Index Insurance, Production Practices, and Probabilistic Climate Forecasts

Miguel A. Carriquiry and Daniel E. Osgood

International Research Institute for Climate and Society
Columbia University

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Agricultural producers around the world face a variety of climate related risks. Climate risks, such as droughts, have profound impacts on developing countries, where agriculture usually makes a significant contribution to their gross domestic product, [1] and insurance markets are under-developed or inexistent.[2]

There are virtually no examples of successful multiple peril crop insurance in the world without use of government funds, for example in the form of subsidies (Skees, Hazell, and Miranda; Hazell). Failures in traditional crop insurance have been attributed mainly to asymmetric information (Just, Calvin and Quiggin; Chambers; Knight and Coble), and the systemic nature of agricultural risks (Miranda and Glauber). The failure of crop insurance as a viable instrument to manage production risks launched a search for alternative instruments such as index insurance.[3] Index insurance is a generic term used to indicate that the insurance is written for a specific event such as area yield loss, rainfall deficits, etc, and not the actual loss (production or income) at the farm. The main difference from traditional crop insurance is that one or more events that cause losses are insured as a way to hedge production risks, but not the loss itself (Turvey).

The viability of index insurance against climatic risk as an innovative alternative to traditional crop insurance is being intensely studied as a form to provide protection to agricultural producers in developing countries (see World Bank 2005 and the references

[1] Agriculture accounted for 27% of GDP in low-income countries compared to only 2% in high-income countries (World Bank 2001).

[2] Since there is a large body of literature on the role of risk in agriculture (see e.g. Just and Pope; Moschini and Hennessy) it is worthwhile to note that there are several sources of risk that are relevant from the producer's perspective, including production, price, technological, and policy uncertainties. The effect of price uncertainty due to random demand has received substantial attention (Ratti and Ullah; Pope and Kramer), with Sandmo's article being salient to this area. Pope and Kramer argue that production uncertainty may have a larger impact than market uncertainty, especially since the advent modern price management tools such as hedging, forward contracting, etc. This is certainly true in countries where instruments to reduce the impacts of uncertainty such as crop insurance are under-developed or unavailable. Since our focus in the present article is on climate risks, a case of production uncertainty, we will assume that prices are non-random.

[3] Although the idea of index insurance is not new (it can be traced back to the work of Halcrow in the 40's), it is now attracting increasing attention as an alternative to traditional crop insurance for developing countries.

therein).[4] One of the main drivers of this research is the belief that if farmers are offered affordable insurance, they will be able to invest more in inputs, and to choose higher return activities, providing means to escape poverty traps. Work in the agricultural economics literature has examined the relationship between insurance and input usage (especially nitrogen, but also pesticides) for both farm level (Ramaswami; Babcock and Hennessy; Horowitz and Lichtemberg; Smith and Goodwin) and index insurance (Chambers and Quiggin; Mahul). In the U.S., where it has been shown that farmers tend, based on ex-post evaluations, to over-apply nitrogen (Babcock 1992), the presence of insurance resulted in conflicting empirical results. Horowitz and Lichtemberg estimated that farmers who purchased insurance increased nitrogen applications by 19%, whereas both Babcock and Hennessy, and Smith and Goodwin find the opposite. Ramaswami concludes (through a conceptual model) that the presence of actuarially fair multiple peril crop insurance will have an indeterminate effect on the use of risk increasing inputs.[5] For the case of index insurance (against climate risks), where moral hazard issues are sidestepped, Mahul showed that insured farmers would use more (less) risk increasing (reducing) inputs than their uninsured counterparts. Chambers and Quiggin, analyze the effects of area-yield insurance on the producer's decisions regarding their exposure to risk. The research just outlined does not consider the possible interaction between insurance, climate forecast, and input decisions.

