ENSO Influence on Agricultural Drought Identified by SPEI Assessment in the Peruvian Tropical Andes, Mantaro Valley

Influencia de ENSO en sequía agrícola identificada por evaluación SPEI en los Andes tropicales peruanos, valle del Mantaro

Del Piero R. Arana-Ruedas[1]; Nabilt Moggiano[1]

1 Universidad Continental, Campus Huancayo, Av. San Carlos 1980, Urb. San Antonio, Huancayo, Junin, Peru

* Autor corresponsal: darana@continental.edu.pe (Del P. R. Arana-Ruedas)

Del P. R. Arana Ruedas: https://orcid.org/0000-0002-3682-5405   N. Moggiano: https://orcid.org/0000-0002-5642-3833

ABSTRACT

Agricultural drought is a serious threat for those locations where one of the most important economic activities is crop production, which occurrence has been rising due to climate change. In addition, different kinds of phenomena could exacerbate agricultural drought frequency, duration, and severity. For example, El Niño Southern Oscillation (ENSO), which mostly occurs in the tropical western and central pacific, directly affects the Peruvian territory. This study aims to understand ENSO's influence on agricultural drought in the Mantaro Valley, Peru since it is one of the most important agricultural lands in the country without clear scientific information linked to drought and ENSO events. For drought assessment using the Standardized Precipitation Evapotranspiration (SPEI) index and for ENSO events through a documentary and numerical analysis under Oceanic Niño Index (ONI) with information from several scientific recent papers to integrate information and formulate a clear event influence understanding. The results show that within Mantaro Valley along its four provinces and their six meteorological stations, 70% of agricultural drought events occurred when ENSO was present between 1990-2021. Also, the severity straight correlation percentage between both, ENSO and SPEI events is quite variable between 9.09%-70%. It is important to keep analyzing those stations with few data since it can provide a new scenario deportment and track new ENSO forecasting methods to rise adaptive capacity and guarantee national and international food security which has as an important supplier to the Mantaro Valley, Peru.

Keywords: Climate Change; Agriculture; ENSO; SPEI.

RESUMEN

La sequía agrícola es una seria amenaza para aquellos lugares donde una de las actividades económicas más importantes es la producción de cultivos, cuya ocurrencia ha ido en aumento debido al cambio climático. Además, diferentes tipos de fenómenos podrían exacerbar la frecuencia, duración y severidad de las sequías agrícolas. Por ejemplo, El Niño Oscilación del Sur (ENOS), que se presenta mayoritariamente en el Pacífico occidental y central tropical, afecta directamente al territorio peruano. Este estudio tiene como objetivo comprender la influencia de ENOS en la sequía agrícola en el Valle del Mantaro, Perú, ya que es una de las tierras agrícolas más importantes del país sin información científica clara relacionada con la sequía y los eventos de ENOS. Para la evaluación de sequía utilizando el índice de Precipitación Evapotranspiración Estandarizada (SPEI) y para eventos ENOS a través de un análisis documental y numérico bajo el Índice Oceánico del Niño (ONI) con información de varios trabajos científicos recientes para integrar información y formular un evento claro. influir en la comprensión. Los resultados muestran que, dentro del Valle del Mantaro a lo largo de sus cuatro provincias y sus seis estaciones meteorológicas, el 70 % de los eventos de sequía agrícola ocurrieron cuando ENOS estuvo presente entre 1990-2021. Además, el porcentaje de correlación directa de gravedad entre los eventos ENSO y SPEI es bastante variable entre 9,09% y 70%. Es importante seguir analizando aquellas estaciones con pocos datos ya que puede brindar un nuevo escenario de comportamiento y rastrear nuevos métodos de pronóstico ENOS para aumentar la capacidad adaptativa y garantizar la seguridad alimentaria nacional e internacional que tiene como importante proveedor al Valle del Mantaro, Perú.

Palabras clave: Cambio Climático; Agricultura; ENSO; SPEI.

1. Introduction

Climate change is a natural phenomenon that is occurring faster way due to unprecedented global warming based on the high levels of greenhouse gas emissions. These huge amounts of emissions are coming from different kinds of anthropogenic activities. It is unequivocal that human activity is the main cause of global warming (IPCC, 2021). It is well known that international agreements regarding climate change such as the Paris Agreement under the United Nation Framework Convention on Climate Change trying to hold the global temperature increase to 2 °C and pursuing efforts to limit it to 1.5 °C above pre-industrial levels.

Additionally, being even more relevant for the present study, increasing resilience and the ability to adapt to different impacts of climate change promotes low greenhouse gas emissions development, which, should not threaten food production (UNFCCC, 2015).

One of the most important impacts of climate change is the rise in frequency, severity, and duration of drought and flood events, which damages goes up to $850 M on a global scale (Byakatonda et al., 2020; Keil et al., 2008). Also, elevated locations like the tropical Andes will have a higher temperature than lower areas (Veettil & Simões, 2019).

Being Peru a mega-diverse country, its tropical Andes are the main source of food production since agriculture is one of the most important economic activities in the area. In that sense, the Mantaro Valley located in the Peruvian Tropical Andes (PTA) contributes to national and international food security. Unfortunately, climate impact drivers (CID) due to mean temperature, precipitation, and evapotranspiration pattern changes are threatening food production, reducing water availability, and increasing agricultural vulnerability (Arana-Ruedas & Moggiano, 2022).

(Islam et al., 2021; Meque & Abiodun, 2015) mention that this threat is strongly linked to a complex climate cycle event, drought. Which has difficulties assessing space and time to obtain local or regional information (Vicente-Serrano et al., 2017). For instance, lack of precipitation and high evapotranspiration triggers agricultural drought (Islam et al., 2021). It is a complex, slowly, developing event impacting the environment, and economic and social spheres (Javed et al., 2021; Karatayev et al., 2022; T. Wang et al., 2022; Zhao et al., 2021).

There are solid reasons to provide farmers with timely and effective climate information under climate-changing conditions to ensure their adaptive response (Gubler et al., 2020) in the Mantaro Valley against drought events. Location, where farmers still practice rain-fed cropping systems and are already affected by poverty (Sanabria et al., 2014).

To understand and assess drought events, the World Meteorological Organization (WMO) suggest some index like the SPEI (Byakatonda et al., 2020), which identify dry periods considering the differrence between precipitation and potential evapotranspiration (PET) (Deivanayagam et al., 2022; Islam et al., 2021). In that sense, this study has applied the SPEI method due to its main role in global warming considerations (Meque & Abiodun, 2015).

Furthermore, aside from the climate impact drives (CID), Peru experiences a natural phenomenon called ENSO. (Byakatonda et al., 2020) mentions that ENSO is somehow related to drought severity. Nevertheless, the correlation between the oscillation and droughts depends on the region (Deivanayagam et al., 2022; Islam et al., 2021), making its analysis even more complex, especially in South America regions (S. M. Vicente-Serrano et al., 2017). Subsequently, concern regarding ENSO events has been evidenced in the Tropical Andes of Peru (Manzanas & Gutiérrez, 2019; Veettil & Simões, 2019) refers that during El Niño events a rise in temperature and reduction in precipitation is evidenced, affecting agriculture and ecosystems in remote areas (Sanabria et al., 2014; Wang et al., 2022).

