# Quinoa

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by

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**FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS**
Rome, 2012

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# Foreword

Sustainable management and utilization of natural resources is part of the *Global Goals* of FAO Member Countries and essential to the mandate of FAO.

The latest FAO assessment of the state of the world's land and water resources clearly indicated that these resources, already scarce today, will be increasingly scarce as we move into the future, threatening food security. In fact, the outstanding food demand projected for the next decades, due to the world population growth and to the anticipated shift in consumption patterns, will face very limited opportunities for further land expansion and the finite availability of fresh water resources. Such a food demand may be satisfied only if we are able to act effectively and sustainably on both sides of the *food* equation, i.e., *production* and *consumption*, and on the inter-linkages between these two variables, including trade, distribution and access.

Efforts are being made by FAO to address major issues on the *production* side, on the fairness of trade, on the *consumption* side (reduction of post-harvest losses and food waste; promoting nutritious and healthy diets) and other emerging challenges. Among these emerging challenges are: *food price volatility*, revealing the vulnerability of some countries in their dependency on imports, leading to increase production inside their national boundaries; *climate change*, causing greater uncertainties on rainfall patterns, thus requiring higher levels of adaptation and increased resilience of the local production systems; *transboundary* rivers and *competing demands* for land and water resources by other sectors of society and by ecosystems.

Under such circumstances, and looking into the future food demand, it is imperative that agriculture improve the efficiencies of use of the limited resources and ensure substantial *productivity* gains. In the case of water, scarcity is a major threat to the sustainability of food production in many areas of the world. The effective management of water in rainfed and irrigated agriculture is thus a major knowledge-based pathway to increase *productivity* and farmers' income. To combine increased productivity with sustainable management of natural resources, without repeating the mistakes made in the past, will be a challenge.

With the contribution of numerous experts, professionals and scientific institutions around the world, including a few *Institutes* of the *Consultative Group on International Agricultural Research* (CGIAR), "*Crop yield response to water*" is published at a time of high demand for assistance by member countries in order to implement effective water management strategies and practices that are environmentally safe and climate-resilient, and enhance sustainable water productivity and yield of their farming systems, therefore alleviating the risks of food insecurity.

José Graziano da Silva
*Director-General*
*Food and Agriculture Organization*
*of the United Nations*

# Preface

The FAO *Land and Water Division* is engaged extensively in the enhancement of global agricultural performance. A part of this effort is the production of landmark publications and guidelines that address food production and water use problems using analytical methods that often serve as standards worldwide.

In the face of growing water scarcity, declining water quality, and the uncertainties of climate change, improving the efficiency and productivity of crop water use, while simultaneously reducing negative environmental impact, is of the utmost importance in responding to the increasing food demand of the growing world population. To this end, irrigated and rainfed agriculture must adopt more knowledge-intensive management solutions.

Moreover, competing demands for water from other economic sectors and for ecosystem services will continue to grow. As agriculture is by far the largest consumer of water, efficiency and productivity gains in this sector would free significant amounts of water for other uses.

Abstracting from the scientific understanding and technological advances achieved over the last few decades, and relying on a network of several scientific institutions, FAO has packaged a set of tools in this *Irrigation and Drainage Paper* to better assess and enhance crop yield response to water. These tools provide the means to sharpen assessment and management capacities required to: sustainably intensify crop production; close the yield-gap in many regions of the world; quantify the impact of climate variability and change on cropping systems; more efficiently use natural resources; and minimize the negative impact on the environment caused by agriculture. These tools are invaluable to various agricultural practitioners including, but not limited to: water managers and planners; extension services; consulting engineers; governmental agencies; non-governmental organizations and farmers' associations; agricultural economists and research scientists.

Representing FAO's state-of-the-art work in water and crop productivity, it is our hope that this publication provides easy access to, and better understanding of, the complex relationships between water and food production and, in this way, helps to improve the management of our precious water resources.

