Effect of temperature on the growth and development of quinoa plants (*Chenopodium quinoa* Willd.): A review on a global scale

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ABSTRACT

The increase in temperature and constant changes in climate negatively affects the development of the plants, which has resulted in an alarming situation for many of the different crops of agricultural and food interest. In the specific case of quinoa, the investigation points to a significant loss in the productivity of the grain crop indicating differences depending on the altitudes of the areas of agriculture production and the availability of water. A current informed description of the responses regarding phonological development under stressful conditions could help us develop appropriate strategies to improve the conditions for the production of quinoa and allow us to propose cultivation of the product under environmental conditions where other products cannot survive. The main discoveries regarding this study were framed within the effect of caloric stress on the germination of quinoa seeds, their phenology, their response to different evaluated cultivars and their effects on their growth as well as their physiological and productive levels. Thus, the analysis is described based on a review of the available scientific documents available in the Scopus database and doctoral work thesis, allowing for the consolidation of the most recent investigations regarding the quinoa and their relationship with temperature.

Keywords: Quinoa, Biodiversity, Climatic change, Stomatal activity, Cultivars, Thermal stress, Physiology.

INTRODUCTION

The diverse effects of climate change has generated a series of modifications regarding the growth and development of plants, generating a concern in the agricultural area that is faced with environmental pressures that drastically influence plant behavior and their agricultural production systems of the world. To face such consequences, the governmental and private entities have begun strategic plans that would allow for the incorporation and enhancement of plant species that have a greater tolerance capability to adverse agricultural and environmental conditions that would, in turn, increase the availability and quality of food for humanity (Padulosi *et al.*, 2013).

However, the greatest problem for agriculture in the last few decades is the increase in temperature, that in accordance to the climatic forecasts, will continue increasing from between 1,5 °C to 6 °C to the end of the XXI century (IPCC, 2018), increasing the incidence in the phenological and physiological behavior of the most important agricultural crops and availability of food around the world. Multiple investigations affirm that the frequent oscillations of the high and low temperatures during shorter periods of time and in combination with longer periods of drought, salinity in soils problems and/or flooding, would place the production of food at risk and consequently the security of food worldwide (Hinojosa *et al.*, 2018).

Hence, as heat stress, which is recognized as the increase in air temperature beyond the threshold required by the plants over a prolonged period of time, it is one of the main causes of irreversible damage to at least one organ of the plant (Taiz & Zeiger, 2006). According to different investigations, heat stress has negative effects on the plants as reported by Hinojosa *et al.* (2018) who highlight three (3) main changes; (a) *morphological*, such as the inhibition of growth in the roots and the increase of ramifications in the main stalk/stem; (b) *anatomical*, which are manifested by the reduction of the cellular size and include the increase of the stomatal density; and (c) *phenological* changes such as modifications over the periods of time for each one of the phenophases that are seen as an increase of precocity or delay in the harvest time depending on the species and include the loss of productive functions at the moment of flowering. For this reason, temperature is a very important climatic variable which needs to be taken into account to understand the behavior of plants, even more so when its influence is so closely related to the accumulation of degrees/heat/day in phenological terms.

Among the plants of great agricultural and world-wide food interest, being presently studied, due to the effect of the environmental temperature regarding their growth and development, are the quinoa plants (*Chenopodium quinoa* Willd.) (Ruiz *et al.*, 2014); this species belongs to the family of the Amaranthaceae that recently has shown a great expansion globally (Bazile *et al.*, 2016), as one of the most promising crops with great relevance in South American countries, mainly in Bolivia and Peru, where production and participation in the global market is close to 84% (Jager, 2015). From 2013, the FAO has highlighted the adaptability of this plant in areas of difficult farming, where other species of agricultural interest do not stand out (Bazile, Pulvento, *et al*, 2016; Choukr-Allah *et al.*, 2016); also, it has recognized important nutritional and agroindustrial qualities (Navruz-Varli & Sanlier, 2016), making it one of the main alternatives for the farmer, as a result of the effects of climate change. However, the agroclimactic conditions continue to change and with these changes come modifications in the morpho-phenological structure of this plant (Jaikishun *et al.*, 2019). As per the above, several investigative results have highlighted the effect of temperature on the productivity of the quinoa, but also describe, some of the adaptability mechanisms that the plant uses to tolerate said agroclimactic situations (Prager *et al.*, 2018).