Currently, the Mantaro Valley does not have a monitoring system for drought events which is urgent to understand the location's vulnerability and plan an efficient water management system as well as boost a resilient and low greenhouse gas emission agricultural development under a preventive approach.

In that sense, this study aims to analyze the correlation between the Oceanic Niño Index (ONI) regarding ENSO and agricultural drought events given in a time scale of 6 and 12 months using the SPEI within the Mantaro Valley.

2. Climate Change and The Andes

The Peruvian tropical Andes has a very complex climate system due to its orography, which has been exacerbated by global warming. The Andes region is mostly characterized by wet and dry seasons, starting from October to April and from May to September, respectively.

It is observed that in the central Andes of Peru, precipitation patterns are declining, but intense rainfall and long dry periods are more often which is expected to continue in coming years (Sanabria et al., 2014). Thus, one of the most important components of climate research is the temporal and spatial variability analysis of precipitation pattern changes (Zubieta et al., 2017).

Furthermore, as in most mountain areas worldwide, glaciers are showing an unprecedented loss of mass based on boosted atmospheric warming (Mark et al., 2017). This kind of melting in the Andes region is a serious issue since most of the time glaciers represent a main source of fresh water, which is highly expected to lack during dry seasons once the inflection point is overcome (Kronenberg et al., 2016).

Consequently, if precipitation and temperature patterns are changed as well as a rapid glacier loss of mass, agricultural activity in the central Andes of Peru is highly vulnerable (Sanabria et al., 2014). This vulnerability will lead to food scarcity affecting current and upcoming generations which in most cases are already struggling with poverty. In that sense, it is mentioned by (Carrasco-Torrontegui et al., 2021) that indigenous knowledge coming from the Andean population

must be valorized and improved with the implementation of new technology to create an adaptive capacity against climate change and its climate impacts drivers such as soil erosion, drought, hailstorm, frost, and flooding.

3. Drought and Agriculture

A drought is a natural event that has exacerbated its impacts due to climate change mainly affecting the agricultural sector in highland areas like the Peruvian Andes. Vicente-Serrano et al. (2017) mentions that drought occurrence is highly linked with the area's climate diversity under spatial and temporal characteristics.

There are several types of definitions for drought in the literature. Also, most of them mention the meteorological, agricultural, and hydrological drought (Nikraftar et al., 2021) with its respective frequency, duration, and severity (Leng et al., 2015). Hence, for this study it will be defined as a complex, slowly, developing event that mostly occurs in many climate regimes with observed trends of warming. It is characterized by below-normal precipitation patterns, reduced water supply, and increased evapotranspiration over an extended period. The drought type and its relation with sustainable development are shown in Figure 1.

Agricultural drought is a consequence where there is a notable reduction in crop production due to a lack of precipitation, below-normal soil moisture, and poor irrigation system during crop forming (T. Wang et al., 2022). All its causes are related to water resources, which are critical for human and ecological normal development.

In that sense, Arana-Ruedas & Moggiano (2022) state that Peru has 31 water and 17 agricultural adaptation measures for climate change by 2050. Nevertheless, a considerable part of them does not have specific targets for the upcoming periods.

Sectors in the Peruvian tropical Andes like the Mantaro Valley do not have a system that let citizens, farmers, policymakers, academia, and other stakeholders know about past and future potential drought events to take appropriate decisions under a preventive approach.

Hence, climate change and agricultural deportment can be analyzed by implementing specific spatial and temporal agrometeorological indices that must involve precipitation, temperature, and evapo-transpiration variables (Vergni & Todisco, 2011) to

provide accurate and useful information to increase resilience against climate change events (Javed et al., 2021).
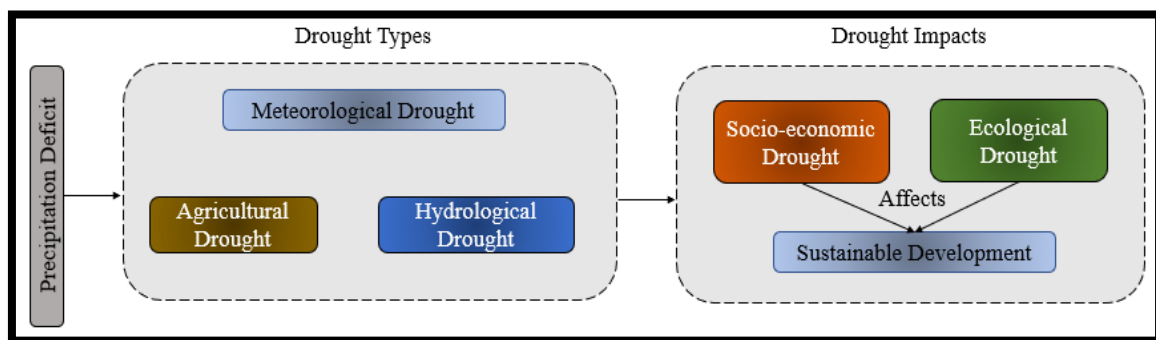
4. El Niño Southern Oscillation (ENSO)

ENSO has two phases, El Niño and La Niña for warming and cooling, respectively; both events show opposite characteristics like severe dry or wet conditions (Deivanayagam et al., 2022; Islam et al., 2021). ENSO can be considered one of the biggest coupled ocean-atmosphere models, which used to appear in the equatorial zone and has a strong influence on weather and climate conditions around the world (Wang et al., 2022). Table 1 shows the Oceanic Niño Index related to La Niña and El Niño.

Table 1
ONI's Value and Category

ONI's Value	ONI's Category
ONI < -1.4	Strong – La Niña
-1.4 ≤ ONI < -1.2	Moderate – La Niña
-1.2 ≤ ONI < -1.0	Weak – La Niña
-1.0 ≤ ONI ≤ 0.4	Neutral
0.4 < ONI ≤ 1.0	Weak – El Niño
1.0 < ONI ≤ 1.7	Moderate – El Niño
1.7 < ONI ≤ 3.0	Strong – El Niño
ONI > 3.0	Severe – El Niño

Source: Estudio Nacional del Fenómeno del Niño, (ENFEN, 2023).

The not usual modification in the sea surface temperature (SST), also related to ENSO, leads to atmospheric circulation variation. It is linked with temperature and precipitation pattern changes which drive events such as drought or flooding worldwide (Liu et al., 2015). Economic, social, and environmental spheres are threatened by climate events like floods and drought exacerbated by ENSO which is one of the biggest concerns in tropical countries like Peru (Manzanas & Gutiérrez, 2019). This area is also affected since its crop production strongly depends on climate variability that is modified by ENSO events (Keil et al., 2008). It has been demonstrated that aside from global warming, annual and decadal variability in SST ENSO has an interaction with the rapid melting of glaciers in the Tropical Andes which was possible due to the rise in the temperature and precipitation reduction strongly evidenced in 1997/98 (Veettil & Simões, 2019).

Figure 1: Drought Types and Sustainable Development.

In that sense, Byakatonda et al. (2020) mention that ENSO weather disaster is likely to continue bringing poverty and suffering. Furthermore, El Niño Southern Oscillation varies in space and time creating inconvenience when forecasters try to analyze its behavior (Wang et al., 2022). Thus, understanding the phenomenon ENSO, its implication from a regional perspective, and its consequences on crop production due to agrometeorological disasters is crucial (Liu et al., 2015). Subsequently, current technology regarding ENSO predictability is helping to mitigate adverse effects to give time to policymakers for their action planification (Manzanas & Gutiérrez, 2019). The inclusion of this accurate forecast will also reduce drought risk and improve water resources management in critical areas (Ganguli & Janga Reddy, 2013).

