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Economic assessment at farm level of the implementation of deficit irrigation for quinoa production in the Southern Bolivian Altiplano

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Abstract

In the Southern Bolivian Altiplano recent research has suggested to introduce deficit irrigation as a strategy to boost quinoa yields and to stabilize it at 2.0 ton ha^{-1}. In this study we carried out an economic assessment of the implementation of deficit irrigation at farm level using a hydro-economic model for simulating profit for quinoa production. As input of the model we worked with previously developed farms typology (livestock, quinoa and subsistence farms), simulated quinoa production with and without irrigation using AquaCrop model, and calculated yield response functions for four different climate scenarios (wet, normal, dry and very dry years). Results from the hydro-economic model demonstrate that maximum profit is achieved with less applied irrigated water than for maximum yield, and irrigated quinoa earned more profit than rainfed production for all farms types and climate scenarios. As expected, the benefits of irrigation under dry and very dry climate conditions were higher than those under normal and wet years, and benefits among farms types were higher for quinoa farms. In fact, profit of irrigated quinoa might be stabilized at around BOB 6500 ha^{-1} (about USD 920) compared with the huge differences found for rainfed conditions for all climate scenarios. Interestingly, the economic water productivity, expressed in terms of economic return for amount of applied irrigated water (BOB mm^{-1}), reached the highest values with intermediate and low level of water availability schemes of deficit irrigation for all climate scenarios.

Additional key words: aqua crop; yield response function; economic water productivity; Monte Carlo simulation.

Introduction

Poverty is one of the most severe problems in Bolivia as highlighted by a human development index of 0.643 in the year 2010, ranked 95th out of 169 countries. Poverty measured in terms of falling below the poverty line affected almost 40% of Bolivians in 2008, and like in all South American countries inequality is very high, reaching a Gini-coefficient of 57.2% for the same year (UNDP, 2010)[1]. In addition, living conditions in the rural areas of Bolivia are even worse with more than 60% of the rural population considered as poor and more than 45% as extremely poor (INE, 2011).

The Bolivian Altiplano is a high plateau of about 200,000 km^2 which constitutes an important part of the Andean region in South America. It is considered one of the highest agricultural areas in the world with an average altitude of 3,900 m.a.s.l. Although the envi-

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Abbreviations used: AIW (applied irrigation water); BOB (Bolivian currency called 'Boliviano'; BOB 7.02 = USD 1.0 in 2010); CWP (crop water production function); Eta (actual evapotranspiration); ETo (reference evapotranspiration); EWP$_{AIW}$ (economic water productivity of applied irrigation water); FI (full irrigation); PDF (probability distribution function); TAW (total available soil water content); WP(water productivity).

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[1] The Gini coefficient is a measure of the inequality of a distribution and it ranges from 0 to 100 when expressed as a percentage. A value of 0% expresses total equality, and a value of 100% maximal inequality.

ronmental conditions of the Bolivian Altiplano are very hard with extreme low temperatures, an irregular rainfall season, low levels of precipitation, high evapotranspiration rates and low soil-fertility, agricultural activities are important involving major part of the rural population (Vacher, 1998; García *et al.*, 2004). Crop farming in the Bolivian Altiplano is limited to the warm and humid summer (middle of October to March) (Vacher, 1998; García *et al.*, 2007). Moreover, the climatic N-S gradient, which is characterized by a higher vapor-pressure deficit and mean temperature in the south, makes farming conditions even more difficult in the Southern Bolivian Altiplano.

Quinoa (*Chenopodium quinoa* Willd.), together with potato, is one of the most important crops in this region. The Peruvian and Bolivian indigenous people have used this native crop for more than 7,000 years (Pearsall, 1992). During the last two decades, quinoa production in the region has increased as a result of an enlarged production area. In fact, quinoa production area in Bolivia has boosted up from 38,800 to almost 70,000 ha for the period between 1990 and 2012, and production has increased from 19,600 to 44,200 ton for the same period (INE, 2000, 2011; IBCE, 2012). Greater quinoa prices on the international market caused by an increasing demand (Jacobsen *et al.*, 2003) as a recognition of the quinoa high nutritive (Repo-Carrasco *et al.*, 2003; Mujica *et al.*, 2006; Comai *et al.*, 2007), might be the main reason for quinoa intensification in the region. As a matter of fact, the price of quinoa at the international market has almost quadrupled from 1989 to 2011 up to USD 3115 ton^{-1} (INE, 2000, 2009; IBCE, 2012).

The changes in the quinoa demand resulted in changes in land use and quinoa cropping (Rojas *et al.*, 2004). Until the 1970's farming systems in the Southern Bolivian Altiplano were mainly based on quinoa and potatoes grown on volcano slopes, whereas lama farming was practiced on foothills and flat land (Hellin & Higman, 2005; Dosso *et al.,* 2006). In the last decades quinoa cropping system has suffered many changes: agricultural frontier has been spread out moving quinoa crops from the hills to the flat land, traditional manual cultivation has been replaced by mechanized system with tractor use for tillage and sowing, and fallow period has been reduced (PNUD-Bolivia, 2008; Felix & Villca, 2009).

Despite of this scenario, crop yield under the traditional rainfed conditions has remained low at only 0.6 ton ha^{-1} (INE, 2008), and even has decreased in the last ten years (MDRyT-CONACOPROQ, 2009). In addition to the reported negative effects caused by the change in the cropping system (Cossio, 2008; Felix, 2008; Felix & Villca, 2009; Jacobsen, 2011), well developed drought and frost resistance mechanism (Jansen *et al.*, 2000; Bosque *et al.*, 2003; García *et al.*, 2003; Jacobsen *et al.*, 2005, 2007; Geerts *et al.*, 2008a), might also explain the low yield of the crop.

Recent research has suggested introducing deficit irrigation as a strategy to overcome the precipitation deficit, and boosting and stabilizing quinoa yields at 2.0 ton ha^{-1} (Geerts *et al.*, 2008a,b, 2009b). However, there is insufficient knowledge about the current farming systems that have emerged following the intensification of quinoa production. More specifically, it is unclear whether current farming systems have the capacity to introduce this innovation. In addition, since quinoa has never been irrigated in the region, an economic assessment of the implementation of deficit irrigation on quinoa crop is needed.

The main purpose of this paper is to carry out an economic assessment of the implementation of deficit irrigation for quinoa production at farm level in the context of the Southern Bolivian Altiplano. For this, we used the AquaCrop model (Steduto *et al.*, 2009), previously calibrated for quinoa by Geerts *et al.* (2009b), for simulating quinoa production under rainfed condition and different irrigation strategies. From the simulation results water production functions were derived for different climate conditions. The water production functions, which provide information on the yield response to water, was used to analyze the economics of applying irrigation on quinoa production with the help of an economic model. In addition, a previously developed farm typology of the region, based on a livelihood analysis (Cusicanqui *et al.*, 2011) was included in the economic model.

Material and methods

Study area

The Bolivian Altiplano is divided into three main regions: the Northern, Central and Southern Altiplano that present different climate, soil and potential agricultural production (IBTA, 1994). The assessment developed in this paper is focused on the Southern Bolivian Altiplano which is a large plateau surrounded by the Easter and Western Mountain range, and located at an altitude that ranges between 3,600 and 4,100 m.a.s.l. The 12.5-km^2 Uyuni Salt Flat typifies the ecological conditions of the area which is dry and characterized by an arid climate (Jacobsen, 2011). The average annual rainfall is between 150 to 300 mm (Aroni, 2001; Aroni *et al.*, 2009), and average reference evapotranspiration of 3.8 mm d^{-1} up to 6.2 mm d^{-1} in the growing season. The variation in maximum and minimum air temperatures is between 31.5 to 22.7°C and –1.7 to –8.3°C, respectively (Geerts *et al.*, 2009b), with high risk of frost (between 174 and 220 d yr^{-1}) (IBTA, 1994; Aroni *et al.*, 2009). Soils in the region are poor and are composed mostly of volcanic ashes and lava. Sandy and sandy loam are the two textural types mainly found in the area with pH slightly alkaline, low organic matter content (below to 2.8%) and very low content of nitrogen (below 0.20%) (Soraide *et al.*, 2011). According to Joffre & Acho (2008) soils at the slopes contain more clay, organic matter and nutrients than the soils of the flat areas.

