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# The Climate Challenge for Agriculture and the Value of Climate Services: Application to Coffee-Farming in Peru

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## Abstract

The use of climate information in economic activities, typically provided by climate services, may serve as a possible adaptation strategy to changing climate conditions. The present paper analyzes the value of climate services aimed at improving agricultural productivity through a reduction in weather-associated risks. In the first part, we provide a theoretical foundation for estimating the value of climate services by proposing a stochastic life-cycle model of a rural household which faces uncertainty with respect to the timing and the size of an adverse weather shock. We subsequently calibrate the model to match the environment of coffee producers in the Cusco region of Peru and provide a range of estimates for the value of climate services for a single average household, the region, and the country as a whole. In the second part of the paper we use empirical data to verify the numerical estimates. We assess the value of climate services in the agricultural sector in Cusco based on a choice experiment approach. Data are analyzed using a standard as well as a random parameter logit model allowing for preference heterogeneity. Farmers show a significant willingness-to-pay for enhanced climate services which is particularly related to the service accuracy and geographic resolution. On average, the yearly value of a climate service in the coffee sector is found to be in the range \$20.64 - \$21.10 per hectare and \$8.1 - \$8.2 million for Peru as a whole.

JEL Classification: C25, D81, H41, O13, Q12, Q16, Q51

**Key Words:** Agriculture, choice experiment, coffee farming, coffee rust, climate change adaptation, uncertainty.

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# 1 Introduction

The direct impact of climate variability on economic performance is currently gaining increasing scientific and public interest due to the ongoing debate on climate change. Alteration in climate conditions, such as an increase in the global temperature and an amplification of temperature variability, impose new challenges on adaptation strategies, which is particularly eminent in climate-sensitive sectors such as agriculture or health (IPCC, 2014). Climate services, as defined by Tall (2013), consist of dissemination of climate information to the public or a specific user. Climate services thus represent an essential instrument for adaptation as they provide end-users with information and predictions which decrease the risk of weather and climate-related disasters and therefore improve the overall efficiency of the decision-making process. In fact, in 2009, the third World Climate Conference (WCC) decided to establish a Global Framework for Climate Services in order to strengthen production, availability and delivery of climate information.

One of the major issues in addressing the challenges of climate change is related to the specific needs of less developed economies, which are usually characterized by less capital and knowledge for adaptation as well as a higher climate vulnerability (Bretschger and Suphaphiphat, 2013). In particular, a typical less developed or emerging economy exhibits a relatively high dependence on climate-sensitive sectors such as agriculture. In this regard, climate services may provide a useful infrastructural contribution, as they assist individuals and organizations in making improved climate-related decisions on livelihood strategies, which generates potential benefits for societies. At the same time, due to high fixed costs, the development and implementation of climate services is likely to be financed and provided publicly. Therefore, as it is outlined by the *Madrid Action Plan* of the *World Meteorological Organization* (WMO, 2007), it is of high importance to quantify the benefits of such services in order to justify the required investments (Freebairn and Zillman, 2002).

In the present study we quantify the value of climate services for the agricultural sector. Needless to say, weather conditions determine to a large extent the quality and the quantity of agricultural output. Natural disasters, such as droughts, intensive rainfalls, floods, frosts,

etc., may have a profound negative impact on the harvest. These events typically cannot be easily predicted by individual farmers as they occur at random points in time and cause a random-size damage. But if their occurrence and intensity could be foreseen, appropriate adaptation mechanisms and precautionary measures could be implemented - in terms of investments, crop and fertilizer choice, field size, dams, irrigation systems, etc. This is why comprehensive climate services may be needed in order to improve the performance of the agricultural sector as a whole and welfare of individual farmers. This issue is relevant for both the developed and the developing countries, especially those where agriculture represents an important share of GDP and particularly those vulnerable to climate change.

Coffee farming is one of the agricultural activities which has been particularly affected by changing climate conditions in the past several years. All the coffee-producing countries of Central and South America have seen drops in production of 30% or more in 2012 - 2014 due to the spreading of the fungus *Hemileia vastatrix*, commonly known as "coffee rust". In these economies coffee represents an essential export commodity with export revenues contributing a considerable share to their GDP, e.g., more than 10% in smaller states such as Nicaragua, Guatemala and Honduras. Moreover, it is the only source of income and subsistence for rural population working on coffee farms. Heavy rainfall and warm temperatures constitute propitious conditions for the development of coffee rust, which threatens livelihood of a large share of rural families, leading to poverty, malnutrition and undermining the global food security. The adverse effects can be mitigated by a timely application of fungicides. The challenge, however, is that they must be applied a few weeks in advance of the onset of humid and warm days, which requires specific knowledge of the *future* weather conditions. Consequently, quality weather services are crucial for harvest preservation and the well-being of agricultural workers.

The contribution of the present study is two-fold. First, we provide a theoretical foundation to determine the value of climate services in an environment characterized by a random occurrence of adverse weather events which completely or partially affect the harvest. The climate service consists of information provided to farmers about the timing and the intensity of an event. The climate service value (CSV for short) is calculated by comparing a repre-

sentative farmer's welfare under two alternative scenarios - one where CS is available and the other where it is not. The model is subsequently calibrated to match the conditions facing coffee farmers in Cusco, one of the major coffee-producing regions of Peru. Peru appears to be especially exposed to changing climate conditions due to the presence of the El Niño phenomenon and its mountainous topography (see e.g. Vargas, 2009). In recent years, Peru, as almost every coffee-producing country in Latin America and Africa, has suffered from outbreaks of *Hemileia vastatrix* and crop losses of up to 40% in hard-hit regions, amounting to several tens of millions of USD annually. The numerical results stemming from the calibrated model suggest that climate services may be worth \$16.25 - \$23.33 per cultivated hectare and approximately \$0.95 - \$1.36 million for the Cusco region.

In the second part of the paper we verify the numerical findings by assessing the economic value of climate services empirically using discrete choice methodology. The corresponding survey was carried out in Cusco in 2014, focusing on coffee and maize crops. As climate services are only rarely implemented in less developed countries and since they exhibit typical characteristics of (quasi) public goods, observability of corresponding market activities is restricted making the use of market data for empirical validation impossible. This analysis is therefore based on a stated preference approach valuating choices between hypothetical climate services - in particular early warning systems - and deriving the willingness-to-pay (WTP) from a sample of survey respondents. We investigate farmers' preferences for key attributes of climate services and use our estimates to identify per hectare economic value of this climate-related information. Results suggest that farmer's valuation varies considerably with regard to their main type of crop cultivation, which is based on differences in the climate sensitivity of the crop as well as on the farmers' possibility to apply preventive production measures based on the provided information. In fact, it turns out that this information generates higher annual values in the coffee sector, amounting to \$20.64 - \$21.10 per hectare, to approximately \$1.21 - \$1.24 million for the Cusco region and to \$8.06 - \$8.24 million on the countrywide level.

As outlined by Freebairn and Zillman (2002), different approaches may be used to assess

the economic value of meteorological services<sup>1</sup>. There exist a few studies using a stated preferences approach for examining the WTP of such services in industrialized countries (Chapman, 1992; Teske and Robinson, 1994; Anaman and Lelleyet, 1996). In particular, Chestnut and Lazo (2002) and Waldmann and Lazo (2011) investigate the economic value of improved weather and hurricane forecasts for U.S. households based on discrete choice methodology. To our best knowledge, this paper represents a first choice experiment approach to the evaluation of climate services for the agricultural sector in the context of a less developed country. We further contribute to this strand of the literature by building the empirical validation on a theoretical fundament.

The remainder of the paper is organized as follows. Section 2 presents the theoretical model. Section 3 describes the calibration and provides preliminary estimates of CSV. Section 4 describes the case study, the econometric model, and presents the empirical results. Section 5 concludes.

## 2 Climate Service Value

In this section we present a theoretical foundation for the determination of the climate-service value (CSV). The model is general enough and can be applied to any crop whose cultivation is affected by weather shocks with random occurrences and random intensities. For the sake of clarity, we shall focus on the specific example of coffee cultivation. The growth process of a coffee plant is highly sensitive to temperature, moisture, and humidity conditions (Cintra et al. 2011, Ghini et al. 2011). In particular, the presence of free water (rain or heavy dew) is propitious for proliferation of coffee rust. The whole process of infection requires about 24 to 48 hours of continuous free moisture, so while heavy dew is enough to stimulate urediniospore germination, infection usually occurs only during the rainy season. The seasonal variation in disease incidence is primarily due to variation in rainfall. Infection occurs over a wide range of temperatures, minimum 15°C, optimum 22°C, and maximum 28°C.<sup>2</sup>

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<sup>1</sup>We use the notation meteorological services as a generic term including weather and climate services.