## 5. Standardized Precipitation Evapotranspiration Index (SPEI)

Drought analysis in countries like Peru where agricultural activity has clear relevance for food security is crucial and it must be done under a spatiotemporal approach (Javed et al., 2021). Currently exist around 60 drought indexes to understand drought episodes and the most used ones are the Standardized Precipitation Index (SPI), SPEI, and the Palmer Drought Severity Index (PDSI) (Wang et al., 2022).

Vicente-Serrano et al. (2010) stands that the SPEI is based on precipitation and PET considering global warming combining the accuracy of the PDSI with the easiest calculation of SPI under multitemporal characteristics. Table 2 shows these index characteristics. Furthermore, it is important to remark that SPEI was proposed by Beguería et al. (2014) and it also provides the capacity to identify different drought types such as meteorological, agricultural, and hydrological. The calculation procedure is pretty similar to the SPI but under a climatic water balance analysis this is the difference between precipitation and evapotranspiration. In addition, SPEI shows an intensity scale between positive and negative values for wet and dry events for periods from 1 up to 48 months (WMO, 2017). Table 3 specify SPEI categories.

Table 2
Drought assessment index characteristics

Palmer Drought Severity Index (PDSI)	The Standardized Precipitation Index (SPI)	The Standardized Precipitation Evapotranspiration Index (SPEI)
Strength		
Enables wetness and dryness values based on water balance taking into account evapotranspiration	It is easy to calculate and can be comparable in different time scales.	Combines the accuracy of PSDI regarding evapotranspiration under changing T° with the easy calculation and the different time scale analysis of SPI.
Weakness		
It has a problem with spatial comparability & short-time scale analysis. Also, its calculation is complex.	It does not take warming into account (T°).	Deemphasizes the role of T° in droughts when potential evapotranspiration (PET) = 0.
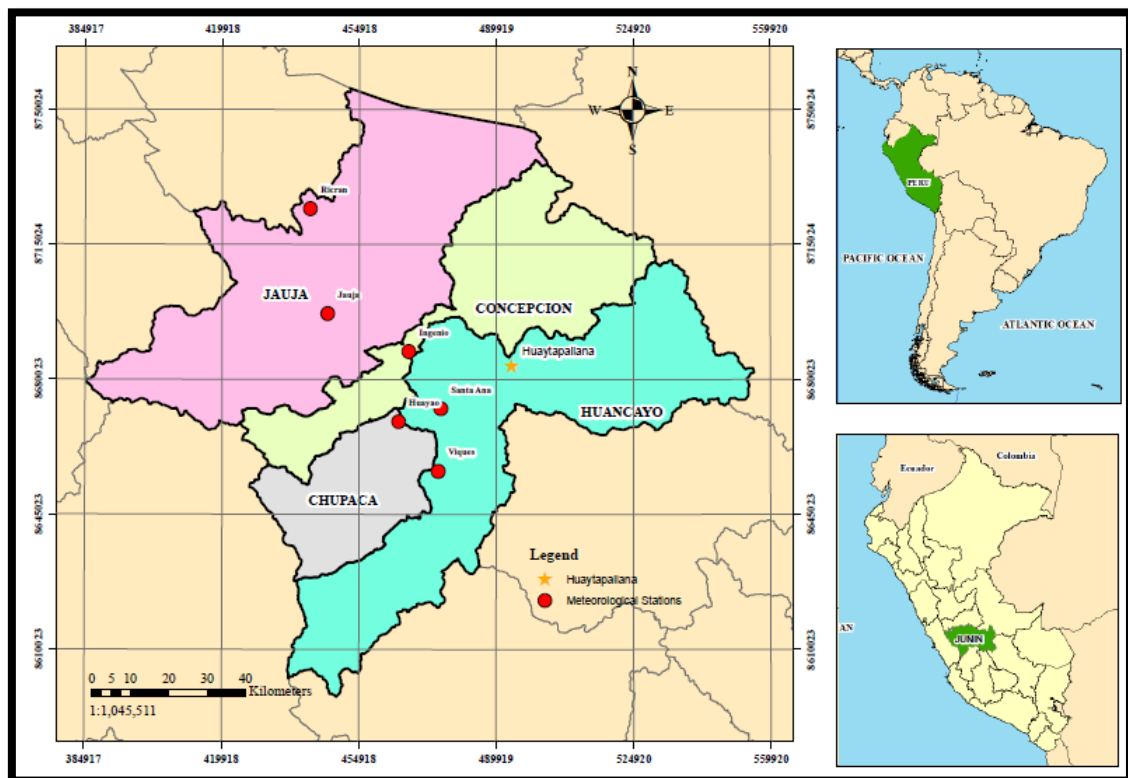
Figure 2: Mantaro's Valley Location.
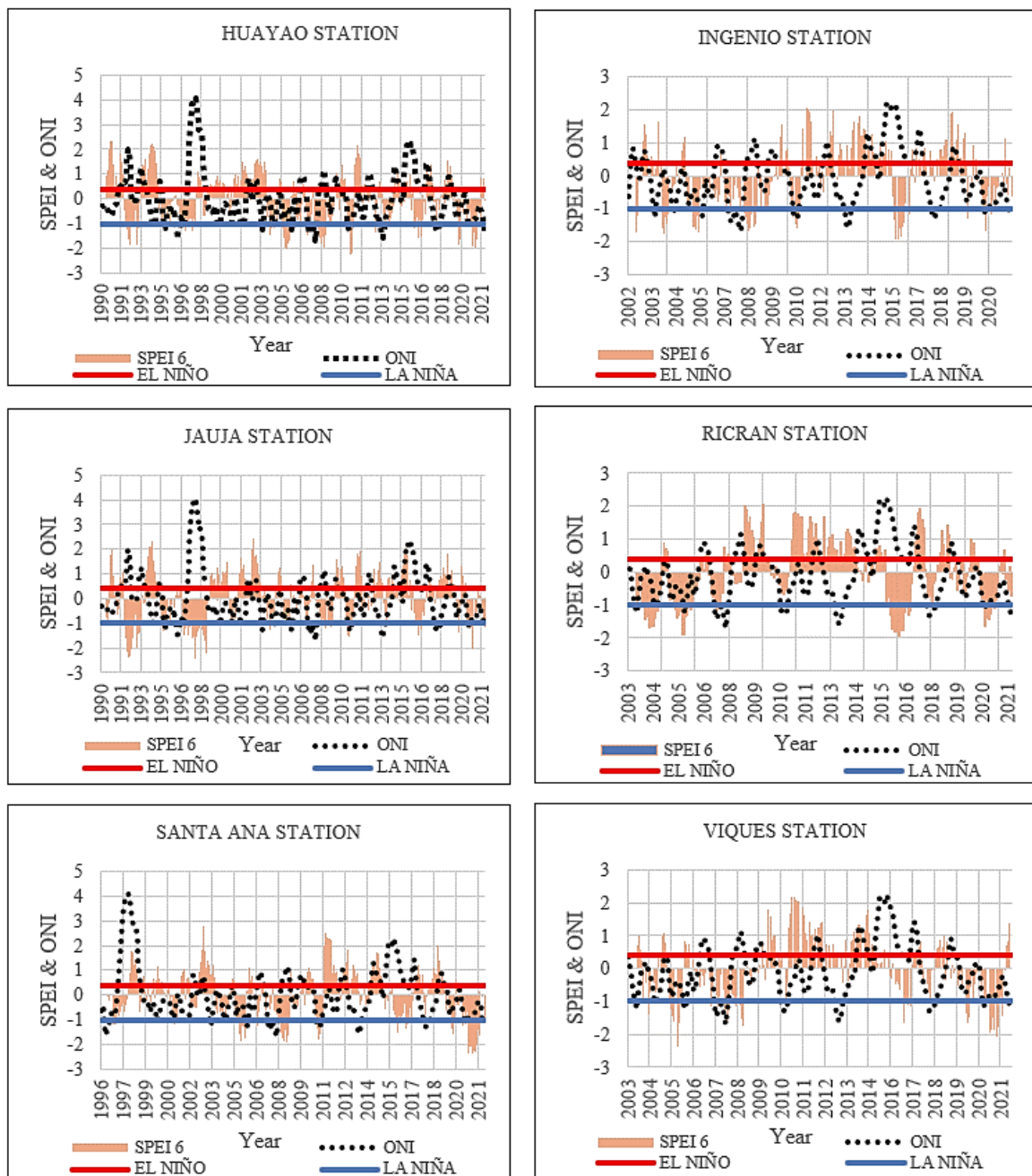
Table 3
SPEI's Values and Drought Categories

