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ORIGINAL ARTICLE

Water management in quinoa cultivation: quantification of the water footprint and climate projections in an inter-Andean valley

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Abstract

Efficient water management in agriculture is key to the sustainability of crops in inter-Andean valleys (IAV), where water availability is at risk due to climate change (CC). Quinoa, as a strategic crop in these ecosystems, requires a detailed analysis of its water use to optimize its production without compromising water resources. This study quantified the water footprint (WF) (green, blue and grey) of three quinoa varieties (INIA 415 Pasankalla, INIA 420-Negra Collana and INIA 441-Señor del Huerto) harvested in a sandy loam soil in an IAV of Peru. In addition, the trend of the WF in 12 agricultural seasons was evaluated, and future climate scenarios (SSP1-2.6, SSP3-7.0 and SSP5-8.5) were projected to estimate the impact of CC on the crop's water demand towards 2090–2100. The results showed significant differences in water-use efficiency among varieties. INIA 441-Señor del Huerto showed the highest water efficiency, with a 3.20 t ha^{-1} yield and a low total WF, making it more sustainable under CC conditions. In contrast, INIA 420-Negra Collana had a higher water demand, making it less viable under water-stress scenarios. Climate projections indicate an increase in water demand for quinoa under scenarios of greater radiative forcing, which underscores the need to develop water management strategies. These findings highlight the importance of selecting more efficient varieties for water use and adopting sustainable practices to mitigate the effects of climate change on quinoa production at IAV.

Keywords *Chenopodium quinoa* · Climate change · Agricultural sustainability · Crop water demand

Introduction

Environmental alterations associated with climate change (CC) have increased agricultural sector's susceptibility, favouring variations in crop performance in the Andes (Lozano-Povis et al. 2021). However, agriculture, forestry, and other productive land uses are responsible for 13–21% of global anthropogenic greenhouse gas emissions during 2010–2019 (Intergovernmental Panel on Climate Change (IPCC), 2023a). Therefore, it is crucial to optimize agricultural processes and resource use, as well as to assess the potential effect of CC on crops (Wang 2025). Rainfed agricultural systems are particularly susceptible to climate change; however, information on their impacts in mountainous regions remains limited (Adler et al. 2023; Chakraborty et al. 2025). This situation could compromise agricultural sustainability and food security in IAV. Climate simulation studies based on Global Climate Models predict that South American countries will experience increasing temperatures, water scarcity, and higher evapotranspiration potential, leading to the loss of major crops (Lozano-Povis et al. 2021).

Access to water represents another challenge. Of the total water on Earth, only 3% is fresh water, and just 0.3% of this is available on Earth's surface, with the agricultural sector accounting for approximately 70% of water consumption (Nassos & Avlonas 2020). However, rapid population growth and the impacts of CC pose significant challenges

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for its sustainable management (UN Water, 2020). Although Peru ranks eighth in freshwater availability (2%), it faces water scarcity due to the inadequate temporal and spatial distribution of water resources (Hatta Sakoda 2016). In this context, basins with agricultural, energy and social importance, such as the Mantaro River basin, are projected to experience a temperature increase of up to 3 °C by the end of this century (SENAMHI 2007). Characterized by semi-arid conditions and high climatic variability, the Mantaro IAV produces around 86% of the food consumed in Peru (Eguren López & Pintado 2015; Gómez Pando & Aguilar Castellanos 2016), with Ayacucho being one of the main national producers of quinoa (INEI 2019, 2024). In that sense, it is essential to implement efficient water management strategies that enable the achievement of the Sustainable Development Goals (SDGs) 6 "Clean water and Sanitation", SDG 12 "Responsible Consumption and Production" and SDG 13 "Climate Action" (FAO 2015).

In that sense, promoting the use of drought-tolerant crops, such as *Chenopodium quinoa* Willd (quinoa), represents a viable alternative for CC adaptation (Ccoyllar-Quintanilla et al. 2021). Currently, it contributes to global food and nutritional security due to its high nutritional value and remarkable adaptability (Ponce De León Saavedra & Valdez-Arana 2021). Its notable genetic diversity has enabled it to spread across different altitudinal zones, ranging from sea level to 4000 m.a.s.l (Apaza et al. 2013) with an average yield of 1790 t ha^{-1} over more than 103,000 ha cultivated (MIDAGRI 2025). Among the main quinoa varieties developed by the National Institute of Agrarian Innovation (INIA) of Peru, the INIA 441-Señor del Huerto, INIA 420—Negra Collana, INIA 415 – Pasankalla, and Salcedo INIA stand out because of their precocity, high yield, pest and disease resistance and adaptability to abiotic stresses (Apaza et al. 2013).

Regarding the current water context, the WF is recognized as a key indicator for evaluating the sustainable use of freshwater consumed during the production process (Hoekstra 2017). This approach not only supports environmental sustainability but also strengthens agriculture's resilience to scarce water (Pegram et al. 2016). The WF comprises three components: Green Water Footprint (rainwater consumption), Blue Water Footprint (Surface or groundwater use), and Grey Water Footprint (volume of water required to assimilate pollutants) (Hoekstra et al. 2012). In this regard, CropWat 8.0 is a highly important and widely used tool in the agricultural sector for WF assessment (Demir & Muratoglu 2025; Islam et al. 2026; Vantarakis et al. 2025). Developed by FAO, it enables accurate estimation of crop water requirements calculation and irrigation scheduling, based on soil, climate, and crop information (Allen et al. 1998; Smith & Nations, 1992). Likewise, this will allow decision-making aimed at maximizing agricultural yield under specific climate conditions while ensuring long-term water supply (Pegram et al. 2016). Regarding quinoa production in Peru, despite its economic importance, studies related to WF estimation remain strongly constrained by the region's realities.

Therefore, the WF study of three quinoa varieties allows us to understand the differences in their genetic traits, cultivation conditions and environmental adaptability. Consequently, it is particularly important to develop WF quantification studies for quinoa, especially in IAV, where water access is limited, and the crop is highly vulnerable to CC impacts. This latter issue could further compromise the availability of this essential resource. Subsequently, the present research aims to quantify the water footprint, including its blue, green, and grey components in three quinoa varieties under CC scenarios, using CropWat 8.0 in IAV conditions of the central Peruvian highlands.

Methods

Location of the study area

The study was carried out under field conditions at the Canaan Agricultural Experimental Station (EEA Canaan) (13° 9′54.59"S; 74°12′14.96"W; 2735 m.a.s.l.), belonging to the National Institute of Agrarian Innovation (INIA), located in the Andres Avelino Caceres Dorregaray district, province of Huamanga, Ayacucho Region. The research took place between October 2023 and March 2024 (Fig. 1). Historical climate averages were calculated from data recorded by the INIA Canaan Meteorological Station (13°9′ S; 74°13′ W; 2761 m.a.s.l.), operated by the National Meteorology and Hydrology Service of Peru (SENAMHI), and the Regional Government of Ayacucho (GRA). The average annual rainfall is 663.2 mm, average minimum temperature 9.5 ºC and average maximum temperature 25 °C (Fig. 2) (SENAMHI 2025a). For the study, quinoa varieties widely cultivated in the Ayacucho region were used: INIA 441-Señor de Huerto, INIA 415 Pasankalla and INIA 420-Negra Collana. The seeds were acquired through the Andean Grains Program of the Canaan Agricultural Experimental Station-INIA.