<sup>2</sup><http://www.apsnet.org/edcenter/intropp/lessons/fungi/basidiomycetes/pages/coffeerust.aspx>

The spreading of the fungus may be prevented by applying a specific type of fungicide or copper. Most importantly, it must be applied in advance of the rainy season. If it is applied too late, it will not be effective. A farmer, essentially, must make a decision about the purchase of the fungicide without knowing beforehand the intensity of the rainfall and when it will occur. Here is where the climate service (hereafter CS) comes into the picture. If available to the farmer, CS provides him with a timely information about the occurrence of a rainfall and its intensity. Based on this information, the farmer can make appropriate decision about the purchase of the fungicide and the required quantity. CS will thus make farming more efficient. A precise quantity of the fungicide will be bought to correspond to the expected intensity of the rain and unnecessary purchase will be avoided if only small rains are expected. We are interested in the question of how much such a service is worth to the farmer and to the coffee sector as a whole.

Consider a representative farmer who cultivates a crop with a given planning horizon of duration  $T$  (say, one year). Time is indexed by  $t$ . During the initial time span lasting from 0 to  $\tau$  (Phase I) the farmer receives a constant flow of income per unit of time,  $y$ , consumes at the rate  $c_t$  and saves the rest to increase his stock of assets denoted by  $k_t$ . The income flow is related to the land size under cultivation. In this sense, a farmer with a larger farm enjoys a higher  $y$ . The assets accumulated up to the end of Phase I,  $k_\tau$ , represent a stock of precautionary capital which will be used at time  $\tau$  for precautionary measures - purchase of the fungicide. As we have mentioned earlier, it must be applied well in advance of the rainy season, so one may think of time  $\tau$  as the last moment at which the fungicide can be applied and still be effective in reducing the incidence of coffee rust. At time  $\tau$  Phase II starts and lasts till the end of the planning horizon  $T$ . Phase II consists of two sub-phases. Phase IIa lasts from time  $\tau$  till  $\tau + \phi$ , where  $\tau + \phi$  is a random date at which an intensive rainfall occurs and causes the onset of the fungus growth. Duration  $\phi$  is essentially the waiting time till the occurrence of the adverse climate event (e.g. heavy rainfall). We assume that event arrivals follow the Poisson process with the constant mean rate  $\lambda$  and thus the arrival time is exponentially distributed with the truncated density  $f(\phi) = \frac{\lambda e^{-\lambda\phi}}{e^{-\lambda\tau} - e^{-\lambda T}}$ .<sup>3</sup> During this sub-

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<sup>3</sup>Truncated density is used since the shock can only occur between  $\tau$  and  $T$ . In the infinite-horizon case, the

phase, the farmer continues to receive  $y$  per unit of time and he does not need to accumulate any precautionary capital. His consumption is thus equal to his income. Once (and if) the event occurs, Phase IIb starts and lasts from  $\tau + \phi$  till  $T$ . During this period, the farmer's income is given by  $\omega y$ , where  $\omega$  is determined by the farmer's investment in crop preservation,  $k_\tau$ , and by the random damage caused by the weather event. We assume that if the farmer makes no investment in crop preservation, the "survived" share of the harvest is just a random variable  $s \in [0, 1]$ , which is determined by the intensity of the shock. Later in the paper we will specify the distribution of  $s$ , while for the moment we note that it is independent of the distribution of  $\phi$ . Let us assume that the function  $\omega$  is given by

$$\omega(k_\tau, s) = s f(k_\tau), \quad f(k_\tau) = A \left[ 1 + (1 + k_\tau^{-\alpha})^{-\frac{1}{\alpha}} \right], \quad (1)$$

where  $f(\cdot)$  is a sigmoid-type function such that  $f'(\cdot) > 0$ ,  $f''(\cdot) < 0$ ,  $\lim_{k_\tau \rightarrow 0} f(k_\tau) = 1$ ,  $\lim_{k_\tau \rightarrow \infty} f(k_\tau) = 2$ , and  $A > 0$ ,  $\alpha > 0$ . The parameter  $A$  denotes a farmer's skill or education level which translates into his ability to apply preventive measures efficiently. More skilled or more educated farmers have a better knowledge about how to effectively use the fungicides and, at a more general level, better manage their land and crops. The sigmoid function is convenient because it is concave and bounded for  $k_\tau \geq 0$ . If  $k_\tau = 0$ , the faith of the harvest is determined entirely by the weather. If  $k_\tau > 0$  and the shock is relatively unfavorable ( $s$  is small), then  $\omega \in (0, 1)$  and the harvest is worth less than  $y$ . If, however,  $k_\tau > 0$  and the shock is favorable ( $s$  is close to one), then  $\omega > 1$  and the farmer earns a premium compared to his regular income  $y$ .<sup>4</sup>

The farmer's problem is to maximize the expected discounted value of welfare during the planning horizon by optimally choosing his saving rate and thus the size of the precautionary capital at the purchase date  $\tau$ . We assume that instantaneous welfare is represented by the standard CRRA utility function  $u(c) = \frac{c^{1-\theta}}{1-\theta}$ , where  $\theta$  is the elasticity of marginal utility.

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density is just the numerator of the expression in the text.

<sup>4</sup>Such a harvesting pattern is indeed common among coffee farmers (pers. comm., SENAMHI).



## 2.1 Optimal Decision-making without Climate Service

Without any CS, the farmer operates in an uncertain environment. There are two sources of uncertainty - the time of the weather shock and the extent of the damage. The farmer's optimization problem may be written as

$$\max_{c_t, k_\tau} \int_0^\tau u(c_t)e^{-\rho t} dt + \mathbb{E}_{\phi, s} \left\{ \int_\tau^T u(\tilde{c}_t)e^{-\rho t} dt \right\},$$

s.t.

$$\dot{k}_t = y - c_t, \quad \forall t \in [0, \tau), \quad (2)$$

$$\tilde{c}_t = y, \quad \forall t \in [\tau, \tau + \phi), \quad (3)$$

$$\tilde{c}_t = \begin{cases} y, & \forall t \in [\tau + \phi, T] \text{ if no shock occurs,} \\ \omega(k_\tau, s)y, & \forall t \in [\tau + \phi, T], \text{ if shock occurs,} \end{cases} \quad (4)$$

where  $\rho$  is a constant rate of time preference and  $\mathbb{E}_{\phi, s}$  denotes the expectation operator with respect to the distribution of  $\phi$  and  $s$ . The evidence suggests that coffee farmers in Peru do not have access to lending and borrowing from financial institutions. Saving takes the form of, essentially, storing money at home, implying a zero interest rate. Therefore, Eq. (2) does not contain a term representing return on accumulated assets.

Phase I of the optimization problem is purely deterministic and thus can be solved with the aid of the standard optimal control methods. The evolution of the optimal consumption rate satisfies the familiar Keynes-Ramsey equation:

$$c_t = c_0 e^{-\frac{\rho}{\theta} t}, \quad (5)$$

which states that consumption declines at the rate of time preference  $\rho$  adjusted by the elasticity of intertemporal consumption substitution  $1/\theta$ . Substituting this optimal path into Eq. (2), we can solve for the initial consumption rate  $c_0$  and the time path of the asset

holdings as functions of  $k_\tau$ :

$$c_0 = \frac{(\tau y + k_0 - k_\tau)\rho/\theta}{1 - e^{-\frac{\rho}{\theta}\tau}}, \quad (6)$$

$$k_t = yt + k_0 - (\tau y + k_0 - k_\tau) \frac{1 - e^{-\frac{\rho}{\theta}t}}{1 - e^{-\frac{\rho}{\theta}\tau}}. \quad (7)$$

The present value of welfare in Phase I is equal to

$$W_1 = \int_0^\tau u(c_t)e^{-\rho t} dt = \frac{(\tau y + k_0 - k_\tau)^{1-\theta}}{1-\theta} \left( \frac{1 - e^{-\frac{\rho}{\theta}\tau}}{\rho/\theta} \right)^\theta. \quad (8)$$

