International Journal of Food and Agricultural Economics
ISSN 2147-8988, E-ISSN: 2149-3766
Vol. 6, No. 4, 2018, pp. 1-19

LONG-TERM CHOICES FOR QUINOA FARMERS IN PUNO, PERU. A REAL OPTIONS STUDY*

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Abstract

The aim of this article is to assess the optimal choices of a smallholder quinoa farmer in the Puno Peru, in terms of their decision if and when to undertake certain investments that are expected to increase quinoa yield and crop resistance to harsh weather conditions, i.e. frost. We focus on two options, namely quinoa variety management and Waru Waru. The former alternative considers the option of the farmer to switch from his business-as-usual quinoa variety to one that has different yield and frost resistance characteristics. The latter alternative refers to the implementation of an ancestral cultivation practice that is estimated to offer benefits in terms of yield increase and resistance to harsh climate conditions. We rely on Real Options Analysis to assess these opportunities for the farmer. The article also discusses how quinoa price dynamics, yield sensitivity to frost, and governmental support impact the decisions of the smallholder farmer.

Keywords: *Quinoa; Smallholder; Real Options; Risk Assessment; Food security; Latin America.*
Jel Codes: *D81, Q01, Q12, Q14, Q16, Q51, P45, O13*

1. Introduction

Food security is one of the main topics on the international development agenda and plays an important role in the achievement of the first two United Nation's Sustainable Development Goals UN (2015). Food security is concerned not only with the capacity to produce enough food to feed the world population, but also with the way production is achieved. In this setting, quinoa stands out as an interesting alternative to efficiently produce protein for human consumption, as recently globally popularized by FAO (Ruales & Nair 1992). However, quinoa production has historically prevailed in localized areas of Peru, Bolivia, and Ecuador, and it remains debatable whether massive global production is a viable and sustainable option.

* This work was carried out during the tenure of an oikos PhD fellowship at the Department of Banking and Finance of the University of Zurich, Switzerland."

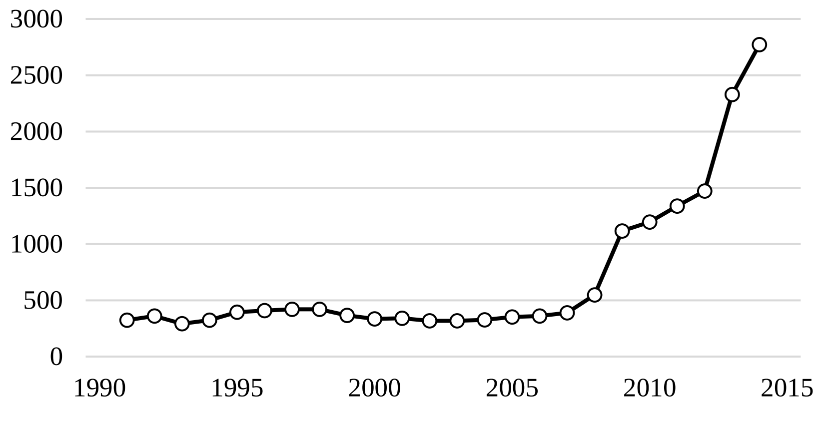
This article aims to evaluate two important decisions available for a smallholder quinoa farmer. We focus on two irreversible options, namely quinoa variety management and Waru Waru. The former alternative considers the option of the farmer to switch from his business-as-usual quinoa variety to one that has different yield and frost resistance characteristics. The latter alternative refers to the implementation of a traditional cultivation practice that is estimated to offer benefits in terms of yield increase and resistance to harsh climate conditions. The ROA approach is especially useful for taking decisions under uncertainty. In finance, an option is a title that gives its owner the right, but not the obligation, to buy (in the case of a call option) or to sell (in the case of a put option) another financial title, such as a stock. Moreover, the ROA allows not only for the identification of the decision whether or not to invest, but it helps determine also the optimal time to exercise the option.

After the option is exercised (if that becomes optimal ever), there is no return to the previous situation. A real option involves a similar decision, except that the approach is applied to a real life decision rather than to a financial instrument (Chesney et al. 2017b). In the context of this article, the representative farmer may choose to invest in a technology that improves the quinoa yield; here, exercising the option means investing in such technology by spending resources to that end; once the investment has been made, the decision is considered irreversible. Irreversibility in this context is then understood as result of the high investment that this option may represent in comparison to the farmer's budget for such end, and/or the specific features and technicalities of introducing a new quinoa variety to their production scheme. However, research regarding costly reversibility has been conducted by Song et al. and could be included in a further approach to this case, but for the purpose of this work we assume once the farmers decide to take an option there are budget constrained to reverse it.

1.2 The Setting of Quinoa Farming In Peru

1.2.1 Quinoa

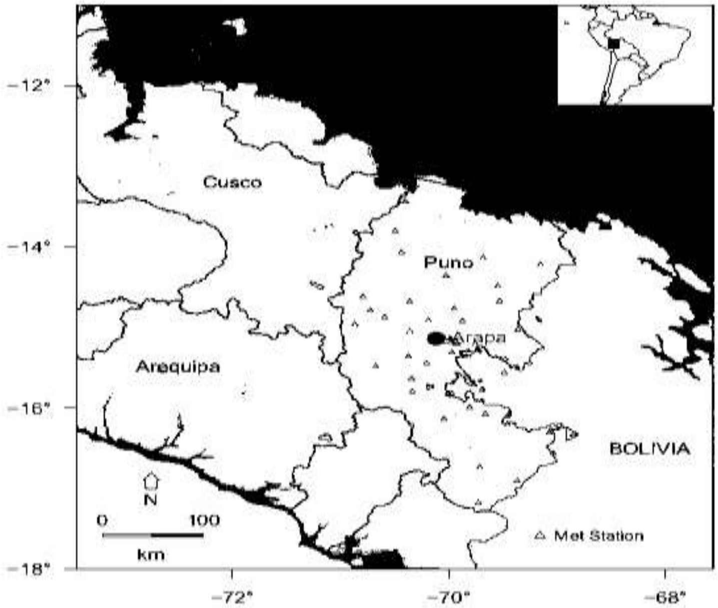
Quinoa or "quinua" is the generic name for Chenopodium Quinoa, a crop from the family of the amaranth. It is commonly believed that quinoa is a grain; however, from a botanical perspective, quinoa is a relative of spinach, beets and chard (FAO 2013a). The main world producers of quinoa are Bolivia and Peru. In 2008, the two countries accounted for 92% of the world quinoa production (FAO 2015).



