income growth, shifts in beverage preferences in traditional tea-consuming countries, the expansion of e-commerce, and product innovation ([28]; World Coffee [29]). Meeting projected demand could require doubling or tripling production by 2050. Without productivity gains, this would likely involve large increases in cultivated area, with implications for deforestation, greenhouse gas emissions, and loss of origin diversity [30].

This study addresses a central question: how much additional agricultural R&D investment is needed for the ROW to sustain or increase its share of global coffee supply under plausible scenarios of demand growth, climate change, and market concentration? To answer this, we assemble new, country-level estimates of coffee R&D investment and intensity—drawing on both public and private sources—and apply an economic model that links yield growth to research investment to quantify the investment gap. The analysis covers major coffee-producing countries in the Global South, representing over 95 % of global production and 99 % of exports.

Our contribution is threefold. First, we provide the most comprehensive and up-to-date estimates of coffee R&D investment in the Global South, incorporating recent data from private-sector and international research organizations. Second, we develop a scenario-based modeling framework that explicitly links R&D investment needs to market-share outcomes under varying demand, climate, and supply diversity assumptions. Third, we identify regional priorities by pinpointing where additional R&D resources would have the greatest impact on sustaining competitiveness and preserving geographic diversity in global coffee supply chains.

By quantifying the scale, distribution, and urgency of investment needs, we offer a clear, evidence-based foundation for designing targeted financing mechanisms and collaborative research strategies that can secure a resilient and diverse global coffee sector.

In this analysis, agricultural R&D investment refers to public and private funding for coffee research in producing countries of the Global South, including South and Southeast Asia (and Pacific islands), sub-Saharan Africa, and Latin America and the Caribbean (LAC). The scope includes innovations in coffee production through improvements in varieties (tree stock), cultural and management practices (agronomy, land and water resources, irrigation, soil fertility, pest control), farm operations (planting, weeding, harvesting, on-farm or near-farm cherry processing), and marketing systems that connect producers to markets. Although other thematic areas (e.g., renovation and rehabilitation, social protection, and financial technologies) also contribute to sector sustainability, this study focuses on production-oriented agricultural R&D for three main reasons.

1) **Innovation as a driver of productivity**. Technological change, typically measured as total factor productivity (TFP) gains, is a major source of long-term agricultural growth [31–34]. Advances such as disease-resistant varieties, precision agriculture, biological pest control, drip irrigation, soil-health monitoring, and regenerative practices have been transformative in other crops [35,36].
2) **Smallholder relevance.** Smallholders produce 66–80 % of global coffee [6], so productivity gains directly affect rural incomes and poverty reduction [37].
3) **Evidence of underinvestment.** We estimate that current coffee R&D investment in the Global South at approximately $140 million annually (in 2020 USD), which represents about 2 % of total agricultural R&D spending in these countries. Compared to coffee's 4.2 % share of agricultural output value, this suggests a sizable disparity relative to a parity-based allocation rule [38] (see Supplementary Appendix A for calculation details).

The remainder of this paper describes the methods (Section 2), presents results on regional investment needs (Section 3), discusses implications (Section 4), and concludes with key messages (Section 5).

2. Method

2.1. Defining the scope

The analysis covers 41 coffee-producing and exporting countries that together represent over 95 % of global coffee production and 99 % of green coffee exports. These countries form the basis for the demand, climate change, and market-share scenarios evaluated in this study. We classify them into four regional groups: (1) Big 3—Brazil, Vietnam, and Colombia; (2) Asia (excluding Vietnam, including Pacific islands); (3) Africa; and (4) Latin America and the Caribbean (LAC, excluding Brazil and Colombia). A full country list and descriptive statistics are provided in Supplementary Appendices B and C.

Globally, two main coffee species dominate production: Arabica (*Coffea arabica*) and Robusta (*C. canephora* var. *robusta*), accounting for roughly 60 % and 40 % of output, respectively. While these species differ in climate adaptability, yield potential, pest susceptibility, and bean quality [39,2], the lack of high-resolution, species-specific production data at the country level means our investment gap estimates are aggregated for total coffee production. This is acknowledged as a limitation.

2.2. Scenario construction

Our methodological approach constructs two demand scenarios—a business-as-usual (BAU) growth rate of 2 % per year and a higher-demand scenario of 2.65 % per year—and three climate scenarios (no climate impact, yield-only decline, and combined yield-plus-area decline). Combining these yields six possible futures defined in a 2 × 3 matrix (Fig. 1).

These six scenarios represent a combination of plausible ranges of future trends in coffee consumption and production based on an extensive review of the literature and our analysis of documented trends in coffee area, production, and yield.

2.2.1. Demand scenarios

The baseline scenario assumes demand will grow by approximately 80 % by 2050, equivalent to a compound annual growth rate (CAGR) of 2 %, which matches the average global coffee production growth rate over the past 30 years (1990–2020). In the last decade (2010–2020), the documented growth rate in production was 2.65 % per year, and in the last five years it was 3.5 % per year. Assuming production and demand have been in equilibrium over this period (i.e., no sustained surplus or deficit), these historical production growth rates serve as proxies for long-term demand growth. Accordingly, we use 2 % per year for the BAU demand scenario and 2.65 % per year for the high-demand scenario.

Multiple studies provide projections that support the plausibility of these rates, though with some variation. For example, Bunn et al [40] estimate a 180 % increase in global coffee demand between 2010 and 2050, equivalent to an annual growth rate of 2.68 %. Kileen and Harper [28] and Conservation International [7] present scenarios to 2050 ranging from 1 % to over 2.5 % annually. Sachs et al [2] project a 13 % increase between 2020 and 2030 (1.36 % annually), while Mordor Intelligence [41] anticipates a much higher 4.65 % CAGR from 2022 to 2027, citing rapid consumption growth in emerging markets.

Taken together, these projections point to a robust upward trend in global coffee demand over coming decades, driven by demographic shifts, income growth, evolving beverage preferences, e-commerce expansion, and product innovation. For this analysis, we adopt the 2.65 % annual growth rate as a realistic yet conservative upper-bound scenario, excluding projections below 2 % as unlikely

		Demand Scenarios	
		Baseline: Consumption increases 2%/year (i.e., 81% by 2050)	Consumption increases by 2.65%/year (i.e., 114% by 2050)
Climate change (CC) Scenarios	Baseline: No climate change effects	Business-as-usual (BAU)	High demand, no climate change
	Yield declines by 0.25%/year; area increases at historical rate (i.e., 0.21%/year or 8.6% by 2050)	Low demand, yield decline	High demand, yield decline
	Yield declines by 0.25%/year and area declines by 0.46%/year (or 12.6% by 2050)	Low demand, yield + area decline	High demand, yield + area decline

Fig. 1. Demand and climate change scenarios for investment gap analysis.