Recent research has shown that seasonal climate is predictable in many regions of the world (Goddard et al.). This seasonal predictability offers the potential to better manage climatic uncertainty through contingent choices of production (Hansen) and insurance practices. Although it is recognized that improved skill in seasonal climate forecasting may have implications for the design and rating of index insurance on weather variables (Skees, Hazell, and Miranda), the effects are usually assumed away by claiming that it would suffice to close sales dates ahead of time. The claim usually makes reference to the lack of skill of long-lead forecasts (Hess and Syroka; World Bank 2005). However the actual relationship has not been formally studied. Work in agricultural and climate science has modeled the impact of probabilistic climate forecasts on the

[4] For a discussion of the pros and cons of index insurance see (Miranda; World Bank 2005).
[5] The moral hazard effect which would induce an insured farmer to use less of the input works in the opposite direction than the risk reduction effect.

production decisions and estimated the value of that information (e.g Solow et al.) but has, with few exceptions (Mjelde, Thompson, and Nixon; Cabrera, Letson, and Podesta (CLP)), ignored the potential impact of insurance. The two exceptions just mentioned relied on numerical simulations to analyze the impact of several government programs (including the US crop insurance) on the value of seasonal forecast information. CLP determined the optimal management practices in the absence of farm programs and climate information and then studied how a subset of the decision, and the resulting financial outcome where affected by ENSO phase and government programs. CLP followed an ex-post approach, since they considered the impact of different ENSO phases, but not of the climate forecasts.

Opportunities for inter-temporal adverse selection in the context of the US yield insurance and based on different forecasts of the growing conditions for the coming season have been explored. Luo, Skees, and Marchant used a combination of soil water content and past and forecast weather to study the possibility of identifying poor growing conditions for corn in the Midwest early in the year. The authors argue that there is enough early season information to allow farmers to adversely select. In a later study, McGowan and Ker found that companies selling wheat yield insurance in Texas could use sea surface temperatures in order to adversely select against the US Risk Management Agency.

Since the fundamental relationship between index insurance, input use, and seasonal climate forecasts has not been addressed, we propose to fill this gap by explicitly modeling input use and index insurance demand given probabilistic seasonal climate forecasts. While seasonal climate forecasts, insurance contracts, and input use choices can each be used to mitigate uncertainty and risk, they each play a different role, and have potential synergies or unanticipated impacts when used together. This is of particular relevance given the parallel efforts to improve the quality and availability of seasonal climate forecasts, establish index insurance markets, and encourage effective input use in developing countries.

It is known that if an index insurance scheme is developed without recognizing the availability of forecasts and adjusting the timing or prices of contracts, the asymmetry of climate information may undermine the insurance system. We find that if contracts are appropriately designed there are important synergies between forecasts and insurance and effective input use. Insurance allows the farmer to map a probabilistic forecast into a much more deterministic payout, allowing the farmer to commit to production choices that take advantage of forecast information that is too noisy to utilize without risk protection. With insurance, the farmer may be able intensify in potentially good years, and thus realize higher average payoffs. When a forecast can increase productivity or the value of insurance, an infeasible index insurance system may become workable, which may have particular relevance in infant insurance markets in developing countries.

We investigate the fundamental relationship just described through a model of input choice, forecasts, and index insurance. The model is highly stylized in order to most clearly represent fundamental features. We derive optimal input and insurance demand as a function of forecast quality and determine production changes with respect to the absence of forecast information and insurance. We also determine under what conditions insurance, forecasts, and inputs complement or substitute for each other, identify the potential synergies or conflicting impacts.

Preliminaries and Base Model

Consider first a competitive farmer with a single crop which has a yield dependent on the level of a controllable input (N , hereafter nitrogen, but may be thought of as an improved seed, or the level of technology employed) and some weather variable (hereafter rainfall). The value of the weather variable is learned after the input has been applied. For simplicity assume that rainfall (r) can only take two values, r_H and r_L (subscripts denote high and low respectively). The farmer knows that the historical probability of observing $r = r_H$ is ω_H . Profits for the farmer are

$$\pi(N,r) = pf(N,r) - p_N N, \; r = r_H \text{ or } r = r_L,$$

where p is the (nonrandom) output price, p_N is the price of the input, and $f(\bullet)$ represents the production function (yields). It is assumed that $f_N(N,r) = \frac{\partial f(N,r)}{\partial N} > 0$, and $f_{NN}\left(N,r\right)=\frac{\partial^2 f\left(N,r\right)}{\partial N^2}\leq 0$. We assume further that $f\left(N,r_H\right)>f\left(N,r_L\right)$, and $f_N\left(N,r_H\right)>f_N\left(N,r_L\right)$ for all N.

