

RESEARCH ARTICLE

Rural livelihood diversification is associated with lower vulnerability to climate change in the Andean-Amazon foothills

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Abstract

The Andean-Amazon foothills region, one of the richest biodiversity ecoregions on earth, is threatened by climate change combined with unsustainable agricultural and extensive live-stock farming. These land-use practices tend to reduce the diversification of rural farming, decreasing households' livelihood alternatives and rendering them more vulnerable to climate change. We studied the relationship between rural livelihood diversification and household-level vulnerability to climate change in a sample of Andean-Amazon foothills households in Colombia and Peru. Firstly, we determined typologies of households based on their rural livelihood diversification, including farming diversification (agrobiodiversity and farming activities) and agroecological management practices. Secondly, we evaluated each household typology's vulnerability to climate change by assessing sensitivity and adaptive capacity based on the 'livelihood assets pentagon', which encompasses the five human capitals: natural, social, human, physical, and financial. We concluded that households with higher rural livelihood diversification are less vulnerable to climate change. However, it is impossible to draw significant conclusions about the relationship between the factors of diversification of management practices and vulnerability to climate change because most households have few agroecological practices. Results may inform future interventions that aim to decrease Andean-Amazon foothills households' sensitivity and strengthen their adaptive capacity to climate change.

Introduction

Rural households are vulnerable to climate change as they directly depend on ecosystem services (e.g., wood for fuel, wild food, and freshwater) that are susceptible to weather and climate variability [1]. The vulnerability of households to climate change can be defined as their propensity or predisposition to be adversely affected by climate change, including extreme climate events [2]. Such vulnerability results from households' social, economic, political, cultural, and environmental conditions. The concept of vulnerability has two components: sensitivity (SE);

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and adaptive capacity (AC) [2]. SE describes a household's susceptibility to a climatic event, depending on their livelihood conditions. AC is the ability of a household to adjust to, reduce, or mitigate the impacts of climatic events [2]. Therefore, vulnerability to climate change is intrinsically related to a household's 'livelihood', defined as the assets (both material and social resources), capabilities, and activities required to sustain a household [3]. For example, a household lacking quality housing materials may be more vulnerable to property damage and potential homelessness due to natural hazard-induced disasters [4]. Similarly, a household without access to education or training on farming techniques is less able to adapt to climatic changes. It may also lack information about recovery strategies compared to more educated households [5]. Likewise, a household whose livelihood is poorly diversified, i.e., with limited livelihood activities, will be more vulnerable to climate change because it will lack livelihood alternatives that might withstand extreme climatic events [6,7].

In particular, rural livelihood diversification is essential for reducing vulnerability to climate change [8,9]. Rural livelihood diversification consists of maintaining and adopting a diverse portfolio of activities to survive and improve living standards [10,11]. This portfolio encompasses on-farm and off-farm activities that help increase income, improve assets, and build resilience to periods of off-peak farming production and risks, including farming diversification and management practices [7,10–12]. Farming diversification, the basic principle of agroecology, includes agrobiodiversity maintenance and incorporation of various farming activities [13–16]. Agrobiodiversity could be maintained by including inter- and intra-species diversity of farms, crops, and animals; this builds resilience to climate change and decreases production losses. Different species and crop varieties respond differently to (and might withstand) various climatic hazards; thus, diversification reduces farmers' vulnerability to climate change [16]. Including various farming activities (e.g., agriculture, poultry, aquaculture, and beekeeping) diversifies food sources, strengthens self-sufficiency, and increases the likelihood that at least some of the farming activities will withstand climate change impacts [16–18]. Agroecological management practices are methods designed to produce substantial quantities of food, care for the ecological processes and ecosystem services, and not depend on conventional techniques such as chemical products [19,20]. Farm diversification and agroecological management practices make agroecosystems better adapted and more resilient to climate change [13,16,21].

The Andean-Amazon foothills region (AAF), also known as the 'Napo Moist Forest Global Ecoregion', is one of the earth's richest biodiversity ecoregions [22]. However, it is threatened by climate change and changes in land use, such as unsustainable conventional agricultural and livestock grazing (e.g., monocultures and extensive livestock farming). Climate projections under Representative Concentration Pathway 8.5 (RCP 8.5) scenario indicated that by 2080 the mean temperature might increase by 4.2°C, and mean rainfall might increase by 12% in the north and 17% in the south of the AAF [23]. Consequently, climate and land-use changes in the region might increase local communities' vulnerability [24]. For example, it is projected that important crops for local diets, such as maize and plantain, will lose suitable climatic areas to grow due to climate change, affecting local food security [23].

Unsustainable conventional agricultural and livestock farming tends to reduce farming diversification by focusing on the cultivation of only a few crops or extensive grazing. Such reduced diversity decreases important rural livelihood alternatives when one activity fails due to climate change impacts [13]. Moreover, unsustainable conventional practices affect ecosystem services and contribute to biodiversity loss, soil erosion, and water contamination. These conditions reduce the agroecosystem's adaptive capacity [16,24–26].

There has been limited research into the links between vulnerability to climate change and rural livelihood diversification [8,9,27]. Moreover, the few existing studies focus mainly on

areas in Africa and Asia [28–30], leaving a knowledge gap on the AAF [31], a biodiverse region and highly vulnerable to climate change [24,31–34]. One of the studies for the AAF shows vulnerability indexes by country calculated with sub-national and national data on health, poverty, infrastructure, conflict, and pressure on resources [31]. However, neither studies assess vulnerability with local indicators nor its relationship with rural livelihood diversification. This study attempts to fill this gap. Accounting for this relationship is crucial for informing future interventions that might decrease AAF households' sensitivity and strengthen their adaptive capacity to climate change.

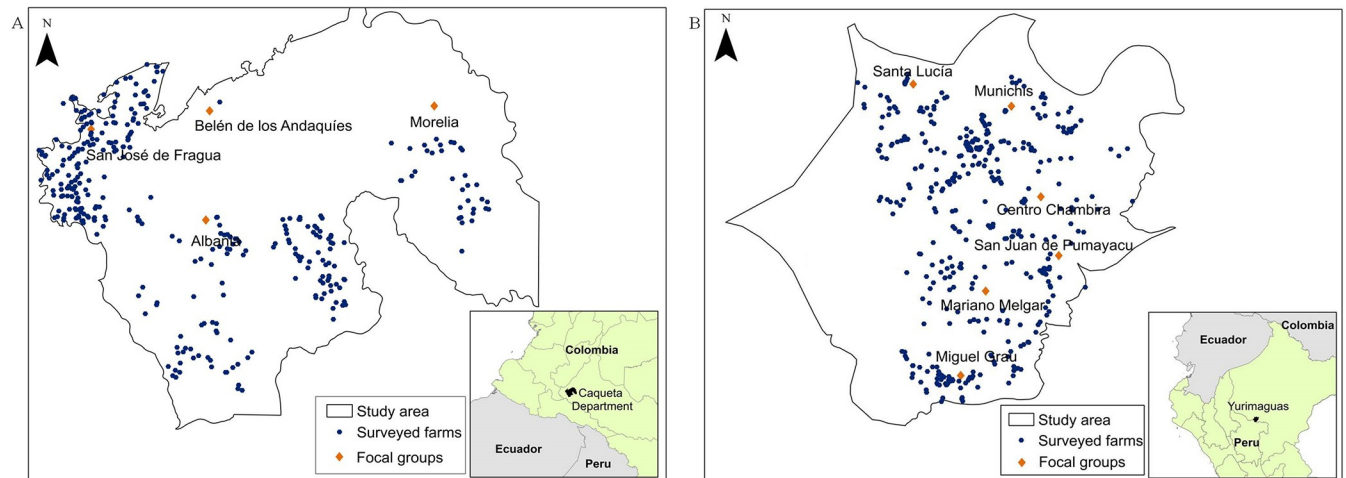
We study the relationship between rural livelihood diversification and vulnerability to climate change in AAF households in Colombia and Peru. We hypothesized that rural households with more diversified livelihoods are less vulnerable to climate change. In this study, rural livelihood diversification includes farming diversification (agrobiodiversity and farming activities) and agroecological management practices. Agroecological management practices (e.g., crop rotation, intercropping, cover crops, organic fertilization, and natural pesticide use) protect biodiversity, soil, and water. They maintain agroecosystem productivity, build the resilience of the agroecosystem in the face of climate change, and decrease household vulnerability [13,35,36]. SE and AC, the two vulnerability factors, can be measured using an integrated approach known as the five livelihood capitals (natural, social, human, physical, and financial) [37]. Natural capital refers to the benefits provided by nature. Human capital is household members' abilities, knowledge, labour capabilities, and health. Financial capital refers to monetary resources. Social capital is the relationship between individuals and their participation in organizations. Physical capital refers to basic infrastructure and assets. All types of capital contribute to household well-being.

This study was based on Caquetá (Colombia) and Yurimaguas (Peru) case studies with *colonos* and *mestizo* communities, respectively. *Colonos* refers to people who migrated to Caquetá from different regions of Colombia. People who relocated to Yurimaguas from other areas of Peru are *mestizos*. *Mestizos* are people from non-Amazonian regions of Peru, and frequently of mixed Indigenous and European cultures. *Colonos* and *mestizos* now make up most of the populations in their respective areas. Each country's government-supported migrations and associated productive projects provide subsistence options to those lacking livelihood or employment opportunities in their places of origin. The resultant *colonos* and *mestizos* are engaged in various farming activities with different management practices.