2.2.2. *Climate change scenario*

The literature on climate change and coffee production identifies two primary pathways of impact: (i) reductions in suitable cultivation area and (ii) declines in yield. Projections vary in magnitude but generally point to significant constraints on production potential by mid-century. For example, Bilen et al [14] report a substantial decline in suitable coffee-growing areas under climate change, while Imbach et al [42] estimate that each 1 °C increase above the optimum during the growing season could reduce Robusta yields by 14 %. Yield losses may also be exacerbated by greater pest and disease pressure, particularly from the coffee berry borer [43], whose range is expected to expand with rising temperatures and altered humidity patterns.

For scenario construction, we adopt the global, net-impact estimates from Sachs et al [2], which incorporate both area expansion in some countries and contraction in others. Their analysis suggests a 13 % global reduction in planted area and a 7 % decline in yield by 2050. In annualized terms, this equates to a 0.46 % per year decline in area and a 0.25 % per year decline in yield over the 28-year projection period (2021–2050).

Other studies have projected larger potential losses. For instance, Kileen and Harper (2018) forecast a ~50 % reduction in suitable area by 2050. However, they note that global availability of suitable land would still exceed projected needs—though about 60 % of this land is currently under natural forest cover. This implies that offsetting climate-related area losses by expanding into new suitable areas would likely result in significant deforestation, especially in the Andes and Southeast Asia.

Based on these considerations, we construct three climate-related production scenarios:

1. **No climate change effect** – yields and area follow historical growth rates.
2. **Yield decline only** – yields decline by 0.25 % annually; area grows at historical rates.
3. **Yield and area decline** – yields decline by 0.25 % annually; area declines by 0.46 % annually.

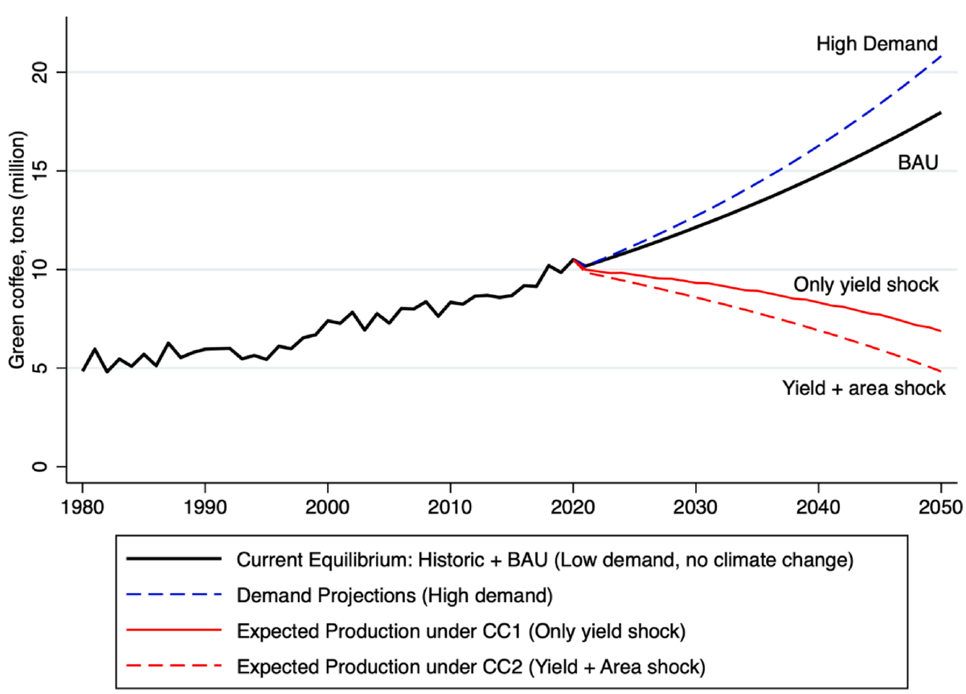

Fig. 2. Historical coffee production (1980–2020) and projections under future demand scenarios (BAU and high) and climate change scenarios (no climate change, only yield decline, yield + area decline) (2021–2050).
Source: Authors' calculations.

We assume that climate-related supply reductions will have minimal effect on global coffee prices in the medium term, given the commodity's low price elasticity of demand (−0.08 for Arabica; −0.15 for Robusta; [2]) and the capacity of major producers, particularly Brazil, to expand production [44]. Consequently, demand growth rates in our scenarios are treated as independent of these modest price effects.

The two demand and three climate change scenarios (including the base scenario of no climate change effect) are combined to produce one BAU and five additional scenarios, as shown in Fig. 1. To help visualize these scenarios, in Fig. 2, we present the historical production trend from 1981–2020 and projections over the next thirty years based on the two demand and three climate change scenarios. Starting in 2021 (Fig. 2), the solid black line shows the projected demand/supply under business-as-usual increases in demand and no climate change effects on coffee production. The dashed blue line represents projected demand if coffee consumption increases by 2.65 %/year (instead of 2 %/year) in the future. The solid and dashed red lines project future production if yields decrease by 0.25 %/year and additionally if the area also decreases by 0.46 %/year because of climate change impacts.

The vertical distance between any two projected demand and production trend lines implies a supply gap that needs to be filled by increasing production. The primary source of this production increase is expected to come from increases in yield. A major contributor to yield growth is an increase in total factor productivity, which requires investments in R&D and the implementation of adaptation strategies. These strategies include breeding more resilient coffee varieties, developing better soil, crop, and pest management practices, better harvesting and post-harvest handling practices, and potentially shifting cultivation to more suitable areas [43]. Estimating the required R&D investments to increase productivity to fill these projected supply gaps under different scenarios is the focus of the economic analysis described below. But we first discuss the construction of two coffee supply diversity scenarios, which will define how the supply gap is met across regions.

2.2.3. *Scenarios on diversity of the coffee supply chain*

In addition to demand and climate change projections, we incorporate assumptions about future geographic concentration of coffee production, given its implications for both market diversity and regional investment needs. Over the past three decades, production has become increasingly concentrated in the three largest producers—Brazil, Vietnam, and Colombia ("Big 3″)—a trend likely to continue if current productivity differentials persist.

We model two contrasting market-share scenarios:

1. **Increased concentration** – The production share of the Big 3 rises from 58 % in 2020 to 79 % by 2050. The remaining share is distributed across Asia (excluding Vietnam, 10 %), Africa (5 %), and Latin America and the Caribbean excluding Brazil and Colombia (LAC, 7 %). This scenario reflects a continuation of historical trends, with the Big 3 maintaining stronger productivity growth, and implies reduced geographic and flavor diversity in the global coffee supply (outer ring, Fig. 3). This outcome is more likely but less desirable from the standpoint of maintaining origin diversity.
2. **Maintained diversity** – Regional production shares remain at 2020 levels: Big 3 at 58 %, Asia 14 %, Africa 12 %, and LAC 16 % (excluding Brazil and Colombia). This scenario assumes productivity growth in other regions is sufficient to sustain current market shares, preserving geographic diversity (inner ring, Fig. 3). This outcome is less likely but more desirable for sustaining diverse coffee origins.

These scenarios are intended to capture a plausible range of supply distribution outcomes. They do not assume specific policy interventions, but differences in projected market shares that directly influence the estimated R&D investment required in each region to close future supply gaps.

