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Planning for Adaptation: A System Approach to Understand the Value Chain's Role in Supporting Smallholder Coffee Farmers' Adaptive Capacity in Peru

Laura V. Morales[1*†], *Valentina Robiglio*[1†], *María Baca*[1†], *Christian Bunn*[2] and *Martin Reyes*[1]

[1] World Agroforestry (ICRAF), Lima, Peru, [2] International Center for Tropical Agriculture (CIAT), Cali, Colombia

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***Correspondence:**
Laura V. Morales
l.morales@cgiar.org

† These authors have contributed equally to this work

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Coffee is a major global commodity whose production is sustained by and provides livelihoods for millions of smallholder families in the tropics. However, it is highly sensitive to climate change and the climate risk family farmer's face from direct impacts on coffee production are often compounded by further impacts on the physical and social landscapes and infrastructure. We examine the vulnerability (sensitivity and adaptive capacity) of smallholder coffee farmers in northeastern Peru *via* the lens of their central participation in a value chain that mediates access to livelihood assets, affecting their adaptive capacity and aspects of their sensitivity. Using a staged and participatory, mixed-methods approach, we sought to understand the territorial climate exposure, the structure of the regional value chain and role of different actors in supporting farmer adaptive capacity, and assess the vulnerability of the entire value chain (including other actors in addition to farmers). We found heterogeneity not only in the potential impact of climate change on coffee production, future adaptation needs and vulnerability of farmers across the territory (among elevational zones and regions), but in the distribution of vulnerability among value chain actors. Farmers are the most vulnerable actors, simultaneously the most sensitive and with the lowest adaptive capacity, issues stemming from their strong territorial dependence and pre-existing social and economic asymmetries with actors in the coffee value chain who are not as territorially dependent (e.g., private companies). We make the case that supporting the adaptation of smallholder farmers in the study region requires moving beyond a value-chain approach to a territorial systems perspective that more intentionally involves those actors with stronger, locally vested interests (e.g., local governments and institutions) in their adaptation and requires the strengthening capacities of these actors in various areas.

Keywords: sensitivity, vulnerability, climate change, *Coffea arabica*, adaptation trajectory, Sustainable Livelihoods Framework, value chain, distribution modeling

INTRODUCTION

Produced in more than 70 countries worldwide, coffee is one of the most valuable globally traded agricultural products. It plays a vital role in Latin America, which accounts for over half of global green coffee production and has an important share of global land cultivated with coffee (5,068,746 Ha, ∼45% of total) (FAO, 2021). This region is particularly dominant in the market of high cup quality varieties, producing the large majority (82%) of the world's Arabica coffee (United States Department of Agriculture, 2021), produced by varieties of *Coffea arabica,* a species that prefers higher elevations with cool temperatures and more than 1,200 mm of annual rainfall (DaMatta and Ramalho, 2006).

Globally, coffee is predominantly a family farmer's crop, produced by an estimated 12.5–25 million farms, of which 70–80% are smallholder households (Browning, 2018; International Coffee Organization, 2019; Panhuysen and Pierrot, 2020). As an international commodity managed by smallholders in landscapes of strategic relevance for biodiversity and ecosystems services provision (Jha et al., 2011, 2014), coffee production is at the center of multiple social, economic and environmental controversies mostly related to the vulnerability of the farmers (Gresser and Tickell, 2003; Rice, 2003; Jha et al., 2011; Guido et al., 2020; Panhuysen and Pierrot, 2020).

There are several drivers of coffee farmers' vulnerability. Price variability is caused by the complex balance between global demand and supply in relation to overproduction in a value chain regulated largely by "buyers" (i.e., brands and transnational companies responsible for export/import, roasting, and distribution), who capture the largest share of the value (Gresser and Tickell, 2003; Rice, 2003). Farmers, as the base producers, have a weak margin for negotiation and risk management as profitability in the short term is highly variable, with shifts in time and space that depend on the interplay of conditions in production territories with global value chain factors, whereas companies can manage their risks by accessing global markets, giving a substantial stability to the global value chain. Over the last few decades market-related risk has been exacerbated by risk generated by the impact of climate change, to which high-value, quality Arabica production is highly sensitive (Guido et al., 2020; Rhiney et al., 2021).

Impacts include rises in minimum growing temperatures and changes in rainfall patterns that directly affect yields and cup quality and consequently, competitiveness of local production. Direct impact combines with the indirect effects of change on yield due to outbreaks of pests and diseases favored by warmer temperatures, as is the case for coffee leaf rust (*Hemileia vastatrix*) and coffee berry borer beetle (*Hypothenemus hampei*) (Pham et al., 2019). Further impacts in production territories includes degradation of natural capital due to landslides, erosion, and floods, including damage to infrastructure (Läderach et al., 2013). In territories highly dependent on coffee production, consequences can be dramatic (Harvey et al., 2021). Combined effects have major adverse consequences on livelihoods including food insecurity and malnutrition of farmers' families and unemployment of seasonal labor, with possible further effects on outmigration and land-use change due to abandonment and other social conflicts (Pham et al., 2019; Avelino and Anzueto, 2020; Harvey et al., 2021) that may result in decreases of areas currently under coffee production. Decline is not the only projected trend. In Andean Amazon countries, changing climate generates favorable conditions for high quality Arabica varieties in upper montane forest areas where expansion is favored by soil conditions and reduced pest and disease loads typical of deforestation frontiers (Ruf and Schroth, 2004). Tradeoffs include negative outcomes for biodiversity (Magrach and Ghazoul, 2015) and ecosystems service provision, affecting the resilience of coffee production landscapes and livelihoods.

All of these factors create an urgent need to plan for climate change adaptation both for the coffee sector and Latin American coffee landscapes, however, there is very limited information on the potential magnitude of change and its impact (Harvey et al., 2021). This study takes the case of the Andean-Amazonian landscapes of Peru to assess how the value chain can contribute to the capacity of coffee farmers to adapt to climate change. Despite Peru's ranking in global markets, high climate change exposure, and potential socio-ecological and livelihood impacts, studies focusing on the impact of climate change on the Peruvian coffee sector are lacking. Peru's production volumes in 2020–2021 place it as the 9th coffee producing country (4th among Arabica producers) (United States Department of Agriculture, 2021) and coffee is a crucial economic sector for the country. Accounting for up to 30% of the market share, it is the main agricultural export and a source of employment for over 2 million people, with about 220,000 families of smallholder farmers (manage < 5 hectares, often solely with family labor) distributed across the upper slopes of Amazonian watersheds (Robiglio et al., 2015, 2017; Harvey et al., 2021). Given the large proportion of coffee farmers in the rural population of some districts (as much as 90%) (Robiglio et al., 2015), the sustainability of coffee production in these territories is strategic for the delicate socio-ecological and economic balance between pressure on biodiversity and ecosystem service provision and livelihoods. By 2050, climate change is predicted to result in little loss but substantial changes in the spatial distribution of suitable areas for *Arabica* coffee production in Peru (Ovalle-Rivera et al., 2015) which, together with existing socioeconomic and governance factors that limit the country's overall adaptive capacity and increase its susceptibility to climate change (i.e., high poverty rates and economic inequality, deficient infrastructure, weak institutional or cross/sectorial coordination, incipient capacity building) (MINAM, 2016; Notre Dame Global Adaptation Initiative, 2022), place Peru and its coffee regions in a vulnerable position.

Here we focused on understanding the vulnerability of the coffee value chain in northeastern Peru to future climate change and how this affects its capacity to support smallholder farmer adaptation. We adopted a mixed-method, participatory approach centered on farmers and the coffee value chain, understanding the latter as a network of components and functions that mediate the adaptive capacity of the farmer by mediating the access to assets. We analyzed the path of change required from within and outside the value chain to support farmers' adaptation process and assessed the capacity of value-chain actors to do so under different scenarios of change, including adaptation and transformation (Rickards and Howden, 2012; Vermeulen et al., 2013). Our analytical framework builds on the approach to livelihood capitals and capabilities in rural development which considers household assets and endowments (typically natural, human, social, physical and financial) mediated by contextual factors including socio-institutional and environmental processes (Bebbington, 1999; Scoones, 2009; Reed et al., 2013) as the basis for farmers to: (1) participate in and benefit from their integration into a value chain (Stoian et al., 2012) and (2) respond to sustainability and environmental goals, including the adaptive capacity to cope with climate change (Rickards and Howden, 2012; Reed et al., 2013).This assets-based framework helps identify what capital can be used for adaptation. In the case of climate change, it admits that different actors may be affected differently and may have different capacities to adapt depending on the asset affected by the change. In the context of a value chain, this impacts the ability of different actors to interact and fulfill their function in the chain and thus, mediate farmers' access to the resources needed to cope and adapt.

MATERIALS AND METHODS

We employed a staged, mixed-methods approach to understanding value chain vulnerability (**Figure 1**). Because coffee production and its value chain involve different spatial and institutional scales across a territory, we collected and interpreted information from different geographic scales. Broadly, we aimed to: (1) assess the current and future territorial distribution of climate change exposure and impact on local coffee production and define the adaptation levels required for smallholder farmers to successfully adapt to expected conditions, (2) assess the sensitivity and adaptive capacity of the value chain by evaluating these attributes for each of the primary actors in the value chain, including smallholder farmers, (3) evaluate the vulnerability of the local coffee value chain and identify opportunities for decreasing it across the existing actors and their interactions. We developed agroclimatic suitability models for the coffee crop to understand future exposure of primary production to climate risk and employed focus groups, workshops, rapid rural appraisal techniques and interviews with experts, farmers and other actors to map the current value-chain, understand perceptions of current climate change impacts on production, and evaluate sensitivity and adaptive capacity.

Study Region

We worked within three growing regions in northeastern Peru (Amazonas, Cajamarca, San Martin) which encompassed ∼50% of the total area under coffee cultivation (387,421 ha) and 59% of all national coffee production (281,000 tons) in 2016 (MINAGRI, 2018) (**Figure 2**). For our fieldwork, we selected three districts, one within each region: Lonya Grande (Amazonas), San Ignacio (Cajamarca), and Moyobamba (San Martin). These districts were chosen based on criteria defined during an initial workshop with national coffee-sector experts: having high coffee production and cultivated land area, perceived experiences of current climate change impacts, and presence of different levels of projected future impact within districts based on our climate models.

Coffee is cultivated between 500 and 2,500 m.a.sl. along the Amazonian slopes of the Andes and is the main perennial crop in all three regions (CENAGRO, 2012), but the regions differ in their total surface area, topography, and production volumes. San Martin is the largest (5,251,483 ha) and has the greatest area under coffee (∼87,200 ha), accounting for 29% of all production in 2016. Amazonas (3,967,506 ha) and Cajamarca (3,317,500 ha) each had ∼53,250 and ∼53,000 ha planted with coffee and produced 12.4 and 17.5% of all coffee in 2016 (MINAGRI, 2018). San Martin has only ∼25% of its land area at elevations >1,000 m.a.s.l, while Amazonas and Cajamarca have ∼45 and ∼80%, respectively (**Figure 2**).

In all three regions, coffee farmers are a large part of the rural population (Proportion of Farmers Planting Coffee: Amazonas 40%, Cajamarca 43 and San Martin 50%) (Robiglio et al., 2017). Most tend to be small-holders farming <10 ha and many lack formal land titles. As with many areas of coffee cultivation in Peru (Díaz Vargas and Carmen Willems, 2017), rural poverty rates are high in the focal study districts (Lonya Grande: 39–49%; San Ignacio: 54–62%, Moyobamba: 23–29%) (INEI, 2018).

Climate Change Exposure, Impact and Adaptation Gradient Mapping

We developed a map of adaptation pathways required to face projected climate change in our study region using the same approach previously used to develop adaptation recommendation domains for Ghanian cocoa production by Bunn et al. (2019). This approach involved: (1) the generation of multi-class agroecological suitability models for coffee production in the study region based on locations of current coffee production in Peru, (2) validation of the resulting agroecological zones (AEZ) and suitability maps with expert knowledge of climate and coffee production zones in Peru during national and regional workshops, (3) the prediction of the future spatial distribution of suitable agroecological zones for coffee production according to climate change projections for 2030, and (4) the determination of required adaptation levels based on the changes between the current and future spatial distributions of suitable coffee growing zones. Full detail of the AEZ modeling methodology and climate projections can be found in **Appendix 1**.