Source: Own Illustration Based On Data From FAO (2017)

Figure 1. Official Price of Quinoa in USD per Hectare as Reported by FAO

Depending on the region where the crop is cultivated, there are five general types of quinoa1[1] (FAO 2013b): (i) dry valley and humid valley, (ii) altiplano (white and colored), (iii) saltflat, (iv) sea level, and (v) the Yunga agroecological zone and subtropics. Only the first two varieties are cultivated in Peru, while the third and fifth varieties are attributed to Bolivia, while the sea level variety is better adapted to Chile.



Source: SENAMHI (2017)

Figure 2. General Location of Weather Stations in Puno

This Andean endemic crop is recognized to have important nutritional properties and to have the potential to become an important part of global agriculture, as a main source of protein or a "Super Food." In fact, the year 2013 was declared by the United Nations "The International Year of Quinoa" or "IYQ" (FAO 2013a) see Figure 1. This acknowledgment helped to draw the world's attention to the role that quinoa could play in providing food security, nutrition and poverty eradication in support of achieving Sustainable Development Goals. The IYQ also allowed for quinoa prices and production to flourish experiencing an atypical increase of between 2012 and 2014 according to official sources. In fact, producer prices increased 139% during the period, while area harvested followed with a corresponding increase of almost 175% (FAO 2017); see Figure 2.

1.2.2 The Study Location: Puno

This study focuses on quinoa smallholder farmers in Puno, one of the 24 departments of Peru, formed by 13 provinces in the southeastern area of the country. Puno is located in the western part of the Lake Titicaca, over the Collao Plateau. The Andean mountains make up to 70% of the department's area, and the rest is covered by part of the Amazon rainforest. There are two very distinct regions in the Department of Puno: the plateau or "Altiplano" and the mountain region or "Sierra". Both areas have a cold and dry climate, with a three-to-four month long rain seasons, and a couple months of a very dry season, usually in June and July. As Puno is located in high altitude, it experiences more extreme meteorological conditions than the rest of the country. Soil characteristics tend to be arid or semiarid. Although water is available near the lake area, it is a limiting factor in most of the region. Puno has also been regarded as the cradle of domesticated potato agriculture and is currently is the main producer of quinoa in Peru (Ministerio de Agricultura y Riego 2017).

According to information provided by SENAMHI[2], there are 44 weather stations located in Puno. However, data from only 5 stations has been cleaned and could be used for analysis at the time of this study[3]; see Figure 2 for a general reference on the location and altitude of the Stations in Puno. The availability of data to be inputted in our model is largely restricted and some of it is not available from local authorities, i.e. Dirección Regional Agraria (2017). Under these conditions, we restricted our analysis to Arapa, whereby both the availability and quality of the data was assessed to be higher.[4]

The article is organized as follows. Section 1 provides a brief description of the setting in which the investment decision will be assessed and points to the main characteristics of the crop of interest. Section 2 gives an overview of the state of research in ROA, particularly related to agriculture decisions. Section 3 provides details on the options considered in the Section 4 outlines the model, while Section 5 presents the main findings. Section 6 concludes.

2. Literature Review

This article evaluates agriculture decisions in Latin America. Given the vast importance of this sector for the economy of the region, it is not surprising that most academic research targeting this area focuses on agriculture. Kaufmann and Snell (1997) assess the sensitivity of corn yield to climatic, social and economic factors. Sietz et al. (2012) identify the patterns of smallholder vulnerability to weather extremes impacting food security in the region. Altieri and Nicholls (2017) focus on the potential role of adaptation and mitigation strategies of climate change for traditional agriculture. They identify the external drivers of vulnerability and point to the potential of Waru Waru raised fields to reduce such vulnerability. In fact, they describe Waru Waru and similar techniques as models of climate smart traditional agriculture. Barrera et al. (2012) study natural resource management in Ecuador and show that the implementation of enhanced management practices contributes to reduced environmental vulnerability and improved welfare.

Our article assesses two long-term investment options for quinoa farmers in Puno. We analyze at the option to switch quinoa varieties and the option to invest in the setup of a Waru Waru agricultural technique. The literature on the latter investment dates quite a while back given the long history of this agricultural approach; however, not many new assessments have been performed in the last decade to update the analysis to present times. Erickson (1986) offers a review of the literature related to raised field practices in agriculture, among which Waru Waru, and provides some information about the potential increases in quinoa yields obtained under Waru Waru compared with the business-as-usual. Mujica Barreda (1997) extends this research and offers a more comprehensive analysis on the profitability of the raised fields in Puno. He specifies the increase in profitability of Waru Waru systems when compared to equivalent fields that do not apply this technology at about 20%.

Lhomme and Vacher (2003) highlight the benefits of using the raised fields approach; in particular, Waru Waru is estimated to reduce the effects of night frost. Although their study focuses only on the cultivation of potatoes, it is expected that their findings apply to quinoa as well. Llerena et al. (2004) review 19 articles that describe the physical characteristics of the raised fields in Peru and particularly account for the historical reasons behind the abandonment of these technologies. It is implied in most cases that such abandonment followed particular historic events, such as the elevated mortality in the Indian population in the pre-Columbian era. Llerena et al. (2004). However, not much is clarified regarding the reasons that explain the current low use of the technique in the Andes.