Physicochemical characteristics of the soil

Before planting, a representative soil sample of approximately 1 kg was collected at a depth of 0.30 m. The sample was sent to the Soil, Water and Foliar Laboratory (LABSAF)—INIA Canaan to determine its physicochemical characteristics. Analyses included texture (NOM-021-RECNAT-2000, 2002), pH (USEPA 2004), electric

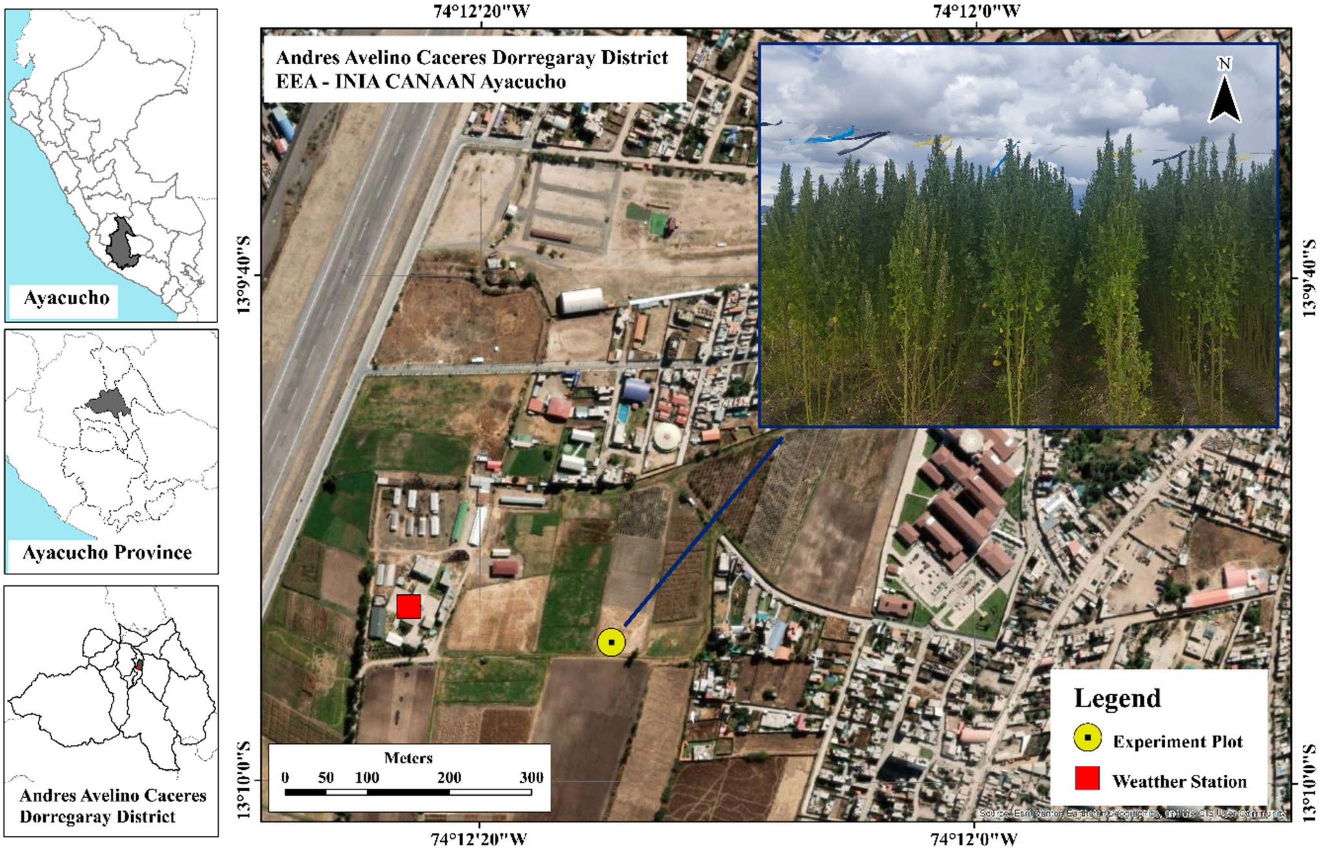


Fig. 1 Experimental field and meteorological station at Canaan Agricultural Experimental Station—INIA, Andres Avelino Caceres Dorregaray district, Huamanga province, Peru

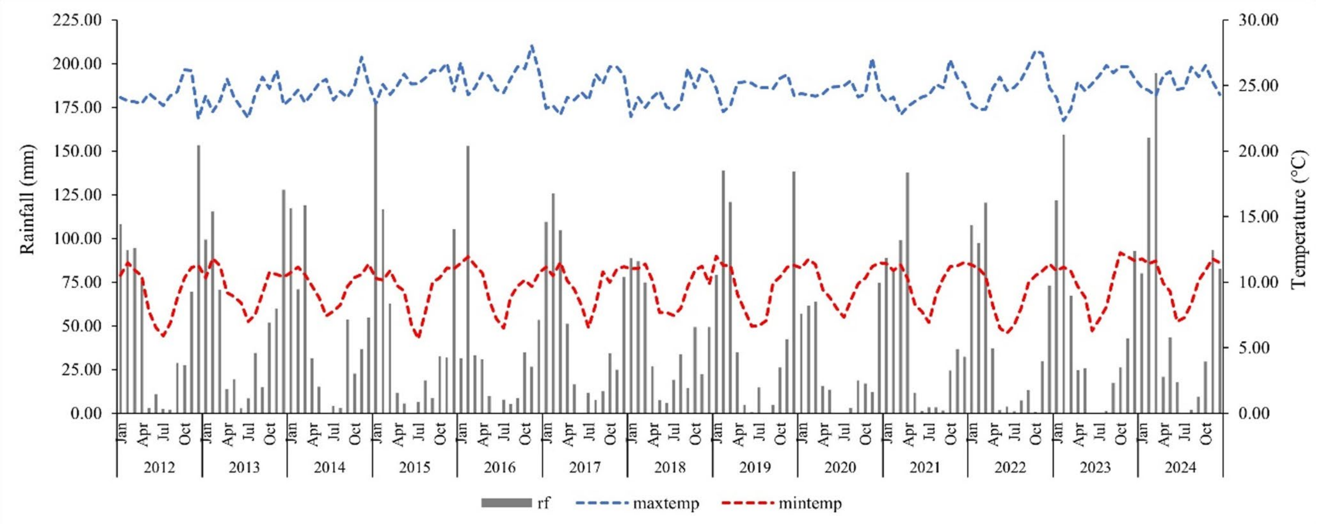


Fig. 2 Weather parameters of 12 agricultural seasons from January 2012 to December 2024. Rainfall (rf), maximum temperature (maxtemp) and minimum temperature (mintemp)

conductivity (EC) (ISO (International Organization for Standardization, 1994), organic matter (OM) (NOM-021-RECNAT-2000, 2002), total nitrogen (ISO (International Organization for Standardization), 1995), available phosphorus (NOM-021-RECNAT-2000, 2002), available potassium (Bazán Tapia 2017), Cation Exchange Capacity (CEC) (Ca^{+2}, Mg^{+2}, K^{+} and Na^{+}) (Bazán Tapia 2017; NOM-021-RECNAT-2000, 2002). The soil water parameters were calculated from the formulas of Bodman and Mahmud (1932) for field capacity, and Kramer (1995) for permanent wilting point. Additionally, the maximum infiltration rate was determined using the double-ring method (ASTM 2018). The results indicate that the soil has a sandy loam texture, a pH of 7.9, and high levels of total nitrogen, potassium and CEC. Considered a soil of moderate fertility with a medium level of organic matter, medium available phosphorus and an alkaline pH that reduces the availability of some micronutrients (Table 1).