Alexander Müller
*Assistant Director-General*
*Natural Resources and Environment*

Parviz Koohafkan
*Director*
*Land and Water Division*

# Contents

# Acknowledgments

This publication has relied on inputs from a large number of people and institutions in various forms, including expert consultations, contributions at project workshops, experimental data and authorship.

Universities and national and international research institutions from many regions of the world have provided data and insights, which forms part of the vast amount of information and knowledge condensed in this state-of-the-art publication *Crop yield response to water.*

Particularly significant has been the involvement of key CGIAR Centres, specifically IRRI, ICARDA, ICRISAT, CIMMYT and CIP, and the FAO/IAEA Joint Division. Working together with the colleagues from these Centres has strengthened the institutional partnership and enhanced the synergy towards filling the gaps between scientific research and field implementation, theoretical knowledge and field practice, investigation and actual operation.

Most of these scientists, experts and colleagues are listed in this publication either as editors, authors or as scientists who have contributed with data and tests for the model *Aquacrop*. We are grateful to all of them for their highly valuable inputs.

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Without this collective and interdisciplinary effort, this outcome could not have been achieved.

Quinoa*

*Flower and grain colour presented in the figure are only an example. Depending on the quantity of anthocyans, this colour varies from green-yellowish to deep purple and even black throughout quinoa varieties.

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# Quinoa

## GENERAL DESCRIPTION

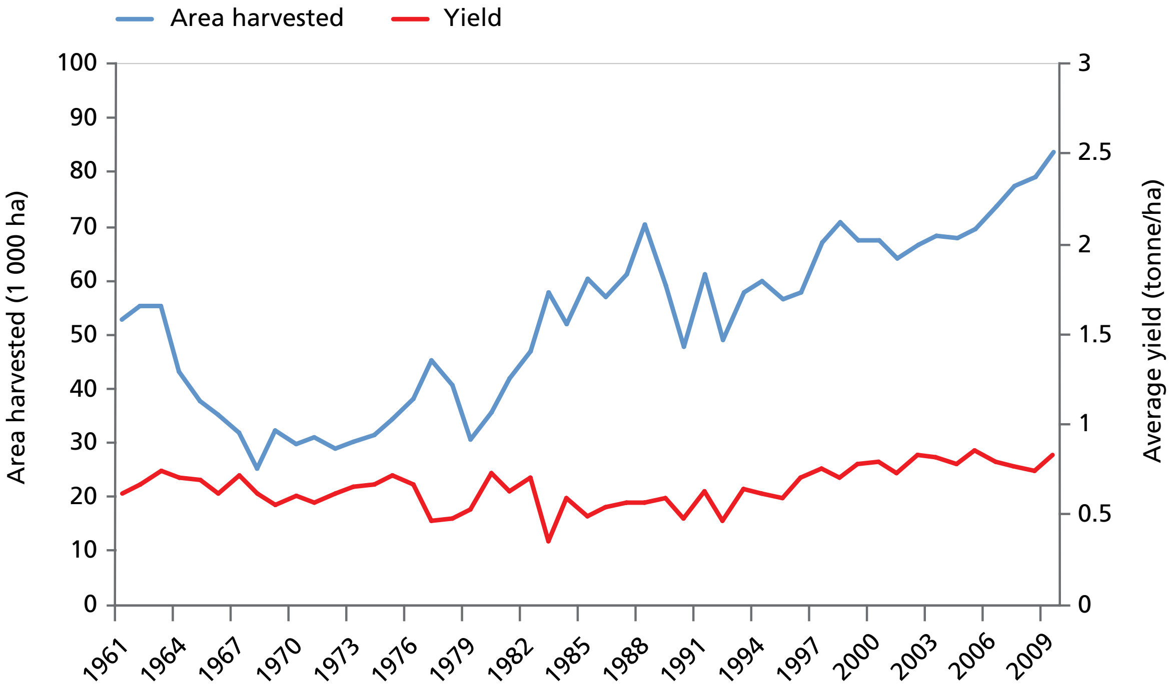
**Quinoa** (*Chenopodium quinoa* Willd.), a species of the goosefoot (*Chenopodium*) genus of the family of sugar beet, beetroot, mangold and spinach, is a grain-like crop grown primarily for its edible seeds. It is a seed crop, rather than a true cereal, or a grain, as it is not a member of the grass family. It is native to the Andean mountains where this traditional seed crop has been cultivated in the Peruvian and Bolivian Andes for more than 7 000 years. Although the production declined significantly during the Spanish conquest, popularity of quinoa rose again in the last century. Production is now widespread in the Andes, covering Bolivia, Peru, Ecuador, Colombia and the north of Argentina and Chile. As a crop with a large food utilization potential, it is rapidly gaining interest globally, being already fairly known in North and Central America, Brazil, Europe and Asia (Schulte auf'm Erley *et al.*, 2005). First results also indicate the potential of quinoa in Africa. In 2009, 83 thousand hectares were sown to quinoa, producing 69 000 tonne of grain at an average grain yield of 0.8 tonne/ha (FAO, 2011). The worldwide trend for cropping area and production over the last 50 years is shown in Figure 1.