In this region quinoa is one of the very few suitable crops, and it has become the biggest quinoa producer with more than 80% (more or less 27600 tons) of the whole production in Bolivia in 2008 (Aroni *et al.*, 2009). Most quinoa production, which is mainly grown in the hills and flat land of the region and it is known as the bitter "Royal quinoa" (quinoa real), is exported and it makes Bolivia the top exporting country of quinoa (Collao Pérez, 2001; INE, 2009; Consorcio ASECAL & Mercurio Consultores, 2011). Nevertheless, agriculture is not the only source of income of the farmers, as they combine cropping production with lama raising and temporary migration to the mines or urban centers. Only during sowing and harvesting, when more manpower is needed (Rojas *et al.*, 2004), people return to the countryside.

Simulation quinoa yield using AquaCrop

Simulation of quinoa yield using AquaCrop model was accomplished in three main steps. Step one involved the rainfall analysis for characterizing and classifying quinoa growing season rainfall. Step two included the development of the water production functions using AquaCrop model in order to simulate quinoa yield for rainfed conditions, full irrigations and different strategies of deficit irrigation. And step three encompassed the development of the yield response function by plotting the applied irrigation water (AIW) *versus* total grain yield for the various climate scenarios.

With the purpose of capturing broader climate variability than previous studies (Geerts *et al.*, 2009b) and also considering the low soil fertility in the region, quinoa yield simulation carried out in this study takes into account a longer historical climatic data, seasonal rainfall was classified in four instead of three different climate scenarios, and soil fertility levels in the model were assumed.

Rainfall analysis

Daily historical climatic data were used as input for the simulations. A frequency analysis on seasonal rainfall was carried out to characterize and classify years by using the Sevkud & Geiger (1981) method. The rainfall during quinoa growing cycle (R) at any probability of exceedance (Pe) was given by:

$$R(Pe) = -\alpha Pe + \beta \ [mm] \qquad [1]$$

where $R(Pe)$ is the amount of rainfall (mm) at exceedance probability of Pe, and α and β are the coefficients of the dependable rainfall response function. Probability of exceedance was the criteria used to classify rainfall during quinoa growing season into four different climate scenarios: a wet year (W) was defined as a season with a total rainfall ≤ 20% probability of exceedance; a normal year (N) with rainfall falling between 20% and 50% of probability of exceedance; a dry year (D) with probability of exceedance between 50% and 75%; and a very dry (VD) year with probability of exceedance ≥ 75%.

Crop water production function

Quinoa yield was simulated with the AquaCrop model (Hsiao *et al.*, 2009; Steduto *et al.*, 2009; Raes *et al.*, 2012) as calibrated for quinoa by Geerts *et al.* (2009b). Simulations were run using 27 years (1983 to 2010) climatic data from Rio Mulatos (19° 41' S, 66° 46' W, 3,815 m asl), which is an agro-climatic station representative for the quinoa production area in the Southern Bolivian Altiplano (Geerts *et al.*, 2006). Recorded daily rainfall and minimum and maximum temperatures, and calculated daily reference evapotranspiration (ETo) (Allen *et al.*, 1998) were used as climatic input. Sowing date was set on September 30th since survey results (Cusicanqui *et al.*, 2011) showed that most farmers sow quinoa in the period between September 20th and October 10th. An initial soil water content of 50% of the total available soil water content (TAW) was assumed before sowing as a way to represent soil conditions at farm level.

For each of the 27 years, simulations were carried out by assuming rainfed conditions, full irrigation and four different strategies of deficit irrigation. In order to guarantee an initial establishment of the crop an irrigation or rainfall bringing the top soil to field capacity right after sowing was assumed.

In order to adequate the irrigation system with the crop management that farmers use for quinoa production, especially the sow system (Soraide *et al.*, 2011), micro-basin irrigation was selected as irrigation system. AquaCrop considers several irrigation modes (Raes *et al.*, 2009), and irrigation schedule can be generated by specifying a time and a depth criterion. For depth criteria it was assumed that after irrigation field capacity was reached in the root zone. For the time criteria it was assumed that the quinoa crop is irrigated when a specific percentage of TAW is reached. Depletion to 50% TAW before flowering and to 61% TAW after flowering for the rest of the irrigation season was assumed for the full irrigation strategy. For deficit irrigation strategies, water is only applied during flowering and the early grain filling phase, which are the most sensitive growth stages of quinoa to drought conditions (Geerts *et al.*, 2008a). In order to evaluate current limitations of water resources in the region, grain yield under different deficit irrigation strategies were simulated. Irrigation was applied when the soil water depletion in the concerned period reached 61%, 70%, 80% and 90% TAW. As such four scenarios of water availability were considered (Table 1).

It is clear that quinoa production in the Southern Bolivian Altiplano is not only stressed by water availability but also for the low soil fertility of the region that has an effect on canopy development and water productivity (Vacher, 1998; García *et al.*, 2004), thus soil fertility stress in the AquaCrop model has been calibrated and adjusted to the farmer conditions. In addition to the values used by Geerts *et al.* (2009b) for soil water content[2], biomass production of 50% that corresponds to 50% of the soil fertility stress was calculated through the calibration process in the crop mode of the AquaCrop model version 4.0.

Table 1. Allowed depletion of soil water in root zone for various deficit irrigation (DI) strategies and levels of water availability

Strategy	Allowable depletion of soil water in root zone (% TAW)	Water availability
DI1	61	High
DI2	70	Intermediate
DI3	80	Intermediate
DI4	90	Low

Close to 200 simulations with the calibrated AquaCrop model were run and the results were summarized in a crop water production function by plotting actual evapotranspiration (ETa) *versus* total quinoa grain yield. Likewise, water productivity, as reviewed by Molden (2003), and defined as the ratio of the crop yield (Y) to the volume of water consumed by the crop (ETa) was plotted. Since ETa refers to water loss both by crop transpiration and by soil evaporation during the crop cycle, they are merged in a term known as actual evapotranspiration (Allen *et al.*, 1998).

Yield response functions

Yield response functions were obtained by plotting the applied irrigation water versus total grain yield for the various climate scenarios (wet, normal, dry and very dry years). By performing a regression analysis a quadratic functional expression was assumed and coefficients were obtained:

$$Y_i = \alpha_i X^2 + \beta_i X + \gamma_i, \qquad [2]$$

where Y_i is the total quinoa grain yield (kg ha^{-1}); X is the amount of applied irrigation water (AIW) expressed in mm; α_i, β_i and γ_i, are the coefficient of the yield response production function, and the subscript i refers to the type of climatic condition (W, N, D or VD).

Economic assessment

The typology developed by Cusicanqui *et al.* (2011) identifies three main farm types: (1) livestock farms, whose income source comes mainly from lama breeding followed by quinoa production; (2) quinoa farms

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[2] Soil water content at permanent wilting point per layer = 5.6%, 4.9% and 5.6% vol. Soil water content at field capacity per layer = 16.9%, 13.5%, 15.0% vol. Saturated hydraulic conductivity = 4,192 mm d^{-1}. Readily evaporable water from the soil = 6 mm.

dedicated mainly to quinoa production for selling; and (3) subsistence farms, which income rely on off-farm work as well as agricultural and livestock activities. This typology was used as input for the economic model.

Following English (1990), English & Raja (1996), and as described by García Vila (2010), the yield response functions were combined with a cost functions to generate profit functions for the different climatic scenarios and farms type. From the profit functions optimal irrigation strategy for different economic and climatic scenarios were obtained.