Required adaptation levels were defined based on observed differences between the current agroecological zonation and future expected zonation of map pixels, employing the adaptation recommendation framework of Bunn et al. (2019). An adaptation gradient requiring increasing levels of adjustment efforts was assigned to areas currently suitable for coffee production depending on the degree of exposure to changed climatic conditions in 2030 (**Figure 3**). Where a suitable area was not projected to change in climatic zone and thus require little to minor gradual changes, it was assigned to "incremental adjustment". Areas expected to remain suitable but shift between AEZs were assigned to "systemic adjustment". Areas where there is high uncertainty as to the climate suitability in the

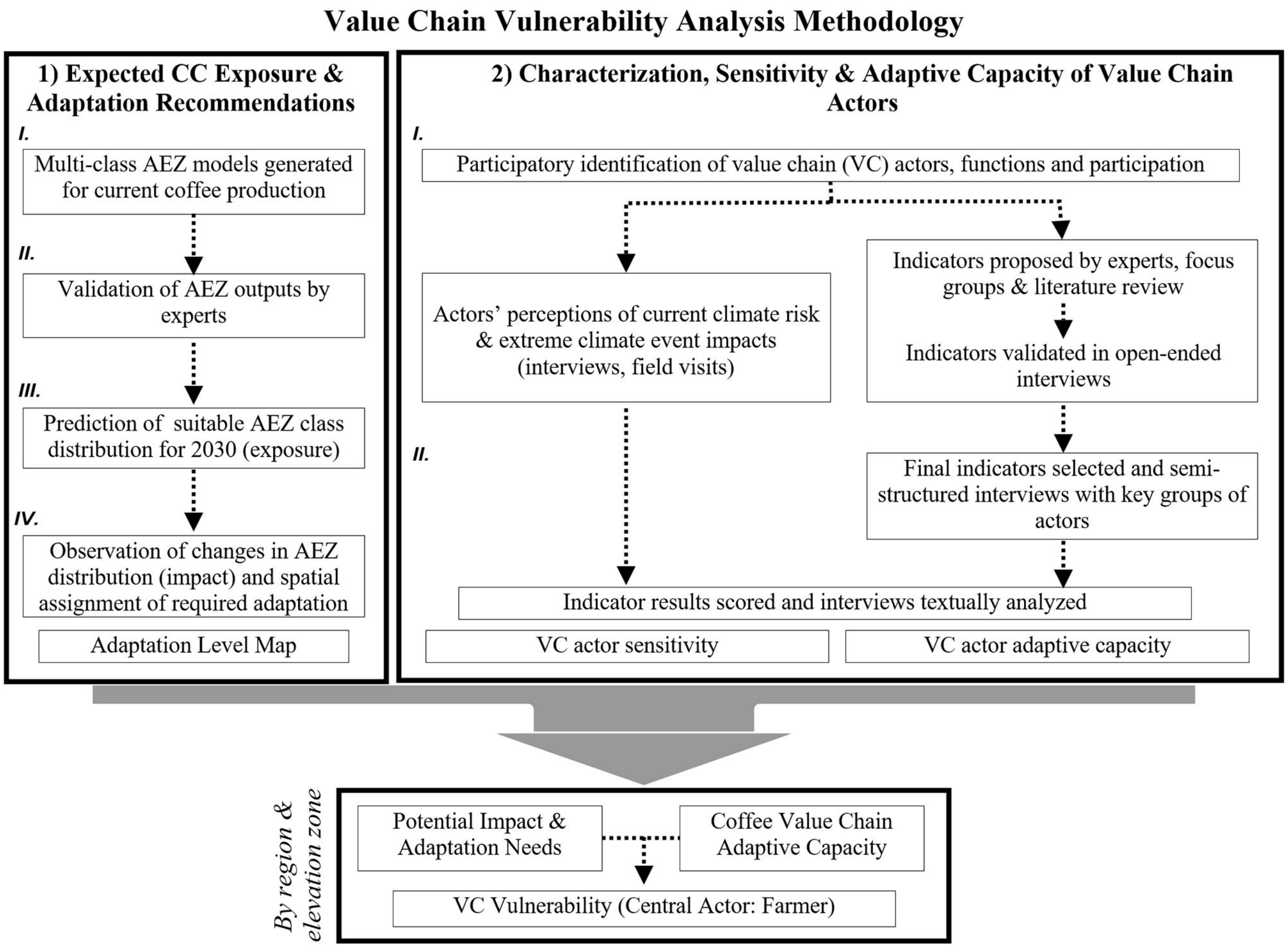

FIGURE 1 | Workflow of methodology used to evaluate the vulnerability of the coffee value chain in northeast Peru to future climate change.

future were assigned to "systemic resilience building". Finally, areas likely to become unsuitable for coffee cultivation were assigned to "transformation." Additionally, unsuitable zones likely to become suitable for cultivation were classified as "opportunity" zones.

The four main adaptation zones capture an increasing scale and scope of efforts required for farmers and local value chain actors to adapt to expected climate shifts, ranging from small adjustments to transitioning away from dependence on coffee production. Incremental adjustment zones are expected to require minor gradual adjustments to respond to normal climate variability, while systemic adjustment areas will require greater changes in local agronomic practices to adapt to new conditions for coffee production (e.g., introduction of new varieties or technology, modifying the design and management of systems, and compatible integration of new products). Systemic resilience building zones, on the other hand, must hedge bets and be prepared to face the possibility of suitability loss by making substantial adjustments aiming to increase the general resilience of the socio-ecological system, as well as changes to household production strategies away from high reliance on coffee in order to create or maintain future options. Transformation zones will require extensive changes to transition entire production systems and value chains away from the coffee economy into other productive strategies. Opportunity zones are areas where coffee cultivation may become a productive option for farmers, barring unfavorable natural or social conditions for this land use.

Value Chain Mapping, Sensibility and Adaptation Capacity Evaluation

A participatory approach engaging all key groups of actors involved with the coffee value chain was used to generate information about the local value chain and the sensitivity to and adaptation capacity for climate change of different groups. This information was gathered in two stages: (1) an exploratory stage using open-ended methods to get descriptive data about the study region, the value chain, farmer perceptions of current climate change impacts and validate indicators and methodologies; (2) a structured interview stage for indicator-based sensitivity and adaptive capacity evaluation. The first stage

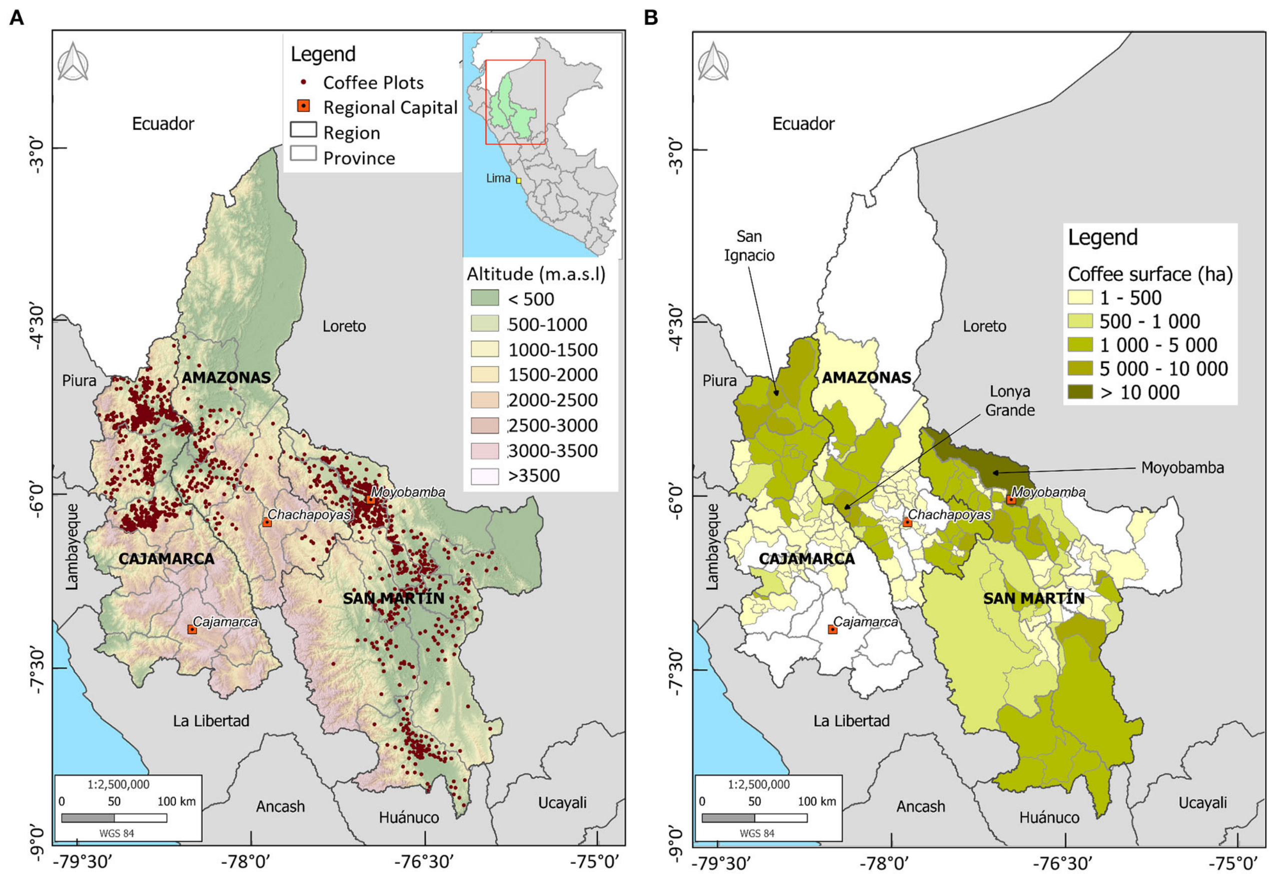

FIGURE 2 | Study area in Northeastern Peru. **(A)** Geographic and topographic distribution of validated coffee cultivation occurrences in 2016. **(B)** Total area dedicated to coffee production by regional district. The three focal study districts where interviews were conducted with farmers, cooperatives and institutions are shown by arrows (Lonya Grande- Amazonas; San Ignacio-Cajamarca; Moyobamba-San Martin).

employed 4 participatory workshops of coffee experts (1 national workshop in Lima and 3 regional workshops), each with 8–12 participants, and open-ended interviews and visits with 1–3 participants per focal region in 5 actor classes (smallholder farmers, cooperative/associations, private companies, service providers, government/agency representatives). The second stage comprised of semi-structured interviews/surveys with 84 smallholder farmers, 14 agricultural cooperatives/associations, 3 private companies and 12 regional government/agency representatives. All fieldwork was conducted between June and November of 2016.

Value Chain Mapping

Participants in workshops and initial interviews participated in presentations and discussions or individual instruction about various concepts involved in this study, including value chains. They then illustrated their understanding of the coffee value chain, identifying key actors, roles, and interactions in groups or individually, generating tables or pictorial representations of these. We used these products and extra information from participants to construct a unified conceptual model of the coffee value chain in the study area including actors, roles, and key interactions.