Grade	SPEI Value	Drought Category
0	-0.50 < SPEI	No drought
1	-1.00 < SPEI ≤ -0.50	Slight drought
2	-1.50 < SPEI ≤ -1.00	Moderate drought
3	-2.00 < SPEI ≤ -1.50	Severe drought
4	SPEI ≤ -2.00	Extreme drought

6. Mantaro Valley, ENSO, and SPEI

Junin region is in the central area of the Peruvian Tropical Andes (PTA), with 44,329 km². It represents 3,4% of the Peruvian territory involving two of the three geographic regions, Andes and Forest, with 20,821 km² (47%) and 23,508 km² (53%), respectively (BCR, 2020). The Andes area is located in the Mantaro Valley, Figure 2 shows its division into four provinces (Huancayo, Chupaca, Concepción, and Jauja).

On the first hand, for SPEI, data were collected from six different meteorological stations with different data set periods due to availability in temperature and precipitation values, as follows: Chupaca (Huayao: 1990-2021), Huancayo (Santa Ana: 1996-2021 & Viques: 2003-2021), Concepción (Ingenio: 2002-2021), and Jauja (Jauja: 1990-2021 & Ricran: 2003-2021). Daily precipitation and Maximum/ Minimum daily temperature were provided by the Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI). On the other hand, ENSO-ONI data were collected from the Estudio Nacional del Fenómeno del Niño (ENFEN) for a period between 1990 – 2021.

In that sense, SPEI values for 6-12 months (agricultural drought) and ONI graphs are shown in Figures 3 and 4, respectively for each of the six meteorological stations across the four provinces (Chupaca, Concepción, Jauja, and Huancayo).

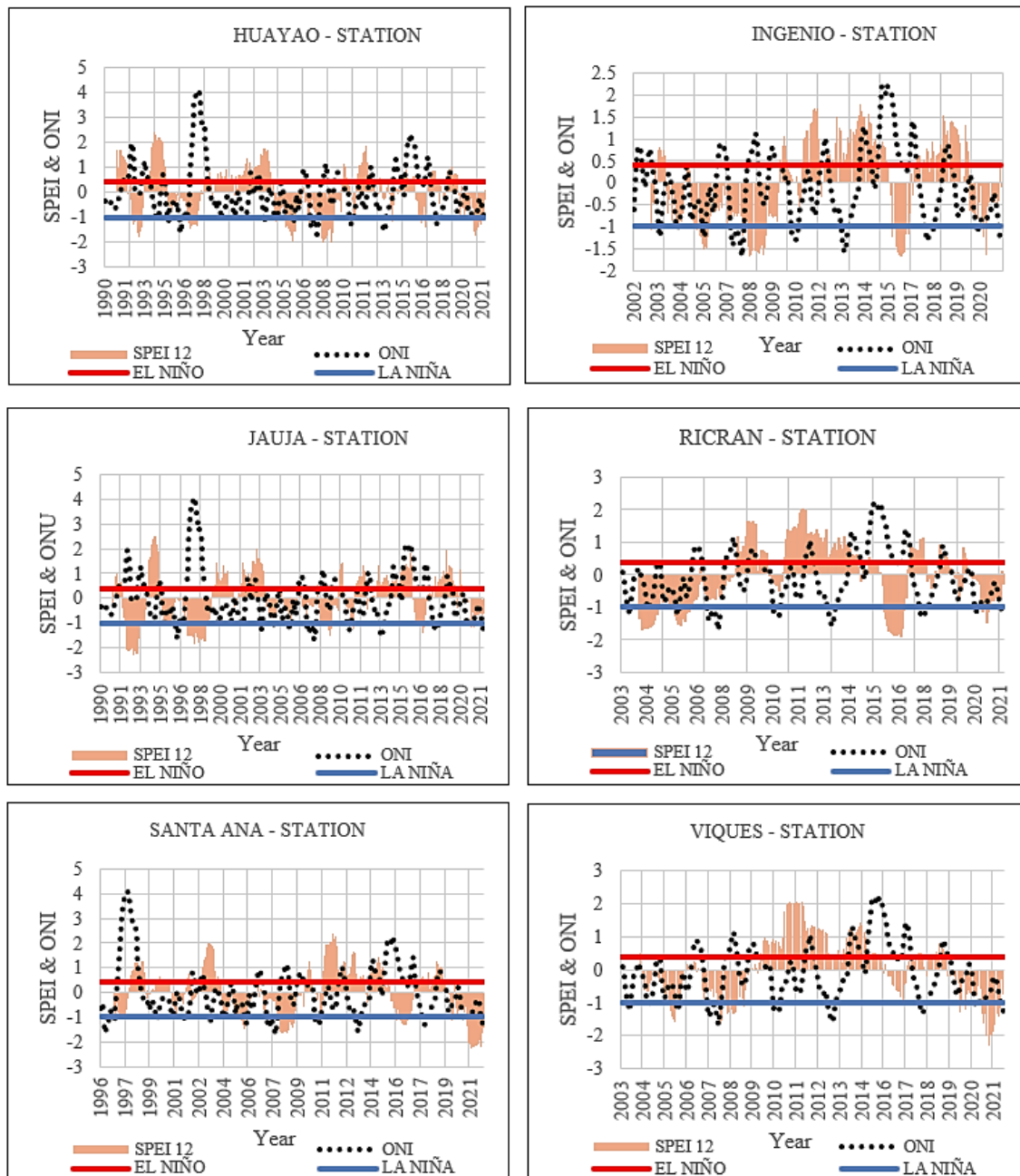**Figure 3**. SPEI 6 Months and ONI – Mantaro Valley.

Figure 4. SPEI 12 Months and ONI – Mantaro Valley.

To clearly explain SPEI and ONI deportment over the years under a spatiotemporal characteristic, Table 4 evidence events occurrence.

The table above describes the percentage of drought events within El Niño, La Niña, or No ENSO events of the analyzed period per each station among the four provinces related to SPEI 6 and 12 months which are linked to agricultural drought. It is important to mention that each "event" refers to "one month" where the phenomenon was taking place over the years.