Economic model

Deficit irrigation is currently not applied to quinoa, and the potential of the technology has only been proved at experimental level. Therefore, an economic model was developed as an ex ante evaluation using cost-benefit analysis (Boardman, 2001; Brent, 2006; Pearce *et al.*, 2006). We estimated the farmer return or profit per hectare as a result of the difference between the cash flow of income and total cost resulting from quinoa production plus any additional costs due to the adoption of irrigation. We assume farmers' decision on whether to irrigate or not is based on risk minimization when they sow crops for self-consumption and profit maximization for cash crops. As mentioned before quinoa crop has moved from food security crop to a cash crop, thus they are free to choose between deficit irrigation for quinoa production or rely on the rainfall.

The basic structure for famer profits per hectare with deficit irrigation are modeled by:

$$\pi_{ij} = [P_q * Y_i * k_j] - [C_{1j} + (C_{2j} * Y_i * k_j) + C_3 + (W_p * X * 10)], \quad [3]$$

where π_{ij} is the profit per hectare (BOB ha^{-1}); P_q is quinoa price received by the farmers (BOB kg^{-1}); Y_i is quinoa yield (kg ha^{-1}), as defined by Eq. [2]; k_j is the yield correction factor related to differences among farms types regarding to crop management; C_{1j} is quinoa cultivation costs per unit area (BOB ha^{-1}); C_{2j} is production costs varying with crop yield (BOB kg^{-1}); C_3 is the cost per year of the investment for the installation of the irrigation system (BOB ha^{-1}); W_p is the price of water (BOB m^{-3}); X is the AIW (mm ha^{-1}); and 10 is the value used for transforming water use from mm to m^3. The water price is not related to any specific charge of use of water for irrigation because Bolivian legislation clearly states that water used for irrigation does not have any price, whereas it is estimated based on the operational cost of the irrigation plus an estimation of the labor used by every farmer for the maintenance of the community system that is related to the amount of water used for irrigation. The subscript i refers to climatic condition and j to farms type. The quinoa price varies according to market demand, whereas yield, production costs and deficit irrigation costs potentially vary for every specific level of applied irrigation water which, at the same time, depends on the climate conditions for the season.

In order to capture the uncertainty related to the climate conditions in the region and the heterogeneity among farmers, resulting from the differences in soil and crop management as well as household assets, a Monte Carlo simulation was used. Instead of using fixed parameters in the model, probability distribution functions (PDFs) for various economic and biological parameters were applied following the methodology introduced by Demont *et al.* (2008), Dillen *et al.* (2008, 2010). Input parameters of Eqs. [2] and [3] as well as the outputs are represented by a distribution function, and results are compared using higher order statistics. In this way we avoid homogeneity bias resulting from using only the mean as comparison parameter. Table 2 summarizes the distribution used for each input parameter, or constant values for those parameters not extracted from the distribution, and the source of these distributions or values. Some specific properties of the simulation model are also listed below.

Prices and yield

Farmers do not have certainty about quinoa yields and prices because the first one depends on the climate conditions, soil and crop management, and the second is related to the market demand internally as well as externally. Hence, uncertainty and heterogeneity are reflected by PDFs as part of Monte Carlo simulation. In the case of yield, we developed normal distributions for each of the coefficient of Eq. [2] from data generated by the AquaCrop model. Also, we used the same distribution for the correction factor (k), which reflects the heterogeneity in quinoa yield due to the identified farms types.

The lognormal PDF on price data is constructed based on the mean and standard deviation of a time series of quinoa export market prices from 1990 to 2009 (INE, 2009) adjusted to quinoa price at farmer level.

Table 2. Distribution function or value and source for parameter used as input in the economic model

Parameter	Function	Data source
Yield correction factor (k)	Normal (μ,σ)	Survey of communities in the region
Quinoa price (BOB kg^{-1})	Lognormal (μ,σ)	(INE, 2009), adjusted at farm level
Seed cost (BOB ha^{-1})	BetaGeneral (α1, α2, min, max)	Survey of communities in the region
Tillage cost (BOB ha^{-1})	BetaGeneral (α1, α2, min, max)	Survey of communities in the region
Sowing cost (BOB ha^{-1})	BetaGeneral (α1, α2, min, max)	Survey of communities in the region
Weeding cost (BOB ha^{-1})	BetaGeneral (α1, α2, min, max)	Survey of communities in the region
Harvest cost (BOB kg^{-1})	BetaGeneral (α1, α22, min, max)	Survey of communities in the region
Fertilization cost (BOB kg^{-1})	RiskExtValue (a, b)	Survey of communities in the region
Transport cost (BOB kg^{-1})	BetaGeneral (α1, α2, min, max)	Survey of communities in the region
Irrigation fixed cost (BOB ha^{-1})	931	Local price for installing an irrigation system
Water price (BOB m^{-3})	Triangular (min, most likely, max)	Estimation based on survey and Duran *et al.* (2003)
Parameter α	Normal (μ, σ)	Generated by AquaCrop simulation
Parameter β	Normal (μ, σ)	Generated by AquaCrop simulation
Parameter γ	Normal (μ, σ)	Generated by AquaCrop simulation

Costs

Beta General PDFs for quinoa cultivation costs (C_{1j}) and production costs varying with crop yield (C_{2j}) were constructed using data collected from a survey at household level by farms type [see Cusicanqui *et al.* (2011) for details]. The C_{1j} include costs from seeds, tillage, sowing and tillage; while reflect fertilization, harvesting and transport costs. In C_{2j} the same way, a fixed price of BOB 931 ha^{-1} was used as the cost per year of the investment for the installation of the irrigation system at farm level. Implementation cost per year was calculated based on materials and installation costs for a micro basin irrigation system, using local materials. A triangular distribution was estimated for water price.

Simulations

The hydro-economic model (Eq. [3]) was setup to be run in Excel, using the @Risk add-in by Palisade Corporation (Ithaca, NY, USA) allowing Monte Carlo sampling in Excel. Each simulation was run for 20,000 interactions to reach convergence in the results. Since the applied irrigation water is the only determinist factor in the model, we carried out three different simulations: rainfed condition, AIW for maximizing quinoa yield, and AIW for maximizing quinoa profit. For the first simulation we used a level of AIW = 0 mm. Before running the other two simulations, we run the Risk Optimizer function in order to obtain the AIW for maximizing quinoa yield and profit for each climate and farms type.

To analyze simulated quinoa profit as an output distribution of stochastic simulations, we used the probability intervals of pair wise differences, as recommended by Griffiths & Zhao (2000). In order to accept the null-hypotheses: *there are no differences for quinoa profit among farms types for any specific AIW*, or *there are no differences for quinoa profit among AIW within specific farms type,* a probability interval of the pair-wise differences of the closest average values should contain the zero value, otherwise we assumed that both farms types for an specific AIW, and AIW for an specific farms type are statistically different.

In addition, since quinoa production of quinoa farms is mostly used for selling (Cusicanqui *et al.*, 2011), we measured the relative contribution of the input parameters to the profit quinoa by running a sensitivity analysis through a normalized stepwise linear regression ($R^2 > 0.90$ always).

Finally, we analyzed the impact of changes in product price by simulating quinoa profit for rainfed conditions and six different schemes of AIW, increasing and decreasing the quinoa price by 5% for the quinoa farms.

Economic water productivity

Economic water productivity can be expressed on the basis of the economic value of the product and water use (Rodrigues & Pereira, 2009), or as in this paper, on the economic value of the product and irrigated water (Playán & Mateos, 2006; García-Vila *et al.*, 2009). We used Eq. [3] to calculate profit for quinoa yield generated by the AquaCrop model for all climate scenarios and for all irrigation schemes and rainfed conditions. The economic water productivity of the applied irrigation water (EWP_{AIW}) in BOB mm^{-1} was calculated as:

$$EWP_{AIW} = (\pi_{ij} - \pi_o) / X_{ij}, \qquad [4]$$

where π_{ij} and X_{ij} are the profit and the corresponding level of AIW for the irrigation scheme and π_o is profit for rainfed conditions. The subscript *i* refers to irrigation scheme (full irrigation (FI), 61% TAW (DI1), 70% TAW (DI2), 80% TAW(DI3) and 90% TAW (DI4); and *j* to climate scenario (wet, normal, dry and very dry). EWP among climate scenarios and irrigation schemes were compared using an ANOVA test.