Sensitivity and Adaptation Capacity Evaluation

Indicators of sensitivity to climate change and adaptive capacity were developed in conjunction with workshop experts and participants in open-ended interviews. This approach was analogous to that previously applied to assess vulnerability of smallholder coffee farmers in Central America (Baca et al., 2014), but extended this process to indicators for other value chain actor groups. For this study we defined sensitivity as the direct and indirect effects of climate change on coffee production and other resources necessary for production for each value chain actor. Adaptive capacity of individual actors was defined as their ability to cope with, adapt and transform to meet production and livelihood challenges brought by climate change and within the value chain context, their ability to sustain or increase the flow of services and resources to allow for other actors to adapt as well. After receiving training on concepts of sensitivity and adaptive capacity, as well as being presented with an initial list of potential indicators suggested in the literature, groups

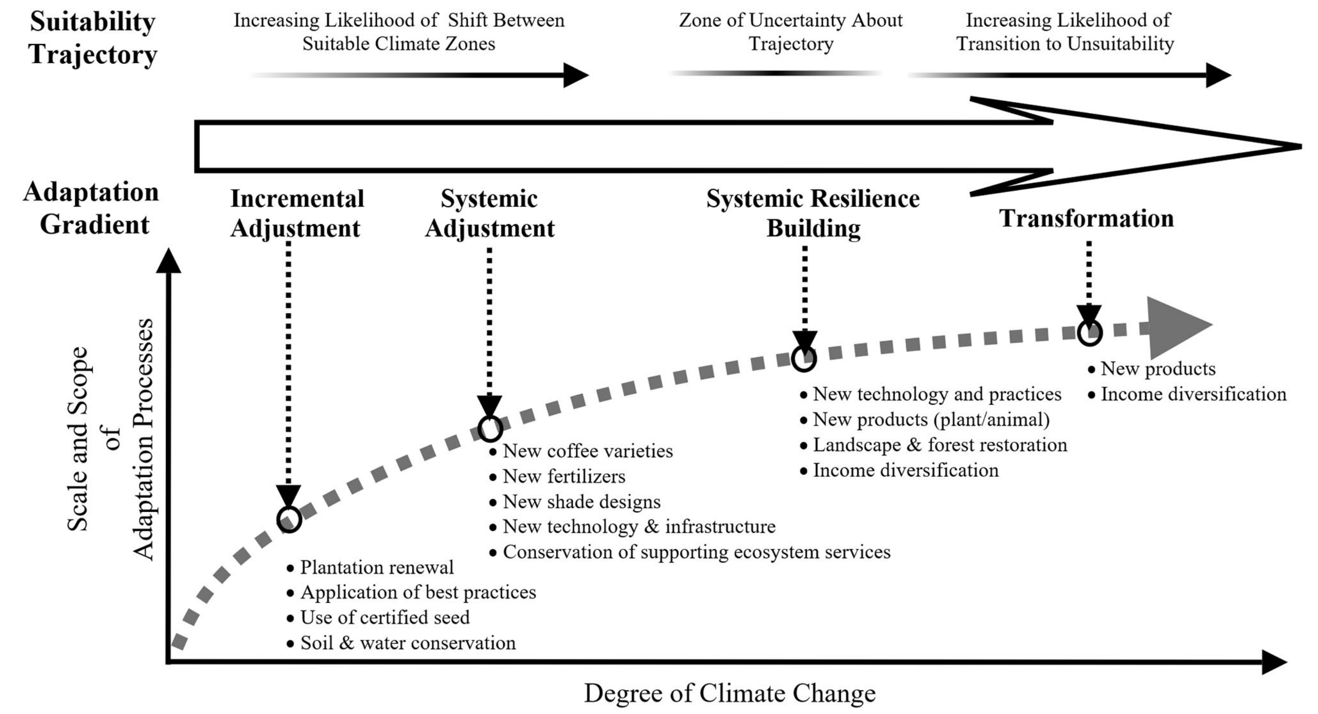

FIGURE 3 | Scheme of gradient of necessary adaptation effort required by increasing degree of climate change. Top: Expected changes in suitability for crop production from climate suitability models (top row) are matched with recommended level of adaptation along the gradient (bottom row), taking into account uncertainty around the expected trajectory. See Section Climate Change Exposure, Impact and Adaptation Gradient Mapping for further details about how these ideas are used to generate adaptation zone maps. Adapted from: Rickards and Howden (2012).

of workshop participants brainstormed a list of key factors for coffee production and marketing in the study region, ranking them according to their relative importance and relationship to climate change. Additionally, they suggested metrics for each indicator. This process was done considering key factors that applied to each group of key actors identified in their value chain descriptions. All lists were then consolidated to generate a list of key sensitivity and adaptive capacity indicators and organized according to the five capital categories of the Sustainable Livelihoods Framework (DFID, 1999). This was done for each following actor groupings: (1) farmers, (2) intermediaries and companies (individuals, cooperatives, private businesses), (3) service providers (suppliers, service providers, public agencies, institutions). For the latter group, chosen indicators focused more on the ability to support farmers in adaptation processes rather than their own adaptive capacity.

This master list of indicators was validated using 19 open-ended interviews with actors in the study region. Adjustments were made and a final list of indicators was selected, from which a semi-structured interview was developed to collect information for quantitative evaluation of sensitivity and adaptive capacity. In each regional district, we interviewed 24–30 smallholder farmers. Because the sensitivity and adaptive capacity of smallholders is closely associated with, and affected by, their farm's location and our exploratory work suggested differences in hazard exposure and climate impacts according to three general elevational zones (Low: ≤1,200 m.a.s.l.; Middle: 1,200–1,600 m.a.s.l.; High: ≥1,600 m.a.s.l.), we stratified our interview sample in each region by these zones, randomly sampling 6–10 farmers per zone. Because other actors participate in the coffee value chain at regional and national scales, they were selected at regional scales. A notable exception were the semi-structured interviews with private companies. We were unable to secure sufficient interviews with local or regional headquarters of private companies and instead interviewed national representatives of parent companies.

After data collection, information from interviews was analyzed qualitatively and quantitively, in the case of semi-structured interviews with farmers and cooperatives. Content analysis of interview recordings, notes and input matrices was used to summarize information on climate change perceptions and other contextual information about value-chain actor interactions, sensitivity to climate and adaptive capacity. Indicators gathered in the semi-structured interviews with farmers and cooperatives were scored on a 3-point scale (1: Low, 2: Medium, and 3: High Sensitivity or Adaptive Capacity) according to predetermined parameters for each. See Section Sensitivity and Adaptive Capacity Indicators of Value Chain Actors for the final indicator list; parameters and scoring scales for each indicator can be seen in **Appendix 2**.

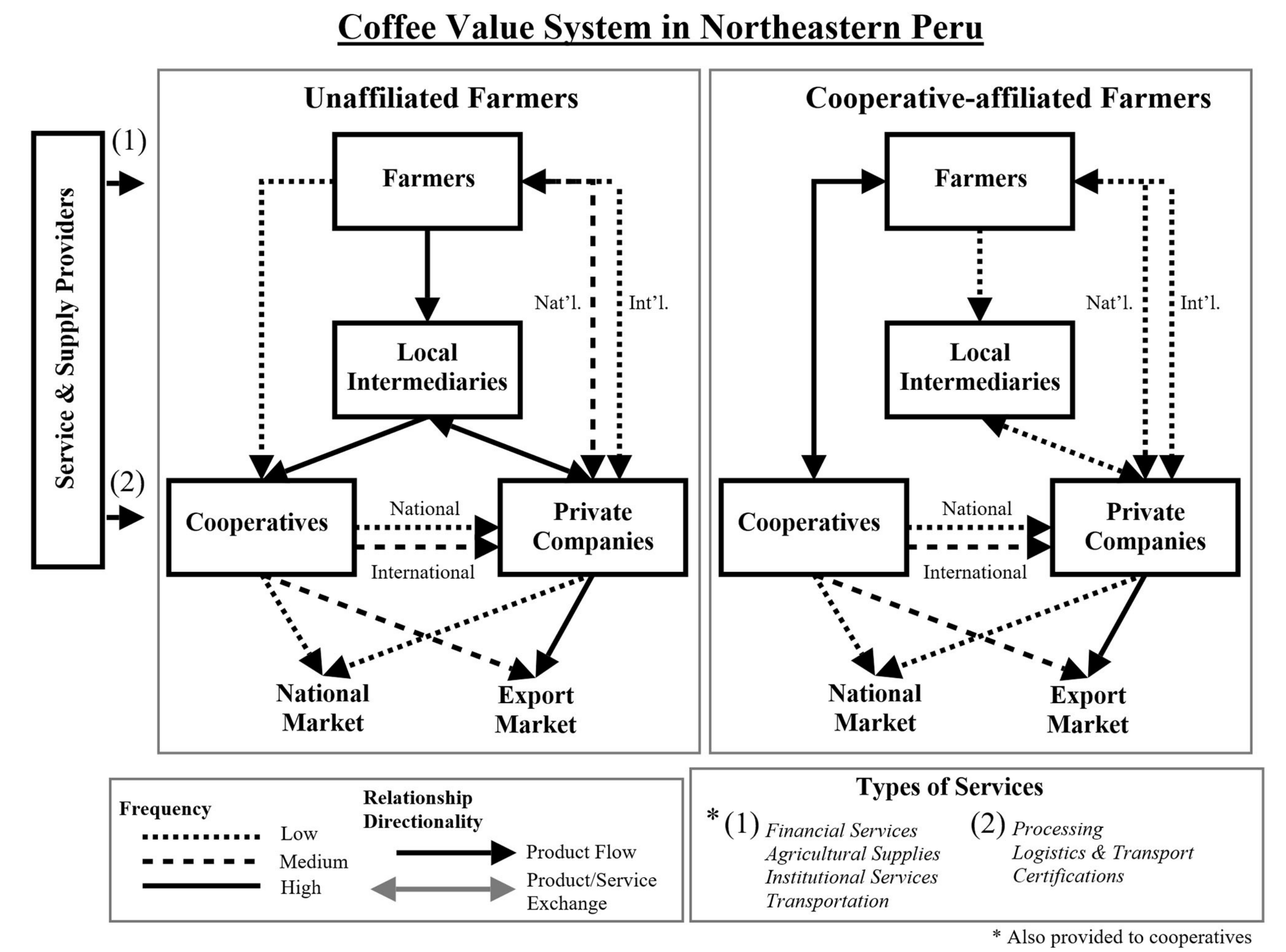

FIGURE 4 | Key actors and relationships of the coffee value system in northeastern Peru for farmers unaffiliated (left) and affiliated with cooperatives (right). Frequencies and directions of product and service flows are shown as arrows of different types. Service providers, some traditionally considered external to the coffee value chain, provide different types of services primarily oriented at individual farmers (1) or cooperatives and private companies (2). Within the coffee value chain in NE Peru, most farmers sell their product primarily as dried parchment coffee already having undergone primary wet-processing, intermediaries and cooperatives also primarily sell dried parchment coffee to private companies, and both cooperative and private companies sell most of their product into national and international export markets as green coffee after additional secondary processing, with only minor sales of roasted or ground coffee.

RESULTS

Key Interactions in the Current Coffee Value Chain

The coffee value chain in northeastern Peru is more aptly described as a coffee value network integrating five major actor groups: farmers, local intermediary stockpilers, cooperatives, private companies, and service providers (**Figure 4**). Farmers are the basal node of the network, interacting with all other major actors, who occasionally overlap in their roles relating to coffee production and commercialization. There are different types of farmers: those unaffiliated and those affiliated with coffee cooperatives (member farmers). Both types of farmers may supply intermediary stockpilers, cooperatives, or private companies with dried parchment coffee, but the frequency with which they sell their coffee to each actor differs. Unaffiliated farmers primarily sell to local intermediaries while cooperative members sell primarily, but not exclusively, to their cooperatives. While cooperatives in principle source only from their members, members often choose to sell part or all their crop to the other buyers or fail to produce enough supply to meet the demand of the cooperative's commercial agreements with higher-level buyers, so coffee cooperatives often also purchase coffee from non-member farmers or local stockpilers to make up the deficit. Local intermediaries stockpile coffee directly from farmers at the hyper-local to district-wide levels, with some farmers working as micro-stockpilers who purchase from neighboring farmers and sell to larger intermediaries. Private companies purchase parchment coffee primarily from larger intermediaries or cooperatives, although they may also purchase from farmers. Private companies can be strictly national or associated with international holding companies. National companies more frequently purchase directly from farmers, while international companies more frequently buy from cooperatives. Companies and some cooperatives are the point of sale for coffee into the national and international markets, with the greatest proportion of sales going into the international market as green coffee exports by companies sourcing from northeastern Peru.