Phase II is the phase which involves uncertainty. The time- $\tau$  expected value of welfare is given by

$$\begin{aligned} W_2 &= \mathbb{E}_{\phi,s} \left\{ \int_\tau^T u(\tilde{c}_t)e^{-\rho(t-\tau)} dt \right\} = \mathbb{E}_{\phi,s} \left\{ \int_\tau^{\tau+\phi} u(\tilde{c}_t)e^{-\rho(t-\tau)} dt + \int_{\tau+\phi}^T u(\tilde{c}_t)e^{-\rho(t-\tau)} dt \right\} \\ &= \mathbb{E}_{\phi,s} \left\{ \int_\tau^{\tau+\phi} u(y)e^{-\rho(t-\tau)} dt + \int_{\tau+\phi}^T u(\omega y)e^{-\rho(t-\tau)} dt \right\} \\ &= \mathbb{E}_{\phi,s} \left\{ u(y) \frac{1 - e^{-\rho\phi}}{\rho} + u(\omega y) \frac{e^{-\rho\phi} - e^{-\rho(T-\tau)}}{\rho} \right\} \\ &= u(y) \mathbb{E}_\phi \left\{ \frac{1 - e^{-\rho\phi}}{\rho} \right\} + \mathbb{E}_{\phi,s} \left\{ u(\omega y) \frac{e^{-\rho\phi} - e^{-\rho(T-\tau)}}{\rho} \right\} \\ &= u(y) \left[ \frac{1}{\rho} - \mathbb{E}_\phi \left\{ \frac{e^{-\rho\phi}}{\rho} \right\} \right] + \mathbb{E}_{\phi,s} \left\{ u(\omega y) \frac{e^{-\rho\phi}}{\rho} \right\} - \mathbb{E}_s \left\{ u(\omega y) \frac{e^{-\rho(T-\tau)}}{\rho} \right\}. \end{aligned}$$

Given that  $\phi$  and  $s$  are independent, the latter expression may be rewritten as

$$\begin{aligned} W_2 &= u(y) \left[ \frac{1}{\rho} - \int_\tau^T \frac{e^{-\rho\phi}}{\rho} \frac{\lambda e^{-\lambda(\phi-\tau)}}{1 - e^{-\lambda(T-\tau)}} d\phi \right] + u(y) \mathbb{E}_s \left[ \omega^{1-\theta} \right] \left[ \int_\tau^T \frac{e^{-\rho\phi}}{\rho} \frac{\lambda e^{-\lambda(\phi-\tau)}}{1 - e^{-\lambda(T-\tau)}} d\phi - \frac{e^{-\rho(T-\tau)}}{\rho} \right] \\ &= \frac{u(y)}{\rho} \left[ 1 - \frac{\lambda e^{\lambda\tau}}{1 - e^{-\lambda(T-\tau)}} \times \frac{e^{-(\rho+\lambda)\tau} - e^{-(\rho+\lambda)T}}{\rho + \lambda} \right] + \frac{u(y)}{\rho} \mathbb{E}_s \left[ s^{1-\theta} \right] [f(k_\tau)]^{1-\theta} \times \\ &\quad \times \left[ \frac{\lambda e^{\lambda\tau}}{1 - e^{-\lambda(T-\tau)}} \times \frac{e^{-(\rho+\lambda)\tau} - e^{-(\rho+\lambda)T}}{\rho + \lambda} - e^{-\rho(T-\tau)} \right] \\ &= \frac{u(y)}{\rho} \left\{ 1 - \Lambda + [f(k_\tau)]^{1-\theta} \mathbb{E}_s \left[ s^{1-\theta} \right] \left[ \Lambda - e^{-\rho(T-\tau)} \right] \right\}, \quad (9) \end{aligned}$$

where  $\Lambda \equiv \frac{\lambda e^{-\rho\tau}}{1-e^{-\lambda(T-\tau)}} \times \frac{1-e^{-(\rho+\lambda)(T-\tau)}}{\rho+\lambda}$ .

The optimal quantity of fungicides to be purchased at time  $\tau$  must be such that the marginal welfare loss in Phase I must be equal to the expected marginal welfare gain in Phase II, in present value terms. That is, the optimal choice of  $k_\tau$  must satisfy:

$$\frac{\partial W_1}{\partial k_\tau} + e^{-\rho\tau} \frac{\partial W_2}{\partial k_\tau} = 0.$$

Using Eqs. (8) and (9), we obtain

$$(\tau y + k_0 - k_\tau)^{-\theta} \left( \frac{1 - e^{-\frac{\rho}{\theta}\tau}}{\rho/\theta} \right)^\theta = e^{-\rho\tau} \frac{y^{1-\theta}}{\rho} [f(k_\tau)]^{-\theta} f'(k_\tau) \mathbb{E}_s [s^{1-\theta}] [\Lambda - e^{-\rho(T-\tau)}]. \quad (10)$$

If we assume that  $\alpha = \theta - 1 > 0$ , then Eq. (10) simplifies to

$$\frac{(\tau y + k_0 - k_\tau) \rho/\theta}{1 - e^{-\frac{\rho}{\theta}\tau}} = \Gamma \left[ k_\tau + (1 + k_\tau^{\theta-1})^{\frac{1}{\theta-1}} \right], \quad (11)$$

where  $\Gamma \equiv \left\{ e^{-\rho\tau} \frac{y^{1-\theta}}{\rho} \mathbb{E}_s [s^{1-\theta}] [\Lambda - e^{-\rho(T-\tau)}] \right\}^{-1/\theta}$ . A solution to Eq. (11) exists if and only if the following condition holds:  $\Gamma \leq \frac{\rho(\tau y + k_0)/\theta}{1 - e^{-\frac{\rho}{\theta}\tau}}$ . We shall assume that this is the case. If a solution exists, then it is unique due to the fact that the left-hand side of (11) is monotone decreasing in  $k_\tau$ , while the right-hand side is monotone increasing in  $k_\tau$ . The RHS may be either concave or convex depending on whether  $\theta \in (1, 2)$  or  $\theta > 2$ , respectively. An analytical solution to Eq. (11) is feasible if we set  $\theta = 2$ . Then the optimal amount of assets to be accumulated by time  $\tau$  is given by

$$k_\tau^* = \frac{\rho(\tau y + k_0) - 2\Gamma(1 - e^{-\frac{\rho}{2}\tau})}{\rho + 4\Gamma(1 - e^{-\frac{\rho}{2}\tau})}. \quad (12)$$

Using (12) in (6), we obtain the optimal initial consumption rate in Phase I,  $c_0^*$ .

Inserting the solutions for the initial consumption rate and the optimal stock of assets into  $W_1$  and  $W_2$ , respectively, we can calculate the maximized present value of the lifetime welfare as

$$W_{max} = W_1(c_0^*) + e^{-\rho\tau} W_2(k_\tau^*). \quad (13)$$

In order to determine the value of climate services, we would need to compare  $W_{max}$  with the present value of the farmer's welfare in a situation where he has access to CS information.

## 2.2 Optimal Decision-making with CS

Let us consider a CS which provides the farmer with information on the timing of a rainfall and its intensity. Let us assume that the information is perfectly accurate. The value of such a CS would thus represent the upper bound since a less precise service is obviously worth less.<sup>5</sup> The CS accurately identifies the time of the adverse weather event  $\phi$  and the survived share of the harvest  $s$ . Obviously, when the farmer has this information he will, in general, choose a different consumption rate in Phase I and a different stock of assets to hold at time  $\tau$ , as compared to our analysis of the previous subsection. Now the farmer's problem may be described as follows:

$$\max_{c_t, k_\tau} \int_0^\tau u(c_t)e^{-\rho t} dt + \int_\tau^{\tau+\phi} u(\tilde{c}_t)e^{-\rho t} dt + \int_{\tau+\phi}^T u(\tilde{c}_t)e^{-\rho t} dt$$

s.t.

$$\dot{k} = y - c_t, \quad \forall t \in [0, \tau), \quad (14)$$

$$\tilde{c}_t = y, \quad \forall t \in [\tau, \tau + \phi), \quad (15)$$

$$\tilde{c}_t = \omega(k_\tau, s)y, \quad \forall t \in [\tau + \phi, T]. \quad (16)$$

The time profile of consumption in Phase I still satisfies Eqs. (5) and (6) but  $k_\tau$  is yet to be determined. The overall present welfare, let us call it  $W^{cs}$  (where "cs" stands for "climate service"), is given by

$$W^{cs} = W_1^{cs} + e^{-\rho\tau}W_2^{cs},$$

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<sup>5</sup>We acknowledge that a perfectly accurate weather forecast is more of a theoretical construct rather than a part of reality. We do, nonetheless, use it in our analysis as it provides a well-defined benchmark for evaluating CSV.