Our article contributes to the literature by developing a dynamic real options model that accounts for market and environmental dimensions of quinoa agriculture in Peru. The concept of option value was introduced in environmental economics since several decades, even before the appearance of real options (Arrow & Fisher 1974; Fisher & Krutilla 1975; Henry 1974). Real Option Assessment is not foreign to Latin America. Numerous studies have been developed to describe different issues within the region; however, the application of this methodology to agriculture in Latin America, and in particular to Peru, is quite novel. Among the few contributions, an application of ROA in Peru is done by Chesney et al. (2017a), whereby the authors focus on REDD (Reducing Emissions from Deforestation and

Forest Degradation) projects and aim to identify the optimal deforestation rate and timing to enter the REDD scheme under different risk aversion scenarios. Finally Song et al (2010 and 2011) offer an interesting approach to asses costly reversibility for perennial energy crops and alternative land use policies, an important contribution to the literature on ROA.

3. Long-Term Investment Options in Quinoa

This section provides details on the two agriculture techniques relevant for the quinoa smallholder farmer in Puno. The model to evaluate the two options and the main results are fully described in the following sections.

3.1 First Option: Quinoa Variety Management

In the world, there are roughly 120 known seed varieties of Quinoa. Among them, only 13 seed varieties appear to be commercially feasible in Peru (FAO 2015). Quinoa varieties come in a diverse palette of colors, with white being the best known globally due to the long tradition of its organic cultivation since centuries; red and black varieties are also gaining relevance on some markets. Aside from color, quinoa varieties come with different levels of yield and resistance to drought or salinity. In fact, according to the survey led by MeteoSwiss, farmers tend to have different preferences for particular quinoa varieties, depending on factors such as tradition, experience, and peer influence.

For the purpose of this study, the management of quinoa varieties was regarded as an independent and exclusive option in which the producer has the opportunity to choose the quinoa variety that optimizes the revenue. Given the data limitations mentioned above, we lead a sensitivity analysis trying to account for a wide range of scenerios.

3.2 Second Option: The Waru Waru Technique

Waru waru is a system of soil management for irrigation purposes and weather mitigation that is believed to have been developed before the raise of the Inca empire in the year 300 B.C. (OAS 2017). Waru Waru is a technique suitable to areas with extreme climatic conditions, such as mountainous areas that experience heavy rainfalls and periodic droughts, and where temperature fluctuations range from intense heat to frost. Despite its expected benefits, the prevalence of the technique remains low. Even more, it appears that even after implementation, Waru Waru has been abandoned in 3 out of 4 projects (Source: Interview with Dr. Alipio Canahua Murillo, April 2017). For the purpose of this study, Waru Waru was regarded as an independent and exclusive option.

3.3 Other Investment Options

In our study the two investment options have been regarded as independent and exclusive. One could argue that the two options should be assessed simultaneously, which could be achieved with the real options approach. However, this would require the estimation of the joint impact of the two options on the revenues of the farmer. Since such correlation has not yet been assessed for these options, the joint evaluation remains out of the scope of the present study, but it could be incorporated in a later stage of the project as information becomes available.

On the same esteem, there are further options that were not included in the current stage of this study such as organic certification, irrigation, technification, climate insurance, use of pesticides, etc. Such options could also result in significant benefits for the producers and could be assessed in a further stage of analysis. Some options, such as irrigation and technification, require that the assessment be led at the community level and not at a farmer's level, which would call for a different theoretical model altogether. Furthermore, important applications of this model could also be implemented for other regions of Peru, including Cuzco, and the coastal area. The model could also be applied to obtain further findings in other countries that are also relevant for Quinoa production, i.e. Bolivia and Ecuador.

4. Model and numerical methods

This section describes the main theoretical setup of our decision-making model that will be solved with the help of the real options approach. We also dig into the main assumptions regarding key model parameters and give details on their calibration.

4.1 Model setup

In this article, we take the view of a smallholder quinoa farmer in the Peruvian altiplano that is considering several investment options that could increase his overall profits. The two long-term decisions he is evaluating are (i) changes in quinoa variety and (ii) the Waru Waru farming technique, as described in Section 3.

The two options[5] consist in very different farming options, the evaluation of their feasibility calls for a fairly similar decision process. Namely, we assume that the representative quinoa farmer is a rational decision maker who will choose to invest if and only if the investment will increase the expected sum of future discounted yearly profits compared to the business-as-usual. We assume that the investment horizon of the farmer is [0;T]; in our numerical solution, we consider T = 20 years and a discount rate of 9%[6].

Under the business-as-usual, where no long-term investment option has been implemented so far, the yearly profit of the farmer will be given by:

$$\pi_t^{BaU} = P_t q_t(W_t) - C(q_t) \quad (1)$$

Equation 1 describes the factors that influence the current yearly profit of the farmer, where P_t is the year *t* price of quinoa. q_t is the quantity the farmer harvests at the end of the planting season. As described below, we allow q_t to be a function of weather conditions (W_t). *C(.)* is the cost production function that depends on the quantity produced that year q_t. Without loss of generality, we assume one hectare of land; thus the quantity harvested q_t is measured in tons of quinoa per hectare.[7]

Quinoa is a highly robust crop with high tolerance for weather variations compared to other crops. However, the plantation of quinoa is not totally immune to weather conditions. In fact, the survey administered to farmers in Puno highlights that the conditions that are of highest concern for quinoa farmers are above all frost, followed by drought and hail. We thus opt here for modelling the quantity of quinoa harvested as a function of frost events, as described below.

To increase their yearly yield and reduce the vulnerability of quinoa production to weather conditions, the quinoa farmer has a set of long-term investment options he can undertake. In our model, if the farmer undertakes an investment *(A)*, his yearly profit would be modified and given by:

$$\pi_t^A = P_t q_t(W_t, A) - C(q_t, A) \quad (2)$$

Where P_t is the time t price of quinoa, q_t is the quantity harvested depending on both weather conditions (W_t) and the long-term adaptation option that has been already implemented *(A)*, and *C* is the cost production function that depends on the quantity produced and the adaptation options already implemented by the farmer. Consider now that the farmer is evaluating the option to undertake a long-term investment in the future. The expected total revenue of the farmer is given by the sum of yearly profits under the business-as-usual and under the new regime after the investment has been made:

$$\Pi = \mathbb{E}\left[\sum_{t=0}^{\tau_A} e^{-rt}\pi_t^{BaU} - IC_{\tau_A} e^{-r\tau_A} + \sum_{t=\tau_A}^{T} e^{-rt}\pi_t^A\right] \quad (3)$$

Where IC_{τ_A} is the one-time sunk cost the farmer incurs with the investment in option A. In Eq. 3, τ_A marks the time of the investment. Formally, τ_A is a stopping time, whereby the farmer moves from the business-as-usual regime to the post-investment one. Let $(\Omega, F, \{F_t\}_{t\in I}, \mathbb{P})$ be a filtered probability space, i.e. a probability space equipped with a filtration of σ-algebras. Then the random variable τ_A is a stopping time if $\{\omega \in \Omega : \tau(\omega) \leq t\} \in F_t$, i.e. the decision to stop waiting and to invest is only based on historical data.