Furthermore, along with Table 4, Figures 5, 6 7, and 8 shows graphs for each station within the four provinces (Chupaca, Concepcion, Jauja, and Huancayo) regarding agricultural drought (SPEI 6 & 12) events among ENSO phenomena (El Niño and La Niña) under a spatiotemporal consideration.

El Niño and SPEI percentage of events with straight positive correlation are described in the following order 33.33%, 40.91%, 25%, 9.09%, 40%, and 50% for Huayao, Ingenio, Jauja, Ricran, Santa Ana, and Viques, respectively. La Niña and SPEI percentage of events with straight negative correlation are described in the following order 14.29%, 33.33%, 53.85%, 33.33%, 20%, and 23.08% for Huayao, Ingenio, Jauja, Ricran, Santa Ana, and Viques, respectively. El Niño and SPEI percentage of events with straight positive correlation are described in the following order 19.23%, 37.5%, 31.91%, 30.77%, 11.11%, and 60% for Huayao, Ingenio, Jauja, Ricran, Santa Ana, and Viques, respectively.

La Niña and SPEI percentage of events with straight negative correlation are described in the following order 60%, 38.46%, 70%, 16.67%, 70%, and 23.08% for Huayao, Ingenio, Jauja, Ricran, Santa Ana, and Viques, respectively.

Table 4
Drought Events Percentage for SPEI 6 and 12 months in El Niño, La Niña, and No ENSO events under different spatiotemporal characteristics over Mantaro Valley

	SPEI 6 Months – Agricultural Drought			SPEI 12 Months – Agricultural Drought		
Stations	El Niño	La Niña	No ENSO	El Niño	La Niña	No ENSO
Huayao-Chupaca (1990-2021)	31.73% out of 104 events	47.73% out of 44 events	29.66% out of 236 events	25% out of 104 events	34.10% out of 44 events	34.32% out of 236 events
Ingenio-Concepcion (2002-2021)	34.92% out of 63 events	38.71% out of 31 events	29.45% out of 146 events	38.10% out of 63 events	41.94% out of 31 events	34.25% out of 146 events
Jauja-Jauja (1990-2021)	42.31% out of 104 events	29.55% out of 44 events	29.39% out of 236 events	45.19% out of 104 events	22.73% out of 44 events	25.85% out of 236 events
Ricran-Jauja (2003-2021)	19.30% out of 57 events	58.06% out of 31 events	31.43% out of 140 events	22.81% out of 57 events	38.71% out of 31 events	33.57% out of 140 events
Santa Ana – Huancayo (1996-2021)	30.49% out of 82 events	36.59% out of 41 events	27.51% out of 189 events	32.93% out of 82 events	24.39% out of 41 events	30.69% out of 189 events
Viques – Huancayo (2003-2021)	17.54% out of 57 events	41.94% out of 31 events	30.71% out of 140 events	17.54% out of 57 events	41.94% out of 31 events	34.29% out of 140 events
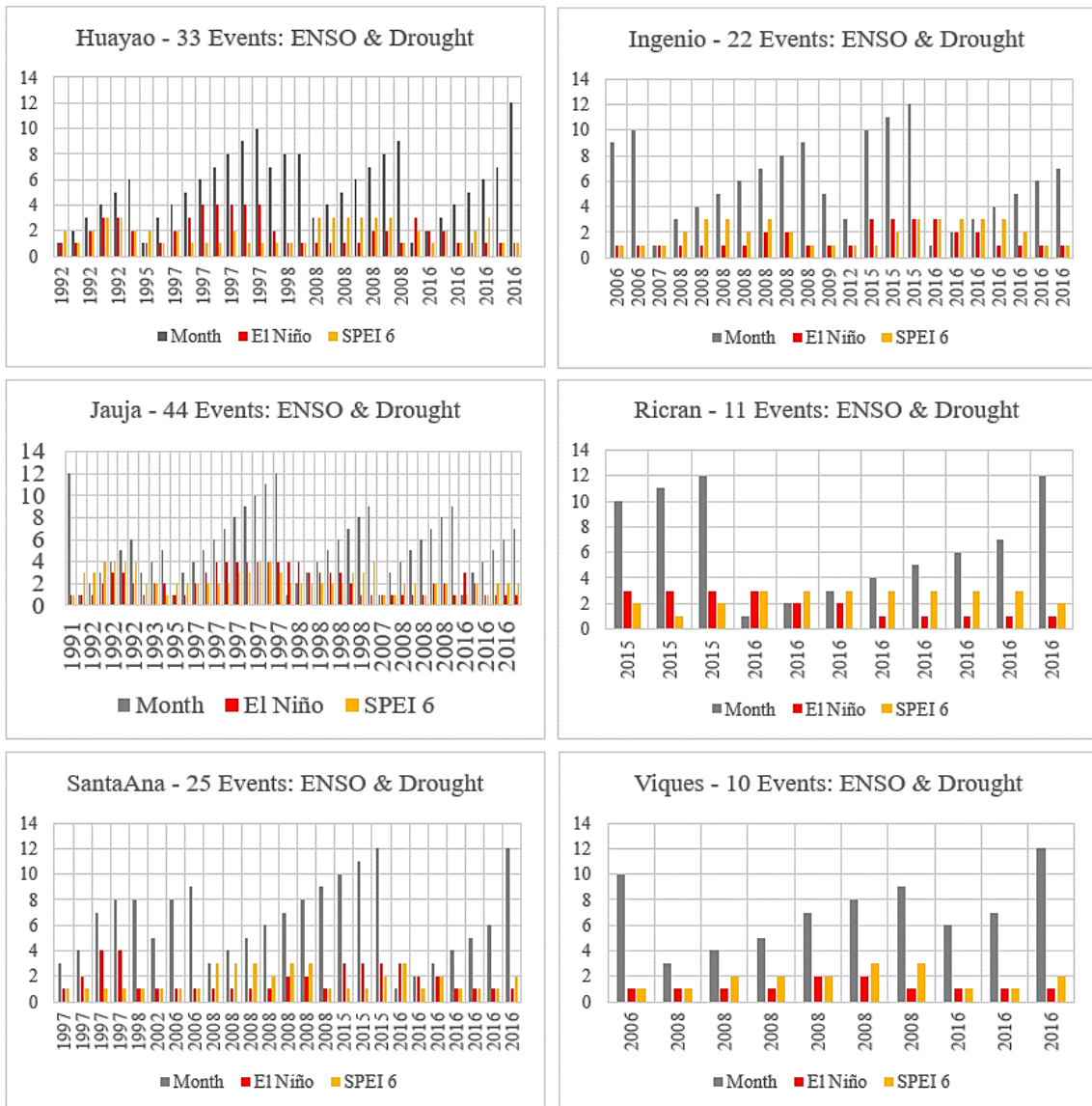
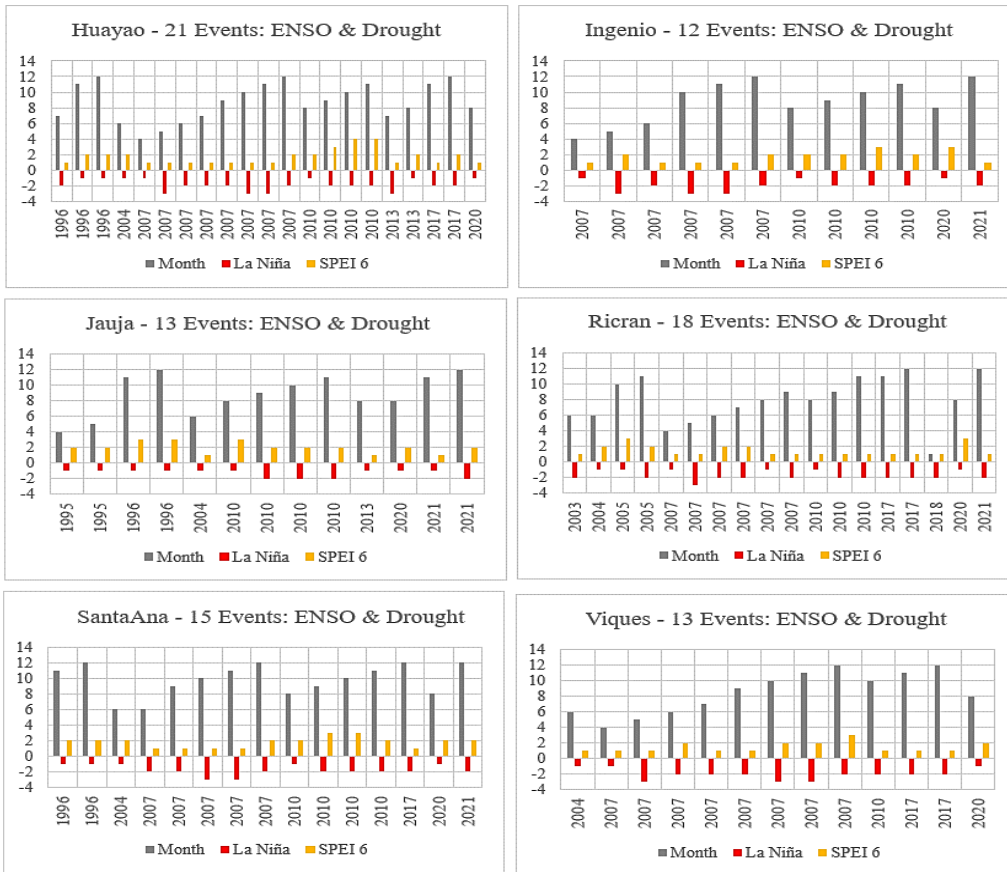**Figure 5**: SPEI 6 (Agricultural Drought) among El Niño Events.

