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Integrating farmers' perceptions into climate change assessment in the data-scarce Peruvian Amazon

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Abstract
Climate change affects agriculture worldwide, with stronger socio-economic impacts in low-income countries where the lack of data hinders the implementation of effective interventions to face climate change effects. The paper proposes an approach to assess local effects associated with climate change in data-scarce contexts, integrating farmers' perceptions with available climate data. The method is tested in the Upper Huallaga basin, in the Peruvian selva. The analysis of climate trends in time series of daily data from a local weather station and ERA-5 reanalysis data is integrated with 73 structured interviews with farmers. The resulting increasing temperature trend of 0.2 °C per decade is consistent with the farmers' perception. On the other hand, farmers also highlight an increase in wind gusts and precipitation, in contrast with the available quantitative data. This is further investigated analysing trends in annual crop water deficit and surplus volumes, which can be viewed as a proxy for plant health conditions, and may influence the farmers' perception of climate change. Results show a recent increase in the annual crop water deficit and surplus volumes, suggesting an increase in sub-daily convective rainfall events, possibly explaining farmers' perceptions. The proposed approach effectively allows for assessing climatic alterations, their effects, and locally driven adaptation measures in data-scarce regions, as well as providing some insights into trends in sub-daily meteorological events.

Keywords Climate change · Data-scarce areas · Integrated approach · Family-based agriculture · Tropical region

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1 Introduction

Climate change poses a significant threat to global agriculture, compromising food availability and security, particularly in the face of a growing global population (IPCC, Mbow et al. 2019). Smallholder farmers are particularly vulnerable to the effects of climate change (Lowder et al. 2016), as their low-tech practices heavily rely on favourable weather and climate stability (Morton 2007; Harvey et al. 2018; Nath et al. 2019; Johnson and Hutton 2014). Indeed, smallholder farmers' deep-rooted agricultural knowledge (Boillat and Berkes 2013) relies on attentive management of natural water resources, seasonal cultivation cycles, and use of local crop varieties (Velasco Hernández et al. 2016). However, this is very likely to be undermined by climate change.

In such contexts, one of the main factors hindering the possibility of reducing agricultural vulnerability is the limited availability, and often also low quality, of climatic records from instrumental observations (Ramirez-Villegas and Challinor 2012). Indeed, in most cases, the available data are insufficient to allow a reliable quantification of typical local climatic conditions, as well as the identification of associated trends in climate change (IPCC, Arias et al. 2021). On the other hand, good quality data would also be crucial for developing reliable monitoring and warning systems (Roudier et al. 2014), supporting farmers' planning of agricultural operations. Installing and maintaining a reliable and representative network of in-situ weather stations is frequently challenging in low-income countries, as the instrumentation costs often exceed the available resources, thereby limiting the establishment of such networks. As an alternative, remote sensing products become increasingly useful for contexts suffering from data scarcity (Yang et al. 2013). Reanalysis products can provide a valuable complementary source of information. They are increasingly used worldwide for several purposes related to climate change assessment, including the detection of climate anomalies and trends from the global (Hersbach et al. 2020) to the local scale (Santos et al. 2018), the analysis of the impacts of climate change on the landscape, both in pristine (Veettil et al. 2018) and human-impacted environments (Dorigo et al. 2017), and the analysis of weather extreme events (Raghavendra et al. 2018; Yu et al. 2019).

Integrated Assessment (IA) emerged as a promising cross-cutting approach not only to overcome quantitative data gaps, combining stakeholders' knowledge and environmental data to assess climate change and related effects (Kloprogge and Sluijs 2006), but also to engage local actors in pursuing adaptation and mitigation initiatives (AMIs, Bizikova et al. 2010). The adoption of AMIs strongly depends on a variety of local factors, such as the socio-economic conditions of farmers (de Matos Carlos et al. 2020), their socio-cognitive processes (Mitter et al. 2019), as well as local political conditioning and public opinions (Ricart et al. 2019). However, beyond these external constraints, the awareness of climate change and the engagement of farmers are the most effective drivers for ensuring the long-term sustainability of AMIs (Haden et al. 2012; Contreras Valencia 2019).

In recent years, the interest in farmers' perception of climate change, as an indicator of their attitude towards adaptation to a changing climate, has grown worldwide. However, most of the literature focused on the social aspects of climate change perception, as emerging from surveys. In particular, these studies aimed to identify the limiting factors hindering farmers' awareness of climate change and the adoption of AMIs, and most of them also compared perceptions of weather regime modifications against data from meteorological observations, either on a monthly (Fatorić and Morén-Alegret 2013; Abid et al. 2016; Ayan-

lade et al. 2017, and Elum et al. 2017), or on a seasonal basis (Budhathoki and Zander 2019). Nevertheless, only a few of them delved into the consistency between perceived and measured phenomena, i.e., questioned to what extent people perceive climate phenomena correctly. Moreover, as highlighted by Soubry et al. (2020), most of those studies considered sociological and environmental datasets separately, without integrating them.

The interest in farmers' climate change perception has also grown in Peru, where 71% of agricultural households are small-scale producers (FAO 2024). In the Peruvian Andes, global warming has been observed to cause glacier melting and reduction in water availability (Mark et al. 2010; Bury et al. 2013). Additionally, it has altered the rainfall regime, affecting rainfed familiar agriculture (Gurgiser et al. 2016; Heikkinen 2018). An increase in temperature was also perceived by farmers in the Amazon region, where, in contrast to the Andean region, more frequent heavy rainfall and stronger winds were also reported (Chavez Michaelsen et al. 2020). Altea (2020) interviewed local institutions in this region, specifically representatives of regional government bodies, regional research organisations and academia, international cooperation groups, and district authorities, and gathered their concerns about the limited availability of historical climatic data. She also suggested using local knowledge to develop adaptation policies in the absence of such pieces of information. However, as pointed out by Fierros-González and López-Feldman (2021), the scientific literature on farmers' perception of climate change in Latin America is still limited despite the urgent need to address this topic. This indicates a clear need for more multi-disciplinary efforts, integrating social and environmental sciences.