Water footprint

The water footprint refers to the volume of water required for crop production, including irrigation and precipitation during all stages of the crop cycle (Demir & Muratoglu 2025). The total water footprint of the crop (WFTotal, m^3t^{-1}), as defined by Hoekstra et al. (2012), is composed by the blue water footprint (WF_{blue}); the green water footprint (WF_{green}) and the grey water footprint (WF_{grey}) (Eq. 1).

$$WF_{Total} = WF_{blue} + WF_{green} + WF_{grey} = \frac{10 * \sum_{d=1}^{n} ETc_{blue}}{Y} + \frac{10 * \sum_{d=1}^{n} ETc_{green}}{Y} + \frac{(\alpha * AR)}{Y * (C_{\max} - C_{nat})} \quad (1)$$

Table 1 Physicochemical characteristics of the experimental plot

Properties	Parameters	Symbol	Unit	Values
Physical	Sand		(%)	48
	Silt		(%)	40
	Clay		(%)	12
	Texture class			Sandy Loam
	Field capacity (−0.03 MPa)	FC	(%)	18.42
	Wilting point (−1.5 MPa)	WP	(%)	11.69
	Bulk density	BD	$g\ cm^{-3}$	1.47
Chemical	pH	pH	–	7.9
	Electrical Conductivity	EC	$mS\ cm^{-1}$	10.12
	Organic Matter	OM	%	2.1
	Total nitrogen	N	%	1.5
	Available phosphorus	P	ppm	27.8
	Available potassium	K	ppm	359.86
	Calcium	Ca^{++}	meq $100\ g^{-1}$	18.3
	Magnesium	Mg^{++}	meq $100\ g^{-1}$	2.52
	Potassium	K^{+}	meq $100\ g^{-1}$	0.37
	Sodium	Na^{+}	meq $100\ g^{-1}$	0.12
	Cation Exchange Capacity	CEC	meq $100\ g^{-1}$	21.3

Y, means the crop yielding in $t\ ha^{-1}$; ETc_{blue} is the crop evapotranspiration related to the availability of irrigation water; ETc_{green} is the crop evapotranspiration related to effective rainfall; $\sum_{d=1}^{n}$, vegetative period of the crop from sowing (day 1) to harvest (day n). From this, it can be indicated that the Crop Water Use (CWU) of the cultivation will depend on the source from which the water is extracted: CWU_{blue} depends on surface or underground sources in $m^3\ t^{-1}$ and CWU_{green} on the water associated with rainfall in $m^3\ t^{-1}$ (Eq. 2).

$$CWU = 10 * \sum_{d=1}^{n} ETc \quad (2)$$

On the other hand, AR is the fertilizer application rate in $kg\ m^{-2}$; α, the fertilizer leaching fraction (exported) to water bodies; C_{max}, the maximum acceptable concentration in mass per volume units and C_{nat}, the natural concentration of mass per volume units. For this research, α and C_{max} were determined according to Franke et al. (2013), and C_{nat} was determined from the water quality analysis of the Huatatas River conducted by Aronés Medina et al. (2018). Fertilization was calculated based on the previously conducted physicochemical characterization of the soil. The grey footprint was taken as the highest calculated value for the nitrogen and phosphorus contributed.

Cultivation modeling

CROPWAT (version 8.0 for Windows) (FAO, 2026) was used to model water requirements in quinoa crops and calculate CWU_{blue} and CWU_{green}. The climatic and precipitation modules were built using daily climate data from the INIA-Canaan meteorological station (i.e. rainfall, maximum, minimum, and average temperatures, relative humidity, hours of sunshine, and wind speed) (Fig. 1). The effective precipitation (Pe) was calculated according to FAO/AGLW (Allen et al. 1998), and the reference evapotranspiration (ETo) using the Penman–Monteith method. Thus, to calculate the CWU_{blue} and CWU_{green} according to Eq. 02, ETc_{green} and ETc_{blue} were obtained by Eqs. 3 and 4 respectively (Hoekstra et al. 2012).

$$ETc_{green} = min\,(ETc, Pe) \quad (3)$$

$$ETc_{blue} = max\,(0, ETc - Pe) \quad (4)$$

The soil module was completed using the previously carried-out physicochemical characterization (Table 1). Secondary information was used for the CROPWAT's crop module (i.e., crop coefficient Kc according to Choquecallata et al. (1992); water depletion fraction (p) and yield response factor (Ky) according to Mirsafi et al. (2024), complemented with data measured in the field for the three varieties evaluated. Irrigation schedule was defined according to field management.

Preparing the fields for variable validation

To validate the yield parameters and adjust the crop development parameters for the CROPWAT model, three plots of 10 rows, each 15 m long, were implemented, with a 0.80 m row spacing and a 1.6 m plot separation. A variety of quinoa was installed in each plot: v1: INIA 415 Pasankalla; v2: INIA 420-Negra Collana; v3: INIA 441-Señor del Huerto. The seeds were acquired from the Andean Grains Program of the EEA Canaan of INIA. The land was previously conditioned using agricultural machinery, including a disc plough, a harrow in cross work, and a furrowing machine. Fertilization was calculated based on the soil's physicochemical analysis: island guano (2000 kg ha^{-1}), diammonium phosphate (100 kg ha^{-1}), potassium chloride (150 kg ha$^{-1)}$, and urea (200 kg ha^{-1}). Fertilizers were applied prior to planting, except for urea. The latter was applied at 50% at sowing and 50% at hilling (41 days after sowing (DAS)), during the phenological phase of the beginning of branching, at a depth of 2 cm. After the fertilizers were covered, the quinoa seeds were sown in a continuous stream at a rate of 12 kg ha^{-1} and at an approximate depth of 3 cm.

The crop received gravity irrigation every 4 days, until the beginning of the rainy season (December). From that moment until the end of the campaign, it was managed by rainfed land. Agricultural work included manual weeding and thinning at 26 DAS (phenological stage 6 true leaves), leaving approximately 15 plants per linear meter. Cyperklin 25 EC (1 L ha^{-1}) was applied at the phenological stage of four true leaves and pasty grain to control *Liriomiza brazilensis*, *Diabrotica speciosa* and aphids. Suckering fungus at emergence was controlled with Vitavax-300 (100 g ha^{-1}). Downy mildew (*Peronospora variabilis*) at the vegetative stage of panicle initiation was controlled with Ridomil Gold MZ 68 WP (3 kg ha^{-1}).