The quinoa is a plant that, according to its origin, presents a variable ability of acceptance to heat (Jacobsen, 2017). However, the areas of lesser latitudes are the ones with a greater production of quinoa and are also the areas that are more susceptible to heat (Lamaoui *et al.*, 2018). Yang *et al.* (2016), have demonstrated that the combination of different levels of temperatures (8-18 °C and 20-25 °C) respectively, and with three (3) types of irrigation (complete irrigation, deficient irrigation and alternate drying irrigation) have indicated changes on the physiological development of the quinoa, generating variations on the biomass production, grain yield and phenological behavior. Thus, they Becker *et al.* (2017) jointly describe changes in photosynthetic activity, size and stomatal density when combined with saline concentrations in the soil.

According to Hinojosa *et al*. (2018), it has been recognized that the increase in temperature during the growth phase of the quinoa, is considered one of the most relevant abiotic factor of this species and said consequences are manifested in changes in its vegetative and reproductive growth, modifications in the physiological functions and alterations in the productive parameters such as yield and quality of the crop. This has been studied and has allowed us to recognize that exposing the quinoa plant to heat stress generates changes in the water movement routes on a vascular level (Bosque Sanchez *et al*., 2003), alterations of the phenological cycles of the plants (Bois *et al.*, 2016), changes in the physiological activities (Becker *et al.*, 2017), as well as modifications in the assimilation activity of CO_2 and its conversion for the production into grain (Bunce, 2017).

Currently, the effects of climate change have jeopardized the food security in different parts of the world and it is expected that, in the case of quinoa, its production will be more affected by the strong variations in temperatures during the daylight and nighttime periods (Hinojosa, Matanguihan & Murphy, 2019). Consequently, scientific initiatives have been generated that connect the climate with the production of the crop, and having the characterization of the quinoa under different agroclimactic parameters, as well as the choice of cultivars and agricultural practices that would be able to confront the variable environmental consequences. This agrees with what has been proposed by Korres *et al.* (2016), who highlight the importance of identifying the species and cultivars that are capable of facing the climatic changes and to generate certain adaptability mainly in the family farm production systems. However, more information is required on the quinoa highlighting the effects of the temperature during the complete growth and development cycles and for this reason, the present study covers a general vision of the actual work taking place in reference to the phenology of the quinoa and its relationship with the adverse effects induced by the changes in temperature and a characterization of the important aspects regarding the selection of quinoa cultivars that are tolerant to thermal stress.

METODOLOGY

In depth studies were made of doctoral thesis and scientific literature available on the Scopus database using articles, books and chapters of books, using the section of advanced search of the database and the outline of the title search, summary and key words. The search formula in English was: *quinoa*, *quinoa* AND *temperature* and *temperature* AND "*crop phenology*". The criteria for the selection of the documents were the following:

- That the theme of the documents searched covered the subject of the temperature and their relationship with plants of agricultural interest and mainly regarding the production of quinoa.

- That they presented indicators of the effect of temperature had on the behavior of the quinoa plants.

- That they covered themes relating to implementation strategies for their mitigation in the selection and production of quinoa cultivars.

At the same time, for the search formula of *quinoa* W/15 *temperature*, tabulation was completed of all the documents obtained up to 2019. After that tabulation was completed, a selection was made of the documents (keeping the criteria previously mentioned in mind) and then they were analyzed using non-lineal regressions following the logistical parameter proposed by Aguilar *et al.* (2012) and modeled after the following equation.

$$f=A(1+e^{\left(-\frac{x-C}{B}\right)}) \qquad \text{Eq. 1}$$

Where,

f = Population over time
A = Superior asymptote
B = Growth parameter
C = Maximum growth rate (infection point)

Likewise, countries that played a greater scientific contribution in the areas evaluated were selected and again, the most relevant documents were selected in the area of the effect that the temperature has on quinoa. The data were validated using the R^2 and analyzed using Sigmaplot 11.0 (Systat Software Inc., San Jose, California) software.