With the flow of coffee from farmers to the market there is also a flow of goods and services among actors, in which external service providers also participate, that enables the central activities of coffee production and marketing. These activities are the basis of the value chain and strongly influence farmers' resources for inclusive participation (**Figure 4**; **Supplementary Table S1**). External service providers are public and private businesses and institutions that participate in the value chain without necessarily being directly linked to the purchase and sale of the product, however, many of them are indispensable for its operation. These businesses and institutions provide farmers, affiliated and unaffiliated, with financial services (i.e., credits), transportation, institutional services (i.e., technical, management assistance, and regulatory assistance), or agricultural inputs needed for production (i.e., fertilizers, seed, tools, and warehouses). Cooperatives often receive the same range of services and supplies as individual farmers at a local level, but cooperatives and companies are additionally clients of logistics and transportation, processing, and certification services by independent businesses at regional and national levels. These two actors (cooperatives and companies) are the medium by which individual farmers who are cooperative members or participate in buyer's arrangements with companies obtain certifications for participation in specialty coffee markets. Like the mediation of certification services, in some cases key services for farmers and cooperatives also are provided "internally" by intermediaries, cooperatives and companies. For example, intermediaries may provide cash, grocery, or supply advances on crops to unaffiliated farmers, companies and cooperatives may provide advances, transportation or technical assistance to cooperative members or farmers with whom they have direct-buy agreements, often replacing or complementing the role of external service providers. Thus, depending on the nature of the relationship between farmers and their buyers, and their cooperative affiliation, supporting services may come from different actors.

Territorial Climate Risk and Required Adaptation

Climate Models and Projected Risk

Climate models estimate that 48.8% (∼6 million ha.) of the surface area of the three regions is currently climatically suitable for growing coffee, coinciding well with current production zones. However, significant changes in the area and spatial distribution of agroclimatic zones between 2016 and 2030 (**Supplementary Figure S1**; **Appendix 1**) are projected to lead to major changes in area suitability for coffee production. Change in the distribution of climatic zones is estimated to lead to a net loss of suitable land area in the region, with a net decline of 10.5% regional surface area or 31% of currently suitable area (**Table 1**).

This exposure risk varies with elevation and topography and so is not uniformly shared across regions—in part because of differing topographies and elevations among them (**Figures 2**, **5**). Suitability losses requiring adaptive transformation are concentrated in elevations below 1,000 m.a.s.l. Mean elevations of currently suitable areas for coffee production vary by region: Amazonas- 1,246 m.a.s.l (Min-Max: 412–3,087), Cajamarca- 1,400 m.a.s.l. (470–3,023), and San Martin- 734 m.a.s.l. (200–1,974). Having more suitable area currently at low elevations, San Martin, which has over half of the total suitable area in the three regions, is expected to lose 43% of its currently suitable area for coffee production (accounting for much of the entire study region's loss), a much higher percentage than the other two (**Table 1**). Of those areas remaining suitable within each region, nearly half are expected to face future climates different enough to require systemic adjustments and resilience building, while the other half will retain climatic conditions similar to present ones that require only incremental adjustments for coping with climate variability within historic means (middle to high elevations).

In contrast, areas where climate may present new opportunities for coffee farming are at the highest elevations, beyond the range of current coffee production (**Figures 2**, **5**). Furthermore, these areas tend to occur to the south of the regions, away from the focal study districts where fieldwork was conducted. This regional variation in climate risk exposure and recommended adaptation level with topography is similarly reflected in the perceptions of on-going climate change impacts by farmers at the district scale.

TABLE 1 | Adaptation levels recommended for areas expected to be suitable for coffee production between 2016 and 2030, based on differences in agroecological zone distribution between 2030 and 2016.

Adaptation level required	Amazonas		Cajamarca		San Martin		Total	
	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
Incremental adjustment	570,995	47	628,292	46	996,128	29	2,195,415	36
Systemic adjustment	377,370	31	405,461	30	573,744	17	1,356,575	23
Systemic resilience building	74,134	6	126,363	9	391,544	11	592,041	10
Transformation	201,356	16	191,821	14	1,479,674	43	1,872,850	31
Opportunity*	184,261	—	156,085	—	242,503	—	582,850	—
2016 Suitable area	1,223,856	100	1,351,936	100	3,441,090	100	6,016,882	100

**Opportunity zones represent areas becoming newly suitable for coffee production in 2030.*

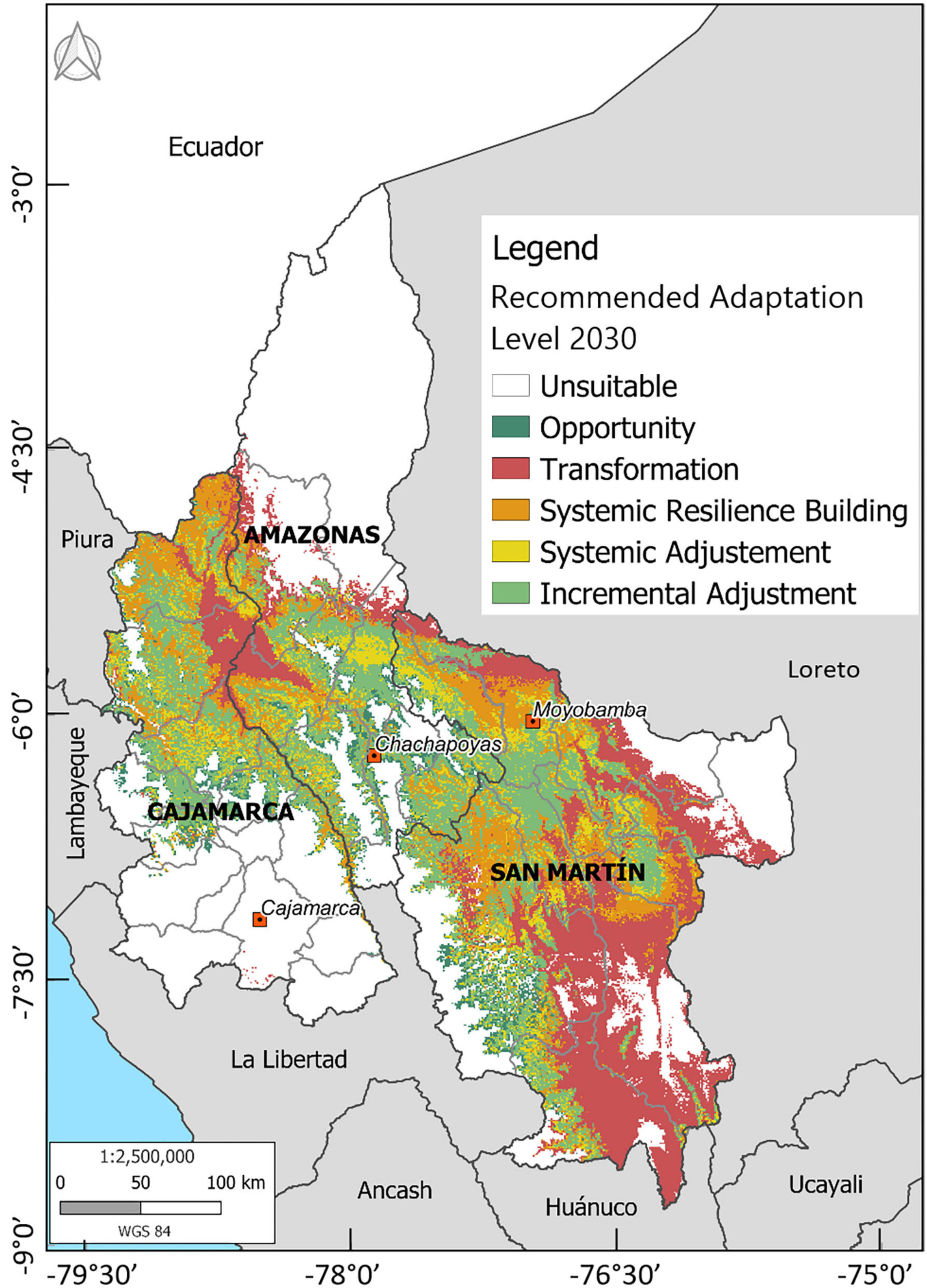

FIGURE 5 | Recommended adaptation levels based on the expected changes in the distribution of suitable agroecological zones for coffee production between 2016 and 2030. Transformation is recommended for currently suitable areas expected to become unsuitable, while areas that will gain suitability may represent opportunities for smallholders in those regions. See Materials and Methods for a complete explanation of the other adaptation levels.

TABLE 2 | Final indicators used to assess sensitivity to climate change of coffee farmers (A) and cooperatives, intermediaries, and private companies (B) according to the classification under the resource types of the Sustainable Livelihoods Framework.

Resource	(A) Farmers			(B) Cooperatives, intermediaries and private companies		
	Indicator	**Sub-indicator**	**Description**	**Indicator**	**Sub-indicator**	**Description**
Natural	Production capacity	Quantity	Trend in the variation of production quantity during recent harvests	Variability in quantity and quality of product collected	Quantity	Variability in the annual volume of coffee collected in the last 4 years
		Quality	Trend in the variation of production quality during recent harvests		Quality (physical and cup)	Trends in the variation of physical and cup quality of coffee from the main collection area
	Soil quality	Fertility	Fertility related soil properties	Sourcing dependence/risk	Dependence on high-risk production areas	Importance of low zones among collection areas
		Erodibility	Terrain slope	—	—	—
	Water availability	Availability	Proportion of year with access to water	—	—	—
	Past impact of climate events	Prolonged drought	Percentage of crop/harvest lost	—	—	—
		Intense rains	Physical damage	—	—	—
		Cold winds, frost or hail	Physical damage	—	—	—
	Past impact of pests and diseases	Prevalence of pests and disease in the crop	Percentage of crop/harvest lost	—	—	—
Human	Health and illness	Health conditions and incidence of new diseases	Cases reported	—	—	—
	Food security	Production of subsistence food crops for family consumption	Production of subsistence crops	—	—	—
Physical	Accessibility and transportation	Quality of transportation infrastructure	Ability to transit with motorized transportation	—	—	—
Financial	Potential impact on income	Dependence on coffee income	Percentage of family's income represented by coffee earnings	Marketing of resistant varieties	Varieties marketed	Importance of leaf-rust resistant varieties in those marketed

Current Climate Impacts at the District Scale

Within the focal study districts, farmers' perceptions reflect high spatial variability of recent changes in climate and their impacts, but there is a consistent grouping of climate impacts along elevational zones. Generally, farmers reported increased variability in precipitation, unpredictability in the onset and duration of rainy seasons and an increase in maximum temperatures since the early 1990's. Some farmers also perceive that extreme climate events (short, high-intensity rainfall or prolonged dry spells) have become more common in their locality, and this tends to vary yearly. Although the complex Andean topography and effects of slope orientation on wind and precipitation introduce high variability in climate and local changes at the district scale, reports of certain kinds of stressors and severity of impacts show a clear trend with elevation. Increasing issues with heat and drought that exacerbate coffee borer (*Hypothenemus hampei*) infestation and damage coffee berries were reported in low zones (900–1,200 m.a.s.l.) of all three districts. High (≥1,600–1,900 m.a.s.l.) elevation zones, in contrast, tend to suffer more from the other extreme, increased exposure to frost and high-intensity rainfall events, often accompanied by strong winds, tend to physically damage coffee-bushes, burn berries, and increase incidence of fungal diseases like leaf rust (*Hemileia vastratrix*) and American leaf spot (*Mycena citricolor*). They also experience increased erosion and damage to rural road infrastructure. In both cases, impacts can lead to reduced quantity and quality of coffee production. Middle elevations (1,200–1,600 m.a.s.l.) tend to be exposed to intermediate effects of both extremes and report intermediate levels of damage to coffee plants and production.