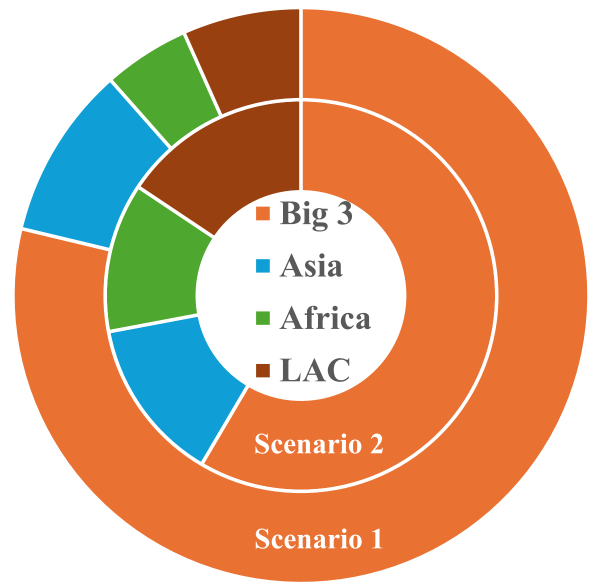

Fig. 3. Market share projections under the assumption of shifting coffee supply chain towards more productive regions (market share scenario 1-Declining diversity) and remaining at the current level (market share scenario 2-Constant diversity). Regions are grouped into the Big 3 (Brazil, Vietnam, Colombia), Asia excl. Vietnam, Africa, and LAC (excl. Brazil and Colombia).
Source: Authors' calculations.

2.3. *Deriving exogenous yield shock variable*

For each combination of demand, climate, and market-share scenarios, we first estimate the total production required to match projected demand in 2050. We then compare this target with projected production under BAU trends for yield and area, obtaining the additional production needed to close the gap.

Because the primary lever for increasing production in most coffee-producing countries is yield growth rather than area expansion, we convert this additional production requirement into an annual, region-specific yield growth rate ($\hat{y}$) for the period 2021–2030. This represents the exogenous "shock" to yield growth that would be required to meet demand under each scenario.

The yield requirement is expressed relative to a reference period (2019–2020), ensuring that the calculated growth rates are anchored to the most recent historical baseline. This approach allows differences across scenarios to be attributed directly to variations in demand growth, climate change impacts, and market-share assumptions, rather than to historical volatility in yields or planted area.

These scenario-specific yield growth rates ($\hat{y}$) are then used as inputs in the economic model described in Section 2.4 to estimate the additional agricultural R&D investments (ΔR) required in each region to close the gap.

2.4. *Economic analysis*

Our economic analysis links the yield growth requirements derived in Section 2.3 to the additional agricultural R&D investment needed to achieve them. The process follows two main steps: (i) estimating key model parameters from historical data and (ii) applying these parameters to project investment needs under each scenario.

2.4.1. *Step 1-Estimating historical model parameters*

We begin by estimating the following parameters, which serve as inputs to the investment gap calculations:

a. Yield growth rate (y): Coffee yield is defined as the ratio of total production (Y) to total area harvested (HA), and measures land productivity (Eq. (1)). Data for production and harvested area is from FAOSTAT.

$$\text{yield} = Y/\text{HA} \quad (1)$$

Region specific yield growth rates (y) are estimated using the following regression model:

$$\text{Ln}(\text{yield}_t) = a + y * \text{Year}_t + \text{errorterm} \quad (2)$$

To allow sensitivity analysis, estimated model coefficients for two time periods are presented in Table 1—t = 1981–2020 (Panel A1) and t = 1991–2020 (Panel A2). Note that regional values for any parameter that is a ratio of two variables, such as yield, are weighted (and not arithmetic) means. They are calculated based on the regional sum of numerator values (in this case production) divided by the total regional sum of the denominator values (in this case area under cultivation).

b. Input growth rate (*x*): To construct the input index, we used data from 1981 to 2020 on land, labor, capital, and materials available from the USDA's website for the whole agriculture sector for nearly every country in this world [45]. These inputs are defined as:

- *Land*: Quality-adjusted agricultural area, 1000 hectares of "rainfed-equivalent cropland"
- *Labor*: Number of economically active adults (male & female) primarily employed in agriculture
- *Capital*: The value of net capital stock, $1000 at constant 2015 prices. This includes machinery stock, animal stock, and tree stock.
- *Material*: This includes two intermediate inputs–fertilizer and feed. In our case, we only included fertilizer input measured as total N, P2O5, and K2O nutrients from inorganic fertilizers, and N from organic fertilizers applied to soils, in 1000 t

We made the following adjustments to estimate the input index for coffee. Land was measured as the total coffee area harvested sourced from FAOSTAT. For labor, capital, and material (i.e., fertilizer) inputs, we first calculated the quantities of these inputs on a per-hectare basis using the total land for all agricultural production from the USDA data. Then, we generated the quantities of labor, capital, and material (i.e., fertilizer) applied to coffee by multiplying per ha labor, capital, and fertilizer input to coffee harvested area. However, the intensity of these inputs for coffee can vary significantly from the overall agricultural sector. Therefore, we made the following adjustments to reflect the input use intensities in coffee.

First, we assumed fertilizer use per hectare in coffee is approximately 50 % of the agriculture sector average. This adjustment reflects prevalent smallholder agroforestry systems (e.g., shade-grown coffee) that rely on natural nutrient cycling and use less synthetic fertilizer than full-sun, high-input cropping systems [46]. While comprehensive crop-specific fertilizer data are limited, evidence indicates that shaded coffee systems require fewer external inputs [47]. Second, we also made downward adjustments in capital input, which is composed of fixed capital (machinery), animal stock, and tree stocks. We assume machinery used per ha of coffee land is 50 % of what is used in the overall agricultural sector. But tree stock per ha is 100 %, and livestock used is 0 %. The paper by Butzer et al [48] reports estimates of tree stock, animal stock, and fixed capital shares of total agricultural capital in middle- and low-income countries by decades (Table 2).

We apply these shares to estimate the average capital stock per ha used in coffee, as shown in Table 3. These percentages vary from 52 % in the 1980s to 65 % in the 2000s.

After calculating the total land, labor, capital, and material inputs for coffee (in physical units), the next step involved generating decade-specific growth rates for each input and averaging them using factor cost shares, as weights. These weighted growth rates represent the growth rate in the total input index. The factor cost shares for each decade are available in the USDA database. We adjusted these decade-specific agriculture sector-wide cost shares for coffee to reflect its relatively lower capital and fertilizer use compared to other commodities. Specifically, we reallocated 40 % of the capital cost share to labor and 50 % of the fertilizer cost share to land.