Phenology of the quinoa

It is extremely important to understand the behavior of the quinoa plants to understand the possible limitations caused by the agroclimactic factors, especially those due to the increase of temperatures. According to what Reguera *et al.* (2018), the quinoa plants exhibit phenological variations with regards to the temperature in the production areas, mainly in the flowering and physiological maturity days.

According to what was found by Sosa-Zuñiga *et al.* (2017), in the phenological standardization of the quinoa using the BBCH Code (Biologische Bundesanstalt Bundessortenamt und CHemische Industrie), this species presents a transitory behavior of nine (9) phases that comprise states from the germination to the senescence, and we found that within each one of these phases, secondary stages that adapt to the changing behavior of the various cultivars, that result from the effect of the environment and its generic character.

Over a period of time, several different methodologies have been used that allow for the characterization of plant behavior under different agroclimactic conditions, and for this reason, at this moment in time, there are two (2) methodologies that are primarily used. The first one is developed using a classic model that is based on the counting of the number of days from the sowing to the interest phase. The other methodology is developed based on thermal times or growing degree-days (GDD), also well known as physiological time; this is determined by using a fraction of the difference of temperatures during a specific period of time, subtracting the base temperature, which is what Hatfield & Prueger (2015) recognized as the maximum threshold wherein the metabolic process of the plant is at its minimum (**Equation 2**).

$$GDD= \frac{T_{Máx} - T_{Min}}{2} - T_b \qquad \text{Eq. 2}$$

Although the ideal temperature for cultivating quinoa is between 15 °C and 20 °C (FAO, 2011), several investigations affirm that this plan tolerates maximum and minimum temperatures between -4 °C and 30 °C respectively (Bazile, Bertero & Nieto, 2014), advantages that have allowed them to expand into different tropical and extra-tropical regions. However, this tolerance ability is related to the agroecological group to which it belongs as well as to the phenological phase where the plant is found. Also, according to some of the authors and the origin of the vegetal material, the temperature base of the quinoa varies between 0 °C and 3 °C -4 °C (**Table 1**).

the enzymatic activation, mainly in the development of the metabolic routes, and for this reason, in the growth of the plants. This affirmation is evident in the actual data described in table 1, where changes in the thermal thresholds (T_b) for each phenological phase of the quinoa, it was found that it was influenced by the character of the agroecological group to which each cultivar belongs, according to the classification proposed by Bazile (2014) based on Tapia (1996) that also allows for the recognition of its influence of the cultivar selected to estimate the production parameters. Bertero *et al*. (1999) have determined that the Nariño cultivar presents the lowest T_b (T_b = 1, 5 °C) compared to varieties registered with a high productive potential that together with cultivars such as Kanckolla (T_b = 2 °C) and Sajama (T_b = 2,1 °C), present greater tolerance to lower temperatures as a result of the production areas (greater than 2500 m a.s.l).

Table 1. Relationship of temperature with the phenological stage.

Agroecological group	Base temperature °C (T_b)	Phenological stages	References
Salares and highlands	-1.9 y 0.2	(0) Germination	Bois *et al.* (2006)
	1	(05) from emergence	
	2	(1) foliar growth	
Inter-Andean Valleys and highlands	1	(0) Germination	Mamedi *et al.* (2017)
-	3	(0) Germination	Jacobsen & Bach (1998)
Inter-Andean valleys, highlands and sea level	3	(6) flowering	Bertero, King & Hall (1999)

According to Taiz and Zeiger (2006), the temperature plays a fundamental part of Figure 1, compares the physiological time studied for different varieties of quinoa, where it was found that there was a similar behavior between the cultivars in the vegetative phases and showing a greater dispersion in the temperature degree accumulation for their development in the reproductive phases, which can be clearly observed between the physiological time elapsed to the maturity of the Achachino and the Blanca de Juli varieties, whose GDD between these two (2) varieties varies by 44.8 %.

Temperature and germination

Germination is the most important phase when establishing the crop (Ceccato *et al*., 2013) since variables such as velocity and percentage of germination are determinants in characteristics such as vigor of plants and seed production (Gómez-Ramirez *et al*., 2017). According to the BBCH scale for the quinoa, three (3) different fundamental phases in germination are recognized: the first corresponds to the phenological 03 phase which begins with the imbibitions from which the water is absorbed due to the difference in the hydrological potential between the seed and the imbibition solution (Melgarejo, 2010); subsequently, the enzymatic activation occurs, whose initial response is manifested in a significant reduction in water absorption, which initiates metabolic transformations, mainly due to an increase in reactive of oxygen species (ROS), molecular mobility and cytoplasmic viscosity, which acts on the cellular signaling pathways release latency (Bailly *et al*., 2018) and inducing the phenological phase 05 (radicula emergency).