Sensitivity and Adaptive Capacity Indicators of Value Chain Actors

A final set of 13 and 14 indicators were selected to evaluate the sensitivity and adaptive capacity of farmers, cooperatives, and private companies (**Tables 2**, **3**). An additional 4 sets of indicators were used to evaluate the ability of service providers (internal and external) to support all other actors in adaptation to climate change (**Table 3**). Chosen sensitivity indicators for farmers (9 indicators, 13 sub-indicators) touched on 4 of the 5 capitals in the Sustainable Livelihoods Framework, focusing on climate impacts on the crop (natural capital), on farmers and their families (human capital), on infrastructure related to production (physical capital) and the potential impact on their income (financial capital). Sensitivity indicators for cooperatives and private companies (3 indicators, 4 sub-indicators) only focused on natural (impact on the ability to source product of sufficient quantity and quality) and financial capital (potential impact

TABLE 3 | Indicators of factors used to assess the adaptive capacity of farmers (A), cooperatives and private companies (B), and the current ability of service providers (C) to contribute to the previous actors' adaptation, according to Sustainable Livelihoods resource type.

Resource	Indicator	Sub- indicator	Adaptation level*
(A) Farmers			
Natural	Coffee plantation characteristics	Soil quality: has soils with good fertility and properties for production	I; S
		Access to water: presence of water at the farm//possibility of establishing an irrigation system	I; S
		Access to quality seed: presence of selected or certified plants	I; S
		Application of best practices for establishment, management, and cost administration	I; S; SR
		Implementation of agroforestry systems (AFS)	I; S; SR
	Farm composition	Implementation of adaptation actions	I; S; SR; T
		Availability of land for renewal of coffee plantations and crop diversification.	S; SR; T
		Availability of land for sustainable management at the farm level (natural resource conservation//forest remnants//secondary forest regrowth)	S; SR; T
Human	Level of knowledge and understanding of topics related to climate-change risk	Access to information, training, and innovation (for the required adaptation level)	I; S; SR; T
	Level of association	Level of "active" participation in producers organizations	I; S; SR; T
Physical	Post-harvest process quality	Presence of a processing plant	I; S
Financial	Access to credit	Access to credit for investment (can distinguish by duration and intervention type)	I; S; SR; T
	Diversification of income	Involvement in other economic activities	S; SR; T
(B) Cooperatives and private companies			
Human	Capacity to provide technical assistance services to farmers	Frequency of technical assistance	I; S
	Attitudes toward interventions related to climate change	Organizational experience with adaptation, mitigation, or other actions	I; S
	Access to information about climate change	Level of access to information about climate change	I; S
	Access to technical assistance from government or NGOs	Level of access to technical assistance by part of the government	I; S; SR
Financial	Investment in production-monitoring systems	Level of investment in systems for monitoring production	I; S; SR
	Access to financial assistance from government or NGOs	Level of access to financial assistance	I; S; SR
	Access to own capital available to invest in new technologies	Level of access to their own capital for investment in adaptation measures	I; S; SR
(C) Service providers			
Human	Support for training in adaptation, innovation and climate-appropriate practices and technologies	Orientation toward technical assistance services; production of technology and formulation of innovative practices	I; S; SR: T
	Provision of information about climate change	Level of provision on information about climate change	I; S
Social	Capacity to innovate in the design of services	Characteristics of the services offered	I; S
	Level of inter-institutional coordination	Coordination and consensus mechanisms between NGOs, ministries, and local/regional government in the coffee sector	I; S; SR

**The last column indicates what adaptation level each factor would be important for: I, incremental adjustments; S, systemic adjustments; SR, systemic resilience building; T, transformation.*

on the ability to market product). Similarly, adaptive capacity indicators for cooperatives and private companies covered only human and financial capital, while factors related to service providers' abilities to support adaptation covered only human and social categories.

Sensitivity and Adaptive Capacity: Farmers

Sensitivity

Overall, farmers scored at an intermediate level of sensitivity, but were highly sensitive in two areas (Avg. Scores > 2.3). High sensitivity to pests and diseases and dependence on coffee were observed across elevational zones and districts (**Figures 6A,C**), although the low elevation zone scored the highest on both. Indeed, among elevational zones, low regions tended to have the highest sensitivity scores across indicators (6 of 9). The high scores on disease prevalence and dependence on coffee income reflects the high susceptibility of local plantations to coffee rust and large contribution of coffee to farmers' income. A sizable number of farmers suffered significant negative impacts on their crop production from the 2012 to 2013 coffee rust epidemic and ∼73% of farmers interviewed earned more than half their annual income from coffee production.

For all other indicators, overall averages from our farmer sample suggest that regionally, sensitivity is intermediate to low in other factors. Notably, interviewees reported high water availability and low impacts on their family's health across elevational zones and regions. However, as with the overall sensitivity index (average of all indices), when we examine the remaining indicators individually we observe that there is greater variability between districts than between elevations. Farmers in San Martin showed the highest overall sensitivity (Score: 2.0), with scores >2.3 in 4 of 9 indicators: production capacity, pest prevalence, accessibility and transportation, and income dependence on coffee. Furthermore, farmers in San Martin reported the highest impacts of extreme climate events on their coffee plantations (Score: 2.2).

Overall impacts of extreme climatic events were intermediate, however, there were differences between elevational zones and regions when impacts were considered separately by type of event. Prolonged droughts had the greatest impact in low and middle regions, while intense rainfall affected farms at high elevations most. Farmers in San Martin also experienced the strongest impacts of prolonged drought and cold events (**Figure 7**).

Adaptive Capacity

While farm families showed intermediate overall adaptive capacities (Scores: 1.7–2.3), scores on half of individual adaptive capacity indicators were low or borderline low, often lowest at low elevations and markedly lowest in San Martin (Overall score: 1.6) (**Figures 6B,D**). The strongest limitations (Scores < 1.7) were in areas important to adaptation of coffee production (access to quality seed and climate-change information, innovation, and training) and their own household economies (income diversification). Most farmers collect their own, haphazardly selected seed, or acquire them from neighbors, stores, and cooperatives without clear knowledge of the quality, characteristics or management requirements of the seed they buy. This agronomic limitation is compounded by relatively low/intermediate levels of knowledge or application of best management practices for coffee cultivation or farm administration (regular fertilization, integrated pest and weed control, soil monitoring, budget and record keeping), including application of agroforestry practices. Nearly 30% of farmers farm without shade trees or integrate only a single tree species and only 10% managed more than 3 tree species in their coffee plantations. As with sensitivity, most of these issues are more pronounced at low elevations and in San Martin. Yet, individual farmers did report implementing some agronomic climate adaptation measures: several at low elevations have installed sprinkler irrigation to counter drought, others were replacing rust-impacted plants with disease-resistant varieties as part of the National Coffee Renewal Program, a few actively used integrated soil management strategies to buffer erosion during extreme rains, and at least one had introduced a heat-resistant variety.

Although most interviewees reported awareness of agronomic and management innovations that could be used for climate-change management, few accessed them or received sufficient training in their use. While the area has intermediate levels of farmer association with cooperatives (50% of interviewees were members, higher than the national average), whose technical assistance services appear to be the main venue for receiving training in best practices, climate-change and other technologies, its level, frequency, and consistency has been insufficient to create true competency among most farmers. Furthermore, despite cooperative membership, most farmers did not report active and involved participation in cooperative activities, except in high elevation zones and Cajamarca. These capacities were once again lowest in low and middle elevations, as well as in San Martin.

Income diversification and availability of land for renewal of coffee plantations or conservation, factors particularly important for higher levels of long-term adaptation (systemic resilience building and transformation) were low and intermediate. Involvement in current long-term and stable, on- and off-farm, income-generating activities unrelated to coffee were low across the board, but particularly pronounced in high elevations and San Martin. Furthermore, across elevations there is limited availability of land for on-farm diversification of production or coffee renewal (Scores: High = 1.8, Middle = 1.7, Low = 1.8) and on-farm conservation (Scores: High = 2.0, Middle = 2.0, Low = 1.4), most pronounced in low elevation areas.

Sensitivity and Adaptive Capacity: Cooperatives

Overall, cooperatives are less sensitive than individual farmers (affiliated or unaffiliated) to effects of climate change, with low to intermediate sensitivity scores and similar tendencies among regional districts across most indicators (**Figure 6E**). Cooperatives interviewed collect coffee primarily from high and middle elevations, areas less vulnerable to climate impacts to date and despite most collecting from varieties susceptible to

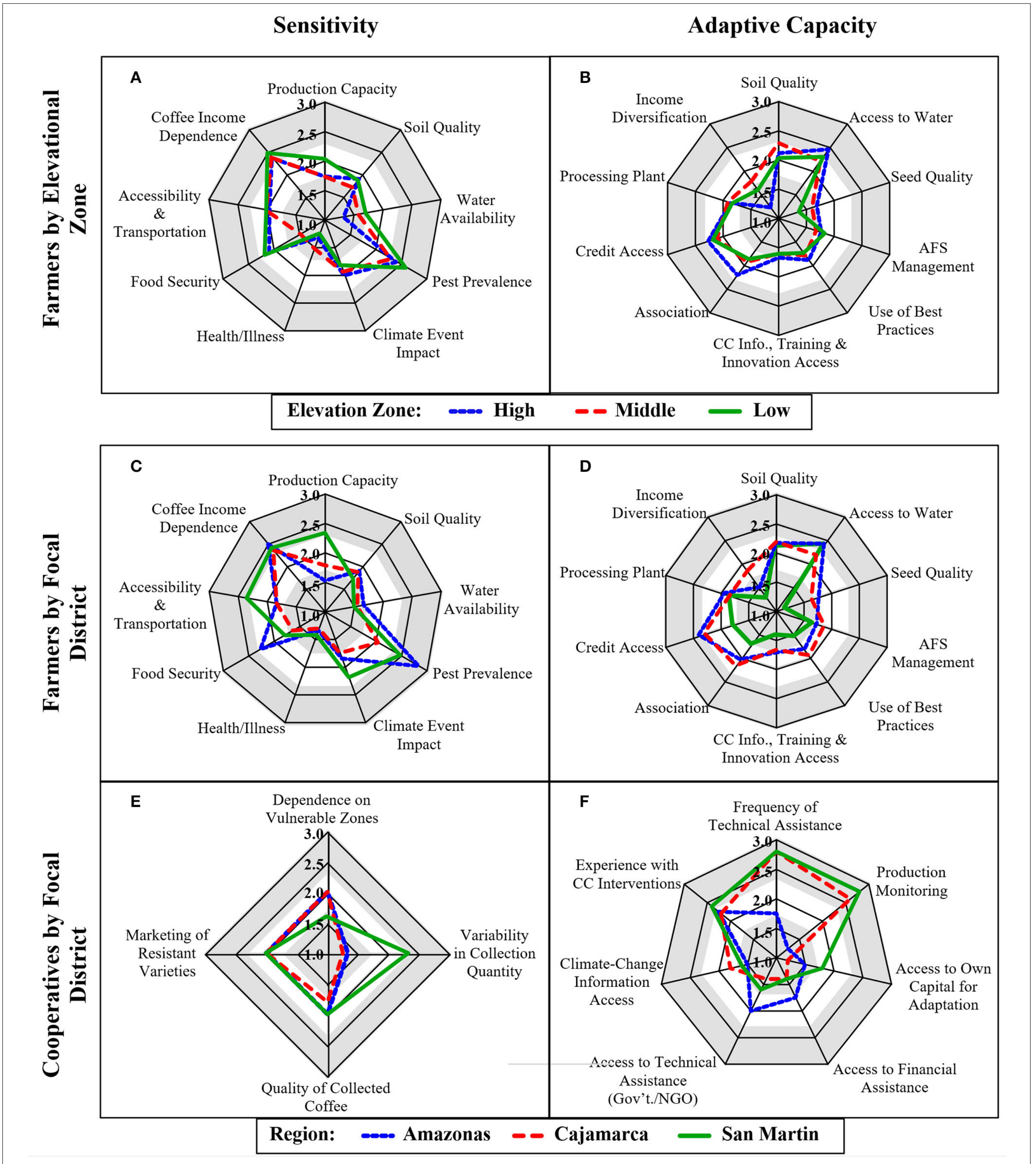

FIGURE 6 | Sensibility and adaptive capacity of farmers **(A–D)** and cooperatives **(E,F)** as assessed by key indicators in the focal study districts: Lonya Grande (Amazonas), San Ignacio (Cajamarca), and Moybamba (San Martin). Thick lines display average indicator scores for farmers grouped by elevational zone **(A,B)** or district **(C,D)**, and cooperatives **(E,F)** grouped by focal study district. Vertical numbered scale varies from low (1) to high (3) sensitivity or adaptive capacity. Shaded zones in the radar charts indicate regions of low and high scores on the scale (low: <1.7, medium: 1.7–2.3, high: >2.3).