The decade-specific total input growth rates were then used to construct an input index using 2015 as the base year (=100). The average growth rate in inputs used in coffee (x) was then estimated using the following regression model.

$$\text{Ln}(\text{input}_t) = a + x * \text{Year}_t + \text{errorterm for } t = 1981 - 2020 \quad (3)$$

Estimated model coefficients for Eq. (3) are presented in Table 1, Panel B.[2]

c. Total Factor Productivity (TFP) growth (*g*): After estimating the historical yield growth rate (y) and input growth rate (x) as explained above, we calculated TFP growth, g, as the ratio of these two values.

$$g = y/x \quad (4)$$

d. R&D investments—historic (R_t) and reference year (R_o): A critical input for estimating future R&D investment needs is the level of investment in the reference scenario (R_o). In this study, we define agricultural R&D investments as expenditures—by both public and private actors—on systematic, science-based activities aimed at generating new knowledge, technologies, and management practices that improve coffee production. This definition is consistent with the scope of agricultural R&D adopted in major R&D monitoring frameworks, such as the OECD Frascati Manual [49] and the African Union Biennial Review Technical Guidelines [50] for tracking agricultural innovation investments, which encompass basic and applied research as well as experimental development targeted at agricultural production systems.

For comparability across regions, we apply a uniform scope that includes: 1) National public sector: primarily National Agricultural Research Systems (NARS) in each producing country; and 2) International private and public sector: organizations such as World Coffee Research (WCR), one multinational company, and a French research institute working on tropical crops (including coffee) in producing regions of the Global South. The geographic coverage includes South and Southeast Asia (including Pacific islands), sub-Saharan Africa, and Latin America and the Caribbean.[3]

Within this scope, coffee R&D investments include work on genetic improvement (varieties, tree stock), agronomy (soil, water, nutrient, and pest management), farm operations (planting, harvesting, post-harvest handling), and adaptation/mitigation practices for climate change. They do not include downstream processing, marketing, or consumer-oriented product development.

We estimate reference-period (2019–2020) and historical levels of coffee R&D from two main sources: the Agricultural Science and Technology Indicators (ASTI) and World Coffee Research (WCR), supplemented by direct communications with private sector actors and

[2] In the investment gap analysis, the estimates are not sensitive to variation in the value of parameter x (input growth). This is because x affects the gap through two offsetting pathways: it enters negatively into TFP growth and elasticity (both of which increase the gap when lower), but also reduces the required future TFP growth rate and θ (both of which reduce the gap when lower). These opposing effects largely cancel each other out, minimizing sensitivity to x. By contrast, yield growth has consistent negative effects on the gap through all channels—TFP growth, elasticity, required TFP growth, and θ—making the estimates highly sensitive to yield assumptions. For this reason, only a single estimate for x is presented and applied in the model. Likewise, we do not conduct sensitivity testing on the assumptions underlying the input index—for example, the assumption that fertilizer use in coffee is 50 % of the average across other agricultural sectors.

[3] Coffee is also produced in developed countries like the US, where some level of investments is occurring on production-oriented coffee R&D (Fuglie, personal communication, 2022). However, in this analysis we exclude USA and several other small coffee producing countries from the R&D investment estimations.

Table 1
Growth rate estimates for coffee yield and input index based on regression analysis.

	Big 3	Asia (excl. Vietnam)	Africa	LAC (excl. Brazil & Colombia)	All
	Panel A1: Dependent variable=ln(Yield) – 1981–2020				
Year	0.030*** (0.002)	0.001* (0.001)	0.004*** (0.001)	0.002*** (0.001)	0.016*** (0.001)
Constant	−59.912*** (4.249)	−3.097** (1.357)	−9.192*** (2.355)	−3.857*** (1.304)	−32.977*** (1.925)
Observations	40	40	40	40	40
R-squared	0.891	0.076	0.224	0.123	0.916
	Panel A2: Dependent variable=ln(Yield) – 1991–2020				
Year	0.035*** (0.001)	0.002* (0.001)	0.0003 (0.001)	0.002** (0.001)	0.016*** (0.001)
Constant	−69.872*** (2.177)	−4.031* (2.032)	−1.595 (3.629)	−4.910** (2.061)	−32.977*** (1.925)
Observations	30	30	30	30	30
R-squared	0.964	0.087	0.0015	0.114	0.916
	Panel B: Dependent variable=ln(input)				
Year	0.010***	0.016***	0.020***	0.013***	0.0132***
	(0.002)	(0.002)	(0.002)	(0.000)	(0.001)
Constant	−15.635***	−28.161***	−36.015***	−21.030***	−22.117***
	(4.068)	(4.584)	(3.246)	(0.607)	(1.367)
Observations	40	40	40	40	40
R-squared	0.466	0.636	0.864	0.979	0.917

Notes: Each column in each panel represents a separate regression model. Model estimators across all panels are OLS. Number of observations corresponds to number of years included in the regression analysis. Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 2
Shares of fixed capital, livestock, and tree stock in total agricultural capital in middle- and low-income countries by decades.

	1970s	1980s	1990s	2000
Fixed capital	0.27	0.32	0.35	0.36
Livestock	0.28	0.32	0.28	0.17
Tree stock	0.45	0.36	0.37	0.47

Source: Butzer et al [48], Table 15.3.

Table 3
Calculation of average capital stock per ha used in coffee as a percentage of total agricultural capital stock, by decade.

Decade	Average capital stock used per ha of coffee as a % of total capital used in the agriculture sector
1980s	36 % + 0.5 × 32 % = 52 %
1990s	37 % + 0.5 × 35 % = 54 %
2000s	47 % + 0.5 × 36 % = 65 %

Source: Authors' calculation (see the explanation in the text).

international research organizations. Full details on the data harmonization, allocation methods, and adjustments are provided in Supplementary Appendix A.

For the model estimation, we require the historical growth rate (r) of coffee R&D investment, estimated via:

$$\ln(R_t) = a + r * \text{Year}_t + \text{errorterm} \quad (5)$$

We estimate r for two periods (1991–2020 and 1995–2020), with results reported in Table 4, Panels A1 and A2. Two timeframes were used to test the sensitivity of results to the length of the estimation period; the shorter window was chosen arbitrarily but ensures a meaningful contrast while retaining sufficient statistical power.

e. Knowledge stock: In our model, the TFP growth is linked to R&D investments through the concept of knowledge stock (K), which is unobservable. The knowledge stock is the capital input in the TFP production function. It is a cumulative sum of past R&D investment lagged n years, that is depreciating at a rate d. We used the method explained in Rosegrant et al [51] (see their Appendix J) based on work by Nin-Pratt et al [52] and Nin-Pratt [53] to construct historical K_t and reference year K_o as follows.

$$K_t = K_{t-1} * (1 - d) + R_{t-n} \quad (6)$$

$$K_o = R_o * [(1 + r) / (r + d)] \quad (7)$$

Where R_o is R&D investment in the reference year (2019–2020), r is the growth rate of R&D investment (from Eq. (5)), d is the depreciation rate of knowledge capital, and n is the research lag. In the literature, assumptions about n vary from 10–14 years, with some crops and types of research requiring a longer time lag between research and adoption, such as tree crops and more basic research. Given the long lifecycle of coffee trees, we assume n to be 14 years in our analysis. The rate of decay is also related to the type of research, and the literature discusses values of d in the range of 0.05 to 0.25, with values of 0.15 most used [51]. We follow the literature and assume the knowledge capital depreciation rate is 0.15 for coffee research.