Determination of crop variables

Phenological monitoring of the plantation was carried out according to Gómez and Aguilar (2016). Biometric and physiologic evaluations were driven according to Sosa-Zuniga et al. (2017). Root depth was measured according to Böhm (1979). Three and ten plants for each variety were extracted at the two-true-leaf and pasty-grain stages, respectively. The root lengths of the previously extracted plants were measured with a 5 m flexometer from the neck of the plant to the apex of the main root. The evaluation of the maximum height was carried out during the phenological stage of pasty grain according to the development of each variety.

To evaluate the yield, the central furrows of each plot were considered (1.6 m edge effect). All plants located within four 1 m × 2 m areas distributed in zigzag along the central furrows of each plot were harvested. To prevent pigeon damage, plants were cut at the pasty grain phenological stage. The panicles were dried in dryers built with a polycarbonate cover at the EEA Canaan. Afterwards, the grains were threshed, vented and weighed.

Exploring climate change

Historical daily-scale rainfall information was extracted from the RAIN4PE gridded product (Fernandez-Palomino et al. 2021) and the PISCO product for minimum and maximum temperature data (Huerta et al. 2018) using the terra package in R (Hijmans et al. 2023). This information was used to reduce the inherent biases in the historical output from the General Circulation Model (GCM). For this purpose, simulated results for the historical period 1981–2014 by the EC-Earth3 GCM were used for the Coupled Model Intercomparison Project Phase 6 (CMIP6) (EC-Earth Consortium (EC-Earth), 2019a). This model has been used in research conducted in South America and the highland Andean zones, demonstrating good performance (Almazroui et al. 2021; Peralta et al. 2025). After extracting rainfall, maximum temperature and minimum temperature data for the study area (using the terra package in R), bias correction was performed using quantile mapping with the Qmap package in R (Gudmundsson 2016). The use of empirical quantiles and robust empirical quantiles methods was proved to be an excellent option to correct the bias of rainfall and temperature data (Enayati et al. 2020).

Based on those results, bias corrections were applied for the EC-Earth3 GCM projections for three combinations of Shared Socio-Economic Pathways' (SSPs) and climate simulations from the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6). Each combination represents an integrated scenario of future climate and societal change, which would be used to investigate mitigation and adaptation issues, as well as the remaining impacts on society and ecosystems (O'Neill et al. 2016). Of these, scenarios identified as high-priority allow for robust research to assess future climate-change impacts (Meinshausen et al. 2020; O'Neill et al. 2016). SSP1-2.6 corresponds to a sustainable human development pathway based on a progressive shift toward sustainable practices, facing low challenges for mitigation and reaching zero CO_2 emissions by 2100 (O'Neill et al. 2016). SSP3-7.0 considers a pessimistic development based on regional rivalries, minimal investment on health and education, and the absence of additional mitigation measures causing that CO_2 emissions would double by 2100 (Intergovernmental Panel on Climate Change (IPCC), 2023b; O'Neill et al. 2016). SSP5-8.5 shows a scenario in which CO_2 concentrations would double by 2050 due to human development (e.g. investment in education and health) based on energy intensification from the consumption of fossil fuels (Intergovernmental Panel on Climate Change (IPCC), 2023b; O'Neill et al. 2016). Thus, for EC-Earth3 model, SSP1-2.6 (EC-Earth Consortium (EC-Earth), 2019b), SSP3-7.0 (EC-Earth Consortium (EC-Earth), 2019c) and SSP5-8.5 (EC-Earth Consortium (EC-Earth), 2019d) were used. To simulate the behaviour of CWU for the periods 2050–2060 and 2090–2100, the results of projected and corrected rainfall and maximum and minimum temperatures were used as inputs to the CROPWAT 8.0 climate module. ETo was calculated according to the Hargreaves method (Allen et al. 1998).

Results

Characterization of quinoa's varieties

The INIA 415 Pasankalla (v1) variety stood out for its earlier maturation, with a vegetative cycle 20 days shorter than that of the INIA 441-Señor del Huerto variety (v3) and 15 days shorter than that of the INIA 420-Negra Collana variety (v2) (Table 2). This difference was observed from the initial stage, with a more marked differentiation at the end of the intermediate stage in v3. In contrast, v2 differentiated itself during the final stage.

The root depth of the crop showed similar values across the three varieties at both the initial and final stages of development (Fig. 3a). Variety v3 caught attention for its greater development, reaching a height of 224 cm, surpassing the other two varieties (Fig. 3b). Yields differed significantly among varieties, with v3 standing out with 4.24 t ha^{-1} (Fig. 3c).

Base period of water footprint

The consolidated Water Footprint (WF) analysis revealed the highest values for the INIA 420-Negra Collana variety (v2: 1525.93 $m^3\ t^{-1}$), followed by INIA 415 Pasankalla (v1: 1396.12 $m^3\ t^{-1}$) and INIA 441-Señor del Huerto (v3: 1338.60 $m^3\ t^{-1}$) (Fig. 4). Accordingly, v2 exhibited the highest green, blue, and grey WF components for the 2023–2024 season. Regarding v1, its high WF_{blue} significantly influenced its position as the second-highest total WF. Furthermore, because a uniform fertilizer dose was applied across all treatments, the variation in WF_{grey} was primarily driven by differences in crop yields among varieties.

The CWU_{green} was estimated for campaigns from 2012 to 2023 (Fig. 5a). Variations in CWU_{green} were observed over the analyzed period. The highest values were estimated for the 2012–2013, 2013–2014 and 2023–2024 seasons for the three quinoa varieties. The lowest values correspond to the 2020–2021 campaign. On average, CWU_{green} were v1: 1906.3 $m^3\ ha^{-1}$, v2: 2024.0 $m^3\ ha^{-1}$, and v3: 2278.5 $m^3\ ha^{-1}$ maintaining this trend throughout the analyzed period. Likewise, CW_{blue} ($m^3\ t^{-1}$) showed variability across the analyzed campaigns (Fig. 5b). An inverse relationship was observed between CWU_{blue} and CWU_{green}, with higher rainfall volumes during campaigns corresponding to reduced CWU_{blue} values. Thus, the highest water requirements were calculated for the 2019–2020 and 2020–2021 campaigns. On average, CWU_{blue} was higher for the Señor del Huerto variety (v3: 4183.6 $m^3\ ha^{-1}$) compared to the other two (v1: 3908.3 $m^3\ ha^{-1}$; v2: 3952.4 $m^3\ ha^{-1}$).