where the expression for  $W_1^{cs}$  is the same as in (8) and  $W_2^{cs}$  is the time- $\tau$  value of the discounted welfare in Phase II, given by

$$W_2^{cs} = u(y) \frac{1 - e^{-\rho\phi}}{\rho} + \omega^{1-\theta} u(y) \frac{e^{-\rho\phi} - e^{-\rho(T-\tau)}}{\rho}. \quad (17)$$

Note that when CS is available, there is no more need to treat  $\phi$  and  $\omega$  as random. The optimal stock of assets to be accumulated by time  $\tau$  is such that

$$\frac{\partial W_1^{cs}}{\partial k_\tau} + e^{-\rho\tau} \frac{\partial W_2^{cs}}{\partial k_\tau} = 0.$$

Using Eqs. (8) and (17), we obtain

$$(\tau y + k_0 - k_\tau)^{-\theta} \left( \frac{1 - e^{-\frac{\rho}{\theta}\tau}}{\rho/\theta} \right)^\theta = e^{-\rho\tau} \frac{y^{1-\theta}}{\rho} [f(k_\tau)]^{-\theta} f'(k_\tau) s^{1-\theta} [e^{-\rho\phi} - e^{-\rho(T-\tau)}]. \quad (18)$$

If we assume again that  $\alpha = \theta - 1$ , then Eq. (18) simplifies to:

$$\frac{(\tau y + k_0 - k_\tau) \rho/\theta}{1 - e^{-\frac{\rho}{\theta}\tau}} = \tilde{\Gamma} \left[ k_\tau + (1 + k_\tau^{\theta-1})^{\frac{1}{\theta-1}} \right], \quad (19)$$

where  $\tilde{\Gamma} \equiv \left\{ e^{-\rho\tau} \frac{y^{1-\theta}}{\rho} s^{1-\theta} [e^{-\rho\phi} - e^{-\rho(T-\tau)}] \right\}^{-1/\theta}$ . A solution to Eq. (19) exists if and only if the following condition holds:  $\tilde{\Gamma} \leq \frac{\rho(\tau y + k_0)/\theta}{1 - e^{-\frac{\rho}{\theta}\tau}}$ . We shall assume that this is the case. If a solution exists, then it is unique.

**Proposition 1:** *If an adverse weather event arrives at the average arrival time and the survived share of harvest is equal to its average, a farmer with access to CS chooses*

- (i) *a smaller amount of precautionary assets and*
- (ii) *a larger initial consumption rate than a farmer without CS.*

**Proof:** (i) The optimal  $k_\tau$  with CS is determined by the intersection of the downward-sloping linear schedule (LHS of Eq. (19)) and an upward-sloping curve which has an intercept at  $\tilde{\Gamma}$  (RHS of Eq. (19)). The LHS of Eq. (19) is identical to the LHS of Eq. (11), while the RHS of Eq. (19) is shifted upwards or downwards, depending on whether  $\tilde{\Gamma} \geq \Gamma$ . Or, equivalently,  $s^{1-\theta} [e^{-\rho\phi} - e^{-\rho(T-\tau)}] \leq \mathbb{E}_s [s^{1-\theta}] [\Lambda - e^{-\rho(T-\tau)}]$ . Since  $\theta > 1$  by assumption,

$s^{1-\theta}$  is convex and therefore  $\mathbb{E}[s^{1-\theta}] > (\mathbb{E}[s])^{1-\theta}$  by Jensen's inequality. Similarly,  $e^{-\rho\phi}$  is convex in  $\phi$  and therefore  $\Lambda = \mathbb{E}[e^{-\rho\phi}] > e^{-\rho\mathbb{E}[\phi]}$ . Hence,  $\tilde{\Gamma} > \Gamma$ , so that the RHS of (19) is shifted upwards, implying that the new equilibrium is to the left of the old equilibrium given by (11).

(ii) The initial consumption rate is a decreasing function of  $k_\tau$  (see Eq. (6)). Since  $k_\tau^{cs} < k_\tau$  by (i), it follows that  $c_0^{cs} > c_0$ . ■

If we look at the full range of values of  $s$  and  $\phi$ , we may state the following

**Proposition 2:** (i) *There exists a threshold level of the share of the survived crop,  $\bar{s}$ , and a threshold arrival time,  $\bar{\phi}$ , such that for  $s > \bar{s}$  and  $\phi > \bar{\phi}$  ( $s < \bar{s}$  and  $\phi < \bar{\phi}$ , respectively) a farmer with access to CS chooses a smaller (larger, resp.) amount of precautionary assets than under uncertainty. (ii) The thresholds  $\bar{s}$  and  $\bar{\phi}$  are smaller than the respective average values, i.e.  $\bar{s} < \mathbb{E}[s]$  and  $\bar{\phi} < \mathbb{E}[\phi]$ .*

**Proof:** (i) The survived crop share  $s$  is bounded on  $[0, 1]$  and  $s^{1-\theta}$  is monotonically decreasing and convex with  $\lim_{s \rightarrow 0} \frac{1}{s^{\theta-1}} = +\infty$ ,  $\lim_{s \rightarrow 1} \frac{1}{s^{\theta-1}} = 1$ . Therefore, there is a unique  $\bar{s}$  such that  $\bar{s}^{1-\theta} = \mathbb{E}[s^{1-\theta}]$ .

(ii) By Jensen's inequality on monotone decreasing and convex functions. The thresholds  $\bar{s}$  and  $\bar{\phi}$  represent the certainty equivalents.

The intuition behind this proposition is easy to grasp. If the adverse event happens too soon ( $\phi < \bar{\phi}$ ) and the damage is relatively large ( $s < \bar{s}$ ), the agent is "under-prepared", in the sense of having too high of a consumption rate and consequently not enough precautionary capital. If the event arrives relatively late and the damage is relatively small, the agent is "over-prepared" by having accumulated too much capital and having consumed too little.

In the case of coffee farming in Peru, the former scenario is more likely. The peak of the rainfall occurs between January and March, while the growth season is between March and June and the harvesting season is between July and November. Thus the rainy season starts right after the period of coffee sale (September to January). The farmers are therefore more likely to be under-prepared for the rainy season and run a risk of crop losses.

The maximized present value of welfare with CS is given by

$$W_{max}^{cs} = W_1(c_0^{cs}) + e^{-\rho\tau} W_2^{cs}(k_\tau^{cs}). \quad (20)$$

Let us now define an intermediate variable  $\Delta$  which stands for the difference between the farmer's welfare with climate services and that without climate services:  $\Delta = W_{max}^{cs} - W_{max}$ . Any parameter of the model which has a positive effect on  $W_{max}^{cs}$  (negative effect on  $W_{max}$ ) will have a positive effect on  $\Delta$  and vice versa. We can state the following

**Proposition 3:** *An increase in the skill/education level of a farmer ( $A$ ) or an increase in the plot of land under cultivation ( $y$ ) results in a larger increase of the lifetime welfare when the farmer has access to climate service than when he does not:  $\frac{\partial \Delta}{\partial A} > 0$ ,  $\frac{\partial \Delta}{\partial y} > 0$ .*

**Proof:** provided in the appendix.

The Proposition says that more educated farmers and farmers with larger plots of land benefit more from climate services than less educated farmers and those with relatively smaller land holdings. The intuition behind these results is that farmers with a higher productivity and larger land holdings are exposed to relatively larger losses in the event of an adverse shock. They therefore have a higher incentive to invest in protection measures which leads to a larger share of survived crop in equilibrium and thus a larger welfare. We shall test proposition 3 in our empirical investigation in Section 4.

We are now in a position to define and analyze the value of climate services. A natural way to identify CSV is to compute the absolute value of percentage deviation of the farmer's welfare when CS is available relative to when it is not. Let  $P$  denote such measure:

$$P = \left| \frac{\Delta}{W_{max}^{cs}} \right|. \quad (21)$$

This measure essentially shows the error, in terms of lifetime welfare, that a farmer commits when he is exposed to uncertainty, relative to the certainty case. Note that the climate service does not eliminate the adverse weather shock but it provides information on its exact

timing and intensity. A farmer operating under uncertainty may be overly optimistic about the weather. In this case he will expect a small damage (large  $s$ ) and a late arrival (large  $\phi$ ) and thus he will overstate his total welfare. Alternatively, he might be overly pessimistic and understate his welfare. In both cases, he commits an error relative to his true welfare (under certainty). In order to assess the magnitude of  $P$  we calibrate our model to the data on coffee farmers in one of the main coffee-producing regions of Peru, Cusco.