Study area

The Andean-Amazon foothills region (AAF), known as the Napo Moist Forest Global Ecoregion, includes Peru's north-western region, Ecuador's Amazonian district, and Colombia's south-western border of the Amazon. It is delimited by the Andean foothills to the west, Peru's Napo river to the east, Caguan in Colombia to the north, and Peru's Marañón river to the south [22,33,34]. The study took place in Colombia's Caquetá department (1°29' and 1°05' N and 76°02' and 75°38' W) (Fig 1A) and Peru's Yurimaguas district (located in the department of Loreto) (5°48' to 6°6' S and 76°24' to 76°4' W) (Fig 1B). Specifically, the study was undertaken in four Caquetá municipalities and 27 settlements of Yurimaguas (see the [Criteria for choosing study area](#) sub-section below).

Colombia's department of Caquetá has an annual average temperature of 26°C, a humidity of 95%, and an annual average rainfall of 3700 mm (<https://es.climate-data.org/>). The capital, Florencia, is located at 240 m above sea level. The department has been significantly impacted by internal migration prompted by a 1970s agrarian reform and funded by international entities [38–40]. This endorsed migration provided subsistence alternatives to people lacking employment, including conventional cattle ranching and agriculture [40–43]. Nowadays,



https://gadm.org/download_country.html

Fig 1. Map of study areas. A) Caquetá department in Colombia and B) Yurimaguas district in Peru. Blue dots represent the households surveyed, and orange dots represent the focus groups. https://gadm.org/download_country.html.

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Caquetá's main productive activity is extensive cattle ranching. This productive sector is the most significant contributor to Colombia's deforestation. Its prevalence in Caquetá has converted the department into a deforestation hotspot [24,44,45]. Agriculture is also an important economic activity; the department's main farm products are cacao, plantain, cassava, rice, maize, and sugarcane. The department's population is about 500,000, round 200,000 live in rural areas [46]. Most of the population comprises *colonos* and, in smaller proportions, indigenous communities from various ethnic groups [34]. Colombia's Amazon region faces significant food insecurity; it has the country's second-highest rate of chronic malnutrition in infants under five years [47]. Moreover, 40.1% of Caquetá's population is classified as living in monetary poverty, defined as the capacity of a household to acquire assets and access services [46].

Yurimaguas district, located 104 m above sea level in Peru's department of Loreto, has an annual average temperature between 22°C-26°C, a humidity of 85%, and an annual average rainfall of 2,200 mm. The Peruvian government also facilitated migration to this region in the 1960s [48], mainly for agricultural employment and not for cattle ranching such as Caquetá. After yields decreased due to soil erosion linked to unsustainable agricultural practices, farmers introduced pastures and cattle ranching. Through the 1970s, the national government supported large-scale cattle ranching projects. After, another wave of immigrants arrived in Yurimaguas, lured by the lucrative gains of illicit coca plantations, further exacerbating deforestation rates [48,49]. Yurimaguas' economy is based on agriculture, cattle ranching, and forestry. The main cash crops are oil palm, maize, cassava, papaya, plantain and rice [50]. The department's population is approximately 63,500, 22% living in rural areas. Most of Yurimaguas' population are *mestizos* but also comprises indigenous communities [51]. One-third of the Peruvian Amazon population is vulnerable to food insecurity due to a lack of food availability and access [52]. For instance, the Loreto department hosts 24% of the country's chronically malnourished children under five years old; such severe malnutrition from conception to the age of two can result in irreversible stunting of cognitive and physical development [53]. Additionally, 41.1% of the Peruvian Amazon's rural population lives in poverty, and 57% of Loreto's population has at least one unsatisfied basic necessity (i.e., food, clean water, secure housing, essential clothing, health, or educational level) [54,55].

Criteria for choosing study area

This study is part of the Sustainable Amazon Landscapes (SAL) project (<https://ciat.cgiar.org/ciat-projects/sustainable-amazonian-landscapes/>). The SAL project generated landscape units (LU) in Caquetá (Colombia) and Yurimaguas (Peru) to select the areas of intervention (i.e., for implementing sustainable agroecosystems to reverse environmental degradation) by overlapping layers of climate, soil, land -uses, geomorphology and physiography [44,56]. In total, there were 9 LU for Caquetá and 32 LU for Yurimaguas. Of these, 2 LUs for Caquetá and 4 LUs for Yurimaguas were prioritized based on the following criteria:

1. LUs that occupy comparatively more geographic space.
2. LUs with active deforestation where the first steps of forest transformation are evident, yet it is still possible to reverse these with sustainable land-use options.
3. LUs that represent the most important land use in terms of economic, agricultural and ecosystem service considerations from the department of Caquetá and Yurimaguas district.

The prioritized LUs for Caquetá were: 1) areas of cattle ranching and 2) areas of agriculture and forest. The prioritized LUs for Yurimaguas were: 1) areas with temporal crops LU, 2) areas of cattle ranching, 3) areas of mixed agriculture in the fragmented forest, and 4) areas of "palmito" (*Bactris gasipaes*).

The municipalities belonging to the chosen LUs from Caquetá (Colombia) were San José de Fragua, Belén de los Andaquíes, Morelia, and Albania. The 27 settlements within the selected LUS from Yurimaguas (Peru) were: Mariano Melgar; Centro Chambira; Miguel Grau; Santa Lucía; Cotacayu; Nueva Barranquita; San Francisco de Pampayacu; Santa Clara; Quinayoc; Santo Tomás; San Francisco; 30 de Agosto; Suniplaya; Belén; Micaela Bastidas; San Roque; Trancayacu; San Luis; San Rafael; Callao; Manguay; Achual Limón; Nueva Vida; Varaderillo; Balsayacu; and Las Palmeras. Most of these municipalities' and settlements' inhabitants are colonos (Caquetá) and mestizos (Yurimaguas).

Methods

Ethics Statement

All households participating in the study did so freely and with prior written informed consent. Although an ethics board did not approve this consent because the CIAT ethics board was in the process of being constituted at the time when the surveys were undertaken, and formal institutional processes had not yet been widely socialized, the survey was aligned with the code of ethics from the Latinoamerican Society of Ethnobiology [57]. Therefore, surveys were revised by local experts of partner institutions of the Sustainable Amazon Landscapes (SAL) project (<https://blog.ciat.cgiar.org/es/paisajes-sostenibles-para-la-amazonia-un-proyecto-que-avanza-dejando-huella-sostenible/>) and CIAT researchers from Social Sciences, Ecosystem Services, and Impact Assessment groups, who have a broad trajectory of working with farmers in Caquetá and Yurimaguas. Local experts and CIAT researchers secured that the survey respected the minimum ethical standards without risk for participants, guaranteeing that their participation did not imply prejudice or personal discrimination.

Data collection comprised two steps: focus group discussions and household surveys. Focus group discussions were used to capture information to identify rural livelihood diversification and build SE and AC indicators parameters based on the livelihood assets pentagon that encompasses the five capitals. Household surveys were used to produce household typologies based on their rural livelihood diversification and assess vulnerability to climate change for each typology [58,59] (Fig 2).

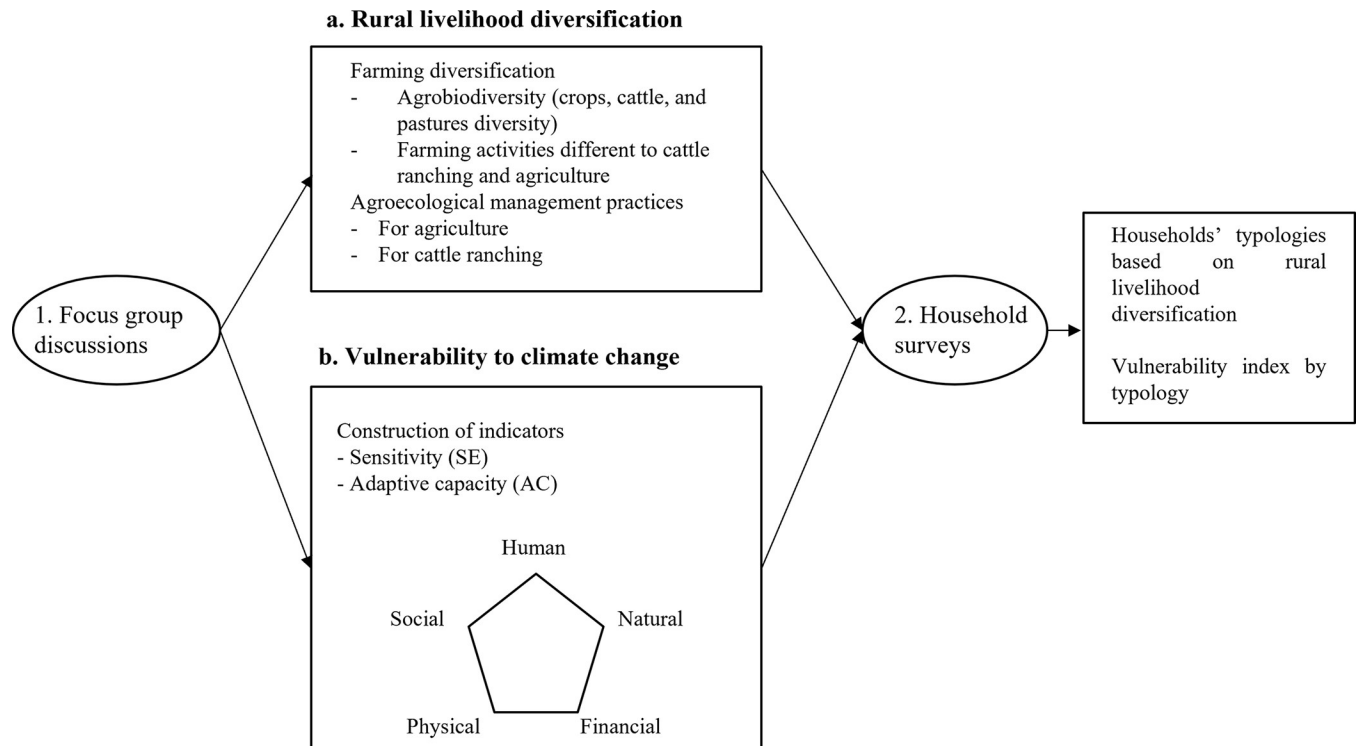


Fig 2. Steps followed for data collection and analysis.