Results

Simulated quinoa yield by AquaCrop

Rainfall analysis

Fig. 1 shows the rainfall during the quinoa growing cycle versus the probability of exceedance at the study area. The rainfall during the quinoa growing cycle (*R*) at any probability of exceedance (*Pe*) is projected to be equal or greater than:

$$R(Pe) = 4.3Pe + 447 \qquad [5]$$

The threshold rainfall between a wet and normal year is 361 mm, between a normal and dry year is 232 mm, and between a dry and a very dry year is 124 mm.

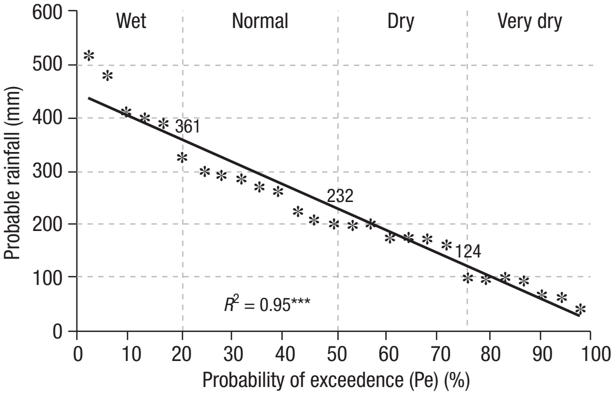

Figure 1. Dependable rainfall in quinoa growing season at Rio Mulatos, Southern Bolivian Altiplano (1983-2010).

Crop water production function

Quinoa grain yields, simulated by AquaCrop, for each year in the 27-year period and for different water availability conditions in the Southern Bolivian Altiplano are presented in Fig. 2. Total quinoa yield *versus* actual evapotranspiration (*ETa*) and the corresponding function are plotted in Fig. 2a. Dotted line shows the logistic tendency of the crop water production function (CWP) for quinoa, and yields produced under rainfed conditions are situated at the lower part of the curve (circles), deficit irrigation strategies are located in the middle (plus signs) and full irrigation in the upper part (triangles).

The corresponding water productivity (WP) is plotted in Fig. 2b. The envelope function above the individual point indicates that WP can be reached for

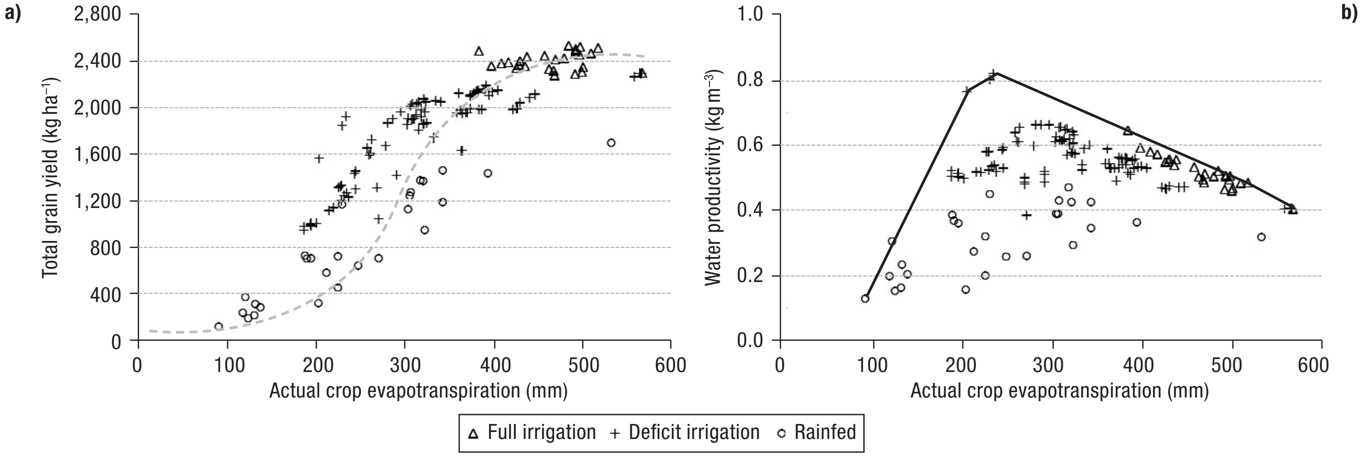

Figure 2. Crop water production function (a) for quinoa under rainfed, deficit and full irrigation in the Southern Bolivian Altiplano with the indication of the logistic curve (dotted line), and the corresponding seasonal water productivity (b) with indication of the upper envelope function (solid line).

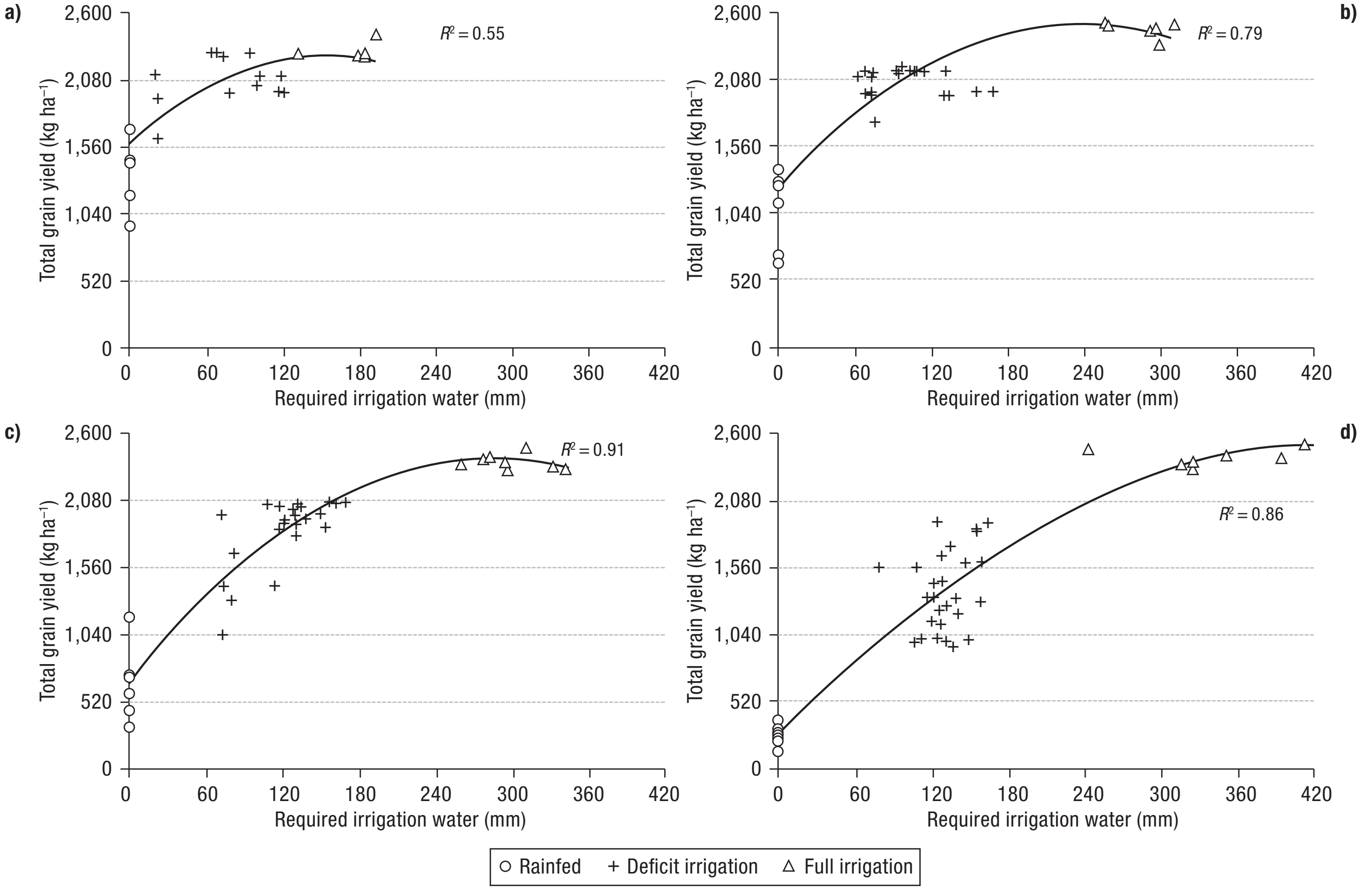

Figure 3. Simulated quinoa grain yield for various amounts of irrigation water for (a) wet, (b) normal, (c) dry, and (d) very dry years.

various ETa. A maximum WP was achieved for an ETa around 250 mm and WP is lower for both rainfed and fully-irrigated quinoa.