Accordingly, the present study evaluates climate change effects in a data-scarce context, combining diverse and multi-sourced quantitative data. In particular, the case study is the Upper Huallaga Valley in Peru, where the predominant agricultural system is rainfed and managed at the family level (average field extension of about 1.4 ha, INEI 2014). Changes detected in the regimes of three climatic variables clearly affecting agriculture - i.e., air temperature, precipitation, and wind - are investigated over the last decades, combining the analysis of homogenised series of observations from in-situ weather stations operated by the Meteorological and Hydrological Service of Peru (SENAMHI) and products from model reanalysis. Quantitative datasets are integrated with 73 structured interviews with local farmers. To better tie farmers' perceptions to climatic data, changes in reference evapotranspiration are also investigated. The reference evapotranspiration can be considered a quantitative proxy to diagnose the state of crop water stress, which is a key factor that may affect farmers' perception of climate change. Finally, the willingness of farmers to implement AMIs is investigated as an additional indicator of the local awareness of climate change and a baseline to consider when promoting AMIs at the basin scale.

2 Material and methods

2.1 Study area

The Huallaga River is a tributary of the Amazon River, whose basin (7°0'S-10°0'S, 75° 5'W-77°5'W) lies between the eastern side of the Andes and the upper Amazon watershed (Fig. 1a). The basin features a very complex terrain, with elevations ranging from 273 m a.s.l to 5691 m a.s.l. The morphological complexity (Fig. 1c), as well as the size of the basin

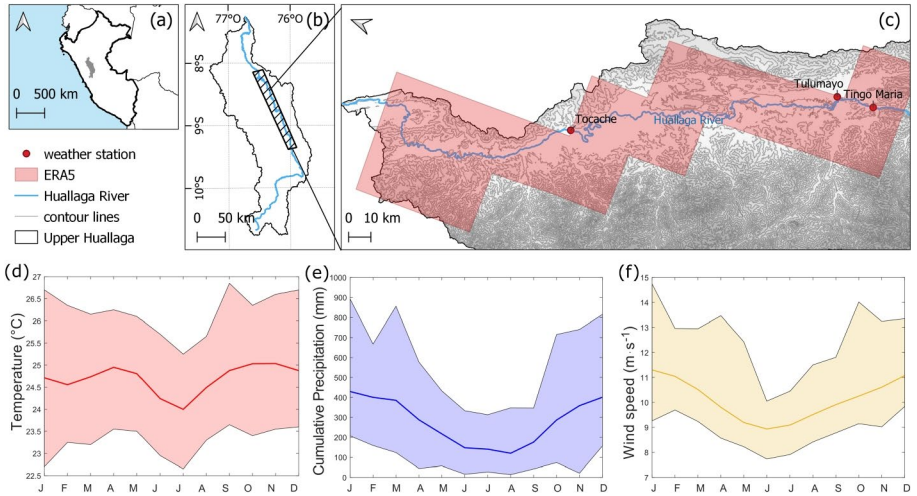

Fig. 1 Study area and its climatic characteristics: (**a**) the Upper Huallaga basin in Peru, (**b**) the Upper Huallaga basin and the study area highlighted, (**c**) zoom-in of the study area with contour lines, the location of the three available weather stations, and the ERA5 tiles covering the valley floor. (**d**) Range of monthly average temperatures, (**e**) range of monthly total precipitation from Tingo María meteorological station in the 1940–2019 period. (**f**) Range of monthly maximum wind speed averaged along the valley floor from ERA5 in the 1950–2019 period

(89'416 km^2), favour a diversity of climatic regions, from Subtropical highland climate (Cfb) to Equatorial climate (Am-Af) (Beck et al. 2018). The area is subject to the variability of the El Niño Southern Oscillation (ENSO), which can influence the local rainfall regime (Lavado Casimiro et al. 2011; 2014)). Additionally, the "Friaje" (also known as "Friagem"), a cold air intrusion from the South, may lower temperatures in the Central Amazon by as much as 10 °C in the May-August period (Ricarte et al. 2015; Camarinha-Neto et al. 2021).

The present work is part of an international cooperation project promoted by a fair-trade non-profit organisation (Mandacarú[1]), which involves a group of banana farmers on the floodplain and low terrace portion of the basin (around 600 m a.s.l.), where the agricultural practices are concentrated. This area is classified as "selva alta" (literally "elevated forest") by Brack and Mendiola (2000), with monthly mean air temperatures typically in the range 22.5–27.0 °C (Fig. 1d) and cumulative annual rainfall up to 3500 mm (Fig. 1e). The average air temperature exhibits slight seasonal variations, as shown in Fig. 1d, while the total monthly rainfall, as well as the maximum wind speed (Fig. 1e, f), may display remarkable seasonal differences. In particular, two main seasons can be identified, namely a dry season (June-September), associated with low wind speeds, and a wet season (November-March), when wind speeds may assume values as high as 15 m s^{-1}, suggesting that these strong winds are generally associated with convective precipitations.

The above environmental and climatic conditions favoured the development of several permanent cultivations in the area, such as cocoa (*Theobroma cacao*), plantain (*Musa Musacae*), and coffee (*Coffea Arabica*) (INEI 2014). Most local farmers employ low-tech agricultural practices, relying on stable and crop-favourable environmental conditions,

[1] https://www.mandacaru.it/

which expose them to severe risks from local weather modifications associated with climate change.

2.2 Climatic data

To reliably assess the local climate of an area from weather observations WMO (2017) recommends using a complete data series no less than 30 years long. However, such extensive series are quite rare, especially in low-income countries. In the present work, data from only three weather stations were available (namely Tingo María, Tulumayo, and Tocache, see Table 1 in Supplementary Information - SI). We complemented them with data from the ERA5 reanalysis dataset (see below). The Mann-Kendall non-parametric test (Mann 1945) and the Sen's slope non-parametric test (Sen 1968) were then applied to detect statistically significant trends. Furthermore, in order to better understand weather events at smaller temporal and spatial scales, a social survey was conducted to partially complement the information needed to describe meteorological phenomena. The above quantitative and qualitative sources were combined into an Integrated Assessment of stakeholders' knowledge and environmental data to evaluate target phenomena at multiple spatial and temporal scales, as illustrated in Fig. 2.