To estimate the growth rate in knowledge capital, we construct historical K_t making a bold assumption that investments in coffee R&D began in 1980. Given our assumption of $n = 14$ years, we then construct historical K_t using Eq. (6) noted above as follows:

$$K_t = R_t \text{ for } t = 1981 \quad (8)$$

$$K_t = K_{t-1} * (1 - d) \text{ for } t = 1982 - 1994 \quad (9)$$

$$K_t = K_{t-1} * (1 - d) + R_{t-n} \text{ for } t = 1995 - 2020 \quad (10)$$

To construct this series, we need estimates of R from 1981 to 1994. We use the estimated growth rates of R&D investment from Eq. (5) and project-back coffee R&D for years 1981 to 1994.

Note that knowledge stock is measured in the same unit as R&D (i.e., in constant 2020 US$), and for any given year t, it can theoretically range from R_{t-n} (if knowledge is transient—i.e., if $d = 1$) to ($K_{t-1} + R_{t-n}$) (if knowledge does not decay at all—i.e., if $d = 0$).

The growth rate in knowledge capital (k) is then estimated using regression analysis using Eq. (11). For sensitivity analysis, the estimated coefficients for k corresponding to two underlying assumptions of r (growth rate in R&D investment) are presented in Table 4, panels B1 and B2.

$$\ln(K_t) = a + k * \text{Year}_t + \text{errorterm for } t = 1995 - 2020 \quad (11)$$

f.Relationship between TFP growth and knowledge stock (e): This is the model parameter that links TFP to R&D investments through changes in the knowledge capital stock. Again, the literature offers some potential values of e that have been applied in other similar analyses. Rosegrant et al [51] provide the estimates of e used in their study (see Table J-1 in Appendix J of [51]) based on the work by Evenson and Gollin [37]. Their estimates are for all agricultural R&D and range (for combined CGIAR and NARS generated knowledge stock) from 0.08 for the Middle East and North Africa region to 0.25 for sub-Saharan Africa. We are unable to use these estimated values for coffee since there are no

Table 4
Growth rate estimates for research expenditures and knowledge stock based on regression analysis.

	Big 3	Asia (excl. Vietnam)	Africa	LAC (excl. Brazil & Colombia)	All
	Panel A1: Dependent variable=ln(R) – 1991–2020				
Year	0.019*** (0.002)	0.012*** (0.004)	0.020*** (0.001)	0.017*** (0.002)	0.017*** (0.002)
Constant	−35.200*** (4.346)	−21.821*** (7.473)	−37.694*** (3.544)	−32.249*** (4.287)	−30.226*** (4.155)
Observations	30	30	30	30	30
R-squared	0.746	0.354	0.932	0.816	0.777
	Panel A2: Dependent variable=ln(R) – 1995–2020				
Year	0.021*** (0.003)	0.022*** (0.004)	0.023*** (0.001)	0.022*** (0.001)	0.022*** (0.002)
Constant	−39.614*** (6.076)	−40.408*** (7.433)	−43.789*** (2.009)	−42.026*** (2.211)	−39.662*** (4.218)
Observations	26	26	26	26	26
R-squared	0.724	0.714	0.974	0.953	0.877
	Panel B1: Dependent variable=ln(K)—1995–2020 \a				
Year	0.058*** (0.010)	0.039*** (0.011)	0.059*** (0.010)	0.049*** (0.010)	0.052*** (0.010)
Constant	−112.447*** (20.417)	−74.448*** (22.205)	−113.189*** (19.868)	−94.838*** (20.735	−99.188*** (20.741)
Observations	26	26	26	26	26
R-squared	0.733	0.495	0.741	0.644	0.675
	Panel B2: Dependent variable=ln(K)–-1995–2020 \a				
Year	0.058*** (0.010)	0.052*** (0.011)	0.061*** (0.010)	0.065*** (0.010)	0.057*** (0.010)
Constant	−112.001*** (20.661)	−99.033*** (21.618)	−117.951*** (19.754)	−125.717*** (19.288)	−110.232*** (20.493)
Observations	26	26	26	26	26
R-squared	0.725	0.644	0.759	0.792	0.724

Notes: Each column in each panel represents a separate regression model. Model estimators across all panels are OLS. Number of observations corresponds to number of years included in the regression analysis. Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.
\a Panel B1 is based on knowledge stock constructed using R&D growth rates from Panel A1 to estimate R&D from 1981–1990. Panel B2 is based on knowledge stock constructed using R&D growth rates from Panel A2 to estimate R&D from 1981–1994.

significant investments in coffee research by CGIAR or any other international research organization at a scale of CGIAR. We, therefore, take the traditional production function approach explained by Rosegrant et al [51], whereby the relationship between TFP and knowledge capital is expressed as:

$$\mathrm{TFP} = \mathrm{A} = \mathrm{K}^{e}\mathrm{Z}^{m} \tag{12}$$

The coefficient e measures the elasticity of output with respect to own R&D capital (K), and Z represents other factors affecting TFP. Productivity growth is expressed, after taking logs of (12), as:

$$\mathrm{dA}/\mathrm{A} = e\,(\mathrm{dK}\,/\,\mathrm{K}) \tag{13}$$

Given that we have estimates of the growth rates of TFP (Eq. (4)) and of the knowledge stock (Eq. (11)), we define parameter e as:

$$e = (\mathrm{dA}\,/\,\mathrm{A})\;/(\mathrm{dK}\,/\,\mathrm{K}) = g/k \tag{14}$$

2.4.2. Step 2-Bringing all the parameters together to estimate the level of R&D investment

Following the literature (e.g., [51,54]), we combine the parameters derived above to estimate the R&D investment ($\check{R}$) needed to offset exogenous yield shocks—our main outcome of interest.

First, we calculate the yield growth needed to close the supply gap under each scenario ($\hat{y}$) and multiply it by the historical share of yield growth attributable to TFP growth (g/y) to obtain the TFP growth required ($\hat{g}$):

$$\widehat{g} = \widehat{y} * (g\,/\,y) \tag{15}$$

Next, we define θ as the ratio of projected TFP growth ($\hat{g}$) to the elasticity parameter e linking TFP growth to changes in knowledge stock:

$$\theta = \frac{\widehat{g}}{e} \tag{16}$$

We then add θ to the assumed depreciation rate of knowledge capital (d) and multiply by the reference-year knowledge stock (K_o for 2020) to obtain the R&D investment required:

$$\check{R} = K_o * (d + \theta) \tag{17}$$

The additional investment needed is the difference between this value ($\check{R}$) and observed R&D investment in the reference period (R_o):

$$\Delta R = \check{R} - R_o \tag{18}$$

$\check{R}$ is positively related to the knowledge stock (K_o), depreciation rate of knowledge capital (d), and θ (which itself increases with the growth rate of knowledge stock k and decreases with historical yield growth y). Its sensitivity to g is negligible because positive and negative effects offset. Sensitivity analysis focuses on the three parameters with the largest influence—k, y, and r (R&D investment growth rate).