Figure 6: SPEI 6 (Agricultural Drought) among la Niña Events.
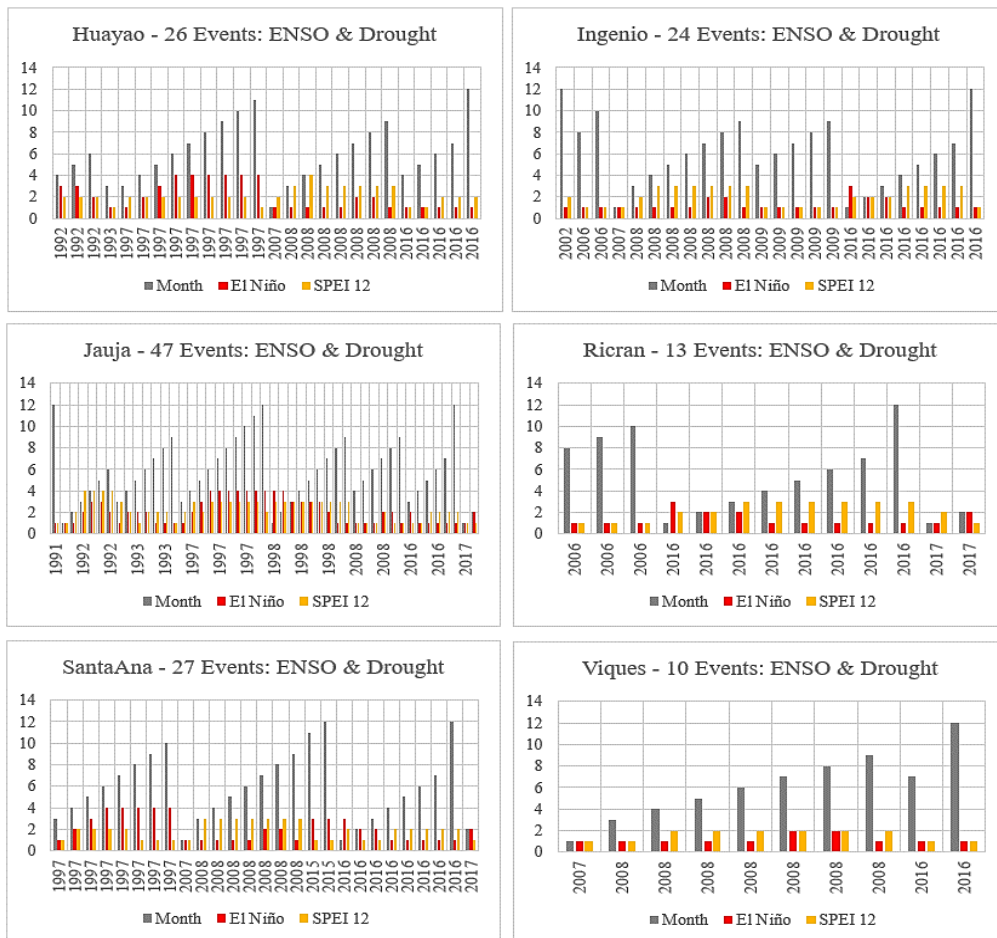

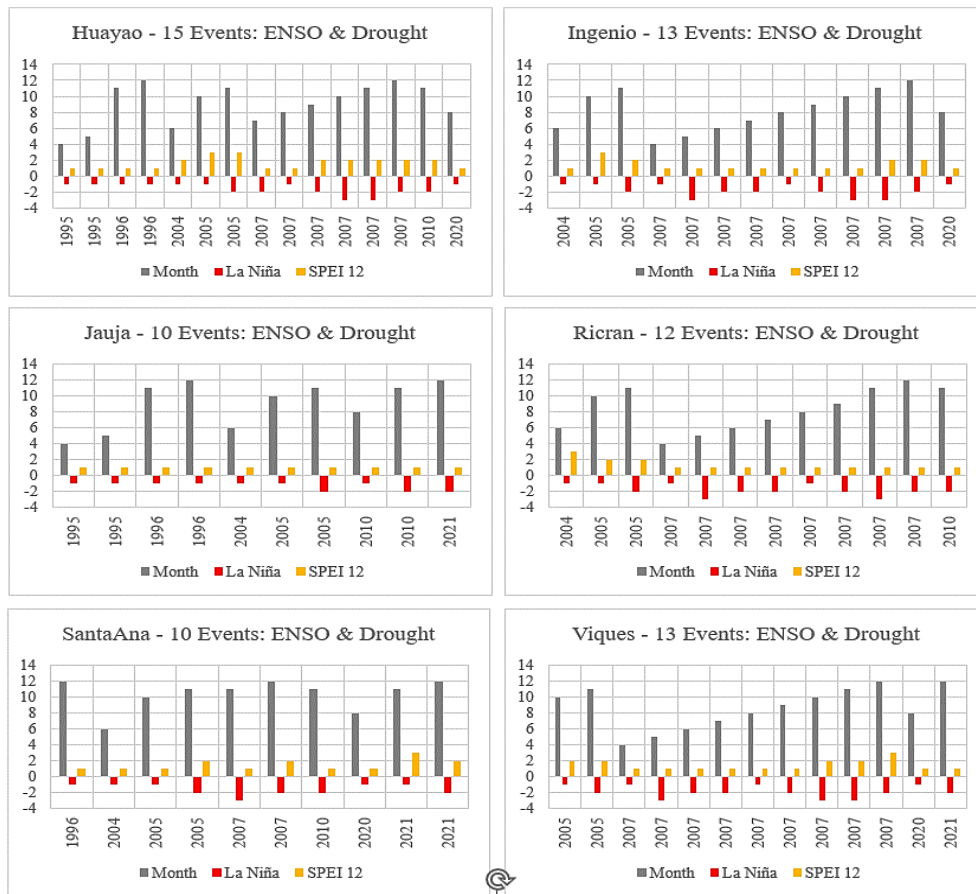**Figure 7:** SPEI 12 (Agricultural Drought) among El Niño Events.