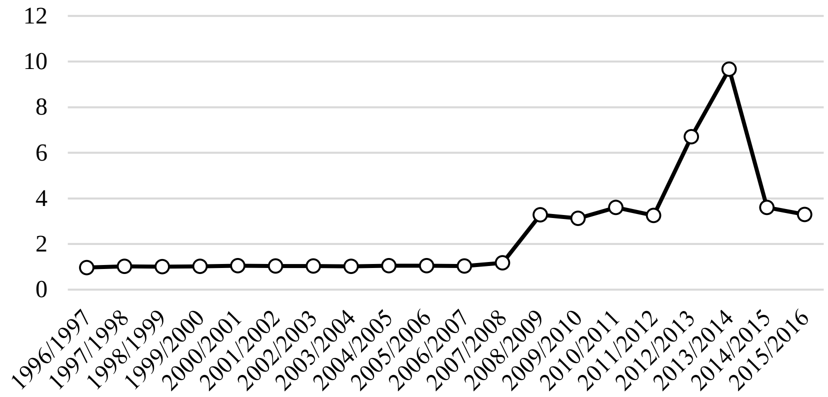
The farmer will decide when to invest in the adaptation option by maximizing his total expected future profits:

$$\max_{\tau_A} \Pi \quad (4)$$

4.2 Assumptions Regarding the Model Variables

4.2.1 The Price of Quinoa

One important model variable is the price of quinoa and its evolution over time. To represent the price dynamics, we rely on the historical distribution of quinoa prices received by the farmer in the Arapa region. Figure 3 below captures the historical quinoa price evolution. While for a long time quinoa prices have been stable at a low level per kilogram (until 2008), with the international increase in the demand for quinoa, prices have experienced severe shocks over the last decade.[8] Based on these historical observations, we suggest to model the quinoa price with the help of a random variable represented by a trinomial tree. Namely, each year the quinoa price received by the producer can (i) remain at the level of the previous year with probability $p_1 = 0.1579$, (ii) increase by 20.28% relative to the previous year with probability $p_2 = 0.4737$, or (iii) decrease by 28.37% percentage points relative to the previous year with probability $p_3 = 0.3684$, where all price movements and associated probabilities have been calibrated on historical data.[9]

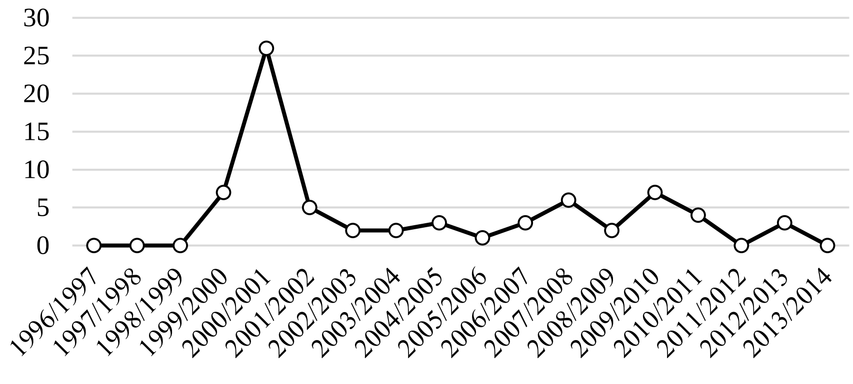


Source: Own Illustration Based On Data From INEI (2017).

Figure 3. Historical Evolution of the Price in Soles per Kilogram of Quinoa as Received by the Producer in Arapa (Puno).

4.2.2 Weather Conditions Impacting the Harvest of Quinoa

Among the weather phenomena impacting quinoa production, we choose to focus on agronomic frost (defined as temperatures at and below -4◦ C), as it is the event farmers seem to be mostly concerned with based on the information gathered in the individual surveys. The number of yearly occurrences of days with frost during the harvest season (September - May) can be modeled as a random independent variable. We rely on historical data to estimate the distribution of the number of frost days during the harvest season. Fig. 4 below captures the evolution of frost days in a harvest year in Arapa (Puno). The historical frequency of the number of frost days impacting the total quantity of quinoa harvested in a year is captured in Table 1.



Source: Own Illustration Based On Data From SENAMHI (2017)

Figure 4. Historical Evolution of the Number of Frost Days in Arapa.

Table 1.Number of Yearly Frost Days and Associated Historical Probability during the Quinoa Planting Season (September - May).

Number of frost days	Historical probability
0	0.2778
1	0.0556
2	0.1667
3	0.1667
4	0.0556
5	0.0556
6	0.0556
7	0.1111
>7	0.0556

Source: Own Illustration Based On Data From SENAMHI (2017)

Let us define $W_t \in [0;\ 30]$ as the number of days events randomly taking place during the planting season.[10] Table 1 captures the observed historical probability of the number of frost days. Assuming an unchanged distribution over time, these probabilities will be used in our model to form expectations about the number of frost days to be expected during the planting season each year.

4.2.3 Estimating the Impact of Frost on the Harvest Of Quinoa

Quinoa production is sensitive to negative temperatures. Analyzing historical data, we observe a negative correlation (-0.14) between the number of days with frost during the planting season and quinoa production.[11] To find out the relation between the number of yearly frost days and quinoa production, we run the following univariate regression:

$$q_t = \alpha + \beta W_t + \varepsilon \qquad (5)$$

Fitting Eq. 5 on historical data proved to be a very challenging task due to very poor data quality available for the region of interest. Faced with this uncertainty, we chose to run the model for a set of benchmark assumptions and then lead a sensitivity analysis around these values. We set α equal to the average annual quinoa production per hectare (expressed in kilograms per hectare) and $\beta = -2$ for the business-as-usual scenario. Equation 5 captures how the quantity of quinoa harvested in year t is affected by frost. The computed expression is used to complete the definition of yearly profits in Eq. 1.