### 3 Calibration to Peruvian Data

In this section we illustrate the determination of CSV with the help of a numerical example. The parameters are calibrated to match the Peruvian data for Cusco region. We assume that the planning horizon corresponds to one farming year or 52 weeks and  $t = 0$  corresponds to the first day of September. The sales period runs from September/October to December. In our model this period corresponds to the duration  $\tau$ , during which the farmer receives an income and makes saving decisions. We thus assume that  $\tau$  may last 12 to 16 weeks. The rainy season starts in January and may last until March, so that  $\phi$  takes values between 0 and 12 weeks. The growth season lasts from March/April to June/July and the harvesting season runs from July to November. There is, of course, an overlap between the harvesting and the sales seasons which we do not model explicitly. We therefore set the cutoff month of the harvest season to August and treat the growth and the harvest season as one, which corresponds to the time span lasting from  $\tau + \phi$  till  $T$  in our model. During the months of March - August the coffee plant develops and reaches its maturity. If it has been infected with coffee rust, the growth process is impeded and only a fraction of total harvest survives. The average crop losses from coffee rust in Peru were around 25% between 2013 - 2014. We therefore set the expected share of survived crop to  $\mathbb{E}[s] = 0.75$ .

The farmer's rate of time preference is assumed to be 10% per year. The recent empirical evidence on the rate of time preference pertaining to rural households is quite sparse, even more so for Peruvian farmers. Lence (2000) is perhaps the most closely-related study, although



it is based on the data on farmers in the US. He finds a statistically significant point estimate of 0.0534 with a 95% confidence interval [0.0441,0.0629]. It should be kept in mind, however, that these estimates are relevant for US farmers which enjoy a much higher income per capita than those in our study. Holden et al. (1998) provide supporting evidence that poverty and/or liquidity constraints are positively associated with higher rates of time preference among rural households. We therefore set  $\rho = 0.1$  in our baseline calibration.

The arrival rate of an adverse climate event is calibrated to match the data on heavy rainfalls during the period 1964 - 2013. An average share of rainy days with precipitation of more than 5mm per day during the rainy season was 18%. An average share of rainy days with precipitation of more than 10mm per day was 7% (SENAHMI, pers. comm.). In our benchmark calibration we therefore set  $\lambda = 0.07$  per half year. We shall also discuss the results for a bracket of probabilities between 5 and 20% as a robustness check.

Another important parameter to calibrate is the parameter entering the utility function,  $\theta$ . Given the assumed structure of preferences,  $\theta$  represents the inverse of the coefficient of relative risk aversion, which is especially relevant in our analysis of decision-making under uncertainty. The evidence on farmers' behavior suggests that they are typically risk averse with the coefficient of relative risk aversion being significantly above unity and the middle value being around 2 (Hardaker et al. 1997), implying a value of  $\theta$  of 0.5. Using the data on US farmers, Lence (2000) finds a point estimate of 1.136 (implying  $\theta$  of approximately 0.88) and argues that farmers attitudes towards risk are unlikely to be logarithmic. Liu (2013) estimates  $\theta$  of around 0.48. Based on this evidence, we set the baseline value of  $\theta$  to the middle value, which is approximately 0.75.

The constant income flow is normalized to ten units per week during the period  $[0, \tau + \phi]$ . Since we are concerned with a relatively poor population of subsistence farmers, we shall assume that their initial asset holdings are relatively small and equal to one week worth of income. When a shock strikes, the flow of income is reduced to  $\omega y$ , where  $\omega$  is determined by the survived share of the harvest,  $s$ , and by the quantity of fungicide,  $k_\tau$ . In the stochastic scenario (when CS is not available) the intensity of the shock is a random variable. We shall assume that  $s$  is distributed according to the Beta distribution with parameters  $a = 6$

Planning horizon	$T$	52
Rate of time preference	$\rho$	$0.1/T$
Productivity	$A$	1
Concavity of $f(k_\tau)$	$\alpha$	0.5
Arrival rate	$\lambda$	$0.07/(T/2)$
Saving duration	$\tau$	14
Income flow	$y$	10
Initial assets	$k_0$	10
Elasticity of marginal utility	$\theta$	0.75
Survived share of harvest	$s$	0.75
Beta function:	$a = 6$	$b = 2$

Table 1: Benchmark calibration.

and  $b = 2$ . The parameters  $a$  and  $b$  are chosen such that  $\mathbb{E}[s] = \frac{a}{a+b} = 0.75$ , i.e. 75% of the harvest survives the adverse weather event on average. The density of  $s$  is given by  $g(s) = s^{a-1}(1-s)^{b-1}/B(a,b)$ ,  $s \in [0, 1]$ , where  $B(a,b)$  is the Beta function. The advantage of working with a Beta-distributed random variable is that it is bound to lie on the interval  $[0, 1]$ , which is convenient for describing a fraction (the fraction of harvest in our particular case). The values of the calibrated parameters are summarized in Table 1.

We illustrate the climate-service value in Figure 1, where the two horizontal axes represent

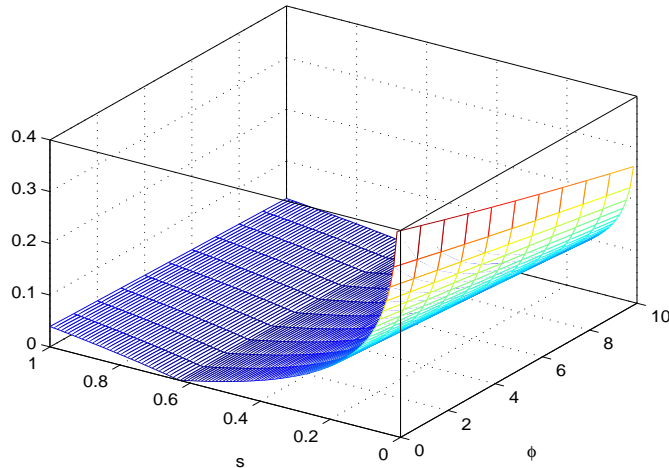


Figure 1: Value of climate services.

the survival rate,  $s$ , and the shock arrival time,  $\phi$ . The vertical axes shows the value  $P$  as defined in Eq. (21). We note that CSV is nonlinear in both variables. It attains its maximum value when both  $s$  and  $\phi$  approach zero, i.e. the crop is entirely infected with rust at an early stage. For any given  $s$ , CSV declines as the arrival time is postponed further into the future. However, for any given  $\phi$ , CSV is non-monotonic in  $s$ . This is because there exists a unique value of  $s$  such that the farmer's welfare is identical with or without climate service. Note that this value *is not* equal to  $\mathbb{E}[s]$ . When the true  $s$  is below this value, while the expectation of  $s$  is above it, the uninformed farmer is overly optimistic and anticipates a relatively high welfare, thus committing an error. As  $s$  increases, the error becomes smaller and therefore CSV declines. The opposite occurs when the true  $s$  is relatively large. We illustrate this in Figure 2 for three different values of  $\phi$ . We chose  $\tau = 14$  (the middle of the possible range) which corresponds to the duration of the saving phase from September and up to mid-December. The rainy season, which sets off propitious conditions for the development of coffee rust, runs from January to March. We shall therefore focus on three possible arrival times of the climate shock: beginning of January, of February and of March. This corresponds to  $\phi = 2$ ,  $\phi = 6$ , and  $\phi = 10$ . The corresponding lines are solid, dashed, and dotted, respectively. The figure confirms that CSV initially declines as  $s$  increases reaching zero at some threshold value from which on CSV increases. At the value of  $s$  equal to its expectation, the value of climate services is given by 5.76% when the shock strikes as early as January, 4.89% at the beginning of February, and 4.04% at the beginning of March.

In order to obtain a monetary equivalent for CSV we turn to the data on coffee farmers in Cusco region of Peru in 2012. The average farm size in this coffee producing region is 2.8 hectares with an average yield of 0.71 tons per hectare. Cusco farmers received a relatively high price for their coffee amounting to 6'488 Peruvian Nuevo Soles (S), equivalent to \$2'314, per ton. The costs of operating a farm were around 2'414 Soles ( $\approx$  \$830) per hectare. The net income of an average farm was thus \$2'276.2 per year. Assuming, for example, that a heavy rainfall strikes in the middle of the rainy season (February), the value of the climate service to a single household is equal to \$55.31 per year. In per hectare terms, the net yearly income from coffee farming is equal 812.94\$/ha and thus the value of the climate service

ranges from 16.25\$/ha to 23.33\$/ha, depending on the timing of the weather shock. An increase in a farmer's productivity by 5% yields an increase in the climate-service valuation by approximately 30%. An increase in the size of a farm by 10% yields an increase in CSV of about 3%.