2.2.1 In-situ data from local weather stations

During the data collection phase, three weather stations on the valley floor were considered, based at Tingo María (TM), Tulumayo (TU), and Tocache (TO), respectively. The trend evaluation was conducted monthly, as recommended by WMO (2017). Monthly mean

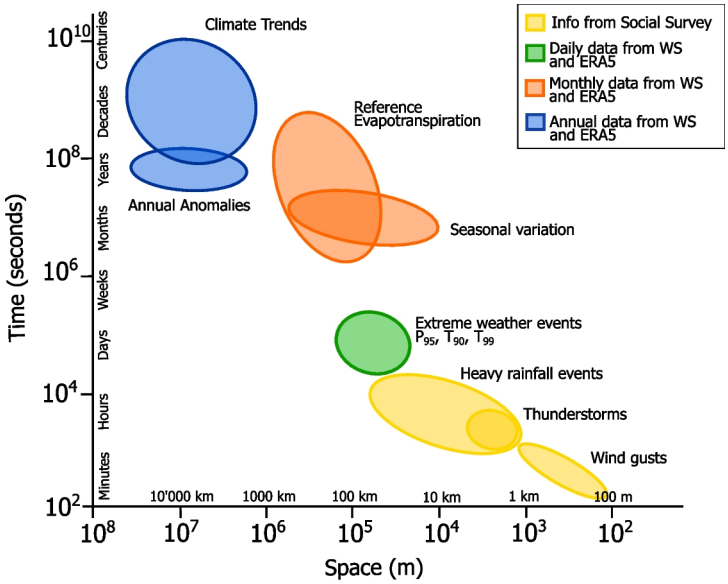

Fig. 2 Time and space scale of the investigated climatological and meteorological phenomena relevant for smallholder agriculture, indicating the data sources used at each scale. *Modified from COMET program material*

temperatures were calculated from mean daily temperatures, while monthly accumulated precipitations were obtained from the sum of the accumulated daily rainfalls. The original series were affected by several gaps, ranging from 6% to 83% (Table 1 in SI).

The time series were homogenised using the CLIMATOL R package (Guijarro 2021) through the built-in routine implementing the Standard Normal Homogeneity Test (SNHT, Alexandersson 1986) and gap-filling. Data from ERA5 were used to obtain the required reference time series from virtual reference stations. This approach is a standard feature of CLIMATOL.

However, data from TU and TO stations turned out to be affected by severe quality issues, making the homogenisation process ineffective. As a result, subsequent analyses were carried out using monthly and daily data from TM only.

In addition to the analysis of climate trends, representing the variation of mean climatic conditions, further indicators were also computed to assess the variation in extreme weather events, as these may strongly influence the perception of climate change (Demski et al. 2017; Bergquist et al. 2019; Sloggy et al. 2021). The characterisation of such events is as crucial to the analysis as it is challenging to achieve, especially when daily data are scarce. Following WMO (2009) and Schär et al. (2016), we used daily data from the TM station in the 1987–2019 period since, unlike the TM monthly data, the daily series presents gaps before 1987. No homogenisation was performed on the daily series because of their intrinsic variability, which could be compromised by the homogenisation process (WMO 2003). In particular, the number of rainy days in a year with total daily precipitation exceeding the 95^{th} percentile and the fraction of annual precipitation accumulated during these days was calculated. Extreme events associated with high temperatures were evaluated by calculating the number of days in a year with maximum daily temperature exceeding the 90^{th} and 99^{th} percentiles, respectively.

2.2.2 ERA5 reanalysis data

The ERA5 reanalysis dataset (ECMWF 2021), provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), was a reference to evaluate the climatic trends detected by the local weather stations. Monthly and daily data of 2-m air temperature and total precipitation in the 1950–2019 period were downloaded in the gridpoints nearest the location of the three weather stations to compare reanalysis data with the in-situ observations. Since wind speed observations from local weather stations were unavailable, daily average wind speed and daily instantaneous maximum wind gusts at 10 m above ground level were also downloaded from ERA5 over a sub-region (7.5 S, 9.2 S, 76.8 W, 76 W). The sub-region was further shaped according to the valley floor mask, as shown in Fig. 1c, from which the average and maximum values representative of the entire valley floor were obtained.

2.2.3 Evapotranspiration and crop water deficit

A monthly reference evapotranspiration time series was then computed from the available climatic time series. This quantity is very relevant as an agronomic parameter directly affected by variations in local climatic conditions. Evapotranspiration, combined with rainfall, indeed provides a measure of the crop water deficit (or surplus), which is likely to

be closely linked to the farmers' perception of climate change. The software CROPWAT 8.0 was used to assess the monthly reference evapotranspiration ET_0 in the 2000–2019 period to consider a period relatively recent and more comparable to what the population remembers. CROPWAT 8.0 implements as the default option the Penman-Monteith equation (Allen et al. 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where Δ is the slope of the saturation vapour pressure vs. temperature, R_n is the net radiation, G is the soil heat flux, γ is the psychrometric constant, T is the 2-m air temperature in °C, u_2 is the wind speed at 2 m above ground level, and $(e_s - e_a)$ is the water pressure deficit. The description of the computation of each variable is available in the SI.

The difference between monthly rainfall and reference evapotranspiration (i.e., not related to any crop species) was calculated to obtain surplus ($P_{month} - ET_0 > 0$) and deficit water volumes ($P_{month} - ET_0 < 0$). In addition, the annual cumulative duration of water surplus and deficit conditions was evaluated by considering the number of water surplus and deficit months per year.