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I. Data collection

Focus group discussions. A total of 64 focus groups were undertaken; these comprised seven focus groups in four communities in Caquetá in July 2015 (Fig 1A) and six focus groups in six communities in Yurimaguas in September 2015 (Fig 1B). Local experts selected the focus groups, which they deemed farmers of different municipalities in the study regions. For example, farmers from Caqueta are mainly dedicated to cattle ranching, but they also cultivate different crops. Farmers from Yurimaguas are mainly dedicated to cultivating oil palm, rice, papaya, and other crops, and they also have cattle ranching. The focus groups were conducted to capture information about local livelihoods, climate change adaptation strategies, and assets to achieve well-being. Information obtained from the focus groups was used to contextualize the variables on livelihood diversification and vulnerability (see below the construction of vulnerability indicators) and include them in a household survey. Each focus group discussion lasted approximately two hours, with an average participation rate of eight farmers per group, 168 farmers for Caquetá and 207 for Yurimaguas. The focus groups included men and women who participated freely and with prior informed consent. Information obtained in focus groups discussion was returned to farmers as brochures and booklets.

Household surveys. Before the surveys, local interviewers were recruited and trained, and a pilot test was conducted. A total of 256 surveys were undertaken in Caquetá and 227 in Yurimaguas. Households were chosen by stratified random sampling with proportional allocation to have a representative sample of the rural households by the municipality, according to the percentage of rural households in the 2005 national census for Caquetá and 2007 national census for Yurimaguas. Only households involved in farming took part in the survey. Surveys were conducted in Spanish, the primary language of *colonos* and *mestizos*. Household surveys

Table 1. Variables used to typify households based on farming livelihoods diversity and agroecological practices. AP-A represents agroecological practices for agriculture. AP-CR are agroecological practices for cattle ranching.

1. Agriculture and cattle ranching diversity	2. Number AP-A	3. Number of AP-CR	4. Number of additional productive activities	5. Land use (Ha)
a. Number of pasture types b. Number of cattle varieties c. Total heads of cattle d. Number of crops	a. Crop rotation b. Intercropping c. No slash and burn d. Cover crops e. Organic fertilizers f. Natural weed control g. Natural pesticides h. No-tillage i. Fallow lands j. Lime application	a. Rotational grazing b. Soil decompaction c. Pasture renovation (drilling legumes seeds in a grass dominated sward) d. Living fences e. Manure reutilization f. Crops-pasture rotation g. Natural pesticides h. Lime application to pastures i. No burning for pastures renovation j. Fallow paddocks k. Pastures and grasses and legumes association	a. Aquaculture b. Poultry farming c. Pig-farming d. Beekeeping e. Fruit trees f. Timber trees g. Food processing	a. Agro-forestry areas b. Silvopastoral area c. Crops area d. Pastures area e. Home-garden area f. Wetlands area g. Forest area h. Farm area

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were undertaken from March to October 2016 in Caquetá, and from June 2016 to January 2017 in Yurimaguas. Households were asked about their farms' agrobiodiversity (i.e., crops, cattle ranching, and pastoral diversity), farming activities, and agroecological management practices. These surveys provided the information required to define household typologies (Table 1). To calculate the indicators of sensitivity (SE) and adaptive capacity (AC) (Table 2), the households were asked about their livelihood assets. We define a household as a group of people sharing food and living in the same house [60]. Family members who have migrated permanently or do not live in the same house were not included in the surveys. Some participants from focus groups might have taken part in the interviews.

II. Data analysis

Farmers' typologies based on rural livelihood diversification. Hierarchical clustering analysis was used to group the surveyed households (from Caquetá and Yurimaguas) into clusters with similar farming diversification and agroecological management practices. We called these clusters household typologies [62]. This analysis was based on 15 variables derived from relevant literature, which indicate a household's diversity in agrobiodiversity and farming activities. These variables are grouped as 1) agriculture, cattle ranching diversity, and pastoral diversity, i.e., diversity of crops, cattle variety, and pasture species, respectively [13,35,63,64]; 2) the number of agroecological practices for agriculture (AP-A) out of 10 different practices over a full calendar year; 3) the number of cattle ranching practices (AP-CR) out of 11 different practices over a full calendar year representing the agroecological principles that aim to protect natural resources [13,35,63,64]; 4) the number of additional productive activities aside from cattle ranching and agriculture, out of a total of seven activities practised in the region [50,65]; and 5) the type of land-use in hectares [50,66] (Table 1).

Two sets of farmers' typologies were obtained for Caquetá and Yurimaguas respectively, because both sites have different contexts. Caquetá is habited by *colonos* and Yurimaguas by *mestizos*, who have arrived at these sites through different historical processes and carry diverse cultural heritage. Firstly, the variables were standardized for Caquetá and Yurimaguas separately, where 0 refers to the dataset's minimum value and 1 to its maximum value [67]. Secondly, the cluster analysis was performed using a hierarchical cluster algorithm using the statistics package R [67,68]. Thirdly, a consistency measure was applied to estimate the optimal number of clusters or typologies required to improve the grouping of households, following

the methodological steps detailed by Sietz and colleagues [68,69]. Then, typologies based on rural farming diversification were obtained for Caquetá and Yurimaguas. Finally, each household was allocated to a typology based on the cluster analysis. All the analyses were performed in the R Studio [70].

Construction of vulnerability indicators. The indicators of SE and AC were chosen for the livelihoods approach’s five livelihood capital assets [59] (Table 2). Some SE and AC indicators, suggested by [6] and [58], were adapted and contextualized based on focus group discussions of the study sites. The remaining indicators were derived from the focus groups (see Table 2, the column indicating the source of each indicator), which are presented in detail in the results section. The SE and AC indicators utilised, per type of capital, are the following.

Natural capital: The indicators used for SE in a household were forest conservation, water access and quality, and soil quality. The lack of these natural capitals could make a household

Table 2. Indicators of sensitivity (SE) and adaptive capacity (AC) of households in Caquetá (Colombia) and Yurimaguas (Peru).

Vulnerability	Capital	Indicator	Parameter	Measure	Source
Sensitivity (SE) <small>(low) SE (high)</small> 0, 1, 2, 3,....	Natural	Forest conservation	Forest areas transformed into pastures or crops	Hectares	Focus groups [58]
		Water access and quality	Source of water for consumption	Aqueduct (0), Non-potable (1),	Focus groups [58]
			Water quality perception	Perception (good (1), regular (2), bad (3))	
	Soil quality	Symptoms of soil degradation	Number of symptoms (lack of water infiltration, decrease in milk production, decrease in crops growth)	Focus groups	
	Financial	Total income	Income from livestock, processed products, and crops sales	Quartiles	Focus groups
		Land tenure	Type of land tenure	Own (0), possessor (1) rented (2)	Focus groups
	Physical	Farm access	Type of road	<u>Paved (0), Unpaved (1)</u>	Focus groups [58]
			Modes of transport	Own transport (1), public transport (2), walking or horse (3)	Focus groups [58]
		Housing quality	Housing material index	High quality (floor: tile, walls: bricks, roof: tiles or cement) (1), acceptable (floor: cement, walls: wood, roof: zinc) (2) Deficient quality (floor: soil, walls: mood, roof: vegetal material) (3)	Focus groups [61]
		Basic services	Electricity	Yes (0), No(1)	Focus groups
			Sanitation services	Toilet connected to sewage system (1), toilet connected to the septic tank (2), toilet without connection (3), latrine with a roof (5), latrine without a roof (4), open-air (6)	Focus groups
		Household crowding	Household crowding index	No (1), medium (2), critical (3)	Focus groups
	Human	Diet diversity	Household dietary diversity score (HDDS)	Number of different food groups consumed over one day (cereals, tubers and roots, vegetables, fruits, meat, eggs, fish, legumes, nuts and seeds, dairy products, oils and fats) (0–12)	[61]
		Food security	Latin America and Caribbean Food Security Scale (ELCSA)	Security (0), mild insecurity (1–5), moderate insecurity (6–10), severe insecurity (11–15)	Focus groups
		Health	People with critical illness	Number	Focus groups,
			Type of medical service	Private (1), public (2), no (3)	
	Social	Social conflicts	Conflicts to which the home is exposed	Number of conflicts (land appropriation, oil companies, mining, national parks, landowners, and others)	Focus groups
		Migration	Migration in the family caused by social conflicts	No (1), yes (2)	Focus groups

(Continued)

Table 2. (Continued)

Vulnerability	Capital	Indicator	Parameter	Measure	Source
Adaptive capacity (AC) (low) AC (high) → 0, 1, 2, 3,....	Natural	Waste management	Organic waste management	Burning -nothing (0), compost (1)	[58]
			Non-organic waste management	Burn—nothing (0), Recycle (1)	
		Water sources	Water sources on the farm	Number	Focus groups
		Soil conservation	Practices to conserve soil	Number	Focus groups
	Financial	Off-farm income	Annual income of non agricultural jobs	Values in pesos (Colombia), Soles (Peru)	[58]
		Remittances	Value in subsidies, donations or remittances in the last year	Values in pesos (Colombia), Soles (Peru)	[6,58]
	Physical	Technology	Technological elements of the farm	Number	Focus groups [6,58]
			Technological elements of the house	Number	
	Human	Education access	Level of education	Number of years completed by the head of the household	Focus groups [6,58]
		Technical assistance	Technical training	Number of training in agriculture topics in the last year	Focus groups [58]
			Applied training	Percentage of applied training	
		Food for self-consumption	Food produced for self-consumption	Number of foods	Focus groups
	Social	Organization	Participation	Number of people in the household who belong to an organization	[6,58]
			Benefits	Number of received benefits	
Personal relations		Quality of familiar relations	Perception (bad (0), good (1)	Focus groups	
		Quality of neighbours relations	Perception (bad (0), good (1)		

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more susceptible to climate change. Thus, we considered them SE indicators. The loss of forest contributes to soil erosion and the loss of shade for people and cattle. Water access and quality are crucial for household well-being; soil quality influences food production. Indicators to evaluate AC were water sources within the farm, soil conservation practices, and appropriate organic and non-organic waste. The number of water sources gives a household a better ability to reduce climate impacts. Thus, if one water source is affected, others can supply it to a household. Soil conservation practices and appropriate organic and non-organic waste management improve the adaptive capacity by preventing environmental pollution that could exacerbate climate effects. For example, soils managed with adequate practices are less prone to eroding during drought. (Table 2) [58,59].