There are a total of 58'585 ha of crop area devoted to coffee production in the region of Cusco. Taking our benchmark numbers for the per hectare valuation of climate services, we obtain that CSV for the overall region equals \$1.1573 million if the shock occurs in the middle of the rainy season. If a heavy rainfall and thus the onset of coffee rust takes place a month earlier, the climate service is valued at \$1.3669 million, while if it happens a month later, CSV amounts to \$0.9525 million. An increase in the arrival rate from 7 to 20% leads to a decline in the CSV, due to the precautionary saving motive, to \$0.9382 million (if the event occurs in March) and to \$1.3526 million (if the event occurs in January).

The next sections provide a rigorous empirical assessment of the value of climate services for coffee production in the Cusco region of Peru. For comparison, we also include empirical results for a second most important agricultural commodity - maize, which is the most widely spread subsistence crop. As will be explained in more detail in the next section, maize production is characterized by different (and more limited) adaptation possibilities than coffee

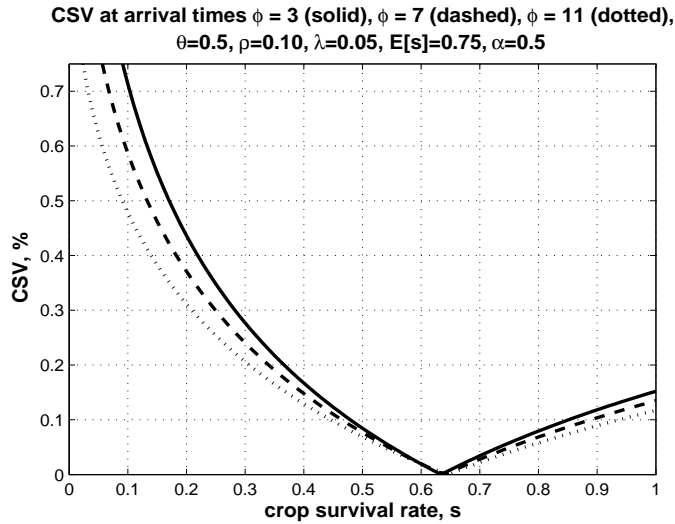


Figure 2: Climate-service value for selected values of shock arrival: January, February, March.

farming, which leads us to expect a lower valuation of climate services for this crop type.

## 4 Empirical Investigation: A Choice Experiment

### 4.1 The Case Study

The data were obtained from an in-person survey with farmers in two areas within the region of Cusco in Peru during May-June 2014. One area is located in the subtropical highland zone of the province Quispicanchis, districts Andahuaylillas and Huaru (henceforth: Quispicanchis), and the other area is located in the tropical savanna of the province La Convencion in the district Santa Teresa (henceforth: La Convencion). Due to different geo-ecological conditions, the two study areas are characterized by different agricultural productions: in Quispicanchis farmers cultivate largely maize and in La Convencion the main crop is coffee. Both types of crop cultivation are essential for agricultural production in the region of Cusco, with coffee being Peru's most important export commodity and maize representing a vital subsistence crop. Also, both crops appear to be especially relevant for this study as they are particularly sensitive to changing climate conditions (Tai et al. 2014, Magrin et al. 2007), which indicates a potential need for climate services. The maize types cultivated in Cusco are optimally adapted to the prevailing climatic conditions. Depending on the growth period, however, the production appears to be sensitive to extreme weather events such as frost, heat waves, heavy rainfall and hail (MeteoSwiss/SENAMHI, 2014).

As we have shown in the previous section, CS help farmers to foresee the occurrence and the intensity of a climate shock which enables them to apply precautionary measures more efficiently, for example planting, irrigation, fertilizer application, and pest management. The economic value of the CS is ultimately determined through the usefulness of the corresponding climate information for mitigating the impact of undesirable climate-related effects which we investigate empirically based on a stated preferences study. We developed a hypothetical climate service in the form of an early warning system, which is characterized by the annual cost to the farmer's household and three attributes (technical characteristics). Identifying

these attributes as well as assigning corresponding levels are crucial steps in the design of a discrete choice experiment. We developed these elements based on interviews with experts, on information from the testing phase as well as on experience from existing studies of an individual's valuation for weather forecasts (Chestnut and Lazo, 2002; Lazo and Waldmann 2011). In addition to the annual costs, the technical attributes used for the final evaluation are: the frequency of updates, the geographic resolution and the accuracy of information. The set of attributes and their corresponding levels are shown in table 2.

Attribute	Levels			
<i>Frequency of updates</i>	every day	every three days	once a week	every two weeks
<i>Accuracy of information</i>	60%	70%	80%	95%
<i>Geographic resolution</i>	10km	30km	100km	140km
<i>Cost</i>	S. 5 a year	S. 10 a year	S. 20 a year	S. 50 a year

Table 2: Climate service's attributes and level

*Notes:*

1. An accuracy of 100% means that all information provided by the climate service is correct.
2. Geographic resolution relates to the area covered by the information provided by the climate service. A grid length of 10 km relates to an are of 100 sq km (10 km per 10 km).
3. Annual costs are indicated in Peruvian Nuevo Soles (S).The exchange rate to US \$ during the field study (May-July 2014) was 2.8 S per \$.

The climate service in the survey scenario is designed to inform the farmer via a mobile phone about climate-related parameters that influence crop growth such as temperature, precipitation and relative humidity<sup>6</sup>. This information contains historical data as well as forecasts which help the farmer to take production decisions. For example, in the case of coffee production the information may serve as an early warning system against the outbreak

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<sup>6</sup>Access to and use of mobile telephony in the study sample almost reaches 100%. This reflects the general trend of an increasing mobile phone coverage in rural areas of developing and emerging countries, see e.g. Aker and Mbiti (2010).

of the climate-sensitive coffee rust allowing the farmers to apply preventive measures more efficiently (e.g. use of fungicides). On the other hand, in the maize sector, preventive measures with regard to climate-related stress factors are more restricted. The options to react to heavy rainfall or hail, for instance, are limited as they require high investments within a very short time period, which is usually not realizable for the farmers. We therefore expect the maize farmers' valuation of the climate service to be smaller than for coffee farmers.

During data collection, 63 farmers were interviewed and each respondent answered 10 choice experiments. In each of these experiments, the farmer chooses between two alternative climate services represented by combinations of different levels of the attributes. Table 3 shows a typical choice set presented in the survey. Due to insufficient census data and difficult accessibility of participants in the study region, nonprobability sampling was applied (chain sampling method). All interviewed farmers are smallholders cultivating 1.5 ha of land on average<sup>7</sup>. The sample is composed of 70% male respondents and the average age is 50 years. 62% of the interviewed farmers have completed secondary school. Using four attributes each with four levels for a two-option choice set design results in  $4^8 (= 65'536)$  possible choice questions. In order to obtain a more manageable number of options, we restrict the choice sets by conducting a search based on D-optimality criterion (Kuhn, 1996). The resulting choice set was blocked over three versions to reduce the number of choice task for the respondents.

	Climate service 1	Climate service 2
<i>Frequency of updates</i>	once a week	every two weeks
<i>Accuracy of information</i>	80%	70%
<i>Geographic resolution</i>	100km	10km
<i>Cost</i>	S. 10 a year	S. 20 a year

Table 3: Example of a choice set

<sup>7</sup>Coffee farmers cultivate greater areas on average (2.5 ha) than maize farmers (0.75 ha).

The questionnaire is adopted from Chestnut and Lazo (2002) and adapted to the local context based on repeated meetings and interviews with experts in the field of climatology and agricultural production in Peru. An initial version was tested in the field and intensively discussed with local partners.<sup>8</sup> After a respective refinement process the final questionnaire was developed for the field study.

## 4.2 The Econometric Model

We apply a Random Utility Model to the choice experiment data, where we use statistical analysis to derive marginal values for the attributes of the climate services. The basic model assumption requires that respondents consistently select those alternatives conferring the highest level of utility. Expressed more formally, individual  $i$  chooses the climate service  $g$  out of alternatives  $k = 1, 2$ , if  $U_i^g \geq U_i^k$ .  $U_i^k$  is the unobserved utility of the climate service  $k$  to individual  $i$ . Following the conventional procedure the utility is modeled as a sum of two components: a linear combination of the observed choice attributes and an unobserved component which is represented as a random term  $\epsilon$ ,

$$U_i^k = \beta' x_i^k + \epsilon_i^k, \quad i = 1, \dots, 630 \quad k = 1, 2, \quad (22)$$

where  $x_i$  is the vector containing the levels of the climate service's attributes (Frequency, Accuracy, Resolution and Costs) and  $\beta$  is the vector of marginal utilities.