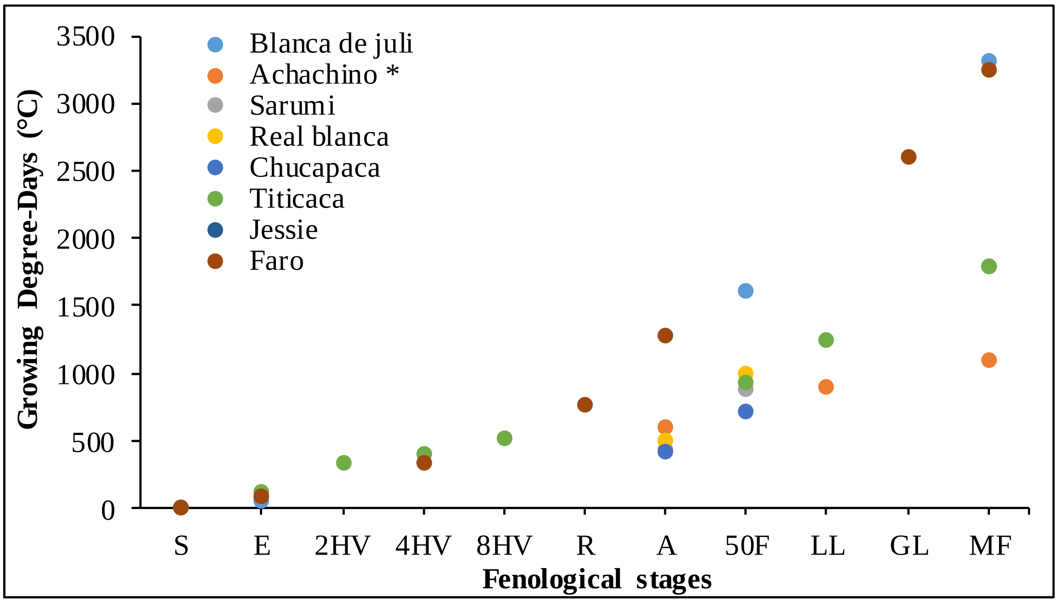

Figure 1. Growing degree-days on quinoa varieties. T_b: 3 °C; *T_b: 1 °C. Adapted from Bois et al. (2006); Melo, (2016); Becker et al. (2017); Präger et al. (2018); Kakabouki et al. (2019). S: sowing; E: emergence; 2, 4 and 8 HV: true leaves; 50F: flowering 50%; LL: grain filling; GL: milky grain; MF: physiological maturity.

According to Marschner (2012), adverse factors such as the relative humidity, the light, the availability of water and the changes of temperature are deciding factors in the seed germination. However, according to the evaluation made by Strenske *et al.* (2017), the quinoa seeds have the ability to keep their viability indexes high under un-controlled warehousing conditions and, in many cases, improve the presence of vitamins and microelements required in the human diet as they get closer to the hypocotyl elongation (Pitzschke *et al.*, 2015).

In different parts of the world, the evaluation of the warehousing conditions of the quinoa seeds has become fundamental, as a result of the accelerated loss of their viability, which, according to Romero *et al*. (2018), indicates that the increase in temperature favors the reduction of the germination percentage as it remains in the warehouse longer. However, the temperature effect on the answers regarding germination can be changeable depending on the cultivar (Gonzalez *et al.*, 2017).

Hinojosa, Matanguihan & Murphy (2019) found that the increase in temperature during the phonological development (from 25-6 °C to 40-25 °C) in quinoa cultivars QQ74 and 17GR had no influence on the size of the seeds, however there were differences found between the weights of the seeds. At the same time, Bertero, King and Hall. (1996) report changes in the size of the seeds of up to 14% when the temperature varies between 21 °C and 28 °C. These indicators highlight the variability of the response during the germination phase (0), which allows for the confirmation of the fact that the quinoa seeds have the ability to adapt easily in soils that reach high temperatures during the day and night within ranges of -1.9 °C to above 48 °C, encouraging the production process and the overall performance of the crop (Hinojosa *et al*., 2018).