The farmer is assumed risk averse with a Bernoulli utility function given by $u\left(\pi\right)$, with $u''\left(\pi\right)\leq 0<u'\left(\pi\right)$.

If the farmer's choice is on the level of the input to apply, his/her problem and necessary conditions (for an interior solution) are

$$\max_N Eu\left(\pi\right)=\omega_H u\left(pf\left(N,r_H\right)-p_N N\right)+\left(1-\omega_H\right)u\left(pf\left(N,r_L\right)-p_N N\right) \qquad (1)$$

$$\omega_H u'\left(\pi^{H*}\right)\left(pf_N\left(N^*,r_H\right)-p_N\right)+\left(1-\omega_H\right)u'\left(\pi^{L*}\right)\left(pf_N\left(N^*,r_L\right)-p_N\right)=0. \qquad (2)$$

Here $\pi^i=\pi\left(N,r_i\right)$, $i=L,H$, and $\pi^{i*}=\pi\left(N^*,r_i\right)$. Since marginal utilities are positive, it must be that marginal profits are positive for one realization of rainfall and negative for the other. The assumption that marginal productivity of nitrogen in higher when rainfall is not limiting crop production implies that the first term in equation (2) is positive, whereas the second is negative. In other words, the farmer would be under-applying (over-applying) nitrogen in good (bad) rainfall years. The farmer is engaging is self-insurance, that is, by choosing the level of inputs in this fashion they are reducing the magnitude of the loss when one occurs (Ehrlich and Becker). Notice that this is true for both risk-neutral and risk averse producers. As is well known, a risk neutral producer will equate marginal costs to expected marginal revenues (i.e. he/she will choose N^{*N} such that $p\left(\omega_H f_N\left(N^{*N},r_H\right)+\omega_L f_N\left(N^{*N},r_L\right)\right)-p_N=0$).[6] However, it can be shown (see the appendix) that $N^*<N^{*N}$.[7] That is, the input under consideration is risk increasing in the sense that a risk-averse producer uses less of it than a risk-neutral producer (Pope and Kramer 1979). Note that this result does not depend on having only two states of the world (see the appendix). The next section introduces the climate forecast, and studies

[6] As is well known, whether the risk neutral producer will increase or decrease his/her input usage under a mean preserving increase in risk depend on the curvature of the marginal production function with respect to the source or risk (Rothschild and Stiglitz).

[7] The same result was obtained by Ratti and Ullah, using additional assumptions on the elasticity of the marginal product curve of the factors. Mjelde, Thompson, and Nixon's numerical simulations results yielded risk averse producers using less nitrogen than risk neutral farmers.

how it affects the decision of the amount of inputs to use and the associated welfare change.

Introducing Climate Forecasts

Suppose now that a skillful probabilistic climate forecast is available to the risk averse farmer before decisions over the controllable input are made. The forecast indicates the future state of the world (high or low rainfall) and an associated uncertainty given by the probability that the forecast is incorrect. For example, if high rainfalls are forecasted, there is probability $\omega_{H|H}$ that rainfall is actually high and a complement $\omega_{L|H} = 1 - \omega_{H|H}$ that realized rainfall is low. A skillful forecast is captured by the assumption that $\omega_{H|H} > \omega_H$, and $\omega_{L|L} > \omega_L$. Assume also that the forecast is unbiased in the sense that the frequency with which a high rainfall forecast is issued (m_H) equals the frequency of high rainfall years (i.e. $m_H = \omega_H$).