The error term is assumed to be independent and identically distributed and follow a Gumbel distribution. Given this hypothesis on the distribution of the error term, the unconditional probability of choosing climate service 1 can be written as the conventional logit probability

$$P_i^1 = P(U_i^1 > U_i^2) = \frac{\exp(\beta' x_i^1)}{\sum_{k=1}^2 \exp(\beta' x_i^k)}. \quad (23)$$

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<sup>8</sup>The most important project partners, which assisted at preparing the survey are *CARE Peru* (local NGO), *Fibl* (research institute of organic agriculture), *Meteodat* (consulting company in the field of hydrology, meteorology, climatology, and information technology), *MeteoSwiss* (the federal office of meteorology and climatology in Switzerland), *SENAMHI Peru* (national service of meteorology and hydrology in Peru), as well as several local agronomists working in the region of Cusco.



This is the usual logit model for dichotomous choice. The probability in Eq.( 23) serves as a basic component for the log-likelihood function, which is used for parameter estimation. In a first step we do not account for the panel structure of the data set, which is given by repeated observations (choice occasions) for the same individual. The marginal monetary value for a unit change in the attributes (MWTP) is derived by calculating the ratio of each marginal utility coefficient to the marginal disutility of costs:

$$\widehat{MWTP} = \frac{\widehat{\beta}_s}{\widehat{\beta}_{cost}}, \quad s = \textit{Frequency, Accuracy, Resolution}. \quad (24)$$

In addition to the basic model specification (henceforth: standard logit model) we apply a random parameter logit model in order to take two more empirical issues into account: first, we allow for preference heterogeneity of the population and, second, we consider the panel dimension of the data. The fundamental idea of the mixed logit model is to extend the parametric structure such that the coefficient vector  $\beta$  is allowed to vary randomly across individuals. That means, other than in the standard logit model, marginal utilities are not fixed but are allowed to be individual-specific,  $\beta_i$ . Furthermore, we extend the model structure by introducing subscript  $j$ , which reflects the presence of repeated observations (choice occasions) for the same individual  $i$ . The unobserved utility for individual  $i$ , at choice occasion  $j$  for climate service  $k$  is specified as follows:

$$U_{ij}^k = \beta_i' x_{ij}^k + \epsilon_{ij}^k, \quad i = 1, \dots, 63; \quad j = 1, \dots, 10; \quad k = 1, 2. \quad (25)$$

The random terms  $\epsilon$  still follow the distributional hypothesis. However, the common individual effect of the  $\beta_i$ 's, which enter utility for each individual's choice alternative, induces correlation in the error structure across choices made by the same respondents. Thus, the model allows to account for dependencies of unobserved individual factors over the choices (Train, 2003).

With the probabilities of the mixed logit model being integrals with no closed form, simulation techniques are usually applied for estimation, where the expected values are replaced

by an arithmetic mean.<sup>9</sup> In the present application we use 1000 Halton draws and assume a normal distribution for the model parameters, except for the cost attribute which is assumed to be non-random.

### 4.3 Empirical Results

The results of the standard logit model are presented in table 4. Coefficients, standard errors and the MWTP are reported for each attribute. In order to account for heterogeneity within the sample, estimations are conducted for demographic subgroups. The first column presents results derived based on the full sample. Columns 2 and 3 represent the agricultural specialization of the farmers, characterized by coffee and maize cultivation. As the type of cultivation is associated with the geographical localization, this sample split also reflects a regional subdivision. Columns 4 and 5 are related to the farm size and columns 6 and 7 represent the farmer's level of education.

The marginal effects, except for the frequency of updates, are mostly statistically significant at the 5% level and reveal economically plausible effects throughout all samples. The accuracy attribute is not significant in the maize and in the *small farm* sample. An increasing accuracy is associated with a positive product valuation. The negative estimate of the parameter on the geographic resolution is also expected as a smaller coverage area means a larger geographic detail which is presumably beneficial for farmers' welfare. The parameter on cost is negative, representing marginal disutility. The frequency of updates appears to be less important as a climate service attribute, with the parameters not being statistically significant for neither sample. Thus, farmers apparently do not expect a frequent actualization of climate information to be useful. This does not necessarily reflect the technological and agrometeorological property of the frequency attribute, but rather the farmer's persistence on existing habits related to meteorological information.<sup>10</sup>

The evaluation of the yearly MWTP reveals some interesting insights. With the frequency attribute not being significant, we do not evaluate the corresponding MWTP. For the other

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<sup>9</sup>For more detailed description of the estimation techniques see Croissant (2014).

<sup>10</sup>Our survey reveals that the average farmer consults weather forecasts only once a month.

Attributes of the climate service	Full sample (n=630)	Main cultivation		Farm size		Education	
		Coffee (n=330)	Maize (n=300)	>2ha (n=224)	<2ha (n=351)	Secondary school (n=368)	Primary school (n=207)
<b><i>Frequency of Updates</i></b>							
$\beta$ estimate	0.006 (0.006)	0.007 (0.008)	0.002 (0.009)	-0.002 (0.010)	0.010 (0.007)	0.006 (0.007)	0.005 (0.010)
MWTP (per update per month)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
<b><i>Accuracy of information</i></b>							
$\beta$ estimate	0.015 (0.006)	0.035 (0.009)	-0.012 (0.010)	0.023 (0.011)	0.014 (0.008)	0.013 (0.008)	0.019 (0.011)
MWTP (per percentage point)	\$0.183	\$0.417	n.s.	\$0.264	\$0.161	n.s.	\$0.164
<b><i>Geographic resolution</i></b>							
$\beta$ estimate	-0.010 (0.001)	-0.012 (0.002)	-0.007 (0.001)	-0.014 (0.002)	-0.008 (0.001)	-0.009 (0.001)	-0.011 (0.002)
MWTP (per 100 sq km)	\$0.122	\$0.143	\$0.092	\$0.161	\$0.092	\$0.132	\$0.095
<b><i>Cost</i></b>							
$\beta$ estimate	-0.082 (0.017)	-0.084 (0.023)	-0.076 (0.023)	-0.087 (0.031)	-0.087 (0.020)	-0.068 (0.020)	-0.116 (0.031)

Table 4: Standard Logit Estimation

*Notes:*

1. Standard errors are in parenthesis
2. MWTP is the marginal monetary yearly value of a unit improvement in the corresponding attribute.
3. MWTP is only indicated for parameter values significant at the 5% level. n.s.= not significant

attributes, accuracy and resolution, the MWTP is defined to represent the marginal monetary value for a unit improvement in the respective attribute. The WTP per percentage point improvement of accuracy moves between \$0.16 and \$0.42. The highest MWTP results in the coffee sample. Also the farmers from the *big farm* sample have a higher MWTP than the farmers from the *small farm* sample. The same differences appear when looking at the resolution attribute. Coffee farmers have a higher MWTP than maize farmers with \$0.143 per

Attributes of the climate service	Full sample (n=630)	Main cultivation		Farm size		Education	
		Coffee (n=330)	Maize (n=300)	>2ha (n=224)	<2ha (n=351)	Secondary school (n=368)	Primary school (n=207)
<b><i>Frequency of Updates</i></b>							
Mean value ( $\beta$ )	0.007 (0.004)	0.010 (0.006)	0.002 (0.006)	-0.002 (0.010)	0.010 (0.006)	0.007 (0.005)	0.004 (0.008)
Standard deviation ( $\beta$ )	0.097	0.096	0.093	0.098	0.100	0.094	0.095
MWTP (per update per month)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
<b><i>Accuracy of information</i></b>							
Mean value ( $\beta$ )	0.025 (0.002)	0.043 (0.004)	0.006 (0.004)	0.030 (0.010)	0.014 (0.003)	0.022 (0.003)	0.030 (0.004)
Standard deviation ( $\beta$ )	0.143	0.143	0.140	0.144	0.144	0.140	0.139
MWTP (per percentage point)	\$0.284	\$0.506	n.s.	\$0.441	\$0.215	\$0.355	\$0.246
<b><i>Geographic resolution</i></b>							
Mean value ( $\beta$ )	-0.007 (0.001)	-0.010 (0.001)	-0.006 (0.002)	-0.012 (0.002)	-0.008 (0.001)	-0.006 (0.001)	-0.009 (0.002)
Standard deviation ( $\beta$ )	0.173	0.173	0.173	0.173	0.173	0.173	0.173
MWTP (per 100 sq km)	\$0.080	\$0.118	\$0.074	\$0.176	\$0.123	\$0.097	\$0.074
<b><i>Cost</i></b>							
Parameter estimate	-0.088 (0.011)	-0.085 (0.017)	-0.081 (0.014)	-0.068 (0.031)	-0.065 (0.023)	-0.062 (0.014)	-0.122 (0.020)