Temperature and growth

The growth of the plants is regulated by their genetic expression and the ability of cellular division and elongation in the tissues (Lemoine *et al.,* 2013), for this reason, exogenous factors such as the availability of water, the presence of some nutrients in the cells and the homeostasis status in and between cells, determine their growth and development response, an effect that is explained by structurally dynamic cell walls that are capable of maintaining the rigidity of the vegetative tissues, in order to achieve support and protection. However, the extensibility of the cell wall due to the effect of auxins, allows the plant to grow, mainly due to the effect of intracellular turgor (Majda & Robert, 2018).

In accordance with the above, the presence of water at the vacuole level is vital for the plant to develop new structures at a radical, foliar and reproductive level. However, the circumstances in the field, do not allow for the constant availability of water required by the plants, and even less in quinoa crops, where the level of technology in countries like Colombia is incipient (Casas-Forero, 2016).

According to Garcia-Villanueva *et al.* (2017), the greatest demand for water is during the vegetative phases that begin, according to Sosa-Zuñiga *et al.* (2017), at the foliar development phase (1) and go on to the emergence of the inflorescence (5), mainly in crops at sea level and in salty areas (Melo, 2016). However, the water activity both within and outside the plant, are determined by the temperature of the environment, reason for which, the evaporation at ground level and the transpiration of the plants, could be modified.

Studies completed by Garcia *et al*. (2003) indicate that the calculations to determine the evaporation-transpiration in quinoa and the implementation of irrigation systems under upland conditions, must remember the external conditions such as day and nighttime temperatures, highlighting that the water stress do not generate relevant changes in the behavior of the plants, although, Eisa *et al.* (2012) affirm that the water deficit does, in fact, have negative repercussions in the synthesis of solutes and the photosynthetic activity of the quinoa.

Temperatures above 35 °C have been shown to influence the flowering phase, which is manifested in a higher percentage of floral abortions, or seeds that develop without perisperm or cotyledon (Murphy & Matanguihan, 2015). Sanabria & Lazo (2018), found a higher rate of cellular damage in different tissues as the lethal temperature (LT) increases, identifying quinoas that show a greater resistance to high temperatures over prolonged periods of time such as Negra Collana e Illpa cultivars.

The increase in temperature also affects the pollen. According to Hinojosa *et al.* (2019), this climate variable reduces the viability of the pollen up to 63 % when the daytime temperature changes from 25 °C to 40 °C, which is reflected by a marked reduction of the flowers that reach the development phase in the mature seed.

During the reproductive development phases, it has been determined that the changes in the temperature may cause unexpected variations regarding the types of seed quality or forage structures such as branches and stems; this is due to the increase in the viscosity of the phloem solution and its difficult diffusion between the source - landfill relationship (Lemoine *et al.*, 2013); Shah & Paulsen, 2003). On the other hand, when the temperature is reduced by values below the tolerance threshhold, the storage of the photo-assimilates is increased as a result of slow growth and a drop in demand, which slows down the activity of the photosynthetic machinery that generates damage at the photo-systemic levels (Lemoine *et al.*, 2013).

Table 2. Country characteristics and its relationship with agronomic performance on quinoa cultivars.

Country	Temperature region (°C)	Varieties	Phenological cycle (días)	Yield (kg.ha^{-1})	References
Italy	28	FLC (20, 27, 31, 58, 86)	167	489 – 1471	Melo (2016)
Grece	5 – 27	No 407	116	812	Noulas *et al.* (2017)
Germany	16,2	Titicaca	-	2227-3440	Präger *et al.* (2018)
Romania	17-22	Jørgen 37	135	1840	Szilagyi & Jornsgard, (2014)
Chile	16,1	Regalona		6000	Lesjak & Calderini, (2017)
Colombia	12	Blanca Soracá	171	2430	García-Parra, et al. (2019)
Spain	324,1 – 4,7	Regalona	138	2606	Reguera et al. (2018)

Within the plant breeding programs with quinoa plants, great progress has been made in obtaining plant materials that respond to variables such as precocity, by increasing the production rates at harvest time and obtaining seeds and fodder that present improved protein and fatty indexes (Bernlabib *et al.*, 2016; Prager *et al.*, 2018), which has led to the successful research developed with genetically stable quinoa crops like the one developed by Melo (2016), who carried out one of the first quinoa production experiences in Italy, using varieties of quinoa that were obtained within the areas of genetic improvement, to find an improved agronomic and productive performance compared to traditional cultivars.