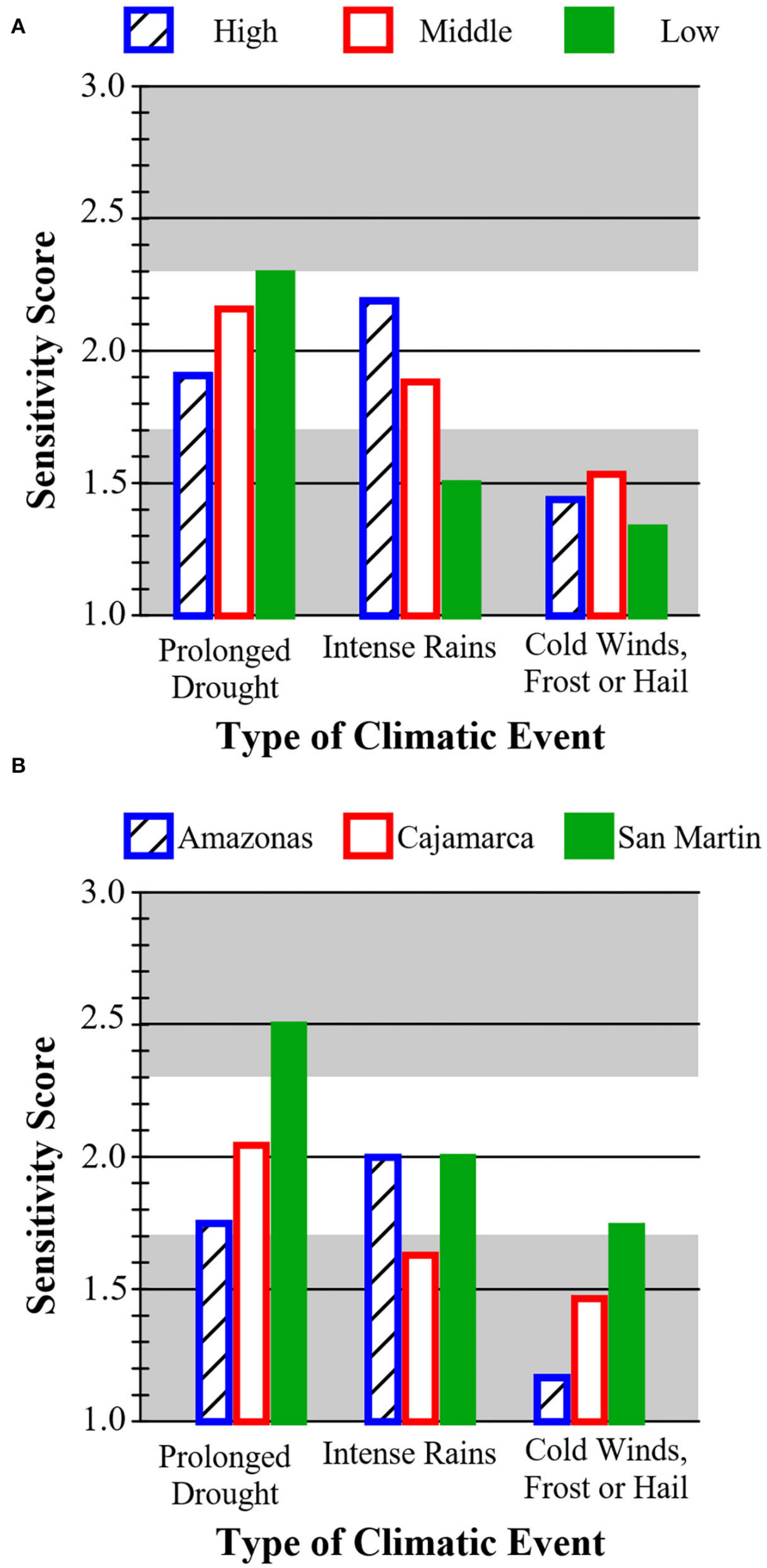

FIGURE 7 | Average impact of extreme climatic events on coffee production at the farm level by elevational zone **(A)** and focal district region **(B)**. Sensitivity scales from 1 to 3 from lowest to highest impact, these range from no event occurrence or no impact to high impacts leading to loss of coffee productivity and quality. Shaded zones indicate regions of low and high scores on the scale (low: <1.7, medium: 1.7–2.3, high: >2.3).

major pests and diseases, they collect and market coffee mixes of multiple varieties, including a few resistant ones. Thus far, except for cooperatives operating in Moyobamba-San Martin, they have been little impacted by pest or climate related events in their ability to collect coffee between 2012 and 2016, with little variability in product volumes and similar variability in bean quality reported. At least one cooperative reported that variability in their ability to collect coffee was primarily due to market fluctuations. However, the greater sensitivity of San Martin cooperatives' ability to collect coffee does correlate with higher impacts on regional farmers' production ability during the same period (high sensitivity in production capacity, climate impacts, accessibility and transportation, see Section Sensitivity), suggesting cooperatives sensitivities are not entirely uncoupled from those of farmers.

Cooperatives' adaptive capacity, in contrast, is low across several indicators (4/7) and markedly lower overall in Amazonas (**Figure 6F**). They are strongly limited by lack of access to internal capital and external financial support from public institutions that they could invest in adaptation measures or technologies, weak and inconstant technical assistance from Peruvian state agencies or NGOs, and sporadic access to climate change information relevant to coffee. Nevertheless, they also reported relevant organizational experience with climate-change adaptation/mitigation interventions through participation in national programs that originated in response to the 2011–2012 coffee rust outbreak (e.g., National Coffee Renewal Program) and more recent programs focusing on climate-appropriate practices sponsored by NGOs. Individual cooperatives reported various strategies which engaged external service providers for support in actions that would bolster resilience after pest outbreaks and other disturbances, including increased assistance in preventative management, aid in financial assistance acquisition, diversification of products marketed, and some environmental stewardship. Furthermore, with the exception cooperatives in Amazonas, they also scored high in aspects related to their reported ability to provide services or invest in technical assistance and monitoring of production.

Sensitivity and Adaptive Capacity: Private Companies

Like cooperatives, private companies sourcing coffee in northeastern Peru showed low sensitivity to climate change effects on coffee production, primarily because they spread their risk by sourcing from multiple elevational areas and regions nationally and internationally. Thus, they buffer variability in production quantities and quality. Furthermore, interviewees indicated that they market different qualities and varieties of coffee mixes *via* different channels and so can use beans regardless of variability in quality or variety. Their field personnel actively monitor and estimate future coffee production and they adjust their buyers' contracts accordingly. Their primary risk is borne when they have already invested locally in stockpiling or processing infrastructure within low elevation or high climate exposure areas in their sourcing network, but processing infrastructure in Peru is mostly located away from primary production regions.

Unlike cooperatives, companies are stronger in financial aspects of their adaptive capacity, although interviewees' responses suggest they tend to be less directly involved in the provision of technical assistance to farmers or local experiences with adaptation/mitigation measures and vary in their access to climate change information. Although governmental financial support for companies is almost non-existent, companies invest their own private capital in their operations and adaptation, but it was not clearly indicated how much of this is actually invested in organizational or on-the-ground adaptation. Adaptation action is primarily limited to sustainability tracking by internal departments, but in general, local technical service provision and locally relevant climate action is rare. Only a single respondent indicated Peru-specific actions (promotion of rust resistant varieties, climate-smart practice testing at model farms), but implemented them outside of the northeastern coffee region. One other company mentioned general support of implementation of rust-resistant varieties and research program implementation in other countries.

Service Provider Contribution to Adaptive Capacity

External service provider support and contribution to the adaptive capacity of farmers and cooperatives was variable among providers (individual agencies and provider types) and shows a frequent lack of coordination among different providers. Government agencies oriented toward agricultural technical assistance provide information locally to farmers, but their services rarely integrate climate-appropriate practices, adaptation, or mitigation systematically nor promote long-term, planned adaptation actions and technologies in the region. They provide some information about climate change but are rarely innovative nor promote innovation adequately. Nevertheless, local agrarian services are the most involved in the provision of information and technical assistance that enables diversification measures. NGOs with local programs provide greater innovation in service provision, targeted information on climate change, and experimentation with delivery of climate-smart practices and technology to farmers and extensionists *via* workshops. However, these remain isolated experiences of limited reach.

In general, provision of information about climate change and associated risks is fragmented and often of limited coverage or inappropriate scope. The national agencies which can provide weather and climate-relevant information (National Agricultural Research Institute-INIA and National Meteorological Service-SENAMHI) lack local presence, while local agencies have limited coverage and information delivery channels. The National Agricultural Sanitary Agency (SENASA) provides climate information and training to farmers upon request as related to direct risks to crops (pests, drought, fire).

Research and technology transfer that could drive innovation and test locally relevant adaptation options is very limited. National institutes in charge of research and technology transfer related to agriculture (INIA and MINAGRI) conduct research but communicate findings very locally and their research stations have highly limited coverage, none in the study districts. Genetic improvement research is virtually non-existent. One private company also mentioned private investment in research on model farms, but again, this information is only shared with affiliated farmers from model farms located outside the region.

Existing financial support *via* formal financial institutions is available, in addition to advances from intermediaries, and farmers can nominally access it, but its appropriateness for fully supporting adaptation and systemic transformation of coffee farmers and cooperatives is unclear. Informal advances are only available for immediate production use. Formal access to credit is not always accessible to farmers, as they fail to meet eligibility requirements. Furthermore, the conditions of use of formal credits are typically restrictive to mid or long-term investment in technology, improved management, or adaptation measures and only recently has financing for investment in measures like agroforestry become available.

Finally, most public service providers, NGOs, and cooperatives report frequent cooperation with other agencies, but respondents indicate little effective institutional coordination on cohesive actions. Cooperatives and private companies alike indicated generally little coordination with other cooperatives and companies. Private companies collaborate with NGO's, but almost never with government providers.

DISCUSSION

Smallholder farmers form the base of a value-chain system that sustains coffee production in northeastern Peru. The supply of coffee by these farmers and their exchange relationships with all other actors enable the marketing of regional coffee to national and international consumers, and the vulnerability of the value chain rests on the ability of different actors to maintain these exchange relationships. This central role suggests that famer vulnerability to climate change would dictate that of the entire coffee value chain. However, our findings suggest that territorial differences in farmers' vulnerability (product of climate-change exposure, sensitivity, and adaptive capacity), coupled with asymmetries in the relationship between farmers and other actors, de-couple the vulnerability of the coffee-value chain from that of individual smallholder farmers, particularly the most vulnerable. Below we discuss why this is the case and why, despite the current importance of coffee production as a smallholder livelihood in the study region, the regional adaptation of smallholder farmers to climate change will require a shift from a single value-chain focus to territorial, systems thinking.