Climate change scenarios

The climate change scenarios analyzed (SSP1-2.6, SSP3-7.0, and SSP5-8.5) show an increasing trend in average annual rainfall with more significant differences towards the decade 2090–2100 (Fig. 6). Up to the period 2050—2060, a similar increase is observed among the three scenarios. After that, the differences in rainfall volumes between wet and dry years were more pronounced, reaching peaks of more than 2800 mm accumulated per year for SSP5-8.5 and average interannual variations of 432 mm for SSP3-7.0. The minimum temperature shows a steady increase of + 6 °C on average across SSP3-7.0 and SSP5-8.5. Only the SSP1-2.6 scenario shows an increase of about + 1 °C. The maximum temperature is expected to increase by an average of 4 °C, steadily up to peak of 29 °C. Thus, by the decade

Table 2 Days after sowing (DAS) when every phenological stage in quinoa plantation is reached

Cultivation stage	Initial	Development				Half			End	
Phenological stages	Emergency	2 True leaves	4 True leaves	6 True leaves	Branch	Panicle	Bloom	Milky grain	Doughy grain	Maturation
INIA 415 Pasankalla	8	13	24	30	45	57	70	102	126	144
INIA 420-Negra Collana	7	10	21	33	50	66	95	106	136	150
INIA 441-Señor del Huerto	13	18	25	37	55	72	105	126	142	165

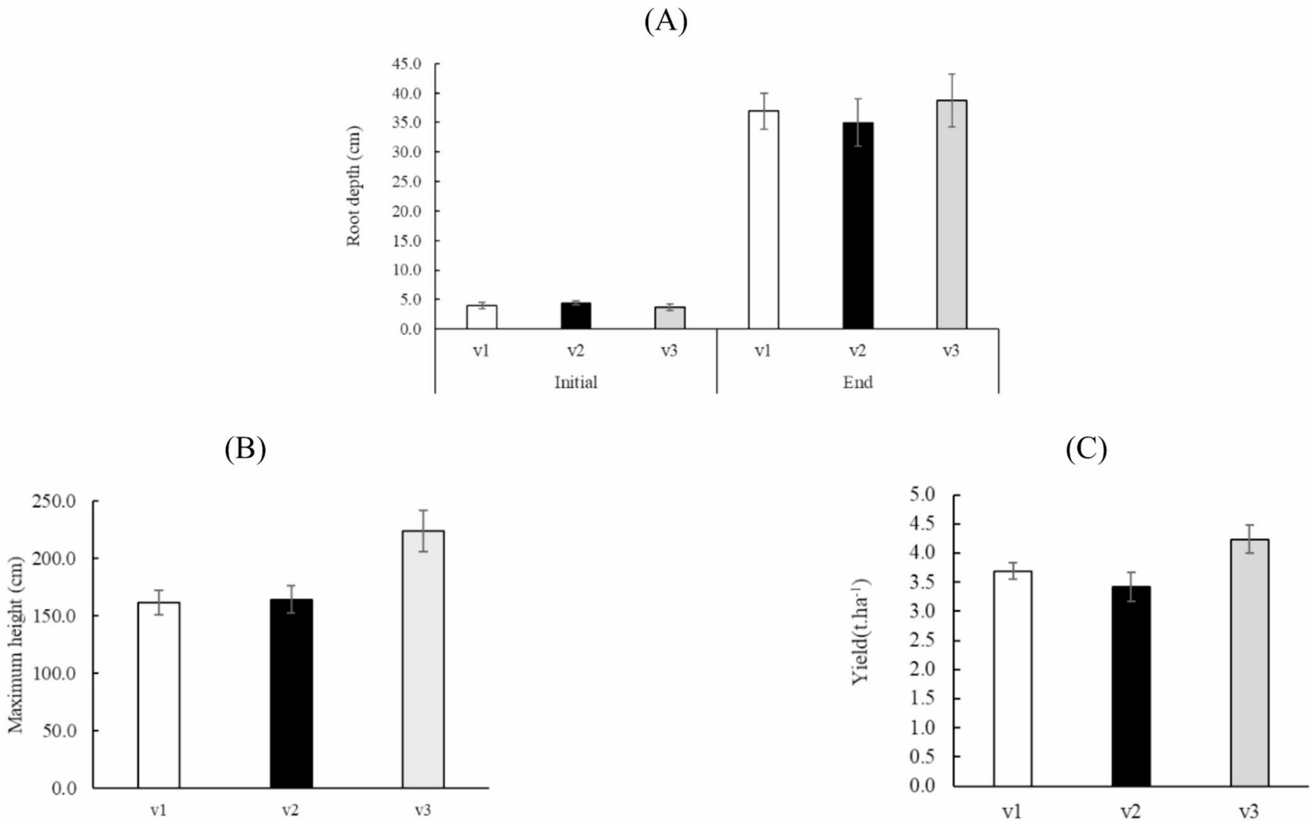


Fig. 3 Characterization of quinoa varieties. **A** Initial and final root depth (m). **B** Maximum height of the crop (m). **C** Crop yield in (t ha^{-1}). v1: INIA 415 Pasankalla, v2: INIA 420-Negra Collana and v3: INIA 441-Señor del Huerto

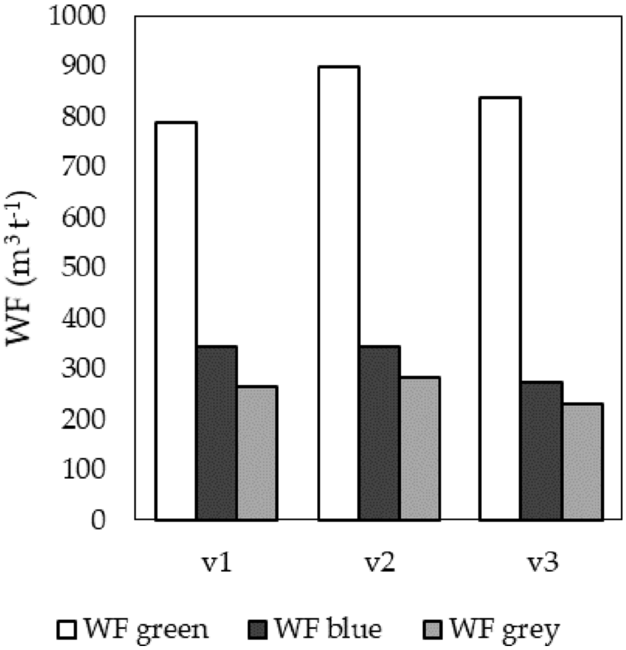


Fig. 4 Water Footprint of varieties v1: INIA 415 Pasankalla, v2.: INIA 420-Negra Collana and v3: INIA 441-Señor del Huerto

2090–2100, SSP3-7.0 showed greater variability in mean interannual rainfall and temperatures.

Projected crop water use

For the period 2050–2060, on average, CWU_{green} v3 trends to higher values than v2 and v1 (Fig. 7). In general, SSP 3–7.0 shows a slight tendency to have higher CWU_{green} values for all three varieties. For the 2090–2100 period, an increase in CWU_{green} was observed for SSP3-7.0 and SSP5-8.5. In particular, in SSP3-7.0 the v3 variety showed an increase 1,818 m3 ha^{-1} compared to the 2050–2060 decade. Furthermore, compared to the other scenarios for the same decade, the CW_{green} of v3 in SSP3-7.0 is 38.9% higher than that for the same variety in SSP1-2.6 and 7.9% higher than that in SSP5-8.5. In all cases, a similar relationship between varieties was maintained: CWU_{green} of v3 was on average 14% higher than v2, and 20% higher than v1.