Yield response functions

Fig. 3 shows the yield response functions for various climatic conditions and irrigation strategies. By performing a regression analysis a quadratic functional expression for yield response function was assumed and coefficients were obtained (Table 3); R^2 varied from 0.55 for a wet year (Fig. 3a) to 0.91 for a dry year (Fig. 3c). As expected, the maximum quinoa yields, between 2.2 and close to 2.6 ton ha^{-1}, was reached with different amounts of applied irrigated water. In each of the four climatic scenarios the amount of irrigation water required to achieve maximum yield was 155, 235, 280 and 450 mm in wet, normal, dry and very dry years, respectively.

Table 3. Irrigation production functions for quinoa in the Southern Bolivian Altiplano as derived by regression analysis from Fig. 3

Climate type	Equation values[1]	Sig.
Wet (W)	$Y_w = -0.0296X^2 + 9.156X + 1574$	***
Normal (N)	$Y_N = -0.0231X^2 + 10.930X + 1201$	***
Dry (D)	$Y_D = -0.0219X^2 + 12.369X + 657$	***
Very dry (VD)	$Y_{VD} = -0.0114X^2 + 10.205X + 250$	***

[1] X: Applied irrigation water (mm). Y: Quinoa yield (kg ha^{-1}). Sig. ANOVA test for regression. *** $p < 0.001$.

Economic model

Estimated values to compose the PDFs for all parameters used as input in the profit Eq. [3] are presented in Table 4. While yield correction factor and production costs parameters are specific for each farm type, yield response function parameters (α, β, and γ) are linked with a particular type of year. Quinoa and water prices, and irrigation fixed cost are the same for all farm types. Values for AIW were calculated using the Risk Optimizer function at @Risk and they correspond to applied irrigation water values to be used in the simulations for maximizing quinoa yield and profit.

Simulations showed that applied irrigation water for maximum yield was larger than the applied water to attain maximum profit for all type of years. The level of AIW to maximize profit were 40, 50, 60 and 105 mm lower than AIW to maximize yield in wet, normal, dry and very dry year respectively. As expected, wet years required less AIW than normal, dry and very dry years for maximizing yield as well as profit. Likewise, simulated yield under rainfed conditions (term in Eq. [2]) was higher for wet years.

Economic optimization

Economic optimization relates all the irrigation costs with the economic benefit from increasing quinoa productivity and takes into account climate variability as well as farms characteristics. In Table 5 the average quinoa profits and the 95% probability interval of the pair-wise differences between the closest values of either farm type or AIW scheme are reported for each type of year. Quinoa profit differences between farm types were detected within each AIW scheme, with exception of maximum profit and maximum yield during very dry years. In general quinoa farms gained the highest average profit throughout all type of years and AIW schemes, ranging from BOB 480 ha^{-1} under rainfed conditions and very dry years to BOB 6810 ha^{-1} with 185 mm of AIW (profit maximization) under a normal climate scenario. It is also interesting to notice that quinoa profit differences between AIW for maximum profit and rainfed conditions for all farm types are larger under dry or very dry conditions. For instance, for quinoa farms and wet year the difference is about BOB 800 ha^{-1}, while the difference for very dry years is BOB 5,030 ha^{-1} for the same farm type.

The Monte Carlo simulation model allows knowing the relative contribution of the input parameters on the quinoa profit through regression-based sensitivity analysis. Results from the analysis showed a relative positive high value of normalized regression coefficients for quinoa price (0.91), and also positive values for the terms β (0.23) and α (0.19) of the yield response

Table 4. Values of the distributions for the input parameters used in the economic model

Parameter	Function	Value Livestock farm	 Quinoa farm	 Subsistence farm
Yield correction factor (k)	RiskNormal (μ,σ)	(0.7897, 0.0502)	(0.9078, 0.0366)	(0.8440, 0.0434)
Quinoa price (BOB kg^{-1})	RiskLognorm (μ,σ)	(5.755, 2.829)	(5.755, 2.829)	(5.755, 2.829)
Seed cost (BOB ha^{-1})	RiskBetaGeneral (α1, α2, min, max)	(1.2, 4.8, 35, 203)	(2.4, 3.6, 47.4, 101.1)	(2.3, 3.7, 40, 117.8)
Tillage cost (BOB ha^{-1})	RiskBetaGeneral (α1, α2, min, max)	(2.1, 3.9, 50, 648.3)	(2.2, 3.8, 39.7, 553.2)	(1.4, 4.6, 91, 998.2)
Sowing cost (BOB ha^{-1})	RiskBetaGeneral (α1, α2, min, max)	(1.7, 4.3, 104.5, 326.5)	(1.5, 4.5, 91.6, 450.9)	(2.3, 3.7, 98.2, 613.7)
Weeding cost (BOB ha^{-1})	RiskBetaGeneral (α1, α2, min, max)	(2.1, 3.9, 0, 308.5)	(0.3, 5.7, 0, 603.1)	(1.5, 4.5, 0, 646.5)
Harvest cost (BOB kg^{-1})	RiskBetaGeneral (α1, α2, min, max)	(1.7, 4.3, 0.4, 4.2)	(1.6, 4.4, 0.3, 3)	(1.6, 4.4, 0.8, 4)
Fertilization cost (BOB kg^{-1})	RiskExtValue (a, b)	(0.172, 0.194)	(0.066, 0.073)	(0.067, 0.110)
Transport cost (BOB kg^{-1})	RiskBetaGeneral (α1, α2, min, max)	(2.11, 3.89, 0, 0.64)	(1.61, 4.39, 0.09, 0.82)	(0.87, 5.13, 0, .99)
Irrigation fixed cost (BOB ha^{-1})	Fixed value	931	931	931
Water price (BOB m^{-3})	RiskTriang (min, most likeli, max)	(0.5, 1, 1.5)	(0.5, 1, 1.5)	(0.5, 1, 1.5)

		Wet year	Normal year	Dry year	Very dry year
Applied irrigated water (mm)	RiskSimTable (Max. Yield, Max. Profit, Rainfed)	(155,115,0)	(235,185,0)	(280,220,0)	(450,345,0)
Term α	RiskNormal (μ,σ)	(–0.0296,0.0135)	(–0.0231,0.0038)	(–0.0219,0.0025)	(–0.0114,0.0028)
Term β	RiskNormal (μ,σ)	(9.156,2.476)	(10.930,1.236)	(12.369,0.851)	(10.205,1.148)
Term γ	RiskNormal (μ,σ)	(1573.338,86.079)	(1200.701,75.225)	(657.356,60.239)	(249.683,96.415)

Table 5. Simulated profit (BOB ha^{-1}) for different climate scenarios and applied irrigation water schemes for the various identified farm types in the Southern Bolivian Altiplano