Financial capital: The main indicator of SE is income which could decrease susceptibility to climate events because it contributes to household resilience during adverse situations caused by climate change. Indicators of AC were sources of off-farm income or remittances that could play an important role in cushioning and recovering households following a climate-related emergency [6,58,59].

Physical capital: Indicators of SE were farm access, housing quality, basic services, and household crowding. The lack of these physical capitals could make a household more susceptible to climate change. Farm access is affected by the type of roads and means of transport. For instance, a farm with unpaved roads and lacking a means of transport has more barriers to

receiving assistance during or following a climate-related emergency. Likewise, house quality determines the level of impact from natural hazards, such as flooding or landslides. A household lacking basic services or experiencing household crowding will be more impacted by climate change than a household with basic services. Meanwhile, AC indicators that give a better capacity to a household to reduce the impacts of climate were farm or household technology (such as radios, televisions, internet connections, or mobile phones). Such technology enables communication and access to climatic information in an extreme climatic event [6,59].

Human capital: Indicators of SE were the lack of food security and the absence of health services. Households lacking food and health security are more vulnerable to climate change than households with access to these services. AC indicators were the head-of-household's educational level, the household's access to technical assistance, and the household's cultivation of food for personal consumption and sale. These indicators reflect a household's capacity to withstand climate-related emergencies because residents with education or technical capacity may find alternate employment opportunities more easily. In addition, cultivating food for self-consumption acts as insurance against household food insecurity during times of crisis, i.e., lack of income or climate-related emergency [6,58,59].

Social capital: SE indicators were migration prompted by the social conflict defined as an incompatibility of positions between people that undermines societal stability [71] and the range of conflicts a household might face, e.g. with oil and mining companies, landowners, or national parks. These conflicts increase household vulnerability to climate change. AC indicators were family participation in social organizations (e.g., farmers and livestock associations, environmental organizations, and local community councils) and good relationships with neighbours. Being a member of these organizations often provides access to resources for recovery from the impacts of climate change. Also, evidence indicates that a community recovers more rapidly from an extreme climatic event if its members work together [6,58,59].

Vulnerability indexes per typology. Calculation of SE and AC indicators: Each SE and AC indicator, per livelihood capital assets, comprises one or two parameters (Table 2). Categorical parameters were measured in scales (see column measurements in Table 2). For example, 'source of water for consumption' was measured on a scale of two (aqueduct = 0, non-potable = 1), and 'water quality perception' was measured on a scale of three (good = 0, regular = 1, bad = 2). Then, the value per indicator was calculated by averaging the parameters. For example, the value of the 'water access and quality' indicator was obtained by averaging the 'source of water for consumption' and 'water quality perception'. The value of the SE and AC indicators were then scaled from 0 to 1, with 0 being the lowest and 1 being the highest SE and AC scores [58]. Each SE and AC indicator was obtained per household. Then, each household was allocated to a typology (see the previous cluster analysis explanation). Finally, the SE and AC indicators of the typologies were compared.

Comparison of SE and AC between typologies: A non-parametrical Kruskal-Wallis statistical test was applied to identify significant differences in SE and AC indicators between typologies [58]. In addition, a Dunn's test, *post hoc* analysis that is applied for non-parametric data with groups of unequal size, was carried out to identify differences between typologies. Thus, if the three typologies differed, they were classified in low, medium, or high levels based on the median. However, when only one typology differed from the other two, typologies were categorized as high-medium or low-medium, based on the median. Subsequently, the typologies were classified with scores of 1 = low, 2 = medium, and 3 = high, following whether most of their SE and AC indicators had low, medium, or high median values following Baca et al. (2014) [58].

Vulnerability calculation: The equation "Vulnerability (VU) = Sensitivity (SE)—Adaptive capacity (AC)" was applied to obtain vulnerability indexes by typology. The equation

represents a household's sensitivity level (SE) and its lack of adaptive capacity (AC). This equation was taken from [58] and [72] but modified according to the new definition of vulnerability, which no longer includes component exposure [2]. On application of the equation, the following possible vulnerability values were obtained: low (-2, -1), medium (0), and high (1, 2). Finally, a value of vulnerability ranging from -2 to 2 was obtained by typology.

Results

Focus group discussions

Rural livelihoods and climate change adaptation strategies for Caquetá. The main livelihood identified by participants in Caqueta was cattle ranching. Households also cultivate some crops, mainly sugar cane, pineapple, cocoa, maize, plantain, cassava, fruit, and timber. However, few households have aquaculture, poultry, pig farming, and beekeeping. In addition, home gardens are less common than in the past because farmers buy vegetables in the market.

The main indicators of climate change identified were abrupt changes in temperature, increases in temperature, and increases in rains. These changes affect pasture production and milk and meat production, which decrease household income. Farmers do pasture rotation, build more drinkers, and cut grass or use sugar cane to feed them to cope with these effects. Some farmers mentioned that they prefer having local varieties of cows as they support better these climate change effects. Also, many times during the year, farmers need to work off-farm to recover their income. When the situation is very critical, they need to sell the cattle. Farmers having aquaculture mentioned that ponds are not affected by these changes. Thus, they have a regular income which alleviates economic effects when cattle ranching is affected. Many locals started implementing aquaculture in 2010. However, some do not show much interest because, in the beginning, fish care was demanding, and fungus contamination was very high.

Climate change decreases the production of most crops (plantain, maize, cocoa, fruit trees). The strategy used to cope with this decrease is applying fertilizers to improve production, which is possible only when the household has a good income. Otherwise, crops suffer, and food security and household income are affected. Crop pests also increase with abrupt temperature changes. Farmers use pesticides to control them only when the household has economic possibilities.

Rural livelihoods and climate change adaptation strategies for Yurimaguas. The main livelihood identified for Yurimaguas was agriculture. Households cultivate rice, oil palms, cocoa, papaya, cassava, maize, plantain, sugar cane, pineapple, and fruit trees. In addition, some households have aquaculture, poultry, pig farming, and beekeeping. Cattle ranching is less common than Caqueta, but it is the main activity for some households. Home gardens are also being lost since farmers buy vegetables in supermarkets more often than in the past.

The leading indicators of climate change identified were increased temperature and heavy rains. These changes affect crops differently. For example, all crops are lost during floods, and household well-being is affected. Rice yield is also reduced when the weather changes abruptly because of a fungus infection. For oil palm, pests increase when temperature increases, the strategy to mitigate this effect is using pesticides. Cocoa yield decreases with high temperatures. Thus, farmers put shadows on fruit trees to alleviate the heat. Cassava, maize, and plantain are more affected by heavy rains that rot the plants. However, this can be mitigated by planting them in pending areas to drain water. Farmers mentioned that some women produce local fruit marmalades, ice creams, and refreshments, including handicrafts that give additional income to the households.

Cattle ranching is affected by high temperatures and rains. Both climate effects decrease grass available for cows. High temperatures dry the grass, and heavy rains increase mud,

making the grass non-suitable for cattle. Thus, milk and meat production decrease affecting household income. As a result, the strategy is to cut grass or sell the cattle and do out-farm work.

Local indicators of sensitivity (SE) and adaptive capacity (AC) for Caquetá and Yurimaguas. Vulnerability to climate change is intrinsically related to a household's assets (both material and social resources), capabilities, and activities required to sustain a household. The most important assets to achieve well-being identified by participants in Caqueta and Yurimaguas were the following. Concerning SE local indicators for natural capital, respondents indicated that forests provide shade for cattle and farmers. At the same time, water access and quality are crucial for household consumption. Likewise, they mentioned that soil quality determines crop yields.

Regarding financial capital, they stated that household income and land tenure provide shelter and the conditions for food production. On physical capital, they mentioned that roads and transport are essential issues for accessing main cities, especially for transporting products. Moreover, they claimed that roads are frequently affected by periods of rain. Additionally, respondents identified that electricity, sanitation services, and a house with bedrooms were key household well-being aspects. For human capital, households mentioned that access to food and health services are essential issues for well-being.

For social capital, households face different types of conflict, such as those relating to land appropriation or those with fossil fuel and mining companies. Local households consider these factors that affect the quality of life and pollute soil and water. They also mentioned conflict with landowners and national park staff, explaining that landowners use water sources and displace local people. National park staff enforces regulations that forbid agriculture and cattle ranching near protected areas. Farmers from Caqueta mentioned that "Do not have to migrate to other places because of armed conflict" indicates well-being. Farmers from Caqueta region have suffered land appropriation and displacement caused by the armed conflict that has obliged persons to migrate to other regions.

Regarding AC local indicators for natural capital, respondents suggested that crucial indicators for food production are conserving farm water sources, securing water availability in drought periods, and conserving soil. They emphasised off-farm income and remittances for generating additional money for household necessities for financial capital. For human capital, informants identified their food production to provide food security in crisis periods, access to tools and technology (e.g., refrigerator to conserve milk), education, and technical training. Participants recognized good relations with family and neighbours for social capital because these relations aid recovery after climate-related emergencies. Moreover, they mentioned the benefits of belonging to different organizations (farmers' associations, environmental organizations, and local community councils). These benefits include securing the market for their produce, receiving training and technical assistance, and accessing resources for recovery from climate change impacts.