Quinoa is characterized by an enormous intra-species variety and plasticity that allows the crop to grow under highly diverse climatic and agronomic conditions. It is well adapted to arid and semi-arid locations and grows from sea-level to high altitudes, up to Andean Altiplano at around 4 000 m above sea level, where its cultivation is of special importance. Quinoa is cultivated as a mono-culture (e.g. Southern Bolivian Altiplano) or in rotation with potato and barley, and sometimes with wheat and maize at the low altitudes. When cultivated as mono-culture, fields are left fallow for 1 to 3 years and sometimes even longer (up to 10-12 years) for pest control, soil fertility regeneration and build up of the soil water reserve. Traditionally, a range of quinoa landraces is cultivated in the same vicinity, though for export purposes a few local cultivars sown in monoculture are generally preferred (e.g. quinoa var. Real Blanca). Daylength neutral cultivars of quinoa can be grown under the long day conditions of northern Europe (Christiansen *et al.*, 2010).

## GROWTH AND DEVELOPMENT

Quinoa is a $C_3$ annual dicot of 0.5 to 2 m height, terminating in a panicle consisting of small flowers, and with only one seed of around 2 mm

**FIGURE 1** World quinoa harvested area and average yield over the period 1961-2009 (FAO, 2011).



produced per flower. In the Andean highlands, quinoa is grown from September to May, and normally without any fertilizer or pesticide. In the Bolivian Altiplano, the sowing date varies between the beginning of September and the end of November, according to the crop cycle length of the different cultivars and local climate, particularly when the soil is moist enough for germination. Sowing practice is the key for the success of quinoa. Superficial sowing runs the risk of seed dehydration or sunburn whereas deep sowing can prevent emergence; in both cases, a poor stand and uneven canopy cover occurs with detrimental effects on final yield. Common practice is to sow between 8 to 15 kg of seeds per hectare in rows 0.4 to 0.8 m apart, either on top of the bed or in the furrow, with plants spaced about 10 cm apart within the row after thinning. Another practice, adapted to arid environments where commercial production is widespread, is to group several plants each in pits spaced about 1 m apart. Less common are transplanting (Inter-Andean valleys) or broadcasting of the seeds. As nutrients are often scarce in the Altiplano, early weeding (± about 30 days after sowing) and thinning of excessive plants are important activities in the areas where rain is sufficient to allow for rapid plant growth. In arid areas, instead, weeding and thinning are not practised, even in commercial production.

Phenological development is highly variable among varieties. Additionally, phenology is highly flexible in response to water stress, with differences in time to maturity of as much as 30 days for the same cultivar (Geerts *et al.*, 2008c). Under no stress conditions, time from sowing to emergence is 3 to 10 days. The time to maximum canopy cover ($CC_x$) depends on plant density and temperature regime. Phenology is further complicated by a response to photoperiod — a short day response for duration of emergence to flowering, and for the duration of all developmental phases in some cultivars (Bertero, 2003). The time from emergence to physiological maturity varies between 100 and 230 days, again because of wide variation among cultivars. Flowering starts between 60 to 120 days, and lasts around 20 days. Canopy senescence starts generally about one month before physiological maturity, and progresses relatively fast. It is important to note that these indicative values are given for cultivars cultivated at high elevations, and could be biased because growing conditions (temperature, fertility, water supply) are not optimal. Roots, often with numerous ramifications, can deepen to 1.80 m depth in cases of drought stress in light soils.