Figure 8: SPEI 12 (Agricultural Drought) among La Niña Events.

7. Critical Appraisal

Peru, naturally, is a mega-diverse country since it poses 38 different kinds of climates with 3 notable regions which involve coast, mountain, and forest. Thus, is scientifically understandable that variables such as precipitation which is the main driver of climate and weather events will cause relevant spatiotemporal variability and should be taken into account agreeing with (Zubieta et al., 2017) statement. In addition, Figures 3 and 4 can graphically evidence a notable difference (spatiotemporal variability) for agricultural drought (SPEI 6 and 12) when ENSO (El Niño and La Niña) events occur even in the same valley of a mountainous Peruvian area.

Furthermore, according to a numerical description in Table 4, it can be deduced that El Niño events use to occur more often than La Niña since 1990, but La Niña events were occurring more often than last century. In that sense, it evidences a challenge to forecast this phenomenon since its occurrence has been changing in the last years which can be linked to exacerbated global temperature rise.

Farther, based on the same table, when ENSO (El Niño or La Niña) occurred, 70% of the agricultural drought was evidenced since 1990 within the Mantaro valley. Nevertheless, regarding SPEI 6 months 5 out of the 6 stations revealed that is more likely to have agricultural drought when La Niña occurs. Meanwhile, under SPEI 12 months 4 out of the 6 stations follow the same deportment. In addition, around 30% of agricultural droughts occurred without ENSO events. In both ENSO cases,

as (Manzanas & Gutiérrez, 2019) expressed; economic, social, and environmental spheres are threatened by drought events.

On the other hand, Figures 5 and 6 reveal important information regarding ENSO and SPEI severity. In the first place, linked to El Niño events for SPEI 6 and 12 months there is variability evidence among the stations where strong or severe El Niño caused slight or moderate droughts and for weak or moderate ones once severe or extreme drought events were identified. In the second place, related to La Niña events, a relation is more stable talking about severity but not straight correlated. In that sense, the severity correlation between ENSO and SPEI for agricultural drought is quite weak. Subsequently, most of the ENSO events related to drought happen between July and December when rainy seasons start around Mantaro Valley.

Consequently, this study agrees with (S. M. Vicente-Serrano et al., 2017) and their statement that drought occurrence is highly linked with the area's climate diversity under spatial and temporal characteristics.

Finally, since agricultural drought is highly probable to occur when ENSO events are present, it is important to follow accurate ENSO forecasts as well to improve water management systems, which goes along with (Ganguli & Janga Reddy, 2013) thought and take into great consideration indigenous knowledge from the Andean population to rise adaptive capacity.

8. Conclusions

The Mantaro Valley is a very important agricultural land where climate and weather phenomena should be seriously considered under a preventive approach. Agricultural drought has been occurring and is highly expected to rise its deportment in the next decades, which could be exacerbated by ENSO events. Furthermore, it is crucial to follow ENSO forecasting to implement adaptive measure under indigenous knowledge and integrate it with current technologies, which will guarantee crop production and food security in Peru and the world.

Since water availability is strongly linked with the analyzed events, it is a national challenge to achieve Peruvian measures regarding water and agricultural activities. This kind of analysis can represent an important opportunity to reduce vulnerability since it let us know the probabilities of agricultural drought when ENSO occurs.

Furthermore, is important to take note that most agricultural drought events occurred since 1990 when La Niña happened, but it also when El Niño occurs. In that sense, measures to ensure agricultural activity cannot be delayed when one of them occurs. Especially due to the variable severity correlation between ENSO and SPEI, which are unpredictable based on several climates and topographic national characteristics.

Finally, it is strongly recommended to keep analyzing those stations with few data since its deportment can be changing given a different scenario understanding, as well as to track improved ENSO forecasting methods worldwide which will be useful since it can provide enough time for the formulation, implementation, and monitoring measures.

REFERENCIAS BIBLIOGRÁFICAS

Arana-Ruedas, D. P. R., & Moggiano, N. (2022). Agriculture and water resources: UNFCCC influence on Peruvian adaptation regulations to increase resilience against climate change. *Scientia Agropecuaria, 13*(3), 221–230. https://doi.org/10.17268/sci.agropecu.2022.020

BCR. (2020). Características Socioeconómicos Del Departamento De Junín. 17–3. http://maps.google.com/?ie=UTF8&ll=-11.79208,-75.157471&spn=4.666206,8.327637&z=71Participaronenla elaboracióndeesteinforme

Beguería, S., Vicente-Serrano, S. M., Reig, F., & Latorre, B. (2014). Standardized precipitation evapotranspiration index (SPEI) revisited: Parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *International Journal of Climatology, 34*(10), 3001–3023. https://doi.org/10.1002/joc.3887

Byakatonda, J., Parida, B. P., Moalafhi, D. B., Kenabatho, P. K., & Lesolle, D. (2020). Investigating relationship between drought severity in Botswana and ENSO. *Natural Hazards, 100*(1), 255–278. https://doi.org/10.1007/s11069-019-03810-1

Carrasco-Torrontegui, A., Gallegos-Riofrío, C. A., Delgado-Espinoza, F., & Swanson, M. (2021). Climate Change, Food Sovereignty, and Ancestral Farming Technologies in the Andes. *Current Developments in Nutrition, 5*(9), 54–60. https://doi.org/10.1093/cdn/nzaa073

Deivanayagam, A., Sarangi, R. K., & Palanisamy, M. (2022). Evaluating the Influence of El Nino–Southern Oscillation (ENSO) Patterns on the Spatio-Temporal Variations of Drought over Southern Peninsular Indian Region. *Journal of the Indian Society of Remote Sensing, 6.* https://doi.org/10.1007/s12524-022-01589-6

ENFEN. (2023). El Niño/La Niña Costeros - IGP. http://met.igp.gob.pe/elnino/lista_eventos.html

Ganguli, P., & Janga Reddy, M. (2013). Analysis of ENSO-based climate variability in modulating drought risks over western Rajasthan in India. *Journal of Earth System Science, 122*(1), 253–269. https://doi.org/10.1007/s12040-012-0247-x

Gubler, S., Rossa, A., Avalos, G., Brönnimann, S., Cristobal, K., Croci-Maspoli, M., Dapozzo, M., van der Elst, A., Escajadillo, Y., Flubacher, M., Garcia, T., Imfeld, N., Konzelmann, T., Lechthaler, F., Liniger, M., Quevedo, K., Ramos, H., Rohrer, M., Schwierz, C., … Wüthrich, B. (2020). Twinning SENAMHI and MeteoSwiss to co-develop climate services for the agricultural sector in Peru. *Climate Services, 20.* https://doi.org/10.1016/j.cliser.2020.100195

IPCC. (2021). Climate Change 2021: The Physical Science Basis - Summary for the Policymakers (Working Group I). In Climate Change 2021: The Physical Science Basis.