2.3 Social survey among farmers

Mixed methods of social research were implemented (Cooper et al. 2013) to conduct a survey along the reach of the Huallaga River between Tulumayo and Aucayacu settlements, covering a representative area of approximately 572 km^2. The main purpose of the survey was to gather more information on the locally perceived variations in the three climate variables investigated (air temperature, precipitation, and wind), covering both long-term climatic alterations and short-term weather events. Climate change adaptation countermeasures already undertaken by farmers were investigated both as evidence of actions taken in response to climate change perception and as bottom-up strategies that could be considered for systematic interventions at larger spatial scales.

The survey was carried out through structured face-to-face verbally conducted interviews (Corbetta 2003), where questions were structured according to three sections (see SI for the full form): (1) personal information of the farmer (age, gender, time spent in the area), (2) climate characteristics (farmer's perspectives on changes of the three climate variables, impacts on banana plantations, and potential initiatives of adaptation already implemented), and (3) crop information (variety, cultivated area, type of farming). The questions were mainly multiple choice with four or more options. Among them, it was always possible to answer "other" and give further information or to choose "don't know".

The sample was limited to banana farmers to avoid interfering differences due to peculiarities of crop species, and to obtain more coherent responses. The rural settlements located in the area, whose coordinates were provided by the Statistical Institute of Peru (INEI), were first uploaded in the Quantum GIS (QGIS) software and then filtered according to the physiography, as floodplain and low terraces generally host a high concentration of plantain cultivation, and the proximity to the river, which was expressed by a 2.5 km wide band. The sample extension *n*, i.e., the number of interviews, was then estimated by using the formula defined by Cochran (1977):

$$n_0 = \frac{Z^2 p(1-p)}{e^2}; \tag{2}$$

$$n = \frac{n_0}{1 + \frac{n_0 - 1}{N}}. \tag{3}$$

Equation 2 defines the sample size, n_0, used for large samples, and Eq. 3 defines the sample size, n, used in the present study for small populations. Z is the standard core (= 1.96, assuming a significance level $\alpha = 0.05$), p is the p-value (= 0.05), e is the assumed error (= 0.05) and N is the number of inhabitants (= 5780) living in the study area, according to INEI (2014), resulting in 73 interviews. A number of villages were then selected using the QGIS random selection tool to minimise any user interference. The number of interviews to be conducted in each village was determined by considering the concentration of banana fields in the area. Subsequently, interviews were conducted by pairs of interviewers with randomly encountered farmers in the identified agricultural areas. Before neutrally reading the questions, the interviewers explained the purpose of the research, stating that the data would be used anonymously.

3 Results

3.1 Climate trends and annual anomalies

The TM series was used for the analyses due to the substantial amount of missing data from TU and TO weather stations and the poor quality of the limited available data. In Fig. 3a, c, the annual time series of homogenised observations from TM are compared to the ERA5 data from the grid cell representative of TM location, while in Fig. 3e the annual mean and maximum wind speed from ERA5 in the valley floor are displayed. The boxplots in Fig. 3b, d summarise the monthly differences between the original observations and the homogenised series, showing small differences both in precipitation (average: μ= 0.2 mm, variance: σ = 24.5 mm, n. outliers = 2) and temperature (average: μ= 0.0 °C, variance: σ = 0.5 °C, n. outliers = 221).

The homogenised precipitation series presented in Fig. 3a exhibits similar trends to ERA5, despite higher values. Also the homogenised annual mean temperature in Fig. 3c displays higher values than ERA5, with differences around 4–6 °C. Despite the approximately constant gap between the two series, both of them show a positive trend in the 1950–2019 period: the homogenised mean temperature increased by about 1.3 °C, while the reanalysis data show an increase of about 1.9 °C. On the other hand, the annual series of monthly mean and maximum wind speed (Fig. 3e) from ERA5 do not show any appreciable trend.

The discrepancies between observations and reanalysis data can be explained by the different representativeness of the two datasets. ERA5 data refer to an average value over a surface of $\sim$ 30 km x 30 km, whereas measurements from the weather stations represent a smaller area. Thus, some differences between the two datasets can be expected, especially where meteorological variables present a high spatial variability, e.g., over complex terrain. In particular, the lower temperatures shown by ERA5 with respect to the in-situ measure-

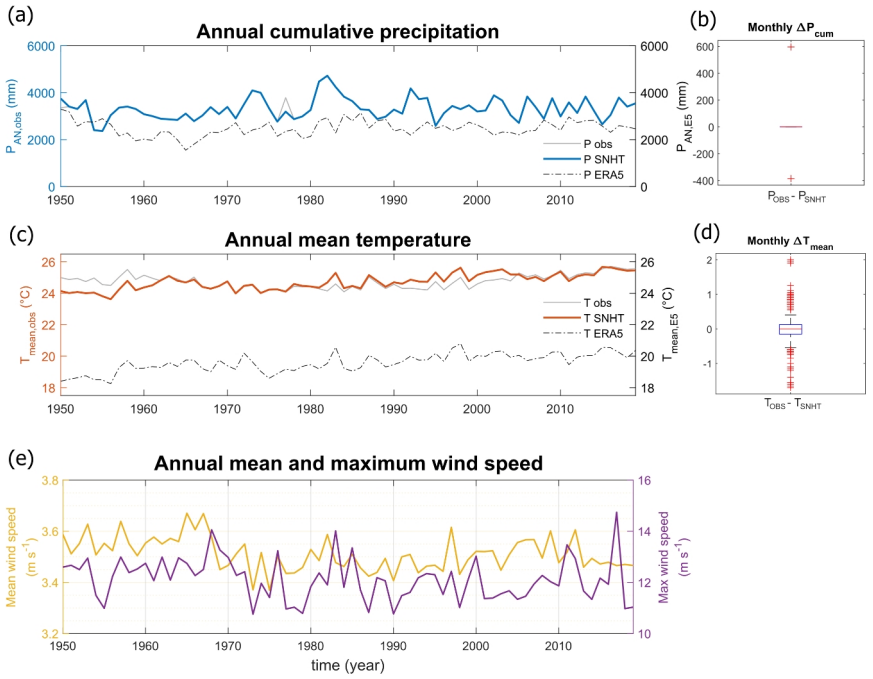

Fig. 3 Annual climate series at TM. (**a**) Homogenised (blue line), original (grey line), and ERA5 (dotted black line) annual cumulative precipitation, (**c**) homogenised (orange line), original (grey line), and ERA5 (dotted black line) annual mean temperature, and (**d**) annual mean (yellow line) and maximum (purple line) ERA5 wind speed referring to the entire valley floor. Boxplots of the monthly differences between original and homogenised series of (**b**) precipitation and (**d**) mean temperature

ments are due to the simplified orography of the reanalysis dataset, which overestimates the height of the valley floor, where the weather station is located.