In the southern Andes, quinoa is harvested in April-May, mainly by pulling out or cutting the plants and leaving them in stacks on the field to dry. Harvest can take up to 1.5 months because of asynchronous flowering and ripening. In principle, realistic simulation of such production practice with *AquaCrop* would entail simulations runs for each maturity group, and then summing up the yields of all groups in proportion to their population density or land area occupied (Figure 2. Example of quinoa).

## WATER USE & PRODUCTIVITY

In midseason, quinoa reaches maximum canopy cover ($CC_x$), shortly after first anthesis. $CC_x$ is largely dependent on the management conditions and, to a large extent, determines quinoa transpiration. For a complete canopy cover of the ground and under non-limiting nutrient conditions, quinoa transpires at a rate similar to the reference evapotranspiration ($ET_o$). Seasonal ET values for quinoa with a normal season length of 150-170 days are around 500 mm under non-stressed conditions. As a $C_3$ crop, normalized crop water productivity (WP*) is low,

**FIGURE 2** Flower and grain colour presented in the figure are only an example. Depending on the quantity of anthocyanins, this colour varies from green-yellowish to deep purple and even black throughout quinoa cultivars.

with typical values around 10.5 g/m$^2$ under the low, natural fertility in the Bolivian Altiplano (Geerts *et al.*, 2009). Still-under poor fertility conditions, a decrease of the reference biomass water productivity (WP*) value only occurs at higher total transpiration sums, and only by 10 percent. The $C_3$ pathway is well adapted to the prevailing low average temperatures in the Altiplano. Reported values of seed yield per unit of water consumed ($WP_{Y/ET}$) are rather low and lie between 0.3 and 0.6 kg/m³ because of the generally prevailing low fertility conditions (Geerts *et al.*, 2009). On the other hand, it is a crop with a large nitrogen-sink thus causing an increased metabolic cost or higher glucose-equivalent per unit dry matter produced. To our knowledge, no research has been conducted on the response of quinoa to increases in atmospheric $CO_2$.

## RESPONSE TO STRESSES

Quinoa is highly resistant to a number of abiotic stresses (Jacobsen *et al.*, 2003). Several drought resistant mechanisms are present in quinoa. Drought in early vegetative stages may prolong its life cycle, allowing the plant to make up for growth lost during the early drought if water is available later. Also, the availability of cultivars with different season length makes it possible to match the water requirement of the quinoa crop to the available rainfall or the stored soil water at a given location. Quinoa tissue is relatively high in osmotic solutes and undergoessubstantial osmotic adjustment under drought, which enable stomata to remain somewhatopen down to a leaf water potential range of -1.5 MPa. During soil drying the plants are able to maintain leaf water potential and photosynthesis due to the complex stomatal response, resulting in an increase of leaf water use efficiency. Root originated ABA plays a role in stomata performance during soil drying. ABA regulation seems to be one of the mechanisms utilized by quinoa when facing drought inducing decrease of turgor of stomata guard cells (Jacobsen *et al.,* 2009). The plant also avoids negative effects of drought through fast and deep rooting particularly in dry soils. Quinoa also reduces its leaf area by controlled leaf senescense under drought.

Quinoa is a facultative halophyte (Bosque-Sanchez *et al.,* 2003) and can grow in non-saline to extremely saline conditions, depending on the cultivar. Seed production is enhanced by moderate salinity (EC in the 5-15 dS/m range) and may not be drastically reduced even at EC of 40 to 50 dS/m in some cultivars (Jacobsen *et al.,* 2003). Osmotic adjustment by the accumulation of salt ions in tissues enables the plant to maintain cell turgor and transpiration under saline conditions.