Farm typologies based on rural livelihood diversification. According to the consistency measure that evaluated the number of clusters or typologies that best explain the variation of households, there are three typologies for Caquetá (S1 Fig) and two or three typologies for Yurimaguas (S2 Fig). Three clusters were chosen for Yurimaguas since they discriminated the households better than the two clusters.

Typologies for households in Caquetá. Fig 3 presents descriptions of the three different typologies of Caquetá, based on the 15 variables of farming diversification and agroecological practices. All three typologies lack silvopastoral, agro-forestry, wetland, and home garden areas.

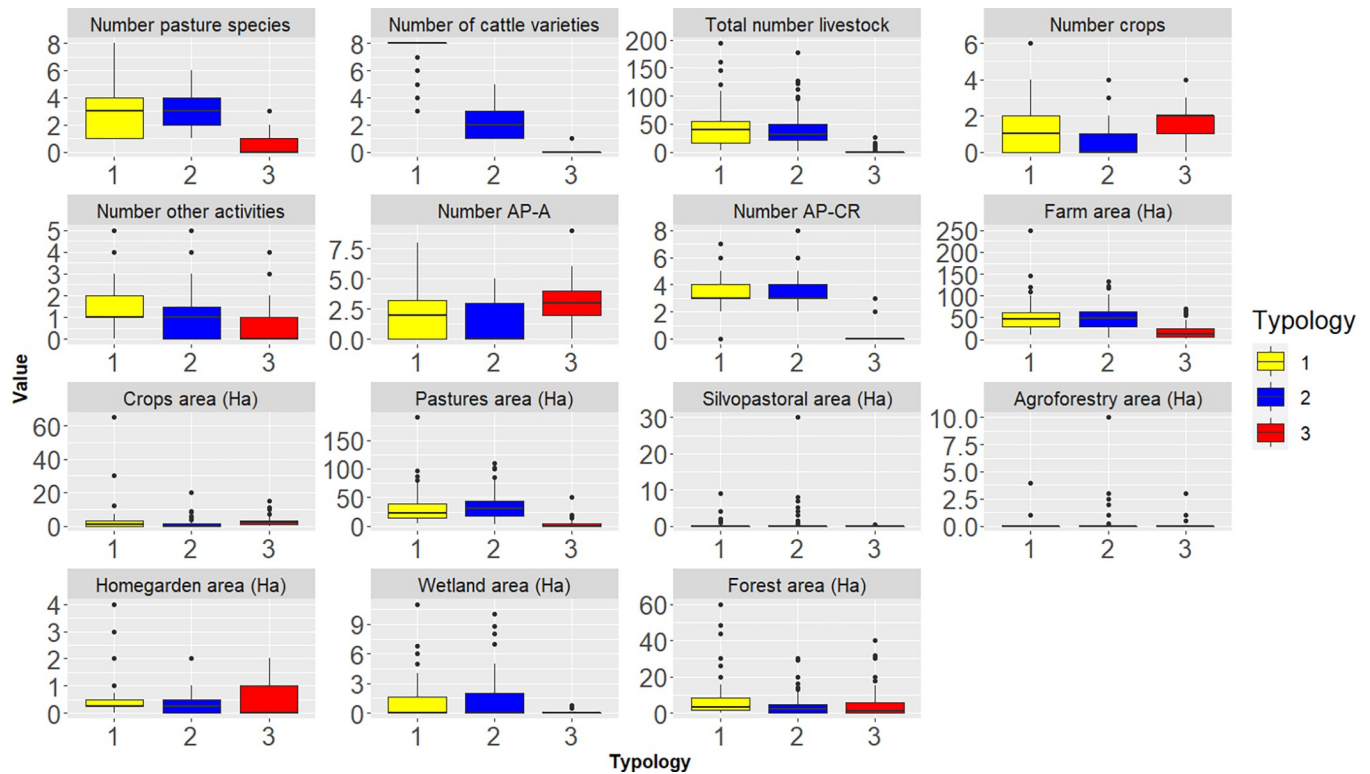


Fig 3. Boxplots of clusters (typologies) versus 15 variables correlated with farming livelihoods diversity and agroecological practices from Caquetá (Colombia). Data were obtained from 256 households in Caquetá. Descriptions of each variable (including their units) are summarized in Table 1. Typology 1: "moderately-diversified livelihoods", typology 2: "slightly-diversified livelihoods", and typology 3: "non-diversified livelihoods". The Y-axis is the value of each variable. Units are explained at the top of each boxplot. AP-A and AP-CR represent agroecological practices in agriculture and cattle ranching.

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Typology 1: "Moderately-diversified livelihoods" (68 households) includes households with agriculture ($\bar{x} = 1.47$, $SD = 1.34$), cattle ranching (total heads of cattle: $\bar{x} = 43.6$, $SD = 37.32$, number of pastures: $\bar{x} = 2.76$, $SD = 1.6$) and households that have up to two additional productive activities ($\bar{x} = 1.5$, $SD = 1.24$), including aquaculture, poultry-farming, pig farming, beekeeping, timber trees, or food processing. Moreover, these households have a high diversity of livestock varieties ($\bar{x} = 7.57$, $SD = 1.06$). Most households reported two out of 10 AP-A ($\bar{x} = 2.37$, $SD = 2.08$) and three out of 11 AP-CR ($\bar{x} = 3.22$, $SD = 1.06$). This typology has more forest area ($\bar{x} = 7.2$, $SD = 11.25$) than the other typologies. Farm area ($\bar{x} = 52.22$, $SD = 36.86$) is similar to "Slightly-diversified livelihoods" typology.

Typology 2: "Slightly-diversified livelihoods" (107 households) includes households that have less diversity of livestock varieties ($\bar{x} = 1.93$, $SD = 0.96$) and crops ($\bar{x} = 0.79$, $SD = 1.02$) than the "moderately-diversified livelihoods" typology. They also have relatively less forest area ($\bar{x} = 4.11$, $SD = 5.67$), productive activities other than agriculture and cattle ranching ($\bar{x} = 0.92$, $SD = 1.06$) and farm areas ($\bar{x} = 40.54$, $SD = 27.43$) than the "moderately-diversified livelihoods" typology. They have fewer AP-A ($\bar{x} = 1.3$, $SD = 1.55$) but the same amount of AP-CR ($\bar{x} = 3.54$, $SD = 1.21$) than the "moderately-diversified livelihoods" typology. Also, this typology has similar numbers of pasture species ($\bar{x} = 2.84$, $SD = 1.32$), and total heads of cattle ($\bar{x} = 39.32$, $SD = 29.15$) to the "moderately-diversified livelihoods" typology.

Typology 3: "Non-diversified livelihoods" (81 households) includes households that only practice agriculture with the production of few crops ($\bar{x} = 1.8$, $SD = 1.01$). These households have slightly more AP-A ($\bar{x} = 2.93$, $SD = 1.41$) than the "moderately-diversified livelihoods"

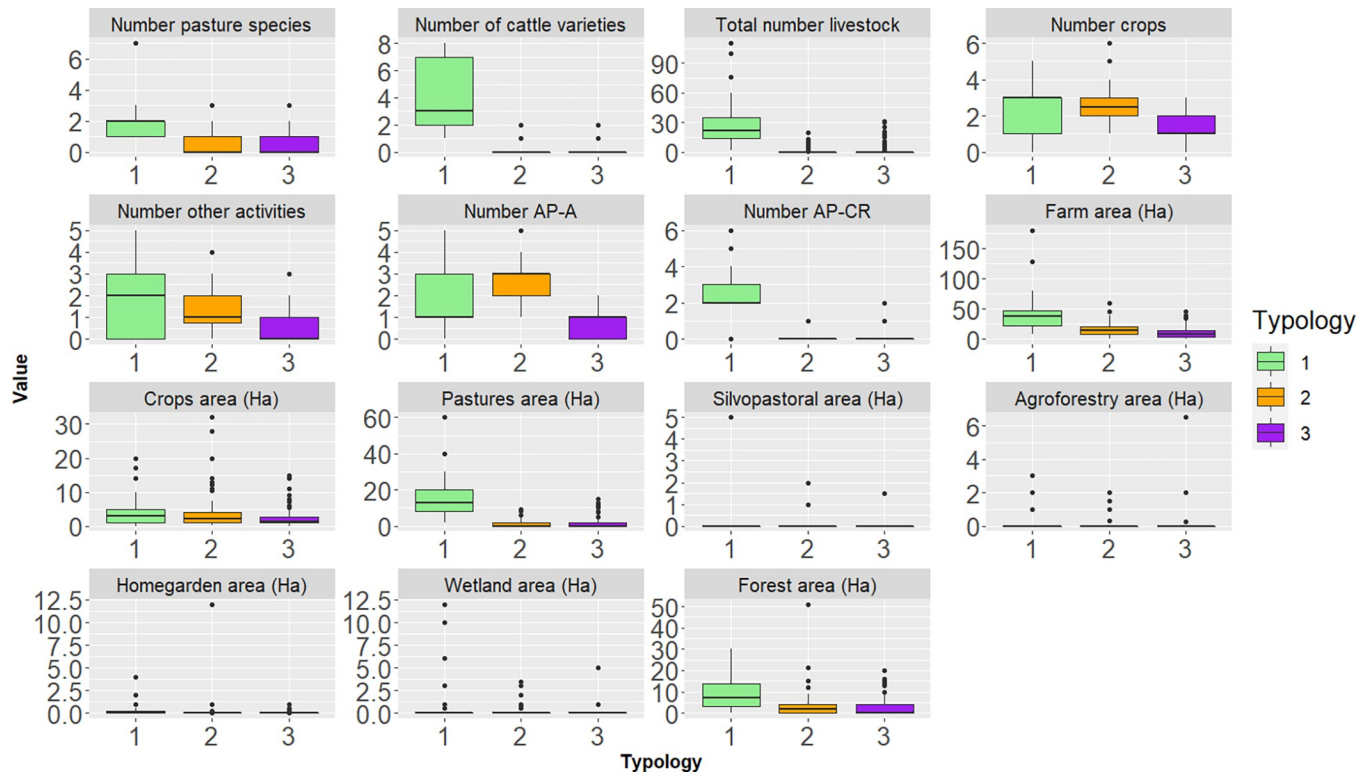


Fig 4. Boxplots of clusters (typologies) versus 15 variables related to farming livelihoods diversity and agroecological practices from Yurimaguas (Peru). Data were obtained from 227 households in Yurimaguas. Descriptions of each variable (including their units) are summarized in Table 1. Typology 1: "moderately-diversified livelihoods", typology 2: "slightly-diversified livelihoods", and typology 3: "non-diversified livelihoods". The Y-axis is the value of each variable. Units are explained at the top of each boxplot. AP-A and AP-CR are agroecological practices in agriculture and cattle ranching.