Regarding CWU_{blue}, the analyses for the periods 2050–2060 and 2090–2100 showed similar values for the quinoa varieties analyzed across all evaluated scenarios. Under SSP5-8.5 conditions, v3 showed a lower CWU_{blue} than v1 and v2 for the 2050–2060 decade. This trend was repeated in the decade 2090–2100 for SSP3-7.0 and SSP5-8.5.

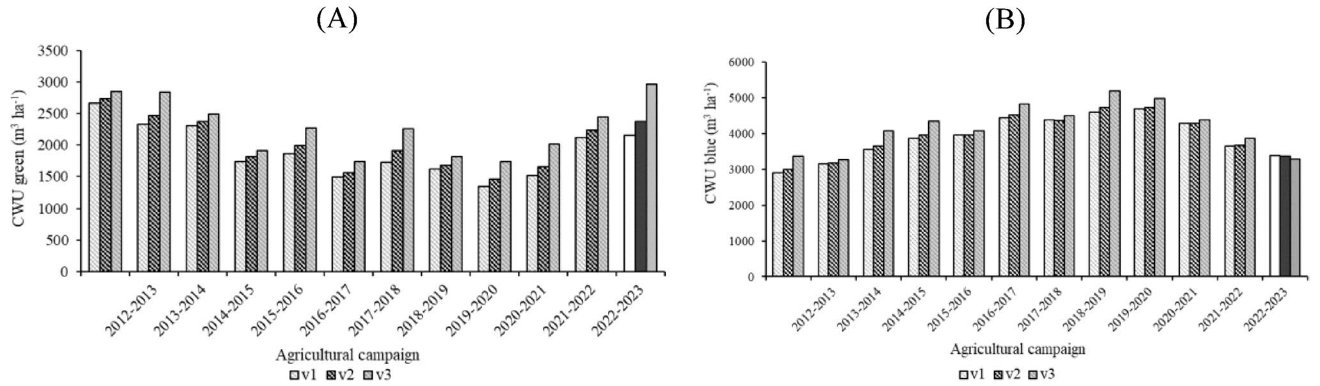


Fig. 5 Crop Water Use (CWU, m^3 ha^{-1}) between the campaigns 2012 and 2023 per cultivated quinoa variety. **A** Green Crop Water Use (CWU_{green}, m^3 ha^{-1}). **B** Blue Crop Water Use (CWU_{blue}, m^3 ha^{-1}). The solid-colour bars were calculated based on field data, and the coloured bars were estimated using the yields from historical meteorological records. v1: INIA 415 Pasankalla, v2: INIA 420-Negra Collana and v3: INIA 441-Señor del Huerto

Under SSP1-2.6 conditions, CW_{blue} experienced an increase of 8–10% during the decade 2090–2100 relative to 2050–2060. For the SSP3-7.0 scenario, a decrease of 52–63% was observed for the last decade of the century in relation to the 2050–2060 period, with a greater incidence on v3. Finally, a decrease of 98–100% was observed between 2090–2100 and 2050–2060 according to the SSP5-8.5 scenario. In this case, it was observed that the need for water supply through irrigation was practically zero by the end of the century.