Both the original and the homogenised series from observations, as well as the series from ERA5 reanalysis data, were statistically analysed through the Mann-Kendall and Sen's slope tests. The results of these tests confirmed the statistical significance of the temperature increase in all the series. In contrast, precipitation did not exhibit a statistically significant trend (p-value < 0.05, see Table 2 in SI).

Climate change perceptions were also investigated through the social survey. The selected sample of local farmers included mostly men aged 35–50, who had always lived in the area (more details in SI). Most of them reported to have noticed an overall variation in climate (69.4% on average), with 82.4% noticing changes in precipitation, 70.2% in temperature, and 55.5% in wind (Fig. 4). Among those who noticed changes, 66.7% on average reported that these were quite recent, indicating the most recent window (i.e., the last 1–5 years) among the suggested options (Fig. 4b), while 24.0% opted for the last 5–10 years. Concerning the type of change perceived (Fig. 4c), most respondents indicated an increase in precipitation (70.5%), as well as in temperatures (86.6%). Moreover, most respondents (73.1%) perceived an increase in the frequency of wind gusts (Fig. 4d).

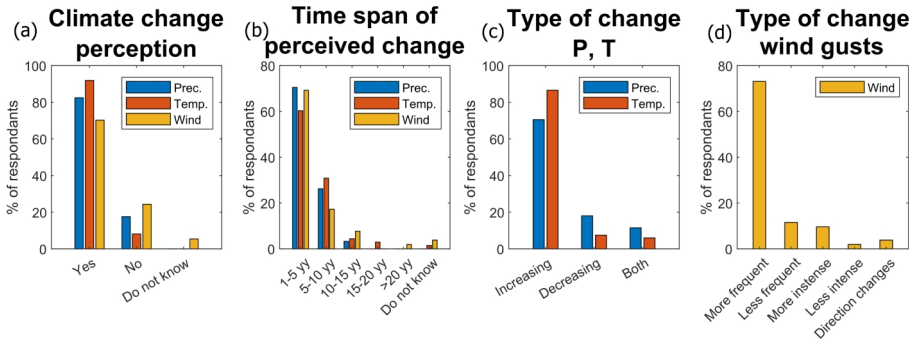

Fig. 4 Social survey's results on climate change perception. (**a**) Perception of changes in precipitation (blue), temperature (red), and wind gusts (yellow). (**b**) Time period (before the interview) in which the change was perceived. (**c**) Type (increase/decrease) of perceived precipitation and temperature change. (**d**) Main perceived change in the occurrence of wind gusts

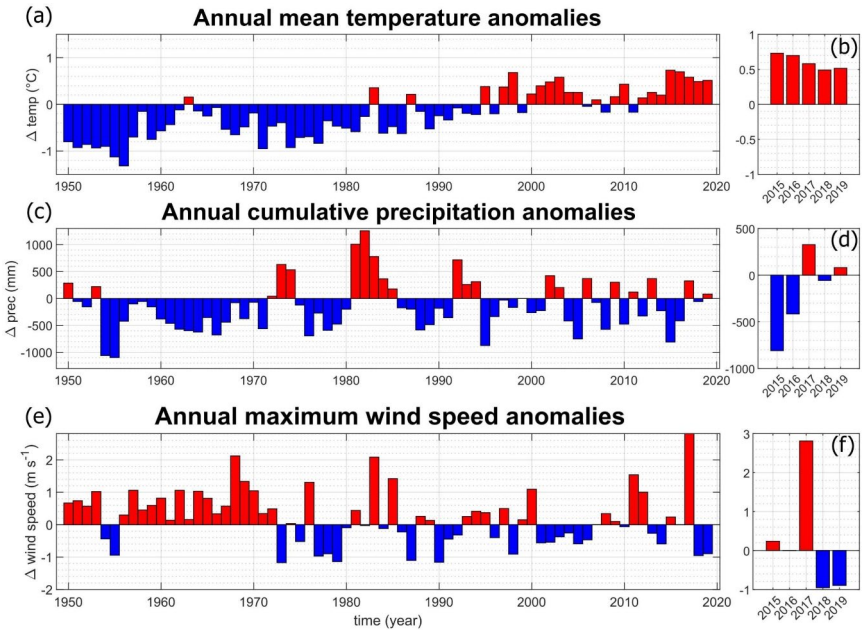

Fig. 5 Annual anomalies observed at TM station with respect to the 1981–2010 average. (**a**) Annual temperature anomalies, (**c**) annual precipitation anomalies, (**e**) annual maximum wind speed anomalies, (**b**, **d**, **f**) zoom-in of the last 5-year period

Figure 5 shows the anomalies compared to the 1981–2010 average, referring to the TM series. A zoom-in on the last five years is also provided to highlight the most frequent time window indicated by the interviewees (Fig. 4b).

Temperature anomalies (Fig. 5a, b) exhibit an overall increasing trend, resulting in positive anomalies since 1995, except for a few years. The positive anomalies observed over the last five years (Fig. 5b) are almost constant, with a value of 0.5–0.6 °C compared to the

30-year average. In contrast, precipitation anomalies (Fig. 5c, d) do not exhibit any trend, alternating positive and negative values. However, the zoom-in in Fig. 5d reveals a positive trend in precipitation over the last five years. In fact, starting from around −800 mm in 2015, anomalies have gradually increased to reach +300 mm in 2017 and +100 mm in 2019. The anomalies of the maximum annual wind speed, shown in Fig. 5e, f, do not exhibit any significant trend: positive and negative anomalies alternate, as for precipitation. It is noteworthy that the year 2017 stands out from the rest of the series with a positive anomaly of 2.78 m s^{-1} with respect to the 30-year average.