5. Results and Sensitivity Analysis

This section presents the results for the optimal times to invest in the long-term adaptation options that are expected to increase the total revenue of quinoa small farmers. All models have been calibrated for the Arapa region in Puno. The analysis also focuses on the way the results change when varying important model parameters, in particular governmental subsidies for implementation, sensitivity of quinoa production to frost, and movements in quinoa prices. The decision horizon of the quinoa farmer is assumed to spread over 20 years. Therefore, whenever the model shows that the optimal switching time is 20, it should be interpreted that the option to invest is not actually optimal for the entire decision horizon of the farmer. Whenever the expected optimal stopping time is 1, it should be interpreted that the farmer is expected to invest in the following year, as implementation is assumed to require some time.

5.1 First option: Crop Management

In this section we present the results regarding the optimal time to switch from a business-as-usual quinoa variety to a different one. Quinoa varieties have different characteristics, in particular in terms of production yield (kilograms per hectare) and crop resistance to frost. Depending on the underlying characteristics, it might be beneficial for the farmer to abandon the quinoa variety he is usually planting in favor of a different one. The real option approach allows us to assess not only whether such a switch would make economic sense, but also to determine the optimal time to do so.

We focus our analysis on three quinoa varieties typical for the altiplano in the Puno region. The three varieties are Illpa, Salcedo, and Kancolla, and they have been identified as the most prevalent in the region by the quinoa farmers in the survey led by Senahmi and MeteoSwiss in December 2016 and also by their commercial relevance as described in the Catalogue of Commercial Varieties of Quinoa in Peru (FAO 2015).

Table 2 captures the production characteristics of the three quinoa varieties considered, as well as the source where the information was gathered from. In the benchmark scenario, we assume that the sensitivity to frost is the same for all quinoa varieties, and we relax this assumption in the sensitivity analysis later on. As well, under the standard set of assumptions, the model fixes the cost of switching from one quinoa variety to another at 10% of the quinoa revenue in the year the switch takes place. This assumption is relaxed later on.

Table 2. Production Characteristics of Three Quinoa Varieties Typical for Altiplano.

Variety	Yield (kg/ha, Alpha in Eq. 5)	Time to physiological maturity (days)	Production cost (USD/kg)	Sensitivity to frost (beta in Eq. 5)
IIIpa	1,672	130.3	0.1038	-2
Salcedo	1,906	129.5	0.1038	-2
Kancolla	1,929	133.6	0.1038	-2
Source	Bertero et al. (2014)	Bertero et al. (2014)	Mujica Barreda (1997)	Own

Table 3 captures the main results when the option to switch from the business-as-usual quinoa variety to a different one is considered. As each of the three quinoa varieties represents the status quo for some of the representative farmers in the Puno region, we run the analysis for all combinations of varieties.

The purpose is to comprehensively assess the benefits of transiting from each quinoa variety to each alternative variety. The model reveals that, under the benchmark assumptions, the Kancolla variety dominates the Illpa and Salcedo varieties.

Table 3. Expected Optimal Time to Switch Quinoa Varieties under Benchmark Assumptions.

	Switch to		
Switch from	IIIpa	Salcedo	Kancolla
IIIpa	-	1	1
Salcedo	20	-	1
Kancolla	20	20	-

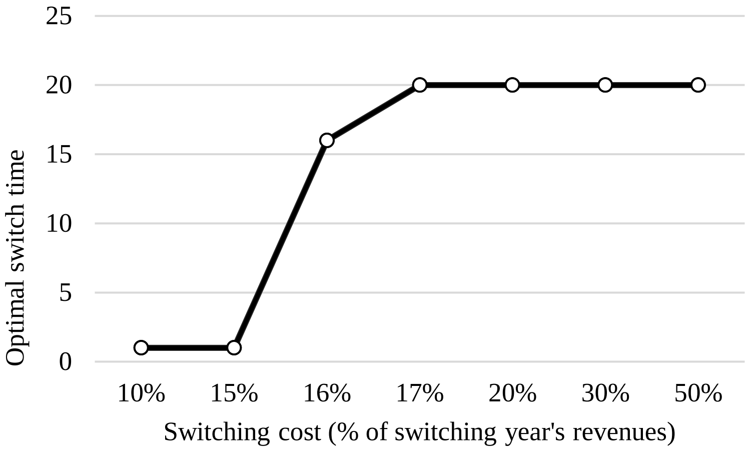


Fig. 5. Expected Optimal Switching Time from the Salcedo Quinoa Variety to the Kancolla One at Different Levels of Switching Cost.

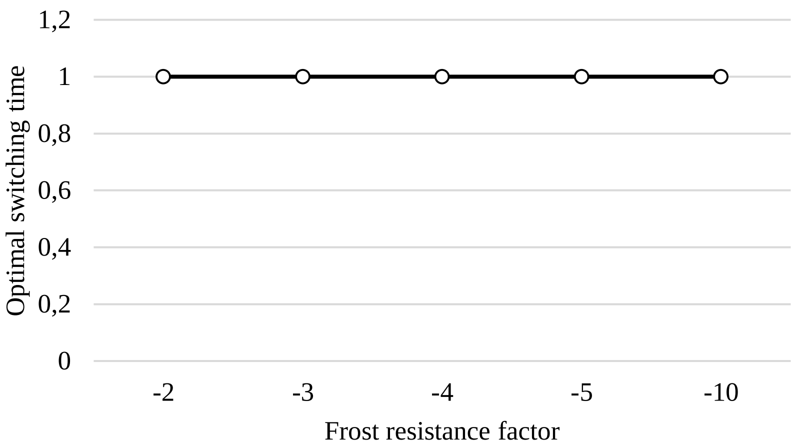


Figure 6. Expected Optimal Switching Time from the Illpa Quinoa Variety to the Salcedo One at Different Levels of Sensitivity to Frost of Salcedo.