We estimate ΔR for each region under six demand–climate change scenarios (Fig. 1) and two market-share assumptions: 1) Shift towards more productive regions (Big 3 share increases; less diversity relative to 2020) – more likely (in the absence of any intervention) but less desirable; and 2) Constant 2020 shares (diversity maintained) – less likely (in the absence of any intervention) but more desirable.

3. Results

This section presents the results of our analysis in two stages. First, we report the estimated values of key model parameters for each region—yield growth, TFP growth, knowledge stock, and elasticity—-which serve as inputs for the investment gap calculations. We compare these values between the three largest coffee producers (Brazil, Vietnam, and Colombia) and the other major producing regions (ROW)—Asia (excluding Vietnam), Africa, and LAC (excluding Brazil and Colombia)—to assess differences in research productivity and capacity. Second, we use these region-specific parameters in the economic model to estimate the additional R&D investments needed for the Big 3 and the ROW under alternative demand, climate, and market-share scenarios.

3.1. Estimated model coefficients

The estimated values of the model parameters are shown in Table 5. Considerable regional variation is evident in research productivity indicators such as historical yield growth, TFP growth, and knowledge stock elasticity.

The Big 3 have the highest levels of R&D investment and knowledge stock growth, reflecting sustained accumulation of research and innovation capacity. They also show the strongest historical yield and TFP growth rates, and the second largest share of yield growth attributable to

Table 5
Model parameter values by region. Regions are grouped into the Big 3 (Brazil, Vietnam, Colombia), Asia excl. Vietnam, Africa, and LAC (excl. Brazil and Colombia).

Parameters		Big 3	Asia	Africa	LAC
Total coffee R&D (2019–2020) (Million)\a	R_o	51.26	35.69	34.90	18.88
Growth rate in R&D (%)	r				
1991–2020		0.019	0.013	0.020	0.017
1995–2020		0.021	0.022	0.023	0.022
Depreciation rate (%)	d	0.15	0.15	0.15	0.15
Knowledge stock in reference period (Million) (2020) \a	K_o	308.62	222.40	209.40	114.76
Growth rate of knowledge stock					
R&D projections based on r from 1991–2020	k	0.058	0.039	0.059	0.049
R&D projections based on r from 1995–2020		0.058	0.052	0.060	0.065
Yield growth rate in the past (%)					
1980–2020	y	0.030	0.001	0.0040	0.0017
1990–2020		0.035	0.002	0.0004	0.0022
Input growth rate in the past (%) \b	x	0.010	0.016	0.020	0.013
Following parameters are calculated based on conservative values of y and k					
TFP growth rate (%)	g = y/x	0.021	0.001	0.002	0.002
Share of TFP in yield growth rate (%)	g/y	0.613	0.500	0.498	0.787
Elasticity of TFP growth with respect to knowledge stock	e = g/k	0.368	0.023	0.035	0.035

Notes: Conservative estimates used in the main analysis are in bold. All percentages are on a scale of 0 to 1.
\a R&D investments and knowledge stock are in constant US$2020.
\b Investment gap estimates are not sensitive to input growth rates. Hence, only one estimate is presented.

TFP. This pattern suggests that productivity improvements in these countries have been primarily driven by technological progress and innovation rather than input expansion. Their elasticity of TFP growth with respect to knowledge stock is also higher, indicating a stronger responsiveness of productivity to research investments.

In contrast, the ROW—Asia (excluding Vietnam), Africa, and LAC (excluding Brazil and Colombia)—lags in most parameters. Asia reports the lowest values for nearly all indicators, while Africa and LAC (excluding the Big 3 members) show more moderate performance. Notably, although two of the Big 3 are located in LAC, the rest of the region performs significantly worse than these leaders—exhibiting much lower research intensity, smaller accumulated knowledge stocks, and slower yield growth rates. This contrast underscores both the exceptional performance of Brazil and Colombia within the global coffee sector and the relative underinvestment in other LAC countries. Across the ROW, these patterns suggest that slower productivity growth is linked to chronic underinvestment or misalignment in production-oriented R&D, particularly in core technologies such as improved varieties and agronomic practices.

Next, we present the results of the investment gap analysis based on the economic model, which incorporates the region-specific parameters described above. Supplementary Appendix D provides five sets of estimates for the additional annual R&D investment required to close the yield gap under alternative demand, climate, and market-share scenarios. These estimates are sensitive to the values of *k* (knowledge stock growth) and *y* (historical yield growth), ranging from $225 million to $865 million in Scenario 1 (declining diversity, i.e., greater concentration in the Big 3) and from $405 million to $1810 million in Scenario 2 (maintaining 2020-level diversity) under the most extreme combination of high demand and climate-induced declines in both yield and area. While estimates based on average parameter values may be more representative, here we adopt a conservative approach by reporting investment gaps based on the parameter combinations that yield lower-bound estimates of the minimum additional funding needed for the ROW to sustain productivity growth in the face of rising demand and climate change.

3.2. Future R&D investments to close the projected demand and supply gap

Supplementary Appendix E reports the estimated yield growth rates required to close the global coffee supply gap under each demand and climate change scenario, along with the corresponding additional annual R&D investment. These calculations use conservative values for *k, y*, and *r*, combined with other region-specific model parameters.

Fig. 4 summarizes the total additional R&D needed globally and its regional distribution. Across the two market-share scenarios, the minimum additional investment requirement is modest—about $10–$126 million/year under BAU demand with no climate change impacts. However, under high demand combined with climate change reducing both yields and suitable area, the total rises sharply to $225–$405 million/year. Fig. 5 provides a direct comparison of additional R&D needs for the Big 3 and the ROW under two alternative market-share assumptions for these two extreme demand and climate change scenarios. The Rest of the World (Asia excluding Vietnam, Africa, and LAC excluding Brazil and Colombia) accounts for a large share of these totals, particularly under more severe scenarios, reflecting both current yield gaps and the higher costs of generating productivity gains relative to the Big 3. We present key results under two alternative supply diversity assumptions.

3.2.1. Market-share scenario 1-Decreasing coffee diversity

Under a scenario where market share shifts further towards the Big 3—reducing geographic diversity in supply—most of the incremental investment under BAU demand with no climate change would be concentrated in the Big 3. The estimated requirement in this case is $10 million/year above current levels. Under high demand without climate impacts, the total rises to $20 million/year, again largely directed to the Big 3 and some to LAC.

When climate change effects are introduced, either through reduced yields alone or through combined yield and area declines, required investments increase substantially. With low demand and yield losses only, the global gap is $129 million/year; with high demand and yield losses, it is $186 million/year. Under the most severe case—high demand with both yield and area declines—the additional investment needed reaches $225 million/year, or about 1.6 times current global coffee R&D spending.