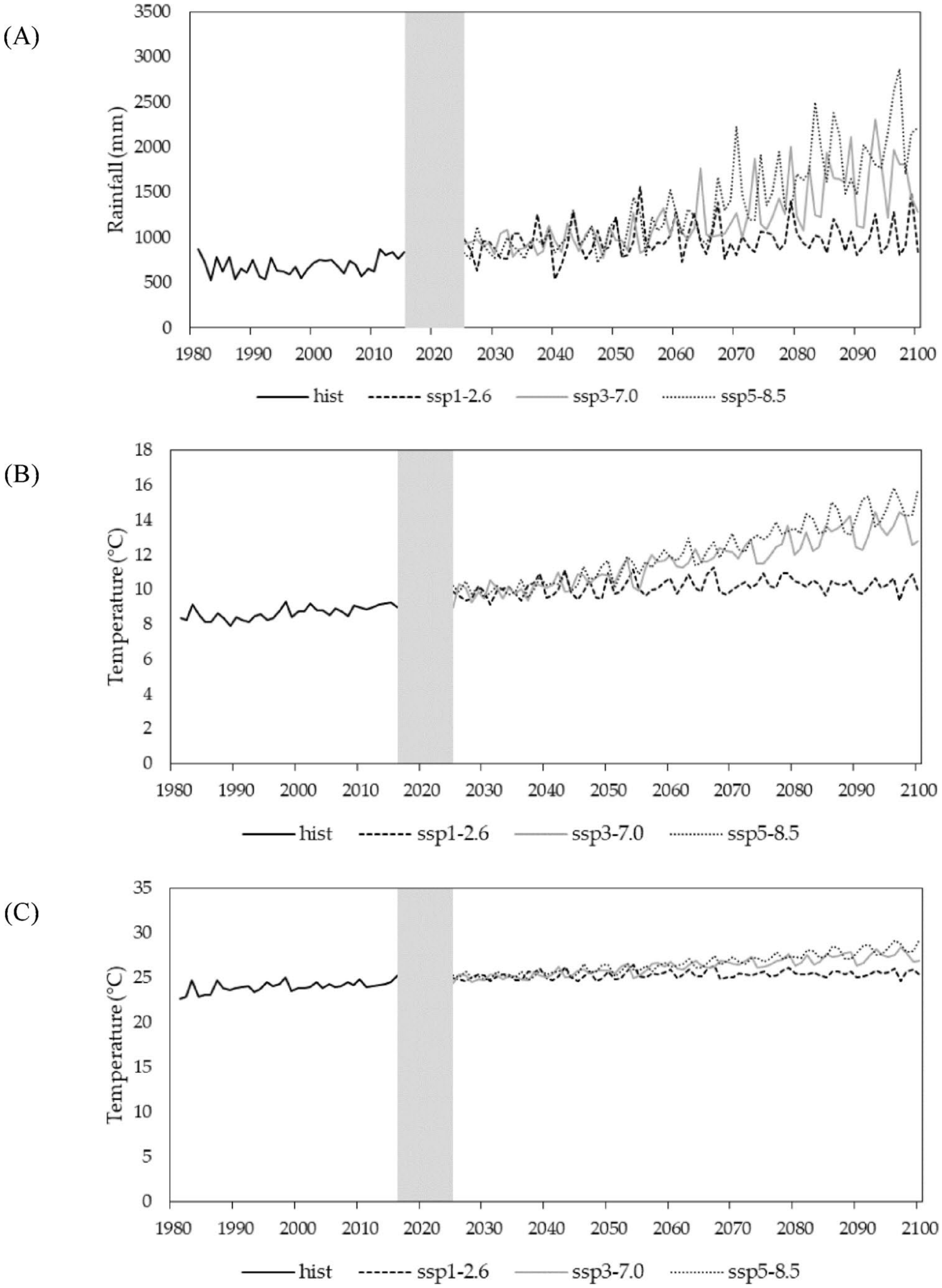
Discussion

Quinoa is a crop with a high adaptive capacity to edaphoclimatic factors (Gómez Pando & Aguilar Castellanos 2016). In the high Andean zone, its yields are between 1 and 7 t ha^{-1} establishing different water consumption patterns. The three quinoa varieties used in this work (INIA 415 Pasankalla, INIA 420-Negra Collana and INIA 441-Señor del Huerto) were grown between October and March on soils of medium fertility, sandy loam texture, good permeability and slightly alkaline. In this sense, we indicate that the results represent well the quinoa edaphoclimatic conditions in the IAV (SENAMHI 2021). For the base period (2012–2024), the developed scheme covered 51–59% of irrigation requirements, and 58–59% of the growing season was accompanied by rainfall, with a rainwater use efficiency of 70–73%. This dichotomy determined evapotranspiration deficits between 17 and 19%, which would have favoured stomatal closure, cell turgor reduction, a decrease in transpiration and carbon dioxide assimilation, and cause detrimental effects on crop growth and yield (Chirinos 2018; Maestro-Gaitán et al. 2022; Mujica et al. 2010; Novoa et al. 2024). Although those effects depend on the phenological stage of the stress and the cultivar grown (Mirsafi et al. 2024), limited research has disaggregated the yield response factor (Ky) by phenological stages (Mirsafi et al. 2024). It can enable efficient and timely irrigation management (López-Olivari 2019).

In the present research, differences in vegetative development among cultivars resulted in distinct patterns of water use. The v3, with a longer phenological development, received and consumed more rainwater during its middle stage than the other varieties. In contrast, the precocity of the cultivar v1 determined a lower volume of rainfall during the whole season. These variations in the duration of phenological stages exposed the varieties to different evapotranspiration deficit cycles during the flowering stage, the most critical phase of quinoa cultivation (Benique Olivera & Ojeda Tito 2024; Gómez Pando & Aguilar Castellanos 2016). Accordingly, the yield of V1 in the field was lower than its maximum potential (4.5 t ha⁻1) but higher than the average yield (3.5 t ha^{-1}) (INIA 2006). The v2 registered a value above the average yield (3.01 t ha^{-1}) (Gómez Pando & Aguilar Castellanos 2016; INIA 2013); however, it could not be compared with a maximum potential value because no citable reference was available. Regarding v3, it has been observed that this value exceeded the maximum potential (Estrada Zúñiga 2020). It would be related to the different patterns of daily thermal variations in the experimental plot at 2735 m.a.s.l. than the release region at 3800–4000 m.a.s.l (Benique Olivera & Ojeda Tito 2024) something that the CROPWAT model cannot simulate (Hoekstra et al. 2012). This suggests that v3 and v2 have a greater adaptive capacity to IAV than v1.

For the base period (2012–2024), WF_{blue} represented 33–44% of WF_{green}, consistent with values previously reported for rainfed agricultural systems (Lordemann et al. 2024) and much higher than systems with pressurized irrigation (Ramírez-Cando et al. 2017). The difference from the Peruvian national average (3665 m^3 t^{-1}) (Pegram et al. 2016) would be linked to the high concentration of

Fig. 6 Climate variable projections for SSP1-2.6, SSP3-7.0, and SSP5-8.5 from data reviewed for the GCM EC-Earth3. **A** Cumulative annual rainfall (mm). **B** Mean annual minimum temperature (°C). **C** Mean annual maximum temperature (°C). hist: historical data from the RAIN4PE gridded product for rainfall and PISCOt for temperatures. The grey band underlines the gap information of the gridded products between 2015 and 2025



quinoa-producing areas in rainfed managed regions and a calculation approach that considers agricultural returns (MIDAGRI 2024).

Regarding CC projections, the elevated temperatures by the end of the century are consistent with the increasing trends observed over the last 50 years (Avalos et al. 2010; Fernandez-Palomino et al. 2024). Thus, Del Aguila and Espinoza-Montes (2024) have reported temperature increases of around 4.5 °C in the worst scenarios. In relation to rainfall, SSP3-7.0 rainfall is expected to intensify, while in SSP5-8.5 it has a generalized increase with more intense and extreme events (Intergovernmental Panel on Climate Change (IPCC), 2023b). In line with this, Avalos et al. (2010) reported a marked seasonality in rainfall increases at the southern sector of the Mantaro River basin. Thus, there is high confidence that the average temperature and the frequency of heat waves will continue to increase; meanwhile, increases in average rainfall and the frequency of high rainfall are not conclusive (Intergovernmental Panel on Climate Change (IPCC), 2023b). GCM have limited reproduction of regional climate characteristics in the Andean regions, mainly due to their complex orography (Fernandez-Palomino et al. 2024). This situation generates a high uncertainty in the management strategies that can be

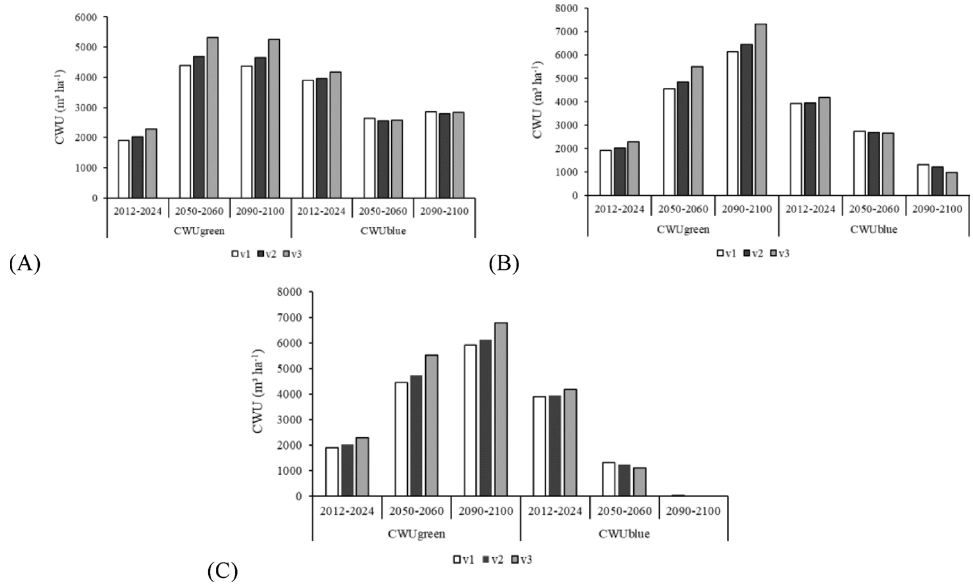


Fig. 7 Crop Water Use (m^3 ha^{-1}) under three climate scenarios: SSP1-2.6 **A**, SSP3-7.0 **B** and SSP5-8. **C** Projections are shown for periods 2012–2024, 2050–2060 and 2090–2100 for each evaluated variety (v1: INIA 415 Pasankalla; v2: INIA 420-Negra Collana; v3: INIA 441-Señor del Huerto)

proposed (Heikkinen 2021), but it is of greater interest to expand research at local and regional scales in order to identify crops and varieties adapted to local constraints (e.g., higher evapotranspiration, lower rainfall) (Landaverde et al. 2022). In this sense, starting with the analysis of SSP3 can be beneficial when developing impact, adaptation, and vulnerability studies, as it presents a combination of a society relatively vulnerable to climate change and a relatively high radiative forcing (O'Neill et al. 2016). In our case, differences in daily thermal variation rates resulted in higher daily ETo in SSP3-7.0 than in SSP5-8.5. Additionally, the rainy season for SSP5-8.5 would begin in October with higher annual accumulated rainfall and more intense events in February. The rainy season for SSP3-7.0 would also start in October, but with higher monthly values accumulated in January. Thus, by the end of the century, the rainy season in the study area would extend until April. As a consequence, assuming the same planting date as in the base period, the three analysed varieties would require larger volumes of rainwater to meet their water demand.