Up to this point, the climate analyses have yielded results that are only partially consistent with the findings of the social survey. While the farmers' perception of temperature changes aligns with both the multi-decadal and recent trends, their perception of precipitation changes aligns only with the most recent anomalies, which show a relative increase. In contrast, their perception of wind changes significantly differs from both the climate trends and the recent anomalies.

3.2 Evapotranspiration and crop water deficit

The section of the interviews dedicated to the impacts of climate change on banana plantations revealed a crucial aspect in framing the farmers' perception. While wind action was associated with three main effects on crops (stress, folding, and felling), changes in temperature and precipitation were reported to have a broader and overlapping spectrum of agricultural impacts (see Figure 4 in SI).

This complexity points out the challenge of identifying the primary meteorological factor responsible for damages, as examining solely the effects might lead to misinterpretations in inferring climate variability over longer periods. In this respect, evapotranspiration can provide bridging information between the two datasets, allowing for an indirect estimation of the combined impact of multiple meteorological variables on plant health, which in turn may influence farmers' perceptions of climate change. The analysis of water volume surplus or deficit (Fig. 6) provides a quantitative proxy of the impact of climate change on vegetation in this context of rainfed agriculture. Notably, the number of months with an estimated

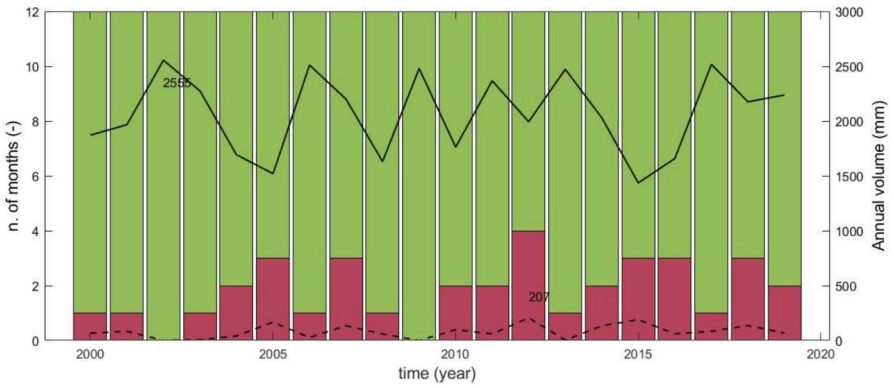

Fig. 6 Bars represent the number of months with surplus (green) and deficit (red) of water. Black lines show the cumulative annual amount of surplus water (solid line) and deficit water (dashed line), evaluated monthly. The two numbers point out the maximum value of surplus water (2555 mm), recorded in 2003, and the highest value of deficit water (207 mm), recorded in 2012

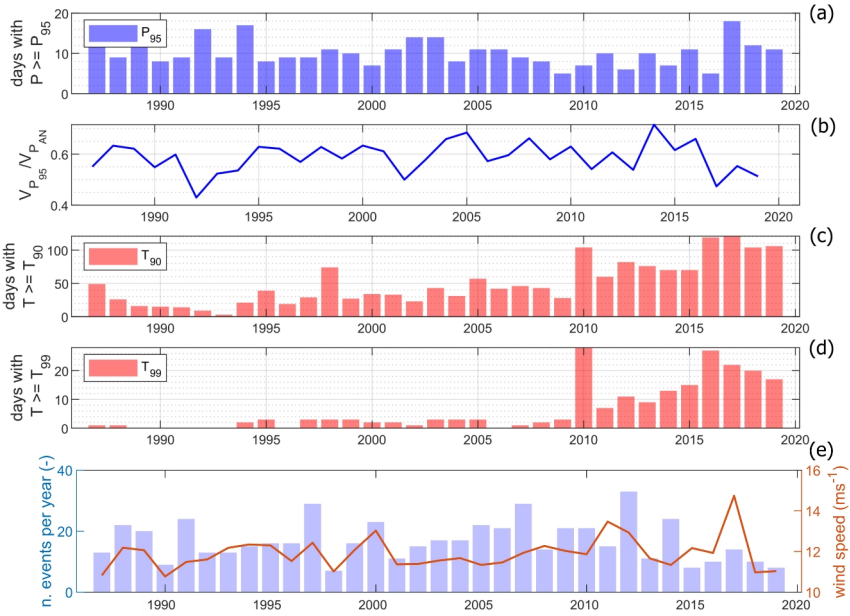

Fig. 7 Characterisation of extreme events in Tingo María in the 1987–2019 period: (**a**) number of days with accumulated precipitation exceeding the 95^{th} percentile of daily precipitation; (**b**) percentage of annual precipitation accumulated during these days; (**c**) number of days with maximum temperature exceeding the 90^{th} percentile of daily maximum temperature; (**d**) number of days with maximum temperature exceeding the 99^{th} percentile of daily maximum temperature; (**e**) number of wind gust events per year exceeding 10 m s^{-1} (blue bars) and annual highest wind speed from ERA5 reanalysis

water deficit has slightly increased in recent years. Indeed, there have been three years with three months of water deficit per year over the 2015–2019 period. It is noteworthy that comparable conditions (at least three months of water deficit) have also been observed on three other occasions in the previous analysed period, but over the course of fifteen years (2000–2014). In contrast, the water surplus volume has recovered from its lowest value in 2015 (1435 mm) and increased over the last 5 years.

This dual behaviour - namely a higher water surplus volume associated with a higher number of deficit months - occurred over a relatively short period, making it difficult to be interpreted as a long-lasting change. However, it could be inferred that precipitation was more concentrated in more intense events during the period 2015–2019, leading to longer periods of water deficit, without altering the overall annual volume.

