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). 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 km² 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-
Environmentsal 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-km² 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).

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:

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

where \( R( Pe) \) is the amount of rainfall (mm) at exceedance probability of \( Pe \), and \( \alpha \) and \( \beta \) 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 \( \leq 20% \) 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 \( \geq 75% \).

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 (ET0) (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 adequately 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, 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.

| 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:

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

where \( Y_i \) is the total quinoa grain yield (kg ha\(^{-1}\)); \( X \) is the amount of applied irrigation water (AIW) expressed in mm; \( \alpha_i, \beta_i \) and \( \gamma_i \), 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 farmer profits per hectare with deficit irrigation are modeled by:

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

where $$\pi_{ij}$$ 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; $$C_{ij}$$ is quinoa cultivation costs per unit area (BOB ha−1); $$C_{ij}$$ is production costs varying with crop yield (BOB kg−1); $$C_j$$ 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 m³. 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.
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.

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 \((\mu, \sigma)\)  | Survey of communities in the region             |
| Quinoa price \((\text{BOB kg}^{-1})\)   | Lognormal \((\mu, \sigma)\) | (INE, 2009), adjusted at farm level             |
| Seed cost \((\text{BOB kg}^{-1})\)      | BetaGeneral \((\alpha_1, \alpha_2, \text{min, max})\) | Survey of communities in the region             |
| Tillage cost \((\text{BOB ha}^{-1})\)   | BetaGeneral \((\alpha_1, \alpha_2, \text{min, max})\) | Survey of communities in the region             |
| Sowing cost \((\text{BOB ha}^{-1})\)    | BetaGeneral \((\alpha_1, \alpha_2, \text{min, max})\) | Survey of communities in the region             |
| Weeding cost \((\text{BOB ha}^{-1})\)   | BetaGeneral \((\alpha_1, \alpha_2, \text{min, max})\) | Survey of communities in the region             |
| Harvest cost \((\text{BOB kg}^{-1})\)   | BetaGeneral \((\alpha_1, \alpha_2, \text{min, max})\) | Survey of communities in the region             |
| Fertilization cost \((\text{BOB kg}^{-1})\) | RiskExtValue \((a, b)\) | Survey of communities in the region             |
| Transport cost \((\text{BOB kg}^{-1})\) | BetaGeneral \((\alpha_1, \alpha_2, \text{min, max})\) | Survey of communities in the region             |
| Irrigation fixed cost \((\text{BOB ha}^{-1})\) | 931 | Local price for installing an irrigation system |
| Water price \((\text{BOB m}^{-3})\)    | Triangular \((\text{min, most likely, max})\) | Estimation based on survey and Duran et al. (2003) |
| Parameter \(\alpha\)                   | Normal \((\mu, \sigma)\)  | Generated by AquaCrop simulation                |
| Parameter \(\beta\)                    | Normal \((\mu, \sigma)\)  | Generated by AquaCrop simulation                |
| Parameter \(\gamma\)                   | Normal \((\mu, \sigma)\)  | Generated by AquaCrop simulation                |

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 a specific AIW, and AIW for a 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:

\[ EWP_{AIW} = (\pi_{ij} - \pi_0)/X_{ij} \]

where $\pi_{ij}$ and $X_{ij}$ are the profit and the corresponding level of AIW for the irrigation scheme and $\pi_0$ 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:

\[ R(\text{Pe}) = 4.3\text{Pe} + 447 \]

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.

**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 ($ET_a$) 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
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. *** $p < 0.001$. 

**Figure 3.** Simulated quinoa grain yield for various amounts of irrigation water for (a) wet, (b) normal, (c) dry, and (d) very dry years.
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 \((\alpha, \beta, \text{and } \gamma)\) 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 \(\beta\) (0.23) and \(\alpha\) (0.19) of the yield response

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

| Parameter                          | Function                               | Livestock farm | Quinoa farm | Subsistence farm |
|-----------------------------------|----------------------------------------|----------------|-------------|-----------------|
| Yield correction factor (k)       | RiskNormal (\(\mu, \sigma\))           | (0.7897, 0.0502) | (0.9078, 0.0366) | (0.8440, 0.0434) |
| Quinoa price (BOB kg\(^{-1}\))    | RiskLognorm (\(\mu, \sigma\))         | (5.755, 2.829)  | (5.755, 2.829)  | (5.755, 2.829)  |
| Seed cost (BOB ha\(^{-1}\))      | RiskBetaGeneral (\(\alpha_1, \alpha_2, \min, \max\)) | (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 (\(\alpha_1, \alpha_2, \min, \max\)) | (2.1, 3.9, 50, 648.3) | (2.3, 2.8, 39.7, 553.2) | (1.4, 4.6, 91, 998.2) |
| Sowing cost (BOB ha\(^{-1}\))    | RiskBetaGeneral (\(\alpha_1, \alpha_2, \min, \max\)) | (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 (\(\alpha_1, \alpha_2, \min, \max\)) | (2.1, 3.9, 308.5)  | (0.3, 5.7, 603.1)  | (1.5, 4.5, 664.5) |
| Harvest cost (BOB kg\(^{-1}\))   | RiskBetaGeneral (\(\alpha_1, \alpha_2, \min, \max\)) | (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 (\(\alpha_1, \alpha_2, \min, \max\)) | (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)   |
| Applied irrigated water (mm)      | RiskSimTable (Max. Yield, Max. Profit, Rainfed) | (155,115,0) | (235,185,0) | (280,220,0) |
| Term \(\alpha\)                  | RiskNormal (\(\mu, \sigma\))           | (-0.0296,0.0135) | (-0.0231,0.0038) | (-0.0219,0.0025) |
| Term \(\beta\)                   | RiskNormal (\(\mu, \sigma\))           | (9.156,2.476)   | (10.930,1.236) | (12.369,0.851) |
| Term \(\gamma\)                  | RiskNormal (\(\mu, \sigma\))           | (1573.338,86.079) | (1200.701,75.225) | (657.356,60.239) |

Wet year                               | Normal year                             | Dry year                              | Very dry year |
|----------------------------------------|-----------------------------------------|---------------------------------------|---------------|
| (155,115,0)                            | (235,185,0)                             | (280,220,0)                           | (450,345,0)   |
| (-0.0296,0.0135)                       | (-0.0231,0.0038)                        | (-0.0219,0.0025)                      | (-0.0114,0.0028) |
| (9.156,2.476)                          | (10.930,1.236)                          | (12.369,0.851)                        | (10.205,1.148) |
| (1573.338,86.079)                       | (1200.701,75.225)                       | (657.356,60.239)                      | (249.683,96.415) |
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<sub>AIW</sub>) 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.

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

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
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 (EWPₐₚᵢₗ, 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 Rodriguez & 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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