Based on these findings, the three analyzed varieties are expected to increase their use of rainwater (CWU$_{\text{green}}$), thereby reducing the need for supplemental irrigation (CWU$_{\text{blue}}$) under SSP3-7.0 and SSP5-8.5. This decrease would be less drastic in SSP3-7.0 than in SSP5-8.5, where the entire crop water requirement could be met with rainfall inputs alone. The supplemental irrigation requirements for v1 would be slightly higher than for v2 and v3, likely due to greater rainfall availability in the first months of the year in the study area. Similarly, the SSP1-2.6 scenario would result in reduced irrigation requirements, a trend that would remain relatively constant towards the end of the twenty-first century. Although the predictions in the two most adverse scenarios (SSP3-7.0 and SSP5-8.5) do not show maximum temperatures above 30 °C, an increase in the minimum temperature of 6–7 °C was observed. These changes exceed the optimal temperature range for quinoa crop's development (15–25 °C) (Gómez Pando & Aguilar Castellanos 2016). Above this threshold, grain production and quality would be jeopardized depending on the phenological stage affected (Kim et al. 2011; SENAMHI 2025b). In addition, high temperatures favor the development of pests and diseases (Skendžić et al. 2021) and would compromise water management. Based on these findings, it is important to expand research on quinoa cultivars to identify more heat-resistant varieties (Serna et al. 2020) that are better adapted to current and future conditions in the IAV.

The preceding analysis underscores the need to implement strategic measures to optimize rainwater management. While interannual rainfall variability is projected to intensify toward the end of the century, temperatures are expected to continue their upward trend. Consequently, storing excess runoff becomes essential to provide supplemental irrigation for high-demand crops, support critical growth stages, or facilitate agricultural expansion. Furthermore, rainwater harvesting and storage techniques can improve water availability by managing aquifer recharge and increasing soil moisture (Herrera-Franco et al. 2024; Jódar et al. 2022; Lalonde et al. 2024). However, since the projected increase in rainfall is likely to be linked to greater intensity, the risk of soil erosion will also increase. Addressing this requires robust erosion control measures developed through a participatory and democratic framework that involves local farmers. Notably, rainwater harvesting and storage practices are inherently well-suited to fostering these collaborative benefits (Herrera-Franco et al. 2024; Lalonde et al. 2024).

The application of indicators, such as the water footprint (WF), enables the identification of gaps in irrigation management, the selection of cultivars with superior adaptive capacity, and the strategic planning for efficient water use. This research provides a preliminary assessment of the water consumption of three regionally significant quinoa cultivars—INIA 415-Pasankalla, INIA 420-Negra Collana, and INIA 441-Señor del Huerto—under current and future climate change (CC) scenarios. However, certain limitations were identified in projecting CC effects on these crops. While implementing more robust models like AquaCrop would improve the prediction of abiotic (e.g., water and temperature) and management-induced stresses (e.g., fertilization and weed control), such models demand extensive biometric, physiological, and soil moisture data. In this study, the limited availability of field-measured parameters restricted the use of these advanced frameworks. To overcome this, long-term experimental plots across diverse locations within the IAV would be necessary to capture variations in crop development and yield under varying environmental conditions. Such efforts would strengthen the baseline information, facilitate model validation, and reduce uncertainties in crop projections. Furthermore, local meteorological data are essential for bias-correcting climate projections for each SSP; however, the low density of weather stations in Peru (Gubler et al. 2017) remains a significant constraint. Consequently, the methodology applied in this study provides a valuable first approximation of crop water requirements while accounting for the critical variations across varieties. It represents a viable alternative for the preliminary assessment of water footprints and irrigation planning when high-resolution biometric and physiological data for more complex models are unavailable. Furthermore, the combined use of crop models and climate projections is a strategic tool for identifying adaptive measures related to the selection of more water-efficient cultivars.

Conclusion

Changes in weather patterns related to climate change are a reality, and their intensity will depend on the development paths humanity follows. Among these, there are remarkable variations in water availability and temperature increase, both with upward trends in the IAV of the south-central highlands of Peru. These alterations directly affect crop water requirements and the need to adjust irrigation strategies. In this context, quinoa is a crop of interest due to its relevance to food security, making it necessary to expand research on responses to future climate scenarios. The use of Crop Water Use and Water Footprint led to quantifying water requirements fractions involved in rain and complementary watering. This research represents a first step toward improving water management for three locally important quinoa harvests under current climatic conditions and future climate projections. It was found that the variety INIA 420-Negra Collana presented the highest total water footprint (WF_{Total}), followed by INIA 415 Pasankalla and INIA 441-Señor del Huerto, along the agricultural campaign 2023–2024. These references were influenced by phenological features and the yield of every variety. In particular, the culture INIA 441-Señor del Huerto had the highest yield, covering up to 75% of its water requirements with rain support. It is projected that, by 2050 and 2100, this variety will increase its use of rainwater, reducing the need for complementary irrigation. Similar trends were observed in INIA 420-Negra Collana and INIA 415 Pasankalla, suggesting opportunities to optimize water use in the future. However, in the most extreme climate scenarios (SSP3-7.0 and SSP5-8.5), estimated increases of 3.5 °C and 5 °C in maximum and minimum temperatures, respectively, could compromise these benefits. Given that quinoa is a crop with high thermal plasticity, it is a priority to direct further research toward evaluating the impact of temperature on its development and yield, to generate more precise recommendations for its adaptation to future conditions. The information obtained in this research will improve the irrigation Schedule in the Central Sierra, promoting the efficient use of water resources in the agricultural system, mainly rainfed and gravity-fed irrigation. It is essential to promote genetic improvement programs that develop varieties that use water more efficiently and are resistant to adverse climatic conditions. Likewise, projects for agricultural adaptation and water footprint reduction must be promoted, alongside sustainable practices that minimize the impact of climate change on quinoa production. Finally, integrating climate models and water footprint studies into agricultural planning will enable anticipating water scarcity scenarios and developing timely mitigation strategies.

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Data availability The data presented in this study are available on request from the corresponding author

Declarations

Competing interest The authors declare that they have not known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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