Territorial Heterogeneity in Farmer Vulnerability to CC

Our results reveal substantial territorial heterogeneity in climate exposure, sensitivity, and adaptive capacity of farmers in different elevations and districts, leading to differences in vulnerabilities depending on farm location. This is due to territorial differences in exposure and lesser differences in adaptive capacities of farmers and their ability to meet required adaptation levels (**Table 4**). Among elevational zones, our results suggest that coffee farmers with farms in low elevation areas are highly vulnerable to expected climate change due to high climate-risk exposure and the inadequacy of current adaptative capacity to match required adaptation levels. With the greatest land area predicted to become unsuitable for coffee, farms at low elevations will require transformational adaptations that would shift livelihoods and agricultural production systems away from coffee, but their adaptive capacity is strongly limited in key areas that contribute to systemic resilience building and transformation. While high and middle elevations are similarly limited, the scope of their adaptation needs is lower and their current capacities better able to match them despite existing deficiencies. More farms at middle elevations, and most farms at high elevations, will likely be able to continue coffee production with the implementation of only incremental and systemic adjustments to agronomic practices and farm management. This, however, is not a challenge to be underestimated as at present, there is a lack of capacity for ordinary agronomic management (e.g., application of best management practices and access to quality planting material).

These elevational differences scale up to observed differences in vulnerability between study districts and regions. The most vulnerable of the three northeastern coffee regions appears to be San Martin, which not only has more of its currently suitable areas at low elevations, but the highest sensitivities and lowest adaptive capacities, also reflecting of the greater representation of farmers with farms at low elevations in our interview sample. However, it is also likely that environmental histories and social and institutional factors condition regional differences in sensitivity and adaptive capacity of both farmers and cooperatives. Regional differences in the legacy of local political and institutional development pathways, and the history of territorial development and colonization of the Amazon cannot be fully evaluated here. Our analysis may also fail to capture aspects of territorial vulnerabilities emerging from social and governance dimensions. For example, while farmers at high elevation regions may be presented with new opportunities to establish or expand coffee production in previously unsuitable areas, they may be unable to do so without generating land-use conflict where government land and forest zonation (e.g., protected areas) or communal land tenure (e.g., indigenous territories) will prevent them from obtaining legal land titles and gaining formal recognition (Robiglio et al., 2015).

The nested-scale, territorial variability in coffee farmer vulnerability described here may be generalizable to most coffee growing regions, which encompass topographically and socially heterogeneous landscapes. Global and regional studies of changes in climatic suitability for coffee or perceived climate impacts have repeatedly demonstrated spatial and topographic heterogeneity in exposure at mid and small scales in most regions (e.g., Bunn et al., 2014, 2015; Schroth et al., 2014; Ovalle-Rivera et al., 2015; Viguera et al., 2019). Similarly, studies in Central America have shown small-scale heterogeneity in coffee farmer's adaptive capacity, climate sensitivity and overall vulnerability (Baca et al., 2014; Holland et al., 2017).

TABLE 4 | Vulnerability matrix for coffee farmers at different elevational zones in northeastern Peru.

Elevational zone	Exposure	Sensitivity	Capacity for incremental and systemic adaptation	Capacity for transformation	Vulnerability
Low	**High**	**Intermediate** • Moderate to strong reduction in coffee production volumes • Strong impacts of pest and diseases • Moderately strong impacts of drought • Moderate food insecurity • High income dependence on coffee	**Low** • Very low access to quality seed • Intermediate application of best practices and agroforestry • Intermediate access to water for irrigation	**Low** • Low access to information, training and innovation related to climate-adapted practices and technology • Low availability to lands for on-farm conservation measures and diversification • Restricted access to capital for investment in diversification or long-term improvements • Low involvement in other income generating activities	**High**
Middle	**Intermediate-high**	**Intermediate/low** • Moderate to strong impact of pests and diseases • Moderate impacts of drought • High income dependence on coffee	**Low/intermediate** • Low access to quality seed • Intermediate application of best practices and agroforestry • Intermediate access to water for irrigation	**Low** • Low access to information, training and innovation related to climate-adapted practices and technology • Restricted access to lands for on-farm conservation measures and diversification • Restricted access to capital for investment in diversification or long-term improvements • Low involvement in other income generating activities	**Intermediate-high**
High	**Low**	**Intermediate** • Strong impacts of pests and diseases • Moderate impacts of intense rains • Moderate food insecurity • High income dependence on coffee	**Intermediate** • Low/intermediate access to quality seed • Intermediate application of best practices and agroforestry	**Low** • Low access to information, training and innovation related to climate-adapted practices and technology • Restricted access to lands for on-farm conservation measures and diversification • Restricted access to capital for investment in diversification or long-term improvements • Very low involvement in other income generating activities	**Low-Intermediate**

Heterogeneity in Vulnerability Among Actors

Significant differences in the direct exposure, sensitivities and adaptive capacity of actors show that vulnerabilities also differ between actors, with farmers by far the most vulnerable in the coffee- value chain. Considering their main role as collectors and movers of green coffee, cooperatives and companies are significantly less sensitive than farmers. The practice of sourcing from multiple elevations, districts, or regions, buffers the impact on their ability to gather coffee of sufficient quantity and quality. Companies and cooperatives are less territorially dependent than farmers for their primary activity and thus less exposed. Cooperatives, more regionally based and with a base of farmer stakeholders, are in theory more exposed and sensitive than companies. While they may be able to weather a certain amount of variability in coffee production by collecting from different areas, this ability appears to be limited when impacts on farmers' coffee production are more severe or widespread regionally, as was suggested in the case of our results in San Martin (see Section Sensitivity and Adaptive Capacity: Cooperatives).

In addition to exposure avoidance *via* territorial diversification in sourcing and buying from intermediaries when volume demand requires it, both actors frequently employ other short-term, commercial risk-avoidance or risk-spreading strategies which buffer the direct impact of climate events on their participation in the chain. For example, they employ coffee mixing, multiple marketing channels, and branding to sell product to consumers regardless of fluctuations in coffee quality. Furthermore, private companies set the terms of buying contracts strategically based on their monitoring of regional climate and market risks.

Like farmers, companies and cooperatives interviewed here scored low on several aspects that could help the coffee sector with building systemic resilience to greater climate stresses: access to information on climate change, technical and financial assistance earmarked for adaptation, and investment in new technologies. However, cooperatives, like farmers, are more limited in human and financial resources for adaptation. Companies have greater resources available to them, the biggest hurdle appears to be in the internal attitudes to proactively pursuing climate change interventions that involve other actors beyond managing their own commercial risk. Within our small sample, there were notable differences in these attitudes between companies and a broader survey would be required to draw generalizable conclusions for companies operating in the region. We know of more recent engagement by companies not interviewed here in climate-smart coffee and deforestation free coffee initiatives led by international cooperation organizations working in Peru. Nevertheless, the difficulty in obtaining greater participation in the study by companies, despite its backing by the National Coffee and Cocoa Chamber of Commerce, may be symptomatic of generally low awareness and possibly low concern and interest in facilitating adaptation interventions due to the flexibility they have in managing their supply chain.

In practice, the success of territorial and commercial diversification of climate risk in reducing the vulnerability of companies possibly disincentivizes other adaptive actions in which companies must invest more resources to support the adaptive capacities of farmers and cooperatives in a given territory. Across elevations and focal regions, low adaptive capacities for facing climate change, stemming from inadequacy in technical support and access to innovations for both coffee and general climate-smart agricultural practices, together with low access to capital for investing in medium and long - term adaptation measures, rather than high sensitivity, are the greatest contributors to both coffee-farmer and cooperative vulnerabilities. With few exceptions and very limited coverage, despite their role as internal service providers companies do not appear to be fulfilling this need in the value chain. Therefore, the main adaptive strategies of companies, and sometimes cooperatives, contributes to inherent asymmetry in the commercial relationships and vulnerability burden among farmers, cooperatives and companies in northeastern Peru.

The coexistence of different relationship pathways for farmers depending on their affiliation with cooperatives or other organizations might also cause heterogeneity in vulnerability among farmers. Despite the limited ability of cooperatives in the region to deliver high-level services fully adequate for adaptation needs, cooperatives are an important, locally based support for farmers. Cooperative members have the option of receiving support services *via* their organizations or external service providers while unaffiliated farmers rely primarily on external service providers and occasionally, private companies. Agricultural cooperatives may be more effective at technology transfer and facilitation or encouragement of new practice adoption when they have high levels of social capital (Candemir et al., 2021), fostered by governance that is responsible to and empowering of its members (such as by participatory decision making) (Ruben and Heras, 2012). Interviewed farmers with organizational affiliation had greater adaptive capacity than unaffiliated peers, with notably greater access to quality seed, information, and training, and increased use of best management practices (**Supplementary Figure S2**), supporting the idea that cooperatives and other base organizations are locally important for decreasing key limitations in adaptive capacity and hence, vulnerability of farmers. However, lower participation in other economic activities by cooperative members reinforces the idea that their support to date has tended to be limited to helping members continue working within the coffee sector rather than diversifying productive options.

Vulnerability of the Coffee Value-Chain and Its Role in Supporting Smallholder Farmer Adaptation in Northeastern Peru

Despite expectations for a substantial reduction of climatically suitable area for coffee, the heterogeneity in vulnerability among territorial locations and value-chain actors suggests that the overall ability of northeastern Peru to continue participating in the coffee sector will be weakened rather than eliminated, but with a highly uneven distribution of impact and adaptation burden among territories and actors. The greatest vulnerability and adaptation burden will be borne by those actors most tied to the territory, individual smallholder farmers, and those territories most exposed to strong changes in climate, low to middle elevation areas. As climate exposure studies have suggested for Indonesian coffee farming (Schroth et al., 2014), this will cause winners and losers at the regional level. Political districts with the highest proportion of vulnerable farmers, like Moyobamba-San Martin, will be the most impacted and require the greatest adaptation efforts. Districts where coffee farming will be a new opportunity may be winners, but as noted above, there are restrictions to expansion on forest and protection land that belongs to the State and that is key to support nature-based adaptation processes.

While companies and other buyers may be able to continue in the coffee sector by changing their sourcing areas locally and nationally, farmers and to some extent, base producer organizations, face scenarios that require some to seek productive adaptations outside, rather than within the coffee sector. Our results suggest that within a decade, many smallholder coffee farmers in low-elevation areas will not be able to participate in the coffee value chain and need to look toward transforming their production systems and livelihoods away from coffee if they are going to stay in their lands. Regionwide, farmers are strongly limited in key areas that would enable them to adapt as required both within (incremental and systemic adaptation, systemic resilience building capacities) and outside the coffee industry (systemic resilience building and transformation capacities). As farmers' adaptive capacity is heavily subsidized by knowledge and material resources provided by other actors "internal" and "external" to the coffee value-chain, the adaptation of smallholder farmers in northeastern Peru will require increased and optimized support in these key areas.

These areas are, not coincidentally, where current support by participants in the role service providers is insufficient (**Figure 8**). Government agencies in the agricultural, development and environmental sectors are the most well-poised to provide many of these services. By their own mandates, agencies are there to provision and regulate public services for the improvement of issues affecting farmers directly, independently of their involvement in the coffee sector. They already provide advice on other agricultural products, for example. Actors that provide services "within" the value chain, like private companies and large cooperatives, in contrast, provide limited coverage and range of services and their relative territorial independence means they have little inherent commercial incentive to improve the scope, depth or type of service provision within a given territory and no incentive to facilitate transformative adaptation. While there is room for innovative strategies for incentivizing the involvement of private companies in territorial adaptation that should nevertheless be pursued, these alone will probably never suffice for improving adaptive capacity of farmers. Government agencies already provide some support on best agronomic practices (fertilization, pest management, etc.). Strengthening these services can go a long way to improving pre-existing conditions in the region that contribute to the vulnerability of coffee production (e.g., low application of best practices, financial management, etc.), but is insufficient for supporting a strategic transformation process of farmers and productive adaptation of the territorial system. A coordinated effort that increases investment in and sharing of technology, information, and productive options from national and research agencies to local agencies, and a cohesive consideration of climate change in the delivery of services in the agricultural and development sectors will be required. This includes the facilitation of financial structures that are truly inclusive of farmers' adaptation needs.