5.1.2 Sensitivity to the Cost of Switching Quinoa Varieties

Under the benchmark case, we showed that the Kancolla variety is the most profitable one and, consequently, farmers should consider adopting it as soon as possible. However, this result holds as long as switching costs do not surpass the benefits of the change. The cost of switching from one quinoa variety to another was assumed to amount to 10% of the total revenue in the year the switch takes place. In this section, we relax this assumption and check whether and when it is optimal to switch to Kancolla, given a large range of switching costs. Figure 5 illustrates the results for the optimal switching time from the Salcedo to the Kancolla quinoa varieties at different levels of the switching cost. The results capture a very high sensitivity of the decision to switch to the level of cost. Incurring a cost of 16% of the year's revenues delays the decision to switch by fifteen years; a further percentage increase in cost renders the option to switch worthless. This high sensitivity to the switch cost is reflective of the fact that switching quinoa varieties from Salcedo to Kancolla results in only modest increases in total revenues that can be easily swiped away when the change is costly.

5.1.2 Sensitivity to Frost Resistance

Our results so far have revealed that the Illpa variety is the least profitable one and the farmers who currently cultivate it would be better of by adopting either the Salcedo or Kancolla varieties as soon as possible. This result is based on the lower yield per hectare attained by Illpa compared to the other two, all other conditions equal. However, there is high uncertainty regarding the ability of the different quinoa varieties to resist to frost. Figure 6 shows the optimal time to switch from Illpa to either Salcedo or Kancolla varieties, when the resistance of Illpa is held at the benchmark level (beta = -2) and the resistance to frost of the other two varieties is allowed to take values between -2 and -10. It is striking that under the considered scenarios, it is never optimal to postpone the decision to switch from Illpa to the other two varieties, no matter the level of resistance to frost. This result is important in that it highlights the reduced role that the resistance to frost has in comparison to the long-term trend in quinoa yield.

For completeness, we also run the model for the situation in which the sensitivity to frost of Salcedo and Kancolla is kept at the benchmark level (beta = -2), while that of Illpa is assumed to be very low (beta = -1). Table 4 confirms that even under this scenario, the farmer is better off switching to the Salcedo or Kancolla varieties, as this would increase the farmer's total profits.

Table 4. Expected Optimal Time to Change Quinoa Varieties when the Resistance to Frost of the Illpa variety is -1 and for Salcedo and Kancolla is -2.

Switch to			
Switch from	IIIpa	Salcedo	Kancolla
IIIpa	-	1	1
Salcedo	20	-	1
Kancolla	20	20	-

5.2 Second Option: Waru Waru

Although fairly expensive, Waru waru is expected to bring important benefits in terms of increase in quinoa yield and reduction in the crop's sensitivity to frost. However, the research on the exact magnitude of these benefits remains scarce, leaving a high uncertainty regarding the parameters the yield (alpha) and frost sensitivity (beta) parameters. Our review of the existing literature leads us to the decision to consider a benchmark case where the sensitivity of quinoa to frost under a Waru Waru regime is kept at the same level as under the business-as-usual, while the increase in quinoa yield per hectare is 20% higher under Waru Waru than under business-as-usual. These assumptions are relaxed further on.

Our model finds that, under the benchmark assumptions, the implementation and maintenance costs needed to ensure a good functioning of the Waru Waru system are prohibitively high and it is never optimal for the farmer to invest in this option. The following sections illustrate how this result changes when we vary the assumptions regarding the key parameters.

5.2.1 Quinoa Price and Sensitivity to Frost

We first analyze the scenario in which the market for quinoa becomes stronger over time and this increase in market maturity is reflected in prices that tend to increase on average over time, and experience only limited down movements. The idea behind this analysis is to be able to pinpoint whether better quinoa prices would overcome the high implementation costs and render Waru Waru a viable option. Fig. 7 below illustrates the optimal time the farmer is expected to invest in the Waru Waru option when the magnitude in the down movement in prices is allowed to vary, all other conditions constant. We find that, under all considered scenarios, the Waru Waru option remains infeasible.

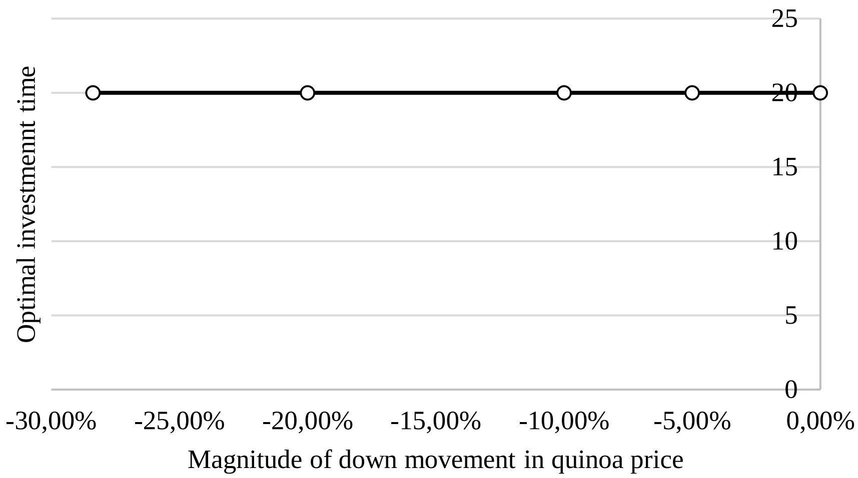


Figure 7. Expected optimal investment times in Waru Waru at different quinoa price changes.

Figure 8 captures the results for the optimal decision to invest in Waru Waru when the sensitivity of production to frost under Waru Waru is allowed to be lower than under the business-as-usual. We find that, despite helping achieve a much lower sensitivity to frost, the implementation cost of Waru Waru is still too high compared to the potentially increased revenues. Even when the sensitivity to frost under Waru Waru is completely wiped out (beta = 0), the farmer would be better off under the business-as-usual. As in the case of the first option, i.e. switching the quinoa variety, the role played by the resistance to frost parameter seems limited.