Islam, A. R. M. T., Salam, R., Yeasmin, N., Kamruzzaman, M., Shahid, S., Fattah, M. A., Uddin, A. S., Shahariar, M. H., Mondol, M. A. H., Jhajharia, D., & Techato, K. (2021). Spatiotemporal distribution of drought and its possible associations with ENSO indices in Bangladesh. *Arabian Journal of Geosciences, 14*(23). https://doi.org/10.1007/s12517-021-08849-8

Javed, T., Zhang, J., Bhattarai, N., Sha, Z., Rashid, S., Yun, B., Ahmad, S., Henchiri, M., & Kamran, M. (2021). Drought characterization across agricultural regions of China using standardized precipitation and vegetation water supply indices. *Journal of Cleaner Production, 313*(June), 127866. https://doi.org/10.1016/j.jclepro.2021.127866

Karatayev, M., Clarke, M., Salnikov, V., Bekseitova, R., & Nizamova, M. (2022). Monitoring climate change, drought conditions and wheat production in Eurasia: the case study of Kazakhstan. *Heliyon, 8*(1). https://doi.org/10.1016/j.heliyon.2021.e08660

Keil, A., Zeller, M., Wida, A., Sanim, B., & Birner, R. (2008). What determines farmers' resilience towards ENSO-related drought? An empirical assessment in Central Sulawesi, Indonesia. *Climatic Change, 86*(3–4), 291–307. https://doi.org/10.1007/s10584-007-9326-4

Kronenberg, M., Schauwecker, S., Huggel, C., Salzmann, N., Drenkhan, F., Frey, H., Giraáldez, C., Gurgiser, W., Kaser, G., Juen, I., Suarez, W., Hernaández, J. G., Sanmartín, J. F., Ayros, E., Perry, B., & Rohrer, M. (2016). The Projected Precipitation Reduction over the Central Andes may Severely Affect Peruvian Glaciers and Hydropower Production. *Energy Procedia, 97*, 270–277. https://doi.org/10.1016/j.egypro.2016.10.072

Leng, G., Tang, Q., & Rayburg, S. (2015). Climate change impacts on meteorological, agricultural and hydrological droughts in China. *Global and Planetary Change, 126*, 23–34. https://doi.org/10.1016/j.gloplacha.2015.01.003

Liu, Y., Liu, B., Yang, X., Bai, W., & Wang, J. (2015). Relationships between drought disasters and crop production during ENSO episodes across the North China Plain. *Regional Environmental Change, 15*(8), 1689–1701. https://doi.org/10.1007/s10113-014-0723-8

Manzanas, R., & Gutiérrez, J. M. (2019). Process-conditioned bias correction for seasonal forecasting: a case-study with ENSO in Peru. *Climate Dynamics, 52*(3–4), 1673–1683. https://doi.org/10.1007/s00382-018-4226-z

Mark, B. G., French, A., Baraer, M., Carey, M., Bury, J., Young, K. R., Polk, M. H., Wigmore, O., Lagos, P., Crumley, R., McKenzie, J. M., & Lautz, L. (2017). Glacier loss and hydro-social risks in the Peruvian Andes. *Global and Planetary Change, 159*, 61–76. https://doi.org/10.1016/j.gloplacha.2017.10.003

Meque, A., & Abiodun, B. J. (2015). Simulating the link between ENSO and summer drought in Southern Africa using regional climate models. *Climate Dynamics, 44*(7–8), 1881–1900. https://doi.org/10.1007/s00382-014-2143-3

Nikraftar, Z., Mostafaie, A., Sadegh, M., Afkueieh, J. H., & Pradhan, B. (2021). Multi-type assessment of global droughts and teleconnections. *Weather and Climate Extremes, 34*, 100402. https://doi.org/10.1016/j.wace.2021.100402

Sanabria, J., Calanca, P., Alarcón, C., & Canchari, G. (2014). Potential impacts of early twenty-first century changes in temperature and precipitation on rainfed annual crops in the Central Andes of Peru. *Regional Environmental Change, 14*(4), 1533–1548. https://doi.org/10.1007/s10113-014-0595-y

UNFCCC. (2015). The Paris Agreement. United Nations. https://doi.org/10.4324/9789276082569-2

Veettil, B. K., & Simões, J. C. (2019). The 2015/16 El Niño-related glacier changes in the tropical Andes. *Frontiers of Earth Science, 13*(2), 422–429. https://doi.org/10.1007/s11707-018-0738-4

Vergni, L., & Todisco, F. (2011). Spatio-temporal variability of precipitation, temperature and agricultural drought indices in Central Italy. *Agricultural and Forest Meteorology, 151*(3), 301–313. https://doi.org/10.1016/j.agrformet.2010.11.005

Vicente-Serrano, S. M., Aguilar, E., Martínez, R., Martín-Hernández, N., Azorin-Molina, C., Sanchez-Lorenzo, A., El Kenawy, A., Tomás-Burguera, M., Moran-Tejeda, E., López-Moreno, J. I., Revuelto, J., Beguería, S., Nieto, J. J., Drumond, A., Gimeno, L., & Nieto, R. (2017). The complex influence of ENSO on droughts in Ecuador. *Climate Dynamics, 48*(1–2), 405–427. https://doi.org/10.1007/s00382-016-3082-y

Vicente-Serrano, Sergio M., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate, 23*(7), 1696–1718. https://doi.org/10.1175/2009JCLI2909.1

Wang, G. G., Cheng, H., Zhang, Y., & Yu, H. (2022). ENSO analysis and prediction using deep learning: A review. *Neurocomputing, 520*, 216–229. https://doi.org/10.1016/j.neucom.2022.11.078

Wang, T., Tu, X., Singh, V. P., Chen, X., Lin, K., Lai, R., & Zhou, Z. (2022). Socioeconomic drought analysis by standardized water supply and demand index under changing environment. *Journal of Cleaner Production, 347*(March), 131248. https://doi.org/10.1016/j.jclepro.2022.131248

WMO. (2017). Handbook of Drought Indicators and Indices (Issue 1173). https://doi.org/10.1201/9781315265551-12

Zhao, R., Wang, H., Chen, J., Fu, G., Zhan, C., & Yang, H. (2021). Quantitative analysis of nonlinear climate change impact on drought based on the standardized precipitation and evapotranspiration index. *Ecological Indicators, 121*, 107107. https://doi.org/10.1016/j.ecolind.2020.107107

Zubieta, R., Saavedra, M., Silva, Y., & Giráldez, L. (2017). Spatial analysis and temporal trends of daily precipitation concentration in the mantaro river basin: Central andes of peru. *Stochastic Environmental Research and Risk Assessment, 31*(6), 1305–1318. https://doi.org/10.1007/s00477-016-1235-5