Climate scenario	**Parameter**	**Farm type**			**95% Prob. intervals of Δ Profits**
		Livestock	**Quinoa**	**Subsistence**	
Wet	Max. Profit, BOB ha^{-1}	4500	6490	4710	(189, 241)
	Profit Max. Yield, BOB ha^{-1}	4280	6300	4500	(191, 246)
	Profit rainfed, BOB ha^{-1}	408	5700	4250	(155, 191)
	95% Prob. intervals of Δ Profits	(209, 232)	(182, 207)	(205, 228)	
Normal	Max. Profit, BOB ha^{-1}	4840	6810	4990	(125, 182)
	Profit Max. Yield, BOB ha^{-1}	4560	6560	4720	(128, 187)
	Profit rainfed, BOB ha^{-1}	2970	4230	3050	(65, 93)
	95% Prob. intervals of Δ Profits	(273, 287)	(240, 255)	(269, 283)	
Dry	Max. Profit, BOB ha^{-1}	4480	6170	4520	(12, 69)
	Profit Max. Yield, BOB ha^{-1}	4180	5910	4220	(15, 74)
	Profit rainfed, BOB ha^{-1}	1350	2080	1290	(51, 68)
	95% Prob. intervals of Δ Profits	(292, 304)	(257, 270)	(288, 300)	
Very dry	Max. Profit, BOB ha^{-1}	3930	5510	3900	(**–4, 58**)
	Profit Max. Yield, BOB ha^{-1}	3350	5010	3340	(**–16, 50**)
	Profit rainfed, BOB ha^{-1}	140	480	64	(158, 167)
	95% Prob. intervals of Δ Profits	(554, 590)	(483, 522)	(543, 580)	

Non-significant differences are identified by 95% probability intervals that contain zero and are indicated in bold.

function (Eq. [2]), while harvest cost (–0.15), and water price (–0.09) reported negative values.

The effect of the fluctuation of quinoa price on the total quinoa profit for quinoa farms as a function of AIW under different climate scenarios is presented in Fig. 4. Differences among the profit response to quinoa price variation at rainfed conditions are smaller for all type of years, and these are even smaller for very dry conditions, but differences increase as profit move toward the maximum that is reached at the same level of AIW (arrow in the Fig. 4 indicates maximum profit). For instance, differences amplified from about BOB 70 ha^{-1} at rainfed conditions to about BOB 690 ha^{-1} at irrigation for maximum profit for very dry year. Moreover, it is noticed that quinoa profit do not vary more than 5% from the maximum when AIW is reduced by 50 mm for all climate scenarios and quinoa prices.

Economic water productivity

Quinoa economic water productivity for applied irrigated water (EWP$_{AIW}$) in five different irrigation schemes and in four different climate conditions is summarized in Table 6. Differences for EWP among climate scenarios were only significant for wet years, and the highest EWP value of 1.17 was achieved with very dry years and full irrigation. As expected, EWP among different irrigation schemes were significant for all climate scenarios with the exception of wet year. EWP highest values of 4.88, 2.61, 2.39 and 2.21 for a 90% of TAW of deficit irrigation strategy were observed for wet, normal, dry and very dry year, respectively.

Discussion

This article aims to carry out an economic assessment of the implementation of deficit irrigation for quinoa production using an hydro-economic model. The rainfall analysis showed that in despite of the fact that we worked with longer climate-data records (27 years), results of rainfall analysis were similar to those reported by Geerts *et al.* (2009a) who defined a dry year as one with a rainfall smaller than 207 mm and a wet year as one with a rainfall larger than 377 mm for seasonal rainfall. However, with the object of reflect in a more accurate way the dryness of the area, which is a characteristic aspect of the arid and semi-arid regions; we generated four different climate groups (wet, normal, dry and very dry year) classified by the amount of seasonal rainfall.

As expected, CWP for quinoa showed in Fig. 2a has a logistic tendency (dot line) logistic and analogous to

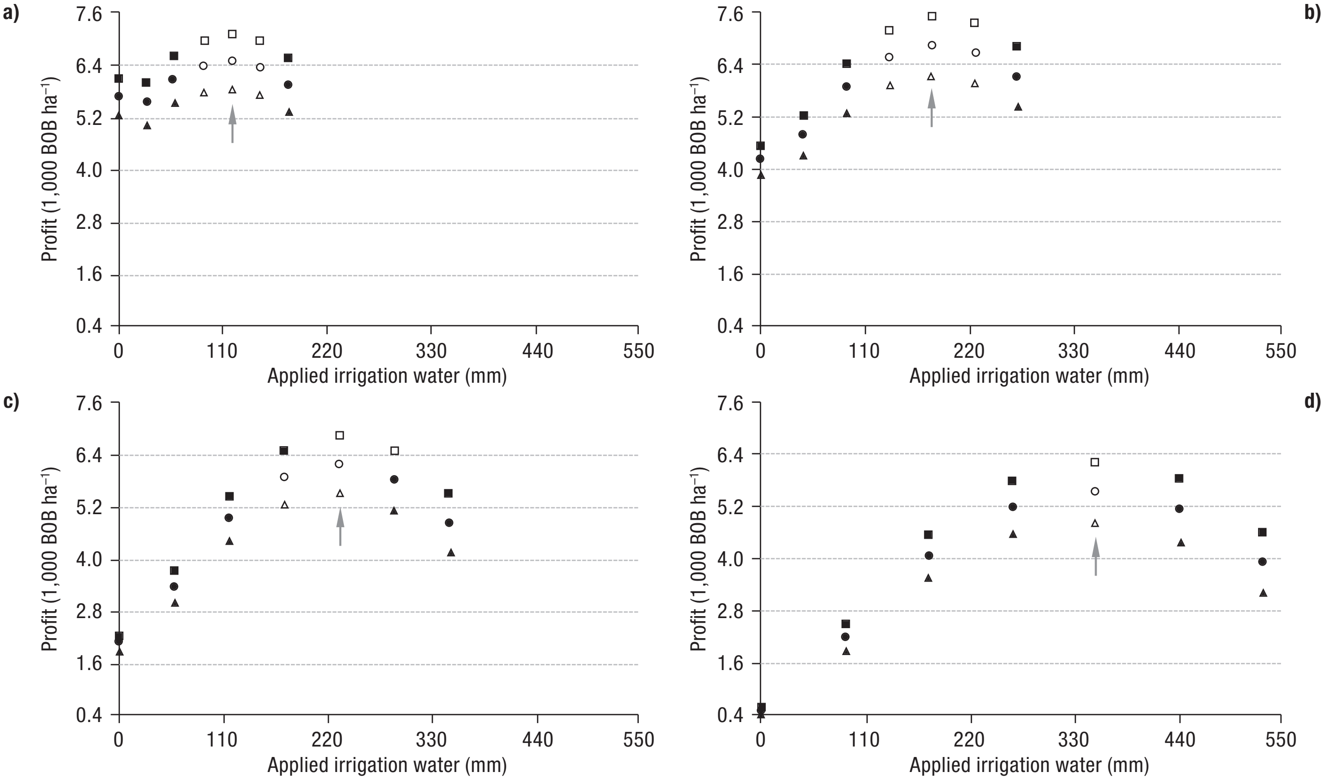

Figure 4. Total profit (π) for quinoa production as a function of applied irrigation water, simulated for average (circles) +5% (squares) and –5% (triangles) variation of quinoa price, for quinoa farms for a) wet, b) normal, c) dry, and d) very dry years. Arrows indicate maximum quinoa profit; open symbols show profit decline less than 5% of maximum profit; closed symbols indicate that maximum profit declines more than 5%.

those found by Hexem & Heady (1978), Taylor *et al.* (1983), DeTar (2008) and Geerts *et al.* (2009a). Moreover, it is important to point out that fluctuation of expected quinoa yield between rainfed and deficit irrigation might be up to three times greater for a similar ETa, that is the result of the timing of the water application under deficit irrigation, which is applied during flowering and early grain filling phase, compared to rainfed conditions that cannot be controlled, which is a competitive advantage of this technology for stabilize quinoa yield.

Quinoa yield for the Southern Bolivian Altiplano under rainfed and different irrigation strategies reported by several authors varied from 0.3 to 2.1 ton ha^{-1} (Aguilar & Jacobsen, 2003; Bosque *et al.*, 2003; García *et al.*, 2003; Geerts *et al.*, 2008b, 2009a,b). These confirm the results found in the present study where quinoa yield was well simulated by the AquaCrop model.