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typology. However, they do not have cattle ranching (livestock varieties: $\bar{x} = 0.14$, $SD = 0.34$; total heads of cattle: $\bar{x} = 1.36$, $SD = 4.21$), nor additional productive activities ($\bar{x} = 0.65$, $SD = 1$). They have the smallest farms ($\bar{x} = 17.85$, $SD = 15.68$) of the three typologies.

Typologies for households in Yurimaguas. Fig 4 presents the description of Yurimaguas' three different typologies based on the 15 variables of farming diversification and agroecological practices. The three typologies lack silvopastoral, agro-forestral, home garden, and wetland areas.

Typology 1: "Moderately-diversified livelihoods" (33 households) includes households with different farming activities. These households have cattle ranching (cattle varieties: $\bar{x} = 3.88$, $SD = 2.86$; heads of cattle: $\bar{x} = 29.18$, $SD = 22$) and agriculture ($\bar{x} = 2.39$, $SD = 1.3$). Most households report two out of 10 AP-A ($\bar{x} = 1.73$, $SD = 1.42$) and three out of 11 AP-CR ($\bar{x} = 2.64$, $SD = 1.34$). The households in this typology have one or more productive activities, in addition to agriculture and cattle-ranching ($\bar{x} = 1.67$, $SD = 1.49$). These activities include poultry, pig, aquaculture, beekeeping, fruit trees, timber, and food processing. They have the most extensive farm size ($\bar{x} = 42.76$, $SD = 33.76$) among Yurimaguas' typologies.

Typology 2: "Slightly-diversified livelihoods" (72 households) includes households with fewer farming activities than the "moderately-diversified livelihoods" typology. They have similar extra activities in addition to agriculture ($\bar{x} = 1.42$, $SD = 1.15$) to the "moderately-diversified livelihoods" typology. They do not have cattle ranching (heads of cattle $\bar{x} = 1.74$, $SD = 3.96$). They grow the same number of crops ($\bar{x} = 0.79$, $SD = 1.02$) and have the same AP-A ($\bar{x} = 1.3$, $SD = 1.55$) as the "moderately-diversified livelihoods" typology. Additionally,

these farms are smaller ($\bar{x} = 16.93$, $SD = 12.54$) than the "moderately-diversified livelihoods" typology.

Typology 3: "Non-diversified livelihoods" (122 households) includes households that only practice agriculture. They cultivate fewer crops than the other typologies ($\bar{x} = 1.29$, $SD = 0.8$). Also, they reported fewer AP-A ($\bar{x} = 0.78$, $SD = 0.67$). In addition, farm areas are smaller ($\bar{x} = 10.78$, $SD = 9.8$) than the other typologies.

Vulnerability to climate change by typologies

The Kruskal-Wallis test indicated that there are statistically significant differences ($p < 0.05$) between the typologies for seven out of the 14 SE indicators and 11 out of the 11 AC indicators in Caquetá (Fig 5 and Table 3) and eight out of the 14 SE indicators and seven out of the 11 AC indicators in Yurimaguas (Fig 6 and Table 4). Tables 3 and 4 show the results of the Dunn's test that reveal which typologies differed by SE and AC indicators for Caquetá and Yurimaguas, respectively. For example, for the deforestation indicator in Caquetá, the "moderately-diversified livelihoods" typology differs from the "slightly-diversified livelihoods" and "non-diversified livelihoods" typologies.

Sensitivity (SE). In the case of Caquetá, results indicate that SE tends to be high only for the "non-diversified livelihoods" typology (Table 5). The main factors that make this typology 'highly sensitive' are total income (financial capital), farm access, housing quality, household crowding (physical capital), and dietary diversity (human capital). There were no differences between Caquetá typologies on SE indicators for social capital.

Total income is low, as this typology has low farming diversification (Fig 5). The households in this typology focus on growing few crops. They neither have cattle nor other productive activities (such as poultry farming, aquaculture, and pig farming), which might generate earnings (Fig 3). The low household income might affect the physical capital, reflected in the lack of house improvements. Most houses from the "non-diversified livelihoods" typology tend to have wooden walls, dirt floors, and zinc roofs, which are materials vulnerable to climatic impacts. Furthermore, they have limited access to roads and modes of transport, which makes them more isolated. Additionally, the lack of farming diversification and low income might be reflected in human capital by the high level of SE to food security (Fig 5).

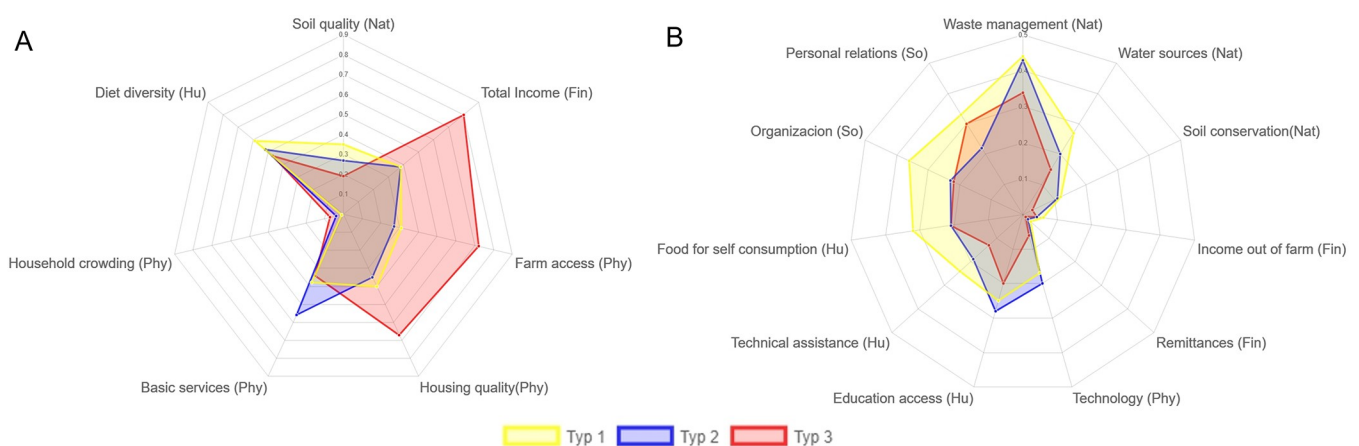


Fig 5. Spider diagrams for A) sensitivity (SE) and B) adaptive capacity (AC) indicators differ significantly from those of typologies (Typ) of Caquetá (Colombia) households (low values equal low SE and AC). Typ1: "moderately-diversified livelihoods", typ 2: "slightly-diversified livelihoods" and typ 3: "non-diversified livelihoods". Data were obtained from 256 households in Caquetá.

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Table 3. Kruskal-Wallis results show differences (by indicators) between the three typologies for Caquetá (Colombia). Typology 1: "moderately-diversified livelihoods", typology 2: "slightly-diversified livelihoods" and typology 3: "non-diversified livelihoods". The average of each indicator is shown by typology. Values of the indicators are 0 = low sensitivity or adaptive capacity and 1 = high sensitivity or adaptive capacity. Dunn's test results reveal the differences between the typologies. Data were obtained from 256 households in Caquetá.

Vulnerability	Capital	Indicator	Average by typology			Chi-square	p	Dunn's test
			1	2	3			
SE	Natural	Forest conservation	0.01	0.02	0.02	19.63	0.07	1–2, 1–3
		Water access and quality	0.25	0.29	0.29	3.47	0.17	
		Soil quality	0.35	0.27	0.19	13.25	0.001*	1–2, 1–3, 2–3
	Financial	Total income	0.38	0.38	0.8	62.9	< 0.05*	1–3, 2–3
		Land tenure	0.01	0.03	0.04	0.45	0.79	
	Physical	Farm access	0.31	0.27	0.72	61.17	< 0.05*	1–3, 2–3
		Housing quality	0.4	0.35	0.67	41.14	< 0.05*	1–3, 2–3
		Basic services	0.38	0.56	0.34	26.78	< 0.05*	1–2, 2–3
		Crowding index	0.01	0.04	0.07	7.24	< 0.05*	1–3, 2–3
	Human	Diet diversity	0.47	0.52	0.59	20.05	0*	1–3,2–3
		Food security	0.3	0.24	0.33	4.61	0.09	1–2, 2–3
		Health	0.26	0.25	0.25	0.48	0.78	
	Social	Social conflicts	0.29	0.32	0.3	0.09	0.95	
		Migration	0.24	0.13	0.11	5.05	0.08	
AC	Natural	Waste management	0.44	0.43	0.34	6.43	0.04*	1–3, 2–3
		Water sources	0.27	0.2	0.15	37.09	< 0.05*	1–2, 1–3, 2–3
		Soil conservation	0.12	0.11	0.03	26.38	0*	1–3, 2–3
	Financial	Off-farm income	0.06	0.04	0.04	9.02	0.01*	1–2, 1–3
		Remittances	0.03	0.02	0.01	8.89	0.01*	1–3, 2–3
	Physical	Technology access	0.17	0.2	0.06	90.92	< 0.05*	1–3, 2–3
	Human	Education access	0.25	0.28	0.2	10.25	0.005*	1–2, 2–3
		Technical assistance	0.24	0.19	0.13	7.35	0.002*	1–3, 2–3
		Food for self consumption	0.32	0.21	0.21	24.27	< 0.05*	1–2, 1–3
	Social	Organizations	0.36	0.23	0.22	30.9	< 0.05*	1–2, 2–3
Personal relations		0.33	0.22	0.3	11.38	0.003*	1–2, 2–3	

*Indicators significantly differ between typologies.