3.3 Extreme weather events

Besides crop health, another key factor influencing farmers' perception of climate change is represented by local extremes. As Fig. 7 shows, on average 10 days per year recorded precipitation above the 95^{th} percentile during the reference period (1987–2019). It should be noted that, although 18 days were recorded in 2017 (well above the average), the percentage of volume accumulated during these extreme events (47% of the annual precipitation volume) is below the average (59% of the annual precipitation volume), as the entire year

recorded intense rainfall (Fig. 7b). Coherently with annual data presented in Fig. 5a, extreme precipitation events do not exhibit significant trends: years with more extreme events (1992, 1994, 2017) alternate with years with less (2009, 2012, 2016).

In contrast, the frequency of days with extreme temperature maxima has significantly increased over the same period. Figure 7c shows the number of days with maximum temperature exceeding the 90^{th} percentile: the highest value (121 days per year) is in 2017 (the same year with the highest number of days with extreme precipitation events). The increasing trend is even clearer for the number of days with maximum temperature exceeding the 99^{th} percentile (Fig. 7d): their frequency started to exceed five days per year from 2010 onwards.

As for the analysis of wind speed series, no significant trends can be detected even considering the frequency of gusts exceeding 10 m s^{-1}, although lower values occurred in recent years (Fig. 7d).

3.4 Adaptation strategies against climate change

As the interviews indicated, 53.3% of the respondents had not yet undertaken any adaptation strategy to climate change. Despite the low percentage of farmers adopting such strategies, many initiatives seemed to yield multiple benefits simultaneously. For instance, reforestation practice mitigates wind gusts (23.2%) and provides diffuse shading, which contrasts high temperatures (22.8%); while discontinuing the practice of weeding protects the soil against high temperatures (7.0%) and increases soil moisture (14.5%). Importantly, the 12 collected initiatives (i.e., excluding "no initiative", "leaving the farming practice" and "buying a new field") show that half of those implemented are low-cost as to installation and maintenance, and only two of them ("use of plastic covers" and "spreading fungicide") are conventional farming practices, highlighting the potential for environmentally friendly and cost-effective solutions.

4 Discussion

Trends and magnitude of climate change in the tropical Upper Huallaga Valley in Peru were quantitatively assessed by integrating the analysis of in-situ weather observations and reanalysis data (ERA5) with the outcomes of a social survey among farmers. In particular, the Integrated Approach focused on the three most impacting variables on low-tech agriculture: precipitation, temperature, and wind. Additionally, attention was paid to bottom-up initiatives adopted by farmers to face climate change impacts, in order to verify the local awareness of climate change and envisage possible scaling-up opportunities for the entire valley.

Data from three weather stations were available in the valley with records that counted more than 30 years. However, an integrated analysis of their quality and homogeneity showed that only one of them (TM) was suitable for long-term research purposes. The ERA5 data played a crucial role in assessing the quality of the in-situ series and adjusting them through the SNHT homogeneity test, confirming their valuable contribution in a context with scarce or absent data. Outcomes from the analysis of the quantitative climatic data sources indicate that temperature anomalies increased over the last two decades (Fig-

ure 5d), with statistical tests confirming the significance of these trends on both original and homogenised series from weather stations, as well as in ERA5 series. In contrast, precipitation and wind speed do not exhibit significant trends. Similar results on precipitation were found by Lavado Casimiro et al. (2013), who analysed historical meteorological series in the Huallaga and Ucayali watersheds, revealing that only two out of thirteen stations showed a negative trend in precipitation in the rainforest area in the 1965–2007 period.

Notably, despite the absence of a multi-decade trend, farmers perceived an increase in rainfall (Fig. 4a-c). This misperception is consistent with findings from other studies investigating social perceptions of climate change (Madhuri and Sharma 2020). Several misleading factors may contribute to this mismatch. First, as outlined by Lehner and Stocker (2015) and Budhathoki and Zander (2019), people tend to focus on the most recent weather events and short time scales, rather than climate trends and longer time scales. Indeed, farmers in the Upper Huallaga Valley may have been influenced by the recent increasing annual anomalies detected in the 2015–2019 period (Fig. 5d), rather than by multi-decade trends, and this would partially explain their answers displayed in Fig. 4b. Second, precipitation trends can be challenging to discern in areas with pronounced inter-annual variability and short, heavy rainfall events, according to Ricart et al. (2022). It is noteworthy that the Upper Huallaga Valley exhibits a markedly seasonal rainfall pattern (Fig. 1e) and is prone to convective weather events. Despite not being addressed in this study, scientific literature highlights that the cultural or social characteristics of the respondents, such as age, educational level, and access to weather information, may also cause potential misalignment between observations and perceptions, as evidenced by Roco et al. (2014). Furthermore, external factors, including land degradation and varying water demand due to increased or decreased productivity, can present additional challenges in achieving a clearer perception of rainfall trends (Hubertus et al. 2023; Ricart et al. 2022).

Among the external bias factors, we evaluated the crop's health by estimating the reference evapotranspiration, followed by the assessment of the number of months with a water surplus or deficit. This physical quantity combines several climatic variables, including air temperature, precipitation, and wind speed, and returns a more comprehensive effect of climate inter-annual variability on crops. Compared to other indexes used in previous studies, such as the Normalized Difference Vegetation Index, NDVI, and the Vegetation Health Index, VHI (Al Sayah et al. 2021), evapotranspiration mainly depends on climatic conditions. The outcomes of this study show that, despite the fluctuating pattern of the annual water surplus volume between 2000 and 2019, the relative increase over the past five years has coincided with a slight increase in the number of months with an average water deficit (Fig. 6). This is consistent with what Funatsu et al. (2021) and Haghtalab et al. (2020) observed in the Amazon basin: an increase in heavy rainfall during the rainy season and a prolongation of the dry season. This recent phenomenon could explain why farmers perceived an increase in rainfall and, at the same time, indicated dryness (14.8%) and stress (31.5%) as negative impacts of rainfall variation, as illustrated in Figure 4 in SI. This scenario would be consistent with the previous considerations on the increasing occurrence of intense precipitation events, which concentrate the volume of rainfall in shorter episodes, giving the impression of greater rainfall volumes (Lehner and Stocker 2015; Budhathoki and Zander 2019).