Table 6. Economic water productivity of applied irrigated water (EWP$_{AIW}$, in BOB mm^{-1}) for the four different climate scenarios and the three farm types in the Southern Bolivian Altiplano

Irrigation schemes	**Climate scenarios**				**Prob. > F**
	Wet	**Normal**	**Dry**	**Very dry**	
Full irrigation	0.86	0.74	1.18	1.57	0.009
DI1 (61% TAW)	3.41	2.14	2.09	1.86	ns
DI2 (70% TAW)	3.47	2.19	2.36	2.18	ns
DI3 (80% TAW)	3.54	2.51	2.52	2.14	ns
DI4 (90% TAW)	4.88	2.61	2.39	2.21	ns
Prob. > F	ns	0.003	0.000	0.004	

The results of the economic model demonstrated that maximum profit from quinoa production can be achieved with less irrigation water than required for maximum quinoa yield in all type of climate scenarios, and that profit differences between rainfed and irrigated quinoa are greater in dry and very dry years. Also, as it was found by other studies (Romero *et al.*, 2006; García-Vila *et al.*, 2009; Pérez-Pérez *et al.*, 2010), the study showed that product price is one of the main forces to drive the use of irrigation for improving crop productivity.

Literature suggested that deficit irrigation increases the water productivity, and therefore economic water productivity (English & Raja, 1996; Fereres & Soriano, 1996; Pereira *et al.*, 2002; Oweis & Hachum, 2009). Geerts *et al.* (2009a) working with quinoa, and Rodrigues & Pereira (2009) working with maize, sunflower and wheat, found that water productivity and economic water productivity are highly dependent on climate conditions. Also, Playán & Mateos (2006) reported higher water productivity for cotton with deficit irrigation than with full irrigation. Results from Table 6 suggested similar conclusions as economic water productivity increases with more restricted water use (90% TAW) of deficit irrigation and any of the deficit irrigation schemes were more efficient in the use of water than full irrigation.

Finally, we must indicate that the study showed the potential of using deficit irrigation for quinoa production in the region not only for increasing and stabilize quinoa yield but also for reducing the pressure on for enlarging quinoa production area in order to cope with the increasing demand.

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References

Aguilar PC, Jacobsen SE, 2003. Cultivation of quinoa on the Peruvian Altiplano. Food Rev Int 19(1-2): 31-41.

Allen R, Pereira L, Raes D, Smith M, 1998. Crop evapotranspiration – Guidelines for calculating crop water requirements. FAO Irrig Drain Paper 56, Rome.

Aroni G, 2001. Producción de quinoa en Bolivia. Primer Taller International sobre Quinoa. Universidad Agraria La Molina. Lima, Perú.

Aroni J, Cayoja M, Laime M, 2009. Situación actual al 2008 de la quinua real en el Altiplano Sur de Bolivia. Fundación AUTAPO: Programa complejo productivo Altiplani Sur, Oruro, Bolivia.

Boardman AE, 2001. Cost-benefit analysis: concepts and practice. Prentice Hall, Upper Saddle River, NJ, USA.

Bosque H, Lemeur R, Van Damme P, Jacobsen SE, 2003. Ecophysiological analysis of drought and salinity stress of quinoa (*Chenopodium quinoa* Willd). Food Rev Int 19(1-2): 111-119.

Brent RJ, 2006. Applied cost-benefit analysis. Edward Elgar Publ Ltd, UK.

Collao Perez FR, 2001. La cadena productiva de la quinoa en Bolivia. World Bank Report.

Comai S, Bertazzo A, Bailoni L, Zancato M, Costa CV, Allegri G, 2007. The content of proteic and nonproteic (free and protein-bound) tryptophan in quinoa and cereal flours. Food Chem 100: 1350-1355.

Consorcio ASECAL SL, Mercurio SL, 2011. Estudio de mercado para la quinoa y la kiwicha en Alemania. Proyecto UE-Peru/PENX. Agencia Peruana de Cooperación Internacional & Comunidad Europea. Lima, Peru.

Cossio J, 2008. Agricultura de conservación con un enfoque de manejo sostenible en el Altiplano Sur. Habitat 75: 44-49.

Cusicanqui J, García, M, Raes, D, Geerts S, Mathijs, E, 2011. Caracterización de los sistemas de subsistencia basados en la producción de quinua en el Altiplano Sur de Bolivia. In: Compendio trabajos de investigación "Proyecto QUINAGUA". La Paz, Bolivia. pp: 111-129.

Demont M, Cerovska M, Daems W, Dilleb K, Fogarasi J, Mathijs E, Muska F, Soukup J, Tollens E, 2008. Ex ante impact assessment under imperfect information: biotechnology in new member states of the EU. J Agr Econ 59(3), 463-486.

DeTar WR, 2008. Yield and growth characteristics for cotton under various irrigation regimes on sandy soil. Agr Water Manage 95, 69-76.

Dillen K, Demont M, Tollens E, 2008. European sugar policy reform and agricultural innovation. Can J Agric Econ 56: 533-553.

Dillen K, Mitchell PD, Tollens E, 2010. On the competitiveness of *Diabrotica virgifera virgifera* damage abatement strategies in Hungary: a bio-economic approach. J Appl Entomol 134: 395-408.

Dosso M, Bres A, Moreau S, 2006. How soil misuse ends with farming system disintegration. A Bolivian altiplano example. 18th World Congress of Soil Science. July 9-15, Philadelphia, PA, USA.

Duran A, Moscoso O, Romero A, Huibers F, Agodzo S, Chenini F, Van Lier J, 2003. Use of wastewater in irrigated agriculture. Countries studies from Bolivia, Ghana and Tunisia. Vol 1: Bolivia. WUR, Wageningen, The Netherlands.

English M, 1990. Deficit irrigation. I. Analytical framework. J Irrig Drain Eng 116(3): 399-412.

English M, Raja SN, 1996. Perspectives on deficit irrigation. Agr Water Manage 32: 1-14.

Felix D, 2008. Cultivo sostenible de la quinua en Bolivia: prácticas individuales y reglas comunitarias. Report of project "Sostenibilidad de los sistemas de producción de las familias indigenas de los municipios de Llica, Tahua y Salinas de Garci Mendoza". Agronomes and Vétérinaires sans Frontiéres, La Paz, Bolivia.

Felix D, Villca C, 2009. Quinua y territorio. Experiencias de acompañamiento a la gestión del territorio y a la autogestión comunal en la zona intersalar del Altiplano Boliviano. Agronomes and Vétérinaires sans Frontiéres. La Paz, Bolivia.

Fereres E, Soriano MA, 1996. Deficit irrigation for reducing agricultural water use. Agr Water Manage 32: 1-14.

García M, Raes D, Jacobsen S, 2003. Evapotranspiration analysis and irrigation requirements of quinoa (*Chenopodium quinoa*) in the Bolivian highlands. Agr Water Manage 60: 119-134.

García M, Raes D, Allen R, Herbas C, 2004. Dynamics of reference evapotranspiration in the Bolivian highlands (Altiplano). Agr Forest Metereol 125: 67-82.

García M, Raes D, Jacobsen SE, Michel T, 2007. Agroclimatic constraints for rainfed agriculture in the Bolivian Altiplano. J Arid Environ 71: 109-121.

García Vila M, 2010. Advances in the optimization of irrigation water use: upscaling from crop to farm. Tesis doctoral. Universidad de Córdoba. Spain.

García-Vila M, Fereres E, Mateos L, Orgaz F, Steduto P, 2009. Deficit irrigation optimization of cotton with AquaCrop. Agron J 101(3): 477-187.

Geerts S, Raes D, García M, Del Castillo C, Buytaert W, 2006. Agro-climatic suitability mapping for crop production in the Bolivian altiplano: a case study for quinoa. Agr Forest Metereol 139: 399-412.