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In the case of Yurimaguas, results revealed that SE is medium-low for the "moderately-diversified livelihoods" typology and is medium for the "slightly-diversified livelihoods" and the "non-diversified livelihoods" typologies (Table 5). The main factors that make the "moderately-diversified livelihoods" typology medium-low, in terms of sensitivity, are total income, land tenure (financial capital), farm access, housing quality, and household crowding (physical capital) (Fig 6). The indicators that make the "slightly-diversified livelihoods" typology moderately sensitive are forest conservation, soil quality (natural capital), total income (financial capital), household crowding (physical capital), and food security (human capital). The indicators that make the "non-diversified livelihoods" typology moderately sensitive are farm access, housing quality, and household crowding (physical capital) (Fig 5). It is noteworthy that the land tenure indicator (financial capital) showed significant differences between the three typologies, being highly sensitive to the "non-diversified livelihoods" typology (Fig 6A). Yurimaguas' "non-diversified livelihoods" typology is characterized by small farms with low farming livelihood diversification (Figs 4 and 6A) and a lack of land tenure. There were no differences between Yurimaguas' three typologies on SE indicators for social capital.



Fig 6. Spider diagrams for A) sensitivity (SE) and B) adaptive capacity (AC) indicators that differ significantly from typologies (Typ) of households in Yurimaguas (Peru) (low values equal low SE and AC). Typ1: "moderately-diversified livelihoods", typ 2: "slightly-diversified livelihoods" and typ 3: "non-diversified livelihoods". Data were obtained from 227 households in Yurimaguas.

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Adaptive capacity (AC). In the case of Caquetá, the AC was lower for the "non-diversified livelihoods" typology than for the other typologies (Table 5). The main indicators that make the "non-diversified livelihoods" typology weakly adapted were waste management, water sources, soil conservation (natural capital), remittances (financial capital), technology access (physical capital), education, technical assistance, and food for self-consumption (human capital) (Fig 5B, Table 3). Regarding the natural capital, households of this typology showed fewer practices in preserving soil, in contrast with the "moderately-diversified livelihoods" typology. For financial capital, the "non-diversified livelihoods" typology receives fewer remittances than the other typologies, which might give it less AC. In the case of the physical capital, the "non-diversified livelihoods" typology has low access to house technologies (such as mobile phones, radios, and televisions) that are effective tools for communication in emergencies and provide access to climatic information to improve AC. For human capital, indicators (such as food for self-consumption and technical assistance) were low for the "non-diversified livelihoods" typology since households of this typology produce few crops, and what is produced is generally sold (rather than used for self-consumption). Technical assistance was higher for the "moderately-diversified livelihoods" and the "slightly-diversified livelihoods" typologies that have more farming activities than the "non-diversified livelihoods" typology that cultivates fewer crops. Education access is the lowest for the "non-diversified livelihoods" typology because head-of-households typically have less education. Indeed, most have not been studied (Fig 5B, Table 3).

Similarly to Caquetá, in Yurimaguas, the AC was lower for the "non-diversified livelihoods" typology than the other typologies (Table 5). The main indicators that make the "non-diversified livelihoods" typology weakly adapted were waste management, water sources (natural capital), food for self-consumption, and technical assistance (human capital). Regarding natural capital, the "non-diversified livelihoods" typology had fewer practices to preserve soils and fewer farm water sources, which decreased AC in drought periods. For human capital, indicators such as food production for self-consumption and technical assistance were lower for the "non-diversified livelihoods" typology. As in Caquetá, Yurimaguas' "non-diversified livelihoods" typology has relatively lower crop production, which might reflect the low levels of food produced for household self-consumption. Moreover, technical assistance is also low because these households have fewer farming activities.

Table 4. Kruskal-Wallis results show differences (by indicators) between the three typologies for Yurimaguas (Peru). Typology 1: "moderately-diversified livelihoods", typology 2: "slightly diversified livelihoods", and typology 3: "non-diversified livelihoods". The average of each indicator is shown by typology. Values of the indicators are 0 = low sensitivity or adaptive capacity and 1 = high sensitivity or adaptive capacity. Dunn's test results reveal the differences between the typologies. Data were obtained from 227 households in Yurimaguas.

Vulnerability	Capital	Indicator	Average by typology			Chi-square	p	Dunn's test
			1	2	3			
SE	Natural	Forest conservation	0.13	0.11	0.07	6.64	0.03*	1–2, 2–3
		Water access and quality	0.42	0.4	0.4	0.1	0.94	
		Soil quality	0.4	0.28	0.15	22.46	< 0.05*	1–2, 1–3, 2–3
	Financial	Total income	0.21	0.34	0.56	36.53	< 0.05*	1–2, 1–3, 2–3
		Land tenure	0.02	0.06	0.12	6.39	0.04*	1–3, 2–3
	Physical	Farm access	0.65	0.74	0.65	5.84	0.053*	1–2, 2–3
		Housing quality	0.77	0.9	0.82	6.78	0.03*	1–2, 2–3
		Basic services	0.36	0.45	0.45	3.95	0.13	
		Household crowding	0.09	0.28	0.24	7.5	0.02*	1–2, 2–3
	Human	Diet diversity	0.58	0.54	0.54	2.03	0.36	
		Food security	0.68	0.45	0.61	12.55	0.001*	1–2, 2–3
		Health	0.22	0.27	0.23	4	0.13	
	Social	Social conflicts	0.22	0.26	0.23	2.89	0.23	
		Migration	0.03	0.07	0.02	3.75	0.15	
AC	Natural	Waste management	0.21	0.23	0.11	11.3	0.003*	1–2, 2–3
		Water sources	0.15	0.15	0.07	23.93	< 0.05*	1–3, 2–3
		Soil conservation	0.07	0.04	0.02	4.87	0.09	
	Financial	Off-farm income	0.09	0.03	0.03	0.06	0.96	
		Remittances	0.02	0.05	0.06	9.91	0.007*	1–2, 2–3
	Physical	Technology access	0.28	0.14	0.16	10.27	0.005*	1–2, 2–3
	Human	Education access	0.41	0.31	0.32	4.64	0.09	
		Technical assistance	0.31	0.19	0.12	9.42	0.008*	1–3, 2–3
		Food for self consumption	0.22	0.18	0.07	28.09	< 0.05*	1–3, 2–3
	Social	Organizations	0.09	0.13	0.09	2.38	0.3	
Personal relations		0.88	0.88	0.88	0.32	0.84		

*Indicators significantly differ between typologies.

Table 5 shows the level of vulnerability by typology. For example, the "non-diversified livelihoods" typology for Caquetá has a high level of vulnerability (VU = 2) since the majority of indicators were high for SE and low for AC (SE = 3, AC = 1). Vulnerability (VU) = Sensitivity (SE)—Adaptive capacity (AC).

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Vulnerability. The "non-diversified livelihoods" typology of Caquetá and Yurimaguas were the most vulnerable typologies (Table 5). The high level of sensitivity (SE = 3) and low level of adaptive capacity (AC = 1) attribute the highest vulnerability to Caquetá's "non-diversified livelihoods" typology (VU = 2). The medium level of sensitivity (SE = 2) and high level of

Table 5. Scores of vulnerability by typology. The scores for sensitivity (SE) and adaptive capacity (AC) are based on counting the majority of indicators in SE or AC levels (1 = low, 2 = Medium, 3 = high) for each typology in Caquetá (Colombia) and Yurimaguas (Peru). Typology 1: "moderately-diversified livelihoods", typology 2: "slightly-diversified livelihoods", and typology 3: "non-diversified livelihoods". Vulnerability is calculated by the equation VU = SE-AC, and possible results are low (-2, -1), medium (0), and high (1, 2). Data were obtained from 572 household surveys (256 households in Caquetá, and 227 in Yurimaguas).

Typologies	Caquetá (Colombia)				Yurimaguas (Peru)				
	SE	AC	VU = SE-AC	Typologies	SE	AC	VU = SE-AC		
Moderately-diversified livelihoods	2	2	0	Medium	Moderately-diversified livelihoods	1–2	2	-1–0	Low-Medium
Slightly-diversified livelihoods	2	2	0	Medium	Slightly-diversified livelihoods	2	2	0	Medium
Non-diversified livelihoods	3	1	2	High	Non-diversified livelihoods	2	1	1	High

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adaptive capacity ($AC = 1$) attributes the highest vulnerability to Yurimaguas' "non-diversified livelihoods" typology ($VU = 1$). Caquetá's and Yurimaguas' "non-diversified livelihoods" typologies are both characterized by having smaller farm sizes and less farming diversification than the "moderately-diversified livelihoods" and "slightly-diversified livelihoods" typologies (Figs 3 and 4). Caquetá's and Yurimaguas' "moderately-diversified livelihoods" and "slightly-diversified livelihoods" typologies were moderately vulnerable. These are characterized by having relatively more farming activities (at least two productive activities, such as cattle ranching, agriculture, aquaculture, poultry farming and pig farming), so their income sources are more diverse than those of the "non-diversified livelihoods" typology.