At the same time, in Greece and Spain, investigations with different varieties that express a highly adaptive potential to the agroclimactic conditions and their response within the composition of the seeds was undertaken, which has generated areas of investigation that favor the production of quinoa in Europe (Noulas *et al*., 2017; Reguera *et al.*, 2018), while in Asian countries and North Africa, the varieties displayed greater adaptability to the changes in the environmental conditions (Bazile *et al.*, 2016). According to table 2 the production of quinoa under ideal conditions (between 15 °C and 20 °C) demonstrated the best productions of seeds such as the ones in Germany, Chile and Colombia.

Thus, according to what was obtained by Sanabria & Lazo (2018), the temperature plays a decisive role in the development of quinoa, however, its influence has a different effect between cultivated varieties and accessions of quinoa, which according to various investigations, manifests itself in improvement of the grain yield and air biomass, which favors forage production at the end of the vegetative phases (Murphy & Matanguihan, 2015).

Temperature and the production of quinoa seeds

The production of quinoa seeds is the result of the genetic expression of the plant, the edapho-climatic factors and agronomic practices developed during the crop cycle. Therefore, knowing the role of temperature in the development of the seeds is an important step according to the results obtained by Lesjak & Calderini (2017), who found significant unfavorable differences in quinoa in terms of growth, grain production and their protein content, when the temperature increases during the flowering phase.

According to the above, the previous phenological phases of the seed development combined with environmental temperatures are decisive in the productive and compositional aspects of the seeds, as well as in their metabolic behavior, as they are a reflection of the stress caused on the plant and the quick response to the estomatic regulation, as well as the redistribution of the photo-assimilates towards the dumps (Marschner, 2012), and at the same time, Ceccato, Bertero & Batilla (2011), recognize that the increase of the temperatures during the development of the seed within the plant, affects its latency patterns, a situation that puts the accelerated germination of the seed at risk, prior to the maturity of the plant, generating problems at harvest time or in its subsequent use as planting material. However, the establishment of improved quinoa crops such as the Puno variety (KVL 37), that even under extremely hot summer trials, achieved a yield of up to 1.727t¹, with a protein level between 15 % and 17 % (Stikic *et al.*, 2012), said results have demonstrated the adaptability of this species, under difficult agroclimatic conditions, with compositional characteristics within the seeds and yields that are similar to the quinoa productions under adequate management conditions in unimproved cultivars.

Production of quinoa affected by the variation of temperatures

During the last decade, the investigations regarding the production and consumption of quinoa have increased tremendously, not only due to the adaptability presented by this plant regarding the effects of the environmental changes, but also due to the constant increase of the global population. However, factors such as the temperature have been decisive in the quantity and quality of fruits and cereals. Tombesi *et al.* (2019) recognizes that the nighttime temperature fulfills a fundamental role in the transport of carbon during the evening hours, which has an impact on the relationship between the source and the dump, due to the fact that the increase of the nighttime temperature, reduces the exporting of the photo-assimilates from the leaves to the fruits such as vines. A similar case took place with rice plants, where their yield was reduced up to 10 % for each increase of 1 °C in the minimum temperature (Peng *et al.*, 2003), while with wheat, its increase in combination with the decreased availability of water dramatically affected the production of seeds (Mukherjee *et al*., 2019).