Table 5: Random Parameter Logit Estimation

*Notes:*

1. Standard errors are in parenthesis.
2. MWTP is the marginal monetary yearly value of a unit improvement in the corresponding attribute.
3. MWTP is only indicated for parameter values significant at the 5% level. n.s.= not significant
4. Standard deviations for  $\beta$ 's are all significant at the 5% level.

sq km and bigger farms seem to value the attribute more than smaller farms with a MWTP \$0.161. Also it seems that farmers with a higher education level have a higher MWTP with \$0.132 than farmers that only completed primary school. These differences in the MWTP are economically plausible: the higher valuation of the climate service attributes for coffee farmers

could be related to the presence of coffee rust in the sample region. As mentioned before, this disease had a devastating economic effect in the year 2013, which may cause the coffee farmers to attach higher expected benefits to the climate service. In the maize sector, preventive measures based on enhanced climate information appear to be rather limited in comparison with the coffee sector, which restricts the usefulness of the climate service. Furthermore, with coffee being a cash crop, the farmers may be more experienced in economic and monetary reasoning, which increases their cognitive ability to plan their production process with the hypothetical climate service in the survey scenario. This latter reason may also apply to the higher MWTP in the more educated sample. Higher education may be related to a better understanding and, thus, to a more precise valuation of the hypothetical product. The higher MWTP in the sample including the bigger farms indicates a scale effect in production, where farmers with a bigger crop area can extract more benefit due to the fixed annual costs assigned to the climate service in the survey scenario.

The above results are robust to the specification in the random parameter logit model presented in table 5. The mean value for the marginal effects of the attribute are statistically and economically significant only for the accuracy and resolution attribute. As before, the coffee farmers appear to attach the highest MWTP to these attributes and bigger farms have a higher MWTP than smaller farms and more educated farmers have a higher MWTP than less educated farmers. The estimated standard deviations indicate a significant heterogeneity of preferences within the samples.

In order to interpret and illustrate these estimates we calculate an individual's yearly WTP for a climate service with intermediate values for accuracy and geographic resolution. So far, no climate services specifically designed for the farmers needs are provided in the study region. There exist, however, different measurement stations, which provide the farmers with basic climate information. Evaluating this status quo based on interviews with local and international agronomists, we consider the baseline values for the attributes to be 10% accuracy and 150km geographic resolution. We derive the attribute values for an intermediate improvement of the climate service by relying on experiences from a well established prediction system (*MARYBLYT*) related to the outbreak of fire blight, a contagious disease affecting

apples and pears. This system uses information on weather and plant phenology in order to generate infection forecasts. Different studies have shown that the according prediction accuracy lies between 60 and 80% (Dewdney *et al.*, 2007; Dewdney and Aldwinckle, 2008). For the case of Switzerland, the system consists of 78 measurement stations translating into an average geographic resolution of 22 km grid length. Expecting that an improvement in accuracy is easier to obtain for the case of Peru, we assume an intermediate enhancement of climate services to represent 80% accuracy and a geographic resolution of 50km grid length. Thus, we have an improvement relative to the baseline of 70 percentage points and 20'000 sq km respectively. Multiplying these numbers by the corresponding MWTP leads to the yearly WTP (or yearly welfare change) induced by the enhancement of the climate service. The numbers are presented in table 6. For interpretation, we only focus on the WTP calculated from the Random Parameter model<sup>11</sup>. The annual WTP in the coffee (maize) sector for one individual is estimated at \$59.02 (\$14.80), which translates into a yearly per hectare value of \$21.10 (\$11.38).<sup>12</sup>

Similar to weather forecasts and meteorological information, the potential development and implementation of climate services is likely to be financed and provided publicly. As outlined by the *Madrid Action Plan* of the *World Meteorological Organization* (WMO, 2007), it is of major importance to quantify the benefits of national meteorological and hydrological services in order to justify the required financial resources. A basic linear interpolation of the yearly per hectare values to the target population on the regional and national level indicate the approximate aggregate WTP for climate services in the agricultural sector. The total crop area for coffee in the region of Cusco is 58'585 ha and for maize 30'388 ha. On the national level, the crop areas are 390'523 ha and 547'527 ha respectively.<sup>13</sup> Multiplying these numbers with the per hectare WTP implies an aggregate valuation of the climate services for the coffee and the maize sectors of \$1.582 million per year for the region of Cusco and \$14.471 million per year at the national level.

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<sup>11</sup>Both model specifications, standard logit and random parameter logit, lead to similar values.

<sup>12</sup>According to our sample, the average farm size is 2.8 ha for coffee and 1.5 ha for maize.

<sup>13</sup>Data related to regional and national agricultural production are retrieved from the peruvian ministry of agriculture and irrigation (Minagri, 2014).

Crop type (model)	Individual WTP	WTP per ha	Aggr. WTP (in Mio.) (Region of Cusco)	Aggr. WTP (in Mio.) (Peru)
Coffee (std.logit)	\$57.79	\$20.46	\$1.209	\$8.060
Coffee (RP logit)	\$59.02	\$21.10	\$1.236	\$8.240
Maize (std.logit)	\$18.40	\$14.15	\$0.431	\$7.748
Maize (RP logit)	\$14.80	\$11.38	\$0.346	\$6.231

Table 6: WTP for the climate service.

*Notes:*

1. The WTP represents annual values.
2. According to our sample, the average farm size is 2.8 ha for coffee and 1.5 ha for maize.

## 5 Conclusion

An increase in the global temperature and an amplification of temperature variability pose new challenges for agricultural producers. The problem is especially relevant for farmers in the developing countries which are presumably more vulnerable to climate change and possess less resources and knowledge for adaptation. In the past several years every coffee-producing country in Latin America experienced a substantial drop in coffee output due to outbreaks of the plant disease known as coffee rust. The infections were amplified by unexpectedly warmer temperatures and more intense rainfalls. Information on future climate and weather conditions – so-called climate services – if communicated to the farmers, has a strong potential for enhancing their adaptation strategies and thus reducing crop losses. Provision of climate services may therefore contribute to improvement in the welfare of rural households and to the security of the global food system.

The contribution of the present study is two-fold. First, we provide a theoretical foundation for determining the value of climate services in the agricultural sector characterized by random occurrences of adverse climate events with random-size damages. Second, we conduct an empirical investigation of farmers' preferences and valuations for climate services in Peru

based on discrete choice methodology. We collected data based on a pilot field survey in the region of Cusco focusing on coffee and maize crops. The econometric analysis is based on a standard logit model and a random parameter logit model.

We developed a hypothetical climate service characterized by annual costs to a farmer's household and three attributes including frequency of updates, accuracy of the information and the geographic resolution. Results indicate a significant willingness to pay for climate services, which is especially related to the accuracy of the information as well as the geographic resolution. Interestingly, farmers in the coffee sector show a higher valuation for climate services. This is most likely due to a higher climate sensitivity related to the presence of coffee rust, a climate-responsive disease currently raging in coffee cultivations across South and Central America. Furthermore, in the coffee sector, farmers appear to have more options for using climate information in their production process. The results from the simulated model, calibrated to the data on Cusco, indicate the yearly value of climate services in the range of \$16.26 - \$23.33 per hectare, depending on the timing of the weather shock. The CSV for the whole region is \$0.95 - \$1.36 million. These estimates may be interpreted as upper bounds on CSV as they presuppose perfectly accurate weather predictions. The results of the empirical estimation suggest that CSV for the coffee sector is approximately 21.10\$/ha per year and \$1.24 million for the region of Cusco.

In light of current initiatives aimed at strengthening provisions of climate services for the most vulnerable population, the present results represent a first step based on economic valuation in indicating a direction for policy design related to a potential implementation of climate services in less developed countries. These services may constitute an important element of climate change adaptation strategies. Further research is required in order to better understand the drivers of economic values related to different types of crops as well as to different climate-sensitive sectors.



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