On the other hand, there is a trend that vulnerable typologies, apart from Yurimaguas' "slightly-diversified livelihoods", have more agrobiodiversity in crops, livestock and pastoral species than the most vulnerable typologies (Figs 3 and 4). Yurimaguas' "slightly-diversified livelihoods" typology is characterized by a lack of cattle ranching, featuring only agriculture. Generally, all typologies implement few agroecological practices in their farms, about three of 10 agroecological practices for agriculture (AP-A) and three of 11 practices for cattle ranching (AP-CR).

Discussion

Vulnerability to climate change and diversification of farming livelihoods

Our results support the original hypothesis. They indicate that households with higher rural livelihood diversification (represented by diversity in agriculture, cattle ranching, pastures and farming activities) are less vulnerable to climate change. Accordingly, households with a higher diversity of cattle, pastures, and crops (the "moderately-diversified livelihoods" typologies of Caquetá and Yurimaguas, and Caquetá's "slightly-diversified livelihoods" typology) tend to be less vulnerable to climate change than households with less diversity (the "non-diversified livelihoods" typology of both countries). Likewise, in both Caquetá and Yurimaguas, households with at least two farming activities (in addition to cattle ranching and agriculture, i.e., the "moderately-diversified livelihoods" and "slightly-diversified livelihoods" typologies) show less vulnerability to climate change. Certainly, it has been reported that rural livelihood diversification is the main strategy that farmers use to maintain well-being and resilience to the uncertainties typical of family farming, such as seasonality and climate change [11]. However, it is impossible to draw significant conclusions regarding the relationship between the diversification of agroecological management practices and vulnerability to climate change because the number of agroecological practices was low for most households.

Diversification of crops (polycultures) helps minimize risks because this approach has higher yield stability during extreme climatic events than monocultures [18]. Likewise, findings indicate that, in hostile climatic conditions, the presence of different cattle varieties (including local breeds) increases the animal survival rate and maintenance of their reproductive levels [73]. In fact, during focus group discussions, farmers from Caquetá mentioned that local breeds stand better climatic effects than conventional races. Indeed, our study showed that households with more agrobiodiversity are less vulnerable to climate change. Along these lines, Tengö and Belfrage (2004) explained that agrobiodiversity helps buffer against climatic fluctuations and reduce yield losses because different species respond differently to change, securing the maintenance of a system's functional capacity after climatic hazards [74].

Diversifying farming activities (such as cropping, livestock, poultry, aquaculture, beekeeping, and off-farm activities) build household resilience to climate change. If one activity is affected by climate change, the others may compensate. Likewise, diversity in farming activities buffers against income instability linked to crop seasonality and sales. For example, harvest

periods generate wages but other periods require alternative activities to generate household income [6]. In the case of caquetá, farmers who practice aquaculture mentioned that they have an extra income by selling fish, compensating for the critical periods for cattle selling caused by climatic effects. In the case of Yurimaguas, women make marmalades, ice creams, refreshments, and handicrafts with local fruits and plants, which generate extra income for the household. Therefore, a highly diverse portfolio of activities secures a household's improved adaptive capacity to climate change [10,11].

Our results also revealed that most households (in the three livelihood typologies in Caquetá and Yurimaguas) have very few agroecological management practices. These results indicate that although livelihood diversification might reduce household vulnerability and increase adaptive capacity to climate change, households' abilities to cope with climate change could be further strengthened by including additional agroecological practices and building capacity for proper implementation. Agroecological practices stimulate soil biota, preserve natural enemies and pollinators, minimize water loss, and enhance soil fertility, pest regulation, and increase crop yields [17,35], thus increasing the agroecosystem's adaptive capacity to climate change. In the aftermath of the 1998 Hurricane Mitch, studies conducted in Central America indicate that agroecological farms suffered less damage than conventional farms [75]. These agroecological farms conserved topsoil and soil moisture. They showed low levels of erosion and resulted in reduced economic losses [18,75].

Our findings suggest that low rural farming diversification is related to lower income, food security, and housing quality in both study regions. Moreover, this relationship is bi-directional. A low income also is associated with low-food security and a lack of possibilities for acquiring extra land and additional crops and livestock species to diversify the farm as an adaptation strategy to climate change [76]. Contrary, a high income is associated with having the possibility of diversifying the farm and improving diet diversity and housing quality. Therefore, most vulnerable households might be trapped in a cascade of causes and effects that draw them into spirals of poverty and vulnerability. It is recommended that future interventions focus on strengthening vulnerable households' adaptive capacity through supporting rural livelihood diversification. Colombian and Peruvian adaptation plans to climate change also include livelihood diversification as an adaptation action to reduce vulnerability to climate change [77,78]. However, funding, training, and accompaniment are needed to implement this action for more vulnerable farmers.

Facing vulnerability through the five livelihood capitals

Vulnerability should be addressed using an integrated approach encompassing the five livelihood capitals. For instance, adaptation efforts should not solely focus on implementing land-use options that preserve biodiversity and the ecosystem services to sustain local communities' livelihoods (natural capital) but should also strengthen a household's financial, physical, human, and social status. For example, this study's results indicate that in Yurimaguas, a lack of land tenure, which contributes to financial capital, was an indicator of vulnerability. Certainly, it has been found that a lack of land tenure increases households' vulnerability to climate change, often resulting in homelessness (or inadequate housing), displacement, and a loss of identity [4]. In addition, mechanisms that facilitate access to land are indispensable for farming diversification and the implementation of agroecology and ensure adequate housing [79].

Adequate housing, road access, and transportation are part of the physical capital contributing to the basic infrastructure underpinning well-being. Most vulnerable households in both regions have low-quality houses, restricted access to roads and transport, and low access to

house technology (mobile phones, television, and radio). Housing materials, such as wooden walls, dirt floors, and zinc roofs, are susceptible to climate impacts. Limited access to roads and transport reduces market access (i.e., affecting a household's capacity to sell or access products and income-generating options). It decreases access to assistance during climatic emergencies. Likewise, low access to house technology increases isolation, and a lack of communication during emergencies reduces access to climatic information [6]. Hence, this study's results suggest that infrastructure is a determinant factor in household vulnerability and should be included in government's climate change adaptation plans.

Human capital comprises food security, formal and informal education (technical assistance), and health, facilitating a household's well-being [6,58,59]. A lack of food security, health and education are considered fundamental dimensions of poverty. The most vulnerable households (in both regions) do not produce food for their consumption but, rather, depend on external food provision channels. Moreover, the income of these households is low, which limits their capacity to purchase food. Because external channels of food provision may collapse during climatic emergencies (thus increasing household vulnerability), cultivating food for self-consumption is considered an important aspect of small farmers' adaptive capacity to climate change [18]. Likewise, the most vulnerable households in both regions lack access to technical assistance or training in agricultural topics. Such capacity is essential for farmers to improve their agricultural management practices, increase their adaptive capacity and decrease their vulnerability [5]. Moreover, the results from Caquetá indicate that the most vulnerable households also have reduced access to education. Reportedly, a lack of literacy in rural Colombia can reduce access to information about agricultural innovations and technologies that might otherwise improve farm productivity and buffer farms against climate change' impacts [29,80,81].

Future directions

Although the vulnerability is assessed using local indicators, it is recommended to adequate the methodology to compare typologies more precisely rather than using low, medium, or high levels of vulnerability. Also, additional research could focus on the potential benefits of integrating agroecological management practices with livelihood diversification as a strategy for climate adaptation in these regions.

Conclusions

This study's results, based on information from rural households in Caquetá (Colombia), and Yurimaguas (Peru), indicate that households with higher rural livelihood diversification in terms of agrobiodiversity (i.e. crop, pasture, and cattle diversity) and diversity of farming activities are less vulnerable to climate change. Therefore, it is strongly recommended that the governments of both countries implement the adaptation plans already established. For example, the adaptation plans to climate change for Colombia and Peru mentioned livelihood diversification as an adaptation action to reduce vulnerability to climate change. However, more funding, training, and accompaniment to implement this activity, prioritising the more vulnerable households, are needed in the field. Moreover, these actions need to be accompanied by a commitment to implementing policies encompassing the five capitals of livelihoods (natural, financial, physical, human, and social), such as securing land tenure, improving infrastructure, and facilitating access to education, food, and technology. In combination, these would decrease rural households' vulnerability to climate change.

Supporting information

S1 Fig. Optimal cluster solution to group households from Caquetá (Colombia), based on farming diversification and agroecological management practices. This analysis was based on 15 variables that indicate a household's diversity in terms of agrobiodiversity and farming activities. These variables are framed around: 1) agriculture, cattle ranching diversity, and pastoral diversity; 2) the number of agroecological practices for agriculture (AP-A) out of 10 different practices; 3) the number of cattle ranching practices (AP-CR) out of 11 different practices; 4) the number of additional productive activities (aside from cattle ranching and agriculture), out of a total of seven activities; and 5) the type of land-use in hectares. Data were obtained from 256 households in Caquetá (JPG)

S2 Fig. Optimal cluster solution to group households in Yurimaguas (Peru), based on farming diversification and agroecological management practices. This analysis was based on 15 variables that indicate a household's diversity in terms of agrobiodiversity and farming activities. These variables are framed around: 1) agriculture, cattle ranching diversity, and pastoral diversity; 2) the number of agroecological practices for agriculture (AP-A) out of 10 different practices; 3) the number of cattle ranching practices (AP-CR) out of 11 different practices; 4) the number of additional productive activities (aside from cattle ranching and agriculture), out of a total of seven activities; and 5) the type of land-use in hectares. Data were obtained from 256 households in Caquetá (JPG)

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