Even in this less-diverse market-share scenario, Asia, Africa, and LAC together would need to supply roughly one-third of global production in 2030. Additional investment requirements for Asia range from 134 to 191 % of current levels, Africa from 82 to 159 %, and LAC from 177 to 297 %. Higher unit costs of productivity growth explain much of this pattern: in the high demand/yield + area loss scenario, the cost of raising yield growth by one percentage point is about $63 million in Asia, $45 million in Africa, and $33 million in LAC, compared to $13 million in the Big 3.[4]

[4] Investment requirements are calculated from the additional yield growth needed to close the supply gap in each region under the high-demand, yield + area decline scenario (Supplementary Appendix E, Table E1). For example, the required yield growth rates are 5.7 % in the Big 3, 2.0 % in Asia and Africa, and 2.3 % in LAC. Corresponding annual R&D investments are $75 million for the Big 3, $126 million for Asia, $90 million for Africa, and $75 million for LAC, implying per-percentage-point costs of $13 million, $62 million, $44 million, and $32 million, respectively.

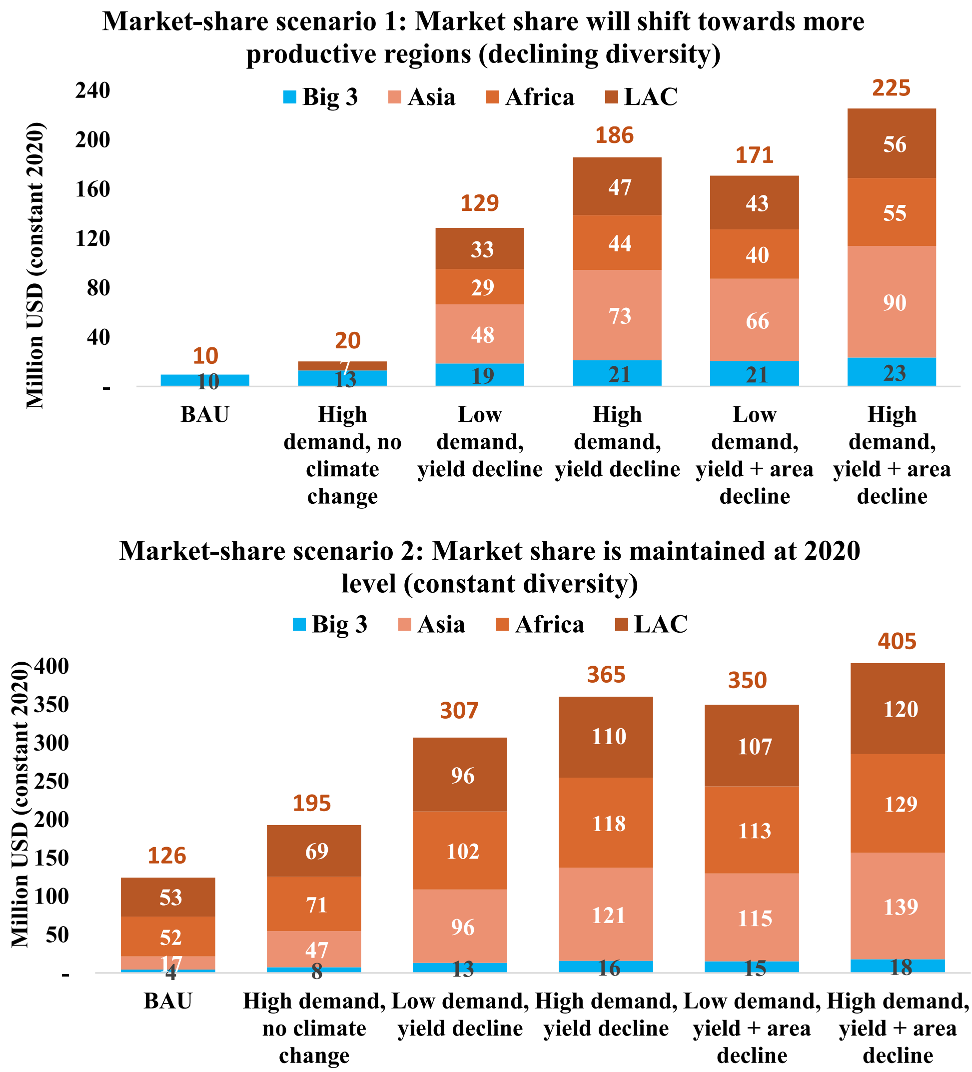

Fig. 4. Additional annual global coffee R&D investments required under six demand–climate change scenarios, by region and market-share assumption, million USD (constant 2020). Regions are grouped into the Big 3 (Brazil, Vietnam, Colombia), Asia excl. Vietnam, Africa, and LAC (excl. Brazil and Colombia).
Source: Authors' calculations. Note: The six scenarios (x-axis) are as defined in Figure 1.

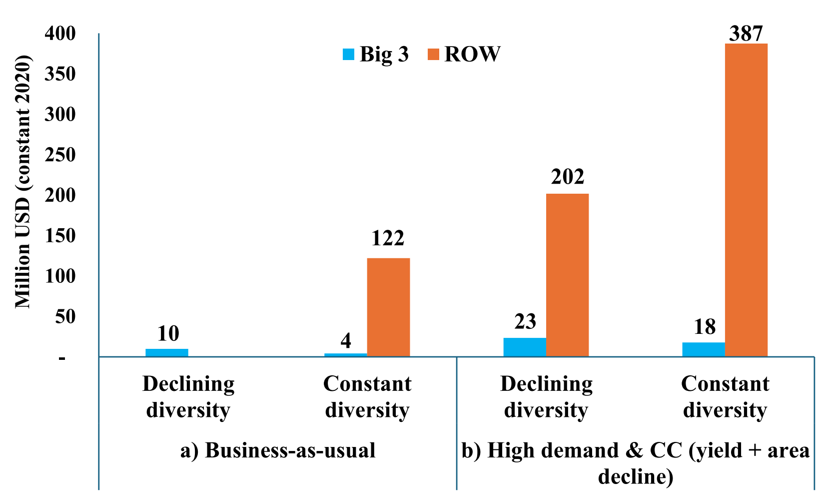

Fig. 5. Additional annual R&D investment needs for the Big 3 versus the ROW under (a) business-as-usual demand with no climate change and (b) high demand with climate change reducing both yield and suitable area, for each market-share scenario.
Source: Authors' calculations.

3.2.2. Market-share scenario 2-Coffee diversity remains constant at 2020 level

Maintaining the 2020 regional production shares (58 % Big 3, 14 % Asia, 12 % Africa, 16 % LAC) requires substantially more investment. The additional R&D needed is at least $126 million/year in the BAU/no climate change case, rising to $405 million/year under high demand with combined yield and area declines.

Under this scenario, most of the incremental resources would need to be directed to ROW regions to maintain their production shares. Total R&D investments will need to be approximately 7.3 times current levels in LAC, 4.9 times in Asia, and 4.7 times in Africa under the severe climate/demand case. Even under BAU demand with no climate impacts, additional needs are significant—about $53 million/year for LAC, $52 million/year for Africa, and $17 million/year for Asia. In the high-demand/yield + area loss case, these rise to $120 million/year for LAC, $129 million/year for Africa, and $139 million/year for Asia, compared with only $18 million/year for the Big 3.