Apart from drought, frost and cold are the other major growth limiting factors in the Altiplano. Quinoa is tolerant to frost, partly because of the protection provided by its heterogeneous canopy (Winkel *et al.,* 2009), although the tolerance varies with cultivar and appears to diminish at the late phenological stages (Jacobsen *et al.,* 2005). Leaf freezing of quinoa occurred only between -5 and -6 °C, and is delayed in case of mild water stress (Bois *et al.,* 2006). The resistance to frost is associated with super cooling of tissue water and tolerance of extracellular ice formation (in the cell wall), as is common for most winter crops.

Linked to frost resistance is a low base temperature ($T_{base}$) for plant processes. In a study of the leaf appearance rate of different quinoa cultivars originating from various altitudes and latitudes, $T_{base}$ averaged 2 °C and the temperature at which maximum rate was reached averaged 22 °C. Other studies found a $T_{base}$ of 3 °C, $T_{opt}$ of 30-35 °C and $T_{max}$ estimated to 50 °C

(Bertero *et al.*, 2000; Jacobsen and Bach, 1998).Temperature sensitivity of quinoa was highest in cultivars originating in cold and dry climates and lower in cultivars from warmer and humid climates (Bertero *et al.,* 2000).

Because soil fertility is generally poor in its centre of origin, cases of quinoa cultivation under non-limiting soil fertility are very rare. Research into nitrogen and phosphorus requirements conducted in Colorado, United States, found that maximum yields over 4.5 tonne per ha are possible when 170 to 200 kg N/ha were applied (Oelke *et al.,* 1992). If these results are confirmed in other studies, the WP* of quinoa under non-limiting fertility would be much higher than the value of 10.5 g/m$^2$ reported earlier for the low fertility natural conditions of the Andean Altiplano. No effect on yield was observed when 34 kg of phosphorus (as phosphoric acid) per ha was applied, in comparison to an untreated field plot (Oelke *et al.,* 1992). In areas of traditional cultivation, some sheep or lama dung is applied when available; but mostly, quinoa is sown in unfertilized fields. If sown after potato, nutrient supply is generally better because of the nutrients left over from the potato fertilization.

## IRRIGATION PRACTICE

As quinoa is drought resistant, it is traditionally cultivated under rainfed conditions, even in semi-arid locations. Researchers, though, started to study the impact of additional water on quinoa production and found that deficit irrigation (DI) was highly beneficial in various experimental locations. DI is already practised for the reintroduction of quinoa in arid regions of Chile. On the other hand, currently quinoa is rarely cultivated under full irrigation, as research of quinoa under full irrigation gave only slightly better results than quinoa cultivated under deficit irrigation (Geerts *et al.*, 2008a and b), besides the issue that sufficient water for full irrigation is mostly unavailable.

## YIELD

Quinoa produces nutritious seeds (Alvarez-Jubete *et al.,* 2009) with high protein content (from 12 up to 20 percent), as compared to maize, rice or even wheat. The balanced amino acids composition makes the protein quality comparable to that of milk, making it an effective meat and milk substitute. Additionally, quinoa is gluten free, which is advantageous for commercial food manufacturing for celiac consumption. On the other hand, the seeds also contain the anti-nutritional component saponin (Mastebroek *et al.,* 2000), that the plant produces as an inherent protection against pests. Saponin is removed by washing or dry polishing before consumption.

Although high yields (up to 4.5 tonne/ha and more) have been occasionally reported for some quinoa cultivars under non-limiting fertility and water conditions, rainfed yields in the Peruvian and Bolivian Altiplano do not exceed 0.85 tonne/ha as an average. Pests, including birds and rodents, and diseases are major causes of yield loss, in addition to low fertility and water deficits. Harvest index (HI) of quinoa in the field ranges between 0.3 and 0.5. Building up of HI takes a short time for the short season cultivars, and up from 80 to 100 days for the long season cultivars. Individual grain size is quite variable among cultivars, with 1 000 grain weight ranging from 1.2 to 6.0 g in non-stress conditions (Rojas, 2003).

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