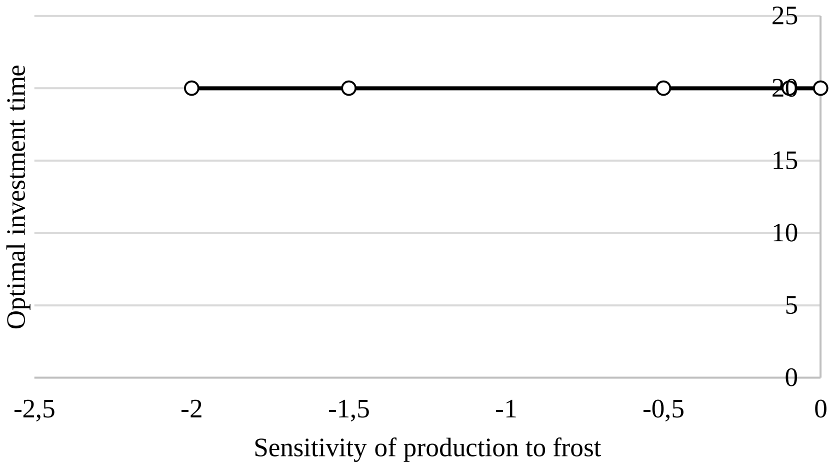


Figure 8. Expected Optimal Investment Times in Waru Waru at Different Sensitivity Levels to Frost.

5.2.2 Governmental Subsidies and Increases in Productivity

In this section we test the robustness of this result by further relaxing the assumptions related to some key model parameters. First, we are interested in understanding whether some governmental support, in the form of subsidies for Waru Waru implementation, would increase the value of the Waru Waru option and by how much. Fig. 11 illustrates the sensitivity of the optimal investment time in Waru Waru at different levels of governmental support. We find that only an almost full (above 80%) subsidy of the implementation cost would render the Waru Waru option interesting for the farmer. The results seem to be highly sensitive to the level of subsidy in this high range, where increasing the subsidy from 90% to 100% would lead the farmer to optimally expedite the investment decision from year 18 to the present year.

Next, we analyze the attractiveness of the Waru Waru option for different levels of increases in productivity compared to the business as usual. The uncertainty for the effect of Waru Waru on quinoa productivity is high and we, thus, consider a broad array of values. As a brief comparison, it has been estimated that the increase of potato production under Waru Waru is 40% higher than under the business-as-usual (Mujica Barreda 1997). We find that, indeed, the impact of the Waru Waru technique on quinoa productivity plays a major role in the decision to adopt quinoa; see Fig. 9. At an increase in the productivity of quinoa of 40% under Waru Waru, the option to invest in this technique is optimal in year 12 of the investment horizon. The results are highly sensitive to increases in productivity above the 40% level, such that at 60% an imminent investment in Waru Waru would be optimal.[12]

Having discovered the paramount role that the increase in productivity under Waru Waru plays for the feasibility of this investment option, we revisit the role of governmental subsidies. Fig. 10 captures the results for the optimal investment times when both the increase in productivity under Waru Waru and the level of government subsidies are allowed to vary. We find that even a modest support from the government (subsidy of 10%) would trigger a fast investment in Waru Waru at increases in productivity above 30%. The results are even more striking for higher subsidies. Our results signal the importance of leading further investigations regarding the capacity of Waru Waru to increase quinoa yield.

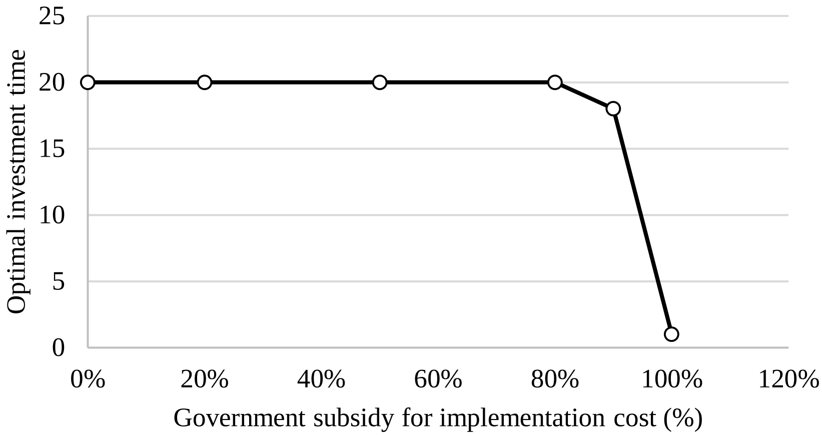


Figure 9. Expected Optimal Investment Times in Waru Waru at Different Levels of Governmental Subsidies for Investment Costs.

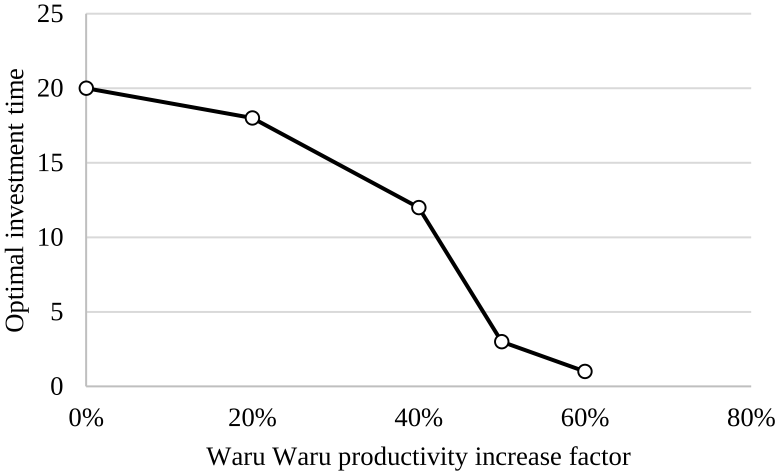


Figure 10. Expected Optimal Investment Times in Waru Waru at Different Levels of Productivity Increases.