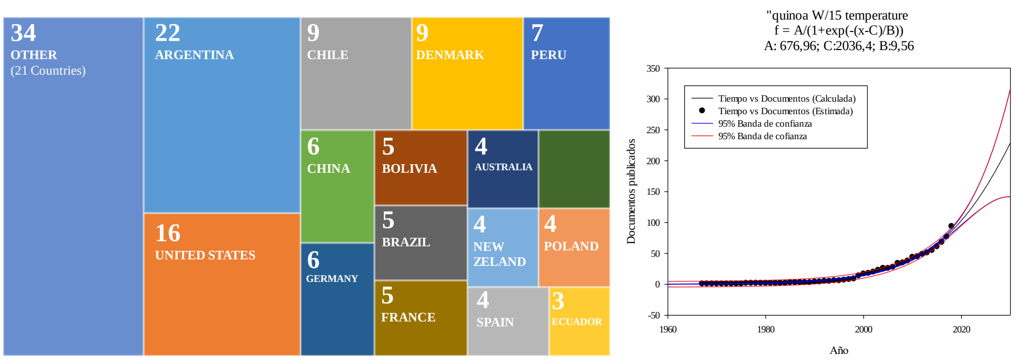

Figure 2. Countries and publications development in *quinoa* W/15 *temperature* according Scopus database.

According to the references detailed in the Scopus database, the investigation regarding temperature and the production of quinoa, have been increasing significantly, and it was found that the first investigation published in this database was reported in 1969, with 107 documents published whose distribution is centered on 102 scientific articles, three (3) conference documents and two (2) chapters of a book. Its positive trend, according to the ¨turning point¨ methodology proposed by Escobar & Zartha (2017), describing the relationship between quinoa and temperature was to be presented in 2036, lies in the ability of different species of the Amaranthaceae family and in particular *C. quinoa*, to tolerate intense changes in temperature during its productive cycle, which has allowed it to become an interesting strategy for the re-colonization of areas with adverse agroclimatic conditions and a promising alternative for food security in different regions.

Table 3. Effect of heat stress on quinoa cultivars.

Cultivar	Effect		References
CO407	Temperature affects the quality and fatty acid concentration on quinoa grains.		Curti *et al*. (2019)
Titicaca	Floral sterility is caused for temperature higher than 38°C		Alvar-beltrn *et al*. (2019)
QQ74	Reduced pollen viability	Increase in branches elongation Increase in máximum photosynthetic rate	Hinojosa *et al*. (2019)
17GR	Increase in seed size	Increase in stomatal conductance	
Cherry Vanilla	The lowest and highest temperatures (between 6 °C and 28 °C), double the average activation energy of RuBisCO and intercellular CO_2 concentration.		Bunce (2018)
Oro de Valle	Temperatures exceeding 32 °C generate pollen sterility and abortion of formed grains.		Buckland *et al*. (2018)
-	Rising temperature reduces water activity in cells of plant and hygroscopic content		Bustos-Vanegas *et al*. (2018)
Pasancalla	Damage cell membrane induced by increase in exposure time to the high temperature (50 °C).		Sanabria & Lazo (2018)
Regalona	Increased night temperatures (4 °C) affects grain yield and biomass.		Lesjak & Calderini, (2017)
Red head	high temperature and CO_2 concentration no have effect on harvest index and biomass in quinoa plants		Bunce, (2017)
-	An increase of the temperature reduces germination rate and increase abnormal seedlings		Strenske et al. (2017)
Achachino	High temperatures increase the net assimilation rate, stomatal conductance and CO_2 concentration.		Becker *et al*. (2017)

Although the variations of temperatures during the year, are more frequent in tropical and sub-tropical areas of the planet (Reid, 1994), the research surrounding their effect on the quinoa plants have been developed mainly for countries that are located in the extra-tropical areas. However, their relevance in Argentina, Chile, Peru, Bolivia, Brazil and Ecuador have been outlined to cover the ability of identifying the cultivars that tolerate an increased level of heat stress, without significantly affecting the yield (Hinojosa *et al.*, 2018), such as the research developed during the last four (4) years in accordance to the Scopus database.

According to the results obtained in the previous table, the modification of the temperatures is manifested in physiological and biochemical damages in the great majority of quinoa cultivars exposed to the modification of this climatic parameter. However, one of the most affected processes is the transport of CO_2, which according to the previously mentioned investigations detailed in **Table 3**, could be due to the dynamic of the stomas and the activity developed by the $RuBisCO_2$ enzyme, which coordinates with the investigation developed by Eustis *et al.* (2020) whose conclusions recognize the susceptibility of the quinoa to the variations of temperatures depending on the status of plant development, affecting the photosynthetic machinery, the organizational changes to the cellular structures, the closure of stomas to reduce the loss of water due to transpiration and the enzyme receptor kinetics of the CO_2.