Overall, the results show a consistent pattern: while the Big 3 currently dominate production and enjoy lower marginal costs of productivity growth, the bulk of additional R&D resources required to sustain a diverse and resilient global coffee supply must be directed to the ROW (Fig. 5). Under less diverse market-share scenarios, the Big 3 capture most incremental investments in mild demand/climate conditions, but Asia, Africa, and LAC still account for the majority of additional needs when climate impacts intensify. Under diversity-maintaining scenarios, the required scale-up in ROW R&D is even more pronounced—ranging from 4 to 7 times current levels—highlighting both the relative underinvestment to date and the higher costs of closing yield gaps in these regions. This Big 3–ROW contrast underscores the central trade-off facing the sector: investing primarily in the most productive countries may meet short-term volume targets but risks further eroding origin diversity, whereas channeling greater R&D to underperforming regions is essential to preserve diversity, manage climate risks, and achieve more equitable benefits across the global coffee value chain.

4. Discussion and implications

Coffee is mainly produced by smallholder farmers in low-income countries, covering over 12 million hectares globally and generating an annual farm-gate value of about $23 billion (in constant 2020 US dollars) [3].[5] Despite its economic importance, coffee R&D receives only about 0.6 cents for every dollar of green coffee produced—equivalent to just 1.3 cents per kilogram. Even without the scenario-based analysis, current investments fall well below the *parity rule* guideline for allocating resources across crops: coffee accounts for 4.2 % of agricultural output value in the countries studied but just 2 % of agricultural R&D investments. By this measure, an additional $140 million annually would be needed to meet the parity benchmark.

Our forward-looking analysis extends this baseline by examining six plausible demand–climate futures and two contrasting supply diversity assumptions. Under the more likely but less desirable "declining diversity" scenario—where supply continues to consolidate in the Big 3 (Brazil, Vietnam, Colombia)—the additional annual investment needed ranges from $10 million (business-as-usual demand, no climate change) to $225 million (high demand, climate change reducing both yield and suitable area). This upper bound aligns closely with the shortfall identified by the parity rule. By contrast, the less likely but more desirable "maintained diversity" scenario—preserving the geographic origins of coffee available to consumers—requires substantially higher commitments: $126–$405 million per year. On the higher-end, this is equivalent to 0.27 % of the industry's annual retail value.

These findings are broadly consistent with prior global and national estimates of agricultural R&D needs under climate change [38,51,55] and reinforce warnings from coffee-specific studies that climate risks will disproportionately affect underprepared producing regions [10,22]. However, unlike these earlier studies, our analysis explicitly quantifies the additional cost of preserving supply diversity versus allowing geographic concentration, and measures the scale of investment shifts required from the Big 3 to the ROW under each scenario. This focus on the distributional dimension of R&D needs—rather than only aggregate global totals—adds a novel perspective to the literature on commodity-specific adaptation planning.

The results also point to an important asymmetry: while the Big 3 can meet projected demand growth with relatively modest incremental investments, the ROW will require significantly larger relative increases—often 3–6 times current spending—due to both historical underinvestment and the higher marginal cost of yield gains in these regions. This mirrors patterns observed in other crops (e.g., [56,37]), where weaker research and extension systems result in higher per-unit productivity costs. Our work confirms this dynamic for coffee and quantifies it at the regional level.

Addressing this imbalance will require both new funding and institutional mechanisms that ensure resources reach where they are most needed. Relying solely on consumer willingness to pay, while feasible given coffee's inelastic demand, may not guarantee that revenues are channeled into R&D—especially if roasters or exporters have little incentive to earmark funds for research. Lessons from the Big 3 suggest that institutional arrangements matter: Brazil's public research agency (EMBRAPA), Colombia's levy-funded National Coffee Research Centre (CENICAFÉ), and Vietnam's integration of coffee research into broader agricultural innovation systems all ensure sustained funding and alignment with farmer needs. Comparable approaches—such as earmarked producer/import levies, regional public–private partnerships, or multi-donor research trust funds—could be adapted for underinvested regions, but would require governance and coordination mechanisms that build trust and accountability among stakeholders.

In this sense, closing the coffee R&D gap is not only about sustaining a globally traded commodity—it is also a lever for advancing multiple Sustainable Development Goals. Targeted investments in underperforming regions can simultaneously reduce poverty (SDG 1), improve food security (SDG 2), promote decent work (SDG 8), and enhance climate resilience (SDG 13), while protecting biodiversity and origin diversity in coffee (SDG 15). The modest scale of resources needed relative to the size of the global coffee economy makes this an attainable and high-return opportunity for coordinated global action.

5. Conclusion

This study provides the first systematic global and regional estimates of the coffee R&D investment gap under plausible scenarios of demand growth, climate change, and supply concentration. Three conclusions stand out:

1) **The sector is underinvesting in R&D by a wide margin.** Current annual investment (~$140 million) falls well below both a parity-based benchmark and the levels required to sustain productivity growth. Even under conservative assumptions, closing the gap will require an additional $126–$405 million per year over the next decade.

[5] We estimate the total value of green coffee by multiplying the total production of green coffee across the countries included in our analysis, which we estimate to be about 10.2 million tons in 2019-2020 (source: FAOSTAT coffee production data accessed October 2022), with the International Coffee Organization's (ICO) composite price indicator (US$2.21/kg) for 2019 (source: ICO's indicator price data accessed October 2022). The ICO composite price indicator represents the weighted average grower price of green coffee across all coffee exporting countries and all coffee types (more details are in Appendix A).

2) **Most of the gap is concentrated in the Rest of the World.** While the Big 3 producers—Brazil, Vietnam, and Colombia—can meet demand with relatively modest increases, Asia (excluding Vietnam), Africa, and LAC (excluding Brazil and Colombia) will require proportionally much larger boosts—often 3–6 times current levels—to meet production shares, prevent yield declines, and sustain diversity.
3) **Diversity comes at a price—but yields broad benefits.** Preserving diverse origins will require channeling over 85 % of new R&D funding to historically underinvested regions, supporting smallholder livelihoods, conserving coffee diversity, and reducing deforestation risks from production shifts.

Closing this gap is both affordable and urgent. For an industry worth over $200 billion, it would require setting aside <0.3 % of retail value—negligible for consumers yet vital for securing coffee's future. Coordinated financing—through levies, public–private partnerships, and regional research consortia—can make it happen. Without it, the global coffee supply will become less diverse, less resilient, and more vulnerable to climate shocks.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT-4 to improve the readability and language of the manuscript. After utilizing this tool, the authors reviewed and edited the content as needed and take full responsibility for the final content of the published article.

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CRediT authorship contribution statement

Mywish K. Maredia: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jose Maria Martinez:** Writing – review & editing, Visualization, Data curation.

Declaration of competing interest

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Supplementary materials

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Further reading

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