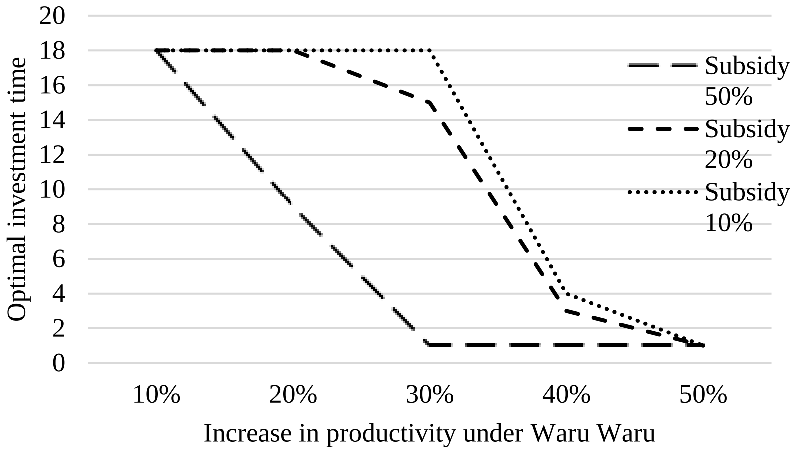


Figure 11. Expected Optimal Investment Times in Waru Waru at Different Levels of Governmental Subsidies for Investment Costs and of Productivity Increases.

6. Conclusion

In this article, we have evaluated two long-term investment options, namely (i) quinoa variety management and (ii) the Waru Waru farming technique. Regarding the first option, our results show that, depending on the current quinoa variety, switching to a different one might be optimal immediately, as better varieties exist that are suitable for the Altiplano and provide higher yields and consequently larger profits. In particular, the Kancolla variety has the highest yield and should be considered right away by quinoa farmers that are currently relying on the Illpa or Salcedo varieties. However, we also show that the decision to adopt new quinoa varieties is highly sensitive to the cost incurred when the switch is made, be it the cost of new seeds or of learning how to handle this new variety. Our results also show that the sensitivity to frost of the different quinoa varieties remains a factor with low power to influence the investment decision. Investment decision is based only in the results of the assessment and does not include any personal preference or traditional values of the farmer.

Regarding the second option, we find that investing in Waru Waru is prohibitively expensive for the quinoa farmer, under benchmark assumptions. The estimates for the impact of Waru Waru on quinoa production lack scientific evidence, leaving room for high uncertainty around this key feature. Our study further puts emphasis on the importance of solving this uncertainty, as our results show that for productivity increases above 20% the quinoa farmer is expected invest in the Waru Waru option in the medium-term future, and at increases above 50% the investment should be immediate. One needs to be cautious when interpreting these results, as high uncertainty remains regarding the actual productivity increase due to Waru Waru. We also analyze the role that governmental support could play for the development of the quinoa market through incentives at the smallholder level. We find that governmental subsidies for the implementation of Waru Waru could play a significant role in bringing the optimal investment time closer to the present, especially at increases in productivity above 20% compared to the business-as-usual.

Our study made best attempts to lead an accurate analysis and formulate clear-cut results that could be relevant for practitioners, policymakers, NGOs, and other stakeholders. However, we also tried to emphasize throughout our report the high uncertainty surrounding many of the key parameters of the analysis. Our results should therefore be interpreted with great care and adapted to the specificities of the context of interest. It is also important to acknowledge that, although the results are sensitive to assumptions, the methodological approach embraced in this study is robust and can be applied to a variety of contexts. Further investment options and different geographic regions could easily be accommodated in a future study.

Acknowledgments

We acknowledge the support of the World Meteorological Organization (WMO) through the project *Servicios CLIMáticos con énfasis en los ANdes en apoyo a las DEcisioneS (CLIMANDES)*, project no. 7F-08453.02 between the Swiss Agency for Development and Cooperation (SDC) and the WMO.

The authors would like to thank Moritz Flubacher from Meteoswiss, Lizet Katherin Cristobal Romero and Hugo Oswaldo Ramon from SENAMHI for their support in the preparation of this report. Their contribution with the climatic data inputted to this model were a valuable asset to the results of this study. We also want to thank Dr. Alipio Canahua Murillo, expert in the field of Quinoa cultivation, and Maurik Bueno de Mesquita, expert in water resources, for their feedback related to the two investment options considered.

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End Notes

[1] This five general Quinoa types are not to be confused to the specific seed varieties described in the Section 3 of this article.
[2] Servicio Nacional de Meterologıa e Hidrologıa del Perú.
[3] These are Desaguedero in the South, Lampa, Puno and Pampahuta in the central part, Arapa, Progreso and Chuquibambilla in the North.
[4] Some other stations, such as Pampahuta, were regarded to be too high in elevation (over 4300 meters above sea level) and resulted to be irrelevant for the study.
[5] Although the two options are equivalent to an investment decision, we recognize that the farmer does not necesarly fund them directly as he can get partial or complete direct funding from third parties, i.e. the government, NGOs, etc.

6 The discount rate was chosen based on advice by interviews with experts in region and information provided by Servicio Nacional de Meterologıa e Hidrologıa del Perú.

[7] The results of the survey of quinoa farmers in Puno reveals that the average plot size sowed with quinoa was of 0.47 hectares during the 2015/2016 harvest.

8 2014 has been named the "International Year of Quinoa" and governmental support for quinoa promotion has boosted the price of quinoa to almost ten times its historical average. Prices have since fallen dramatically but fluctuate above the long-term mean.

9 The probabilities and respective percentage moves have been estimated based on the historical distribution of the quinoa price received by the producer in Arapa. A historical price change in the range [-1%;1%] has been considered insignificant and therefore counted as a zero change in price. The percentage changes have been computed as averages of upward and downward moves.

10 The historical data available for Arapa includes only one registered event that had more than 7 days of frost during the quinoa planting season in the period 1996 - 2014. Namely, in the quinoa season 2000 - 2001, 26 days of frost have been registered.

11 The coefficients have been calibrated for Arapa in the Peruvian Altiplano over the period 1996 - 2012, based on yearly observations.

12 The values considered by our study for the increase in productivity due to Waru Waru are only illustrative; further research could bring evidence for or against some particular values.