Table 4. Selection criteria of quinoa cultivars for tolerance to heat stress.

Determination criteria	References
Growth and phenology	
Germination percentage	Bois et al. (2006); Mamedi et al. (2017); Strenske et al. (2017)
Plant Height	Hinojosa (2018)
Phenological stages	Bertero et al. (1999); Spehar & Santos, (2005); Alvar-beltrn et al. (2019)
Plant maturity time	Reguera et al. (2018)
Pollen viability	Hinojosa et al. (2019)
Physiological	
Damage cell percentage	Sanabria & Lazo (2018)
Photosynthesis and stomatal conductance activity	Yang et al. (2016); Bunce (2017); Becker et al. (2017)
Chloropyll fluorescence (Fv/Fm)	Eustis et al. (2020)
RuBisCO activity	Bunce (2018)
Yield and quality	
Grain production	Aranda et al. (2013)
Grain oil quality	Curti et al. (2019)
Grain protein content	Lesjak & Calderini (2017)
Saponins content	García-Parra et al. (2018)

All of the previously mentioned consequences decisively affect the growth and development of the plant, whereas the gaseous interchange on a stomatal level favors the production of starches, proteins and lipids mainly, which are a structural part of all the plant´s organs, even more so in quinoa plants, whose photosynthetic activity is C3 and its ability to fix the CO_2 levels compared to the C4 and CAM plants is less efficient (Taiz & Zeiger, 2005; Marschner, 2012).

Perspectives of the quinoa regarding the increase in temperature

One of the main strategies developed regarding the climate changes effects is the implementation of cultivars that have been developed based on genetic improvement programs, which found, through the identification of genetic basis methodologies that they are able to tolerate the effects of heat stress generated by strong field temperature variations.

According to Akter & Islam (2017), the selection criteria to identify the best cereal materials such as wheat (*Triticum aestivum* L.) are based on the most resistant to temperature cultivars that address aspects associated with higher grain yield; said methods have also been used in the choice of cultivars of maize, beans and quinoa (Naveed *et al.*, 2016; Golicz *et al.*, 2019; Soltani *et al.*, 2019) and which have been detailed in **Table 4** detailing such variables as: growth, phenology, physiology, yield and quality.

According to the information recorded in the previous Table, the selection of cultivars tolerant to heat stress that show desirable field characteristics for agronomic production and food products, must have a holistic view of variables that reflect their phenological, physiological performance and compositional need of its seeds, finding levels of tolerance to the thermal stress (TL50), that would contribute to the selection of cultivars with a higher tolerance level based on this climatic parameter.

Likewise, progress has been made in the study of *Hsf* thermal shock transcriptionists, identifying 23 genes in the Real Blanca ecotype at high temperatures (23 °C), describing the *CqHsfs3* and *CqHsfs9* genes that indicate a higher expression level after six (6) hours of thermal treatment, while the *CqHsfs4* and *CqHsfs10* genes indicated a higher expression level after reaching twelve (12) hours of thermal treatment (Tashi *et al.*, 2018).

CONCLUSIONS

According to the bibliographical review, it was determined that the effects of the temperatures strongly influence the parameters linked to the accumulation of degrees/heat during the day in the different quinoa cultivars and that, in this way, the phenological development of this plant is influenced by the variations of temperatures not only during the day but also at night. It was also possible to identify the main effects that occurred in the growth and development of different quinoa cultivars, mainly finding a great influence in the gaseous exchange, in the viability of the pollen and in the cellular stability of the different plant tissues.

At the same time, it was possible to identify several aspects to take into account when selecting cultivars capable of tolerating thermal stress, by measuring the susceptibility or damage in important variables of phenological, physiological and seed quality. All these aspects are very important to understand the adaptation of quinoa to the effects of climate change in the Andes as well as in the new countries that are now cultivating quinoa worldwide. The conclusions of the existing studies show that the differentiation between ecotypes is of greater relevance for this adaptation, but it is possible to consider the different destinations of quinoa, since high temperatures do not affect the different parts of quinoa in the same way. So, considering the cultivation of quinoa for dual purposes (human consumption and forage for animals) it has opened new perspectives into the uses of quinoa in areas that are most affected by climate changes.

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