Extreme weather events (Fig. 7) were analysed using the daily time series of TM. A higher frequency of extreme heat days was observed, whereas extreme rainfall days did

not exhibit a discernible pattern. Daily precipitation, namely cumulative precipitation in 24 hours, does not accurately represent intense events, which typically occur at sub-hourly time scales (Fowler et al. 2021). Nevertheless, the population survey provided crucial insights that could be used to supplement the quantitative dataset, better characterising the sub-hourly events. Indeed, people mentioned the increase in the frequency of wind gusts, irrespective of the direction of their provenance (i.e., suggesting that they do not mainly depend on the orography of the valley) and with a connection with heavy rainfall, which is coherent to what is currently ongoing in the wider Amazon basin (Feng et al. 2023). Although the interpretation of these results would support the hypothesis that the increase in temperatures is causing a higher frequency of convective phenomena (Westra et al. 2014; Fowler et al. 2021), the lack of quantitative sub-hourly data does not allow us to properly validate this assumption, as pointed out by Gurgiser et al. (2016). However, it confirms the importance of integrating quantitative and qualitative datasets to enhance the understanding of the ongoing climate change in remote and data-scarce areas (Haag et al. 2021).

Concerning the AMIs adopted by farmers, it turned out that, despite most farmers being aware of climate change (Fig. 4a), more than half admitted they had taken no initiative. Although farmers who experienced local impacts of climate change express a higher willingness to implement AMIs (Haden et al. 2012), internal drivers (such as education, farming experience, and economic income), combined with external factors (such as poor access to institutional services, farm location, and weather information services) may hinder farmers in their adaptation process (Ayanlade et al. 2017; Abid et al. 2016). In this case, it seems that the history of illegal coca cultivation and violent repression in the Upper Huallaga Valley (Paredes and Manrique 2021) has led to a pervasive distrust of neighbours and institutions. Despite numerous governmental and non-governmental interventions, there remains a deep mistrust of cooperative systems, as outlined by Mazeres-Gaitero (2020), which in other circumstances could facilitate more effective self-organization of farmers and ease information sharing. However, the strategies implemented to date, such as reforestation or maintenance of wetlands (Figure 2 in SI), have proven to be cost-effective and environmental-friendly, aligning with the FAO's recommended practices for climate resilience (Alvar-Beltrán et al. 2021). The affordability of these strategies is encouraging, and, despite the mistrust constraints, this will undoubtedly facilitate the dissemination of these good practices within similar contexts.

5 Conclusions

A novel integrated qualitative-quantitative approach for assessing climate change in a data-scarce context has been applied to the Peruvian tropical valley of the Upper Huallaga River. Results of a social survey on climate change perception were combined with quantitative data sources, namely historical meteorological series and reanalysis data (ERA5), to outline climate dynamics at different spatio-temporal scales.

The quantitative data enabled the estimation of climate trends and anomalies. This revealed that temperatures increased at a rate of approximately 0.2 °C per decade, while precipitation and wind exhibited a more variable trend, with no clear patterns. Conversely, the use of more qualitative information derived from 73 interviews with local farmers provided several insights that complemented conventional climatic data and described the impacts

of climate change on crop health. In particular, the farmers gave useful, albeit qualitative, information about sub-hourly events, which suggested that the local wind gusts were more likely to originate from convective than orographic processes.

Surplus water volumes exhibited positive trends in the 2015–2019 period despite a slight increase in the number of months experiencing water deficit. Indeed, the frequency of prolonged dry conditions (at least 3 months per year) has increased, passing from 3 times in 15 years (2000–2014) to 3 times in 5 years (2015–2019). These alterations could lead to the assumption that precipitation events are becoming more intense and shorter, a hypothesis consistent with that of an increase in convective phenomena. This finding is consistent with the perception of 70.5% of farmers, who reported an increase in annual precipitation, which, however, contrasts with the quantitative data. This perception may be biased by an increased frequency of sub-daily heavy rainfall events. Unfortunately, the lack of local data with sub-daily or higher temporal resolution precludes the verification of these assumptions. This underscores the importance of improving networks of meteorological stations capable of recording data at a sub-hourly frequency in data-scarce contexts.

The involvement of farmers was crucial not only for better characterising the local climate at 30-year, annual, monthly, and daily scales, but also for investigating adaptation initiatives already adopted in the valley. Bottom-up initiatives, such as reforestation, can be easily embraced by local communities, scaling up their implementation thanks to their affordability, easy setting-up, and simple maintenance.

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Author contributions All authors contributed to the study’s conception and design. Material preparation and data collection were performed by A1, A3, and A4. The first draft of the manuscript was written by A1 and A2, and all authors (A1, A2, A3, A4, A5, A6) commented on previous versions of the manuscript. All authors have read and approved the final version.

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Data availability The ERA-5 data analysed during the current study are available in the Climate Data Store repository provided by the European Centre for Medium-Range Weather Forecasts, https://cds.climate.copernicus.eu/cdsapp#!/home. The three historical meteorological series of Tingo María, Tulumayo, and Tocache weather stations were provided by SENAMHI. These are not publicly available due to the restrictions of the institution but can be requested for research purposes. Data collected during the social survey are available at https://doi.org/10.5281/zenodo.7729276 upon request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

Ethics approval and consent to participate Participants in the survey were verbally informed of the purpose of the interview and verbally declared their consent to participate. The methodology of the social survey was approved by the "Comité de Ética para la investigación científica" at the Universidad Nacional Agraria de la Selva, Tingo María (PE) (approval n. 001-2022). Furthermore, the data were collected anonymously.

Consent for publication The respondents were verbally informed of the wish to publish the results of the survey in an anonymous and aggregated form and verbally consented to this.

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