A holistic effort to facilitate the adaptation of smallholder coffee farmers must also consider the best ways to achieve adequate coverage in the delivery of services and reduce current gaps in support to farmers. While cooperatives and other local producer organizations appear to be mediums by which farmers can get more support in certain adaptive capacities, regionally and nationally, cooperative members are the minority of smallholders (CENAGRO, 2012). Despite the existence of virtuous examples of coffee cooperatives that have grown by improving the capacities of their producers for better production in quantity and quality, access to niche markets, and fostering diversification based on small-scale forestry and agroforestry, in our personal experience we have observed an increasing trend for cooperatives to be run like enterprises to the detriment of members' or elected member board empowerment, effectively reflected in a weakened membership and a potential limitation to their effectiveness in capacity building and technology transfer. Agencies and allied actors will need to access funds and invest in being innovative in reaching organized and unorganized farmers to achieve better outcomes territorially. Finally, although much emphasis is typically placed on support of economic/productive diversification of smallholders so they can remain in the same territory, aside from socio-economic and knowledge limitations on ability, numerous cultural or social factors (age, willingness to experiment, attitudes toward new technologies, perceptions of benefits, land tenure) may prevent a good coffee farmer from pursuing other products or additional products in more complex agricultural arrangements (e.g., agroforestry) (Atangana et al., 2014; Nguyen et al., 2021). In addition, our experience suggests challenges to diversification might also come from contextual factors in coffee production territories such as limited accessibility, remoteness or unclear tenure rights that might reduce the scope for successful integration into new value chains.

Because of this, migration to high-elevation, ecologically fragile areas for conversion to coffee planting may present an attractive adaptation strategy for some farmers, leading to continued deforestation and impingement on future nature-based adaptation options for territories. Greater consideration of socio-cultural factors and environmental impact during the design of service delivery and adaptation options by service providers, rather than single-focus strategies, may be a way the value chain can aid internal efforts like the adoption of sustainability standards, and external efforts like market certifications and governmental land zoning, in avoiding these environmental externalities. This requires both for actors along the value chain to be aware of territorial governance in their supplying territories and increased leadership and capacity of local governments to plan and enforce land policies that reconcile production with forests and watershed protection. One opportunity emerging in Peru is the recently introduced legal mechanism of agroforestry concession, which seeks to conserve forest and restore forest related ecosystem functions by acknowledging farmers' role in sustainable forest management and agroforestry-based restoration at forest frontiers (Robiglio and Reyes, 2016; Pokorny et al., 2021). In clarifying land rights in remote forest frontier areas, Agroforestry Concessions are also expected to favor opportunities for diversification and facilitate market access and inclusion of farmers by granting rights for the legal sale of forestry products from the area. Principles of adaptation should be integrated in the guidelines that will orient the design of interventions at the local level, including investments by public agencies and private sector such as cooperatives and companies expected to support farmers in complying with the mechanism.

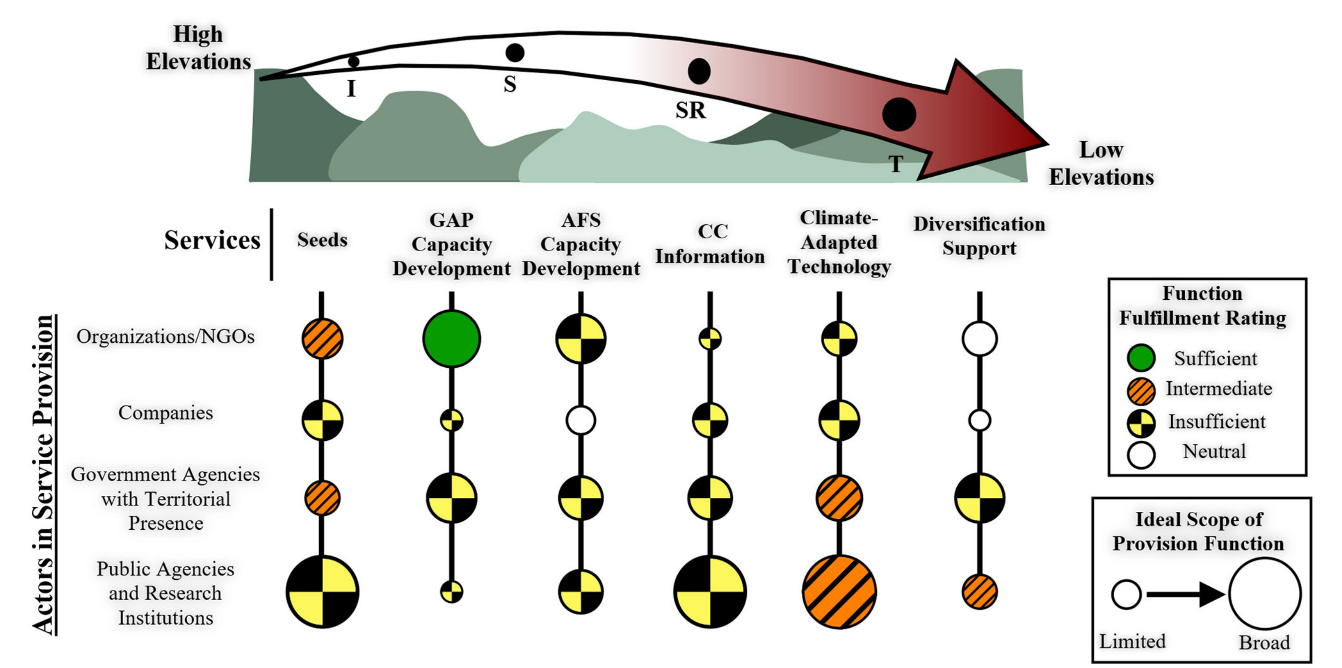

FIGURE 8 | Visual summary of actual and necessary contribution of the coffee value chain to farmer adaptation in coffee producing territories of northeastern Peru. Scope of required adaptation processes (I, Incremental adaptation; S, Systemic adaptation; SR, Systemic resilience building; T, Transformation) for farmers along the elevational gradient (top sector), the resources most needed by farmers for these adaptations (middle sector: Services) and the current capacity of different value chain actors in service provider roles to fulfill these functions (bottom sector: Actors in Service Provision). Size of the symbols indicates the relative importance of different actors in the provision of the necessary resources to farmers. Symbol color and type indicates the sufficiency of the actors in fulfilling these functions. GAP, Good Agricultural Practices; AFS, Agroforestry System; CC, Climate Change.

Stronger land governance capacity is also key in enabling conditions for private companies to adopt voluntary sustainability standards, as they reduce the risks for standards to be met as well as costs for traceability (Lambin and Thorlakson, 2018). There is a rising interest for matching sustainably produced and zero-deforestation agricultural commodities with territorial (jurisdictional) approaches to reduce deforestation; in this context territorial brands or landscape labels have been proposed a promising strategy for the private and public sector to advance toward their respective sustainability agendas under so called "hybrid" governance arrangements (see Diaz-Chavez and van Dam, 2020). However, there is not yet evidence about how state and private regulations can be combined in generating environmental nor climate change adaptation impact at the landscape level. In NE Peru, the Regional Government of San Martin, has sought to launch the brand "Marca San Martin Region" since 2016 to position agricultural products produced in San Martin, conceived as a way to implement a "Production Protection and Social Inclusion" (PPI) approach to incentivize public-private cooperation in sustainable agricultural development of the region (Robiglio et al., 2017; Diaz-Chavez and van Dam, 2020; Reyes et al., 2020). Since then, and following a change of government, there has been no significant progress in achieving territorial outcomes that can be attributed to the brand. Beside uncertainty about environmental outcomes, such branding strategies may have limited territorial effectiveness in relation to adaptation processes due to the existing heterogeneity in regional climate risk compared to the broader territorial focus of most geographical origin designations and the reality that they are not in practice fully designed to prioritize support to the adaptation of smallholder farmers vs. other value chain actors or stakeholders (Grabs and Ponte, 2019). They could best be considered complementary rather than replacements for targeted measures of adaptation support to coffee farmers discussed above.

Limitations and Strengths of Study Indicators

To our knowledge, this study is the first to develop indicators that assess the sensitivity and adaptive capacity of coffee value-chain actors besides farmers within a climate change context. They enabled us to look at the vulnerability of coffee production beyond farmers and simultaneously consider the vulnerability of farmers in relation to their interaction with other actors and their vulnerability or adaptive capacity. Nevertheless, they had some limitations that should be considered for future work seeking to apply or expand this approach.

Indicators for cooperatives, companies and service providers were chosen together with expert actors in the Peruvian coffee sector and in that sense, considered legitimate indicators of the capacity of these actors to participate in the coffee chain. However, they narrowly considered sensitivity and adaptive capacity within the actors' transactional role in the chain and ignore other aspects that could affect their capacity to continue operating or providing services within the coffee sector. For example, impacts on their internal human resources, physical resources such as transportation infrastructure, or other financial aspects that could represent constraints to value-chain participation. A fuller treatment these actors under the Five-Capitals Approach, as was applied to farmers, may yield richer information. Additionally, aside from cooperatives, we did not treat the indicators for these actors quantitatively. The broadness of some of the information gathered, together with the small sample size made such attempts difficult and further work is required to develop and test questions and scoring scales for generalized application.

Finally, further indicator development and in-depth study is required to understand the relationships between indicators used for different actors and how the specific questions used to probe them may be modified to understand them. We observed an apparent contradiction in the assessed frequency of cooperatives' ability to offer supporting services and farmers' reported access to supporting services that could be covered by these. While part of this can be explained by the fact that not all farmers interviewed were cooperative members, it may also be that this may be due to the formulation of questions (i.e., asking farmers about qualitative perceptions of service access vs. asking cooperatives more quantifiable aspects of frequency of service provision) or a general feature of actor self-assessment in participatory approaches.

CONCLUSIONS

In summary, there is a territorial patchwork of potential climate impact on coffee production in NE Peru, with the greatest vulnerability of smallholder farmers at low elevations. While this is expected to lead to lower coffee production overall from the region, the vulnerability of the coffee value-chain is intermediate, because not all farmers are expected to be equally impacted and other actors are able to buffer changes in regional supply by diversifying their sourcing territories. Heterogeneity in impact leads to heterogeneity in territorial adaptation requirements ranging from incremental adaptation strategies to full adaptive transformation away from coffee livelihoods. Such a range of location-based needs calls for a concerted territorial strategy for supporting the adaptation of the gamut of smallholder farmers currently participating in the coffee value chain where local and national providers of public services independent of the value-chain lead efforts.

While there is room for involvement for other actors (private companies) operating within the coffee value-chain to contribute, the global nature of this chain uncouples their climate risk from that of farmers within a particular location. Such uncoupling may be a general feature of global commodity value chains and provides little inherent commercial incentive for companies to be important contributors to adaptation needs of individual farmers or production territories. In this way, climate change may exacerbate pre-existing information and power (Grabs and Ponte, 2019; Panhuysen and Pierrot, 2020)—and hence economic, social and environmental—asymmetries of the coffee value chain. Therefore, supporting the adaptation of smallholder farmers requires moving beyond a value-chain approach to a territorial systems perspective that more intentionally involves those actors with stronger, locally-vested interests in their adaptation, such as government institutions. This will require strengthening the capacities of local actors for technical and service delivery innovation, adaptation planning, public-private cooperation, and governance.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because further data consolidation and translation is required. Requests to access the datasets should be directed to v.robiglio@cgiar.org.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

LM conceptualized, wrote, and revised the manuscript, revised data analysis, and conceptualized figures. VR conceptualized the original study, wrote, and revised the manuscript and performed data analysis. MB conceptualized the original study, conducted fieldwork, curated databases, performed original data analysis, and tables and figures. CB conceptualized and performed climate modeling. MR produced maps and aided in the interpretation of spatial data and information. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2022.788369/full#supplementary-material

Supplementary Figure S1 | Climate suitability zones for coffee production in study region of northeast Peru under current climate (2016) **(A)** and projected future climate in 2030 **(B)** under RCP 6.0. For explanation of suitability classes see **Appendix 1**.

Supplementary Figure S2 | Climate Sensitivity **(A,C)** and Adaptive Capacities **(B)** of farmers affiliated vs. unaffiliated with cooperatives or other organizations.

Supplementary Table S1 | Activities that form the basis of relationships between coffee value chain actors in NE Peru.

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