Geerts S, Raes D, García M, Vacher J, Mamani R, Mendoza J, Huanca R, Morales B, Miranda R, Cusicanqui J, 2008a. Introducing deficit irrigation to stabilize yield of quinoa (*Chenopodium quinoa* Willd.). Eur J Agron 28: 427-436.

Geerts S, Raes D, García M, Condori O, Mamani J, Miranda R, Cusicanqui J, Taboada C, Yucra E, Vacher J, 2008b. Could deficit irrigation be a suitable practice for quinoa (*Chenopodium quinoa* Willd.) in the Southern Bolivia altiplano? Agr Water Manage 95: 909-917.

Geerts S, Raes D, García M, Taboada C, Miranda R, Cusicanqui J, Michel T, Vacher J, 2009a. Modeling the potential for closing quinoa yield gaps under varying water availability in the Bolivian Altiplano. Agr Water Manage 96: 1652-1658.

Geerts S, Raes D, García M, Miranda R, Cusicanqui J, Taboada C, Mendoza J, Huanca R, Osco V, Steduto P, 2009b. Simulating yield response of quinoa towater availability with AquaCrop. Agron J 101(3): 499-508.

Griffiths W, Zhao X, 2000. A unified approach to sensitivity analysis in equilibrium displacement models: comment. Am J Agr Econ 82(1): 236-240.

Hellin J, Higman S, 2005. Crop diversity and livelihood security in the Andes. Development in Practice 15: 165-174.

Hexem RW, Heady EO, 1978. Water production function for irrigated agriculture. Iowa State Univ Press.

Hsiao T, Heng L, Steduto P, Rojas-Lara B, Raes D, Fereres E, 2009. AquaCrop – The FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. Agron J 101(3): 448-459.

IBCE, 2012. Quinua en Bolivia. Instituto Boliviano de Comercio Exterior, Santa Cruz, Bolivia.

IBTA, 1994. Annual Report 1993-1994 Quinoa National Program. Instituto Boliviano de Tecnología Agropecuaria, La Paz, Bolivia.

INE, 2000. Anuario Estadístico 1999. Instituto Boliviano de Estadísticas, La Paz, Bolivia.

INE, 2008. Anuario Estadístico 2007. Instituto Boliviano de Estadísticas, La Paz, Bolivia.

INE, 2009. Estadísticas de Comercio Exterior 2008. Instituto Nacional de Estadísticas, La Paz, Bolivia.

INE, 2011. Anuario Estadístico 2010. Instituto Nacional de Estadística, La Paz, Bolivia.

Jacobsen SE, 2011. The situation for quinoa and its production in Southern Bolivia: from economic success to environmental disaster. J Agron Crop Sci 197: 390-399.

Jacobsen SE, Mujica A, Ortiz R, 2003. The global potential for quinoa and other Andean crops. Food Rev Int 19(1-2): 139-148.

Jacobsen SE, Monteros C, Christiansen J, Bravo L, Corcuera L, Mujica A, 2005. Plant responses of quinoa (*Chenopodium quinoa* Willd.) to frost at various phenological stages. Eur J Agron 22: 131-139.

Jacobsen SE, Monteros C, Corcuera L, Bravo L, Christiansen J, Mujica A, 2007. Frost resistance mechanisms in quinoa (*Chenopodium quinoa* Willd.). Eur J Agron 26: 471-475.

Jansen C, Jacobsen SE, Andersen M, Nuñez N, Andersen S, Rasmussen L, Mogensen V, 2000. Leaf gas exchange and water relations of field quinoa (*Chenopodium quinoa* Willd.) during soil drying. Eur J Agron 13: 11-25.

Joffre R, Acho J, 2008. Quinoa, descanso y tholares en el sur del Altiplano Boliviano. Revista Habitat 75: 38-48.

MDRyT-CONACOPROQ, 2009). Política nacional de la quinua. Ministerio de Desarrollo Rural y Tierras-Consejo Nacional de Comercializadores y Productores de Quinua, La Paz, Bolivia.

Molden D, 2003. A water productivity framework for understanding and action. In: Water productivity in agriculture: limits and oportunities for improvement (Kijne J, Barker R, Molden D, eds). Int Water Manage Inst, Colombo, Sri Lanka. pp: 1-18.

Mujica A, Ortiz R, Bonifacio A, Saravia R, Corredor G, Romero A, Jacobsen SE, 2006. Agroindustria de la quinoa (*Chenopodium quinoa* Willd.) en los países andinos. UNDP, Concytec (Perú), PROINPA (Bolivia), UNC (Colombia), Puno, Peru.

Oweis T, Hachum A, 2009. Optimizing supplemental irrigation: tradeoffs between profitability and sustainability. Agr Water Manage 96(3): 511-516.

Pearce D, Atkinson G, Mourato S, 2006. Cost-benefit analysis and the environment: recent developments. OECD, Paris.

Pearsall DM, 1992. The origins of plant cultivation in South America. In: The origins of agriculture (Cowan CW, Watson PJ, eds). Smithsonian Inst Press, Washington DC. pp: 173-205.

Pereira LS, Oweis T, Zairi A, 2002. Irrigation management under water scarcity. Agr Water Manage 57: 175-206.

Pérez-Pérez JG, García J, Robles JM, Botia P, 2010. Economic analysis of navel orange cv. 'Lane late' grown on two different drought-tolerant rootstocks under deficit irrigation in South-eastern Spain. Agr Water Manage 97(1): 157-164.

Playán E, Mateos L, 2006. Modernization and optimization of irrigation systems to increase water productivity. Agr Water Manage 80: 100-116.

PNUD-Bolivia, 2008. El Altiplano. El potencial de la agricultura orgánica y la fibra de camélidos de los Andes. Programa de las Naciones Unidas para el Desarrollo-Bolivia, La Paz, Bolivia.

Raes D, Steduto P, Hsiao TC, Fereres E, 2009. AquaCrop – The FAO crop model to simulate yield response to water: II. Main algorithms and software description. Agron J 101(3): 438-447.

Raes D, Steduto P, Hsiao TC, Fereres E, 2012. AquaCrop Reference Manual. FAO, Land and Water Division. Rome.

Repo-Carrasco R, Espinoza C, Jacobsen SE, 2003. Nutritional value of use of the Andean crops quinoa (*Chenopodium quinoa*) and kañiwa (*Chenopodium pallidicaule*). Food Rev Int 19: 179-189.

Rodrigues GC, Pereira LS, 2009. Assessing economic impacts of deficit irrigation as related to water productivity and water costs. Biosyst Eng 103(4): 536-551.

Rojas W, Soto JL, Carrasco E, 2004. Study on the social, environmental and economic impact of quinoa promotion in Bolivia. PROINPA Foundation, La Paz, Bolivia.

Romero P, García J, Botía P, 2006. Cost-benefit analysis of a regulated deficit-irrigated almond orchard under subsurface drip irrigation conditions in Southeastern Spain. Irrig Sci 24(3): 175-184.

Sevruk B, Geiger H, 1981. Selection of distribution types for extremes of precipitation. World Metereological Organization, Operational Hydrology Report No. 15, WMO-No. 560, Geneva.

Soraide D, Revilla R, Claver MP, Gutiérrez Z, 2011. La quinua real en el Altiplano Sur de Bolivia. Fundación FAUTAPO – Educación para el Desarrollo, La Paz, Bolivia.

Steduto P, Hsiao TC, Raes D, Fereres E, 2009. AquaCrop - The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. Agron J 101(3): 426-437.

Taylor HM, Jordan WR, Sinclair TR, 1983. Limitations to efficient water use in crop production. Am Soc Agron Crop Sci Soc Soil Sci Soc of America. Madison, WI, USA.

UNDP, 2010. Human Development Report 2010. 20th Aniversary Edition. United Nations Development Programme, NY, USA.

Vacher J, 1998. Responses of two main crops, quinoa (*Chenopodium quinoa* Willd) and papa amarga (*Solanum juzepczukii* Bulk) to drought on the Bolivian Altiplano: significance of local adaptation. Agr Ecosyst Environ 68: 99-108.