In this situation, the decision of the farmer will depend on the forecast received. If a good year is forecasted, the decision of the farmer boils down to maximizing expected utility of profits, given the forecast as

$$\max_N Eu\left(\pi \left| H\right.\right) = \omega_{H|H} u\left(pf\left(N, r_H\right) - p_N N\right) + \left(1 - \omega_{H|H}\right) u\left(pf\left(N, r_L\right) - p_N N\right).$$

The first order condition for this problem is

$$\begin{aligned}&\omega_{H|H} u'\left(pf\left(N^{*H}, r_H\right) - p_N N^{*H}\right)\left(pf_N\left(N^{*H}, r_H\right) - p_N\right) + \\ &\left(1 - \omega_{H|H}\right) u'\left(pf\left(N^{*H}, r_L\right) - p_N N^{*H}\right)\left(pf_N\left(N^{*H}, r_L\right) - p_N\right) = 0\end{aligned}, \tag{3}$$

where N^{*H} is the optimal amount of nitrogen application when a good year is forecasted. That amount will depend on the skill of the forecast. Again we find that the farmer self insures by applying less than the amount of nitrogen that would maximize profits if it was known with certainty that rainfall is going to be high (marginal profits are positive (negative) when realized rainfall is high (low)). From equation (3), if the forecast have no skill (i.e. $\omega_{H|H} = \omega_H$ then the farmer will apply the same amount of nitrogen as if the forecast is not available (compare with equation (2)). An analogous problem can be written for the case where a low rainfall year is forecasted.

In this framework, it is straightforward to show that as the forecast becomes more skillful, the amount of nitrogen applied departs more from the decision without the forecast. For the high rainfall case, a forecast of higher skill will be obtained when $\omega_{H|H}$ increases. Thus, we need to sign $\frac{\partial N^{*H}}{\partial \omega_{H|H}}$. By the implicit function theorem, and since the second order conditions for a maximum hold,

$$\operatorname{sgn}\left(\frac{\partial N^{*H}}{\partial \omega_{H|H}}\right) = \operatorname{sgn}\begin{pmatrix} u'\left(pf\left(N^{*H}, r_H\right) - p_N N^{*H}\right)\left(pf_N\left(N^{*H}, r_H\right) - p_N\right) - \\ u'\left(pf\left(N^{*H}, r_L\right) - p_N N^{*H}\right)\left(pf_N\left(N^{*H}, r_L\right) - p_N\right) \end{pmatrix} \geq 0 .$$

Analogously, it can be shown that the amount of nitrogen applied when a low rainfall forecast is issued is lower that what it is applied in the absence of a forecast, and that difference increases with the skill of the forecast. The skillful forecast is allowing producers to reduce the degree to which they self-insure. Increasing the skill of the forecast will reduce the uncertainty, and move the amount of nitrogen application towards what would be applied if the future state of the world were known. The ex-ante total amount of nitrogen applied can be higher or lower than in the absence of a forecast depending on the relative probabilities and on the skill of the forecast.

It can also be shown that in this simple scenario without price effects (see Babcock, 1990), that the forecast increases producers welfare. The welfare change from introducing a skillful forecast is expressed in terms of the change in expected utility as

$$\Delta Eu(\pi, s) = m_H Eu(\pi | H) + (1 - m_H) Eu(\pi | L) - Eu(\pi), \tag{4}$$

where s is the skill of the forecast, $Eu(\pi | i)$, $i = H, L$ denotes the expected utility when a good, or bad year is forecasted respectively, and $Eu(\pi)$ is the expected utility if the forecast is not available, or is not used. Equation (4) is clearly positive, indicating that the skillful forecast improves producer's welfare. In the absence of any skill, the production decisions with and without forecast coincide and equation (3) is zero. Equation (4) is non-decreasing in the skill of the forecast (s), indicating that information benefits producers in this case (see the appendix).

Introducing Insurance

Suppose now that insurance becomes available to the producers, who must decide how much of it to buy (and no forecast is issued). In this case the objective function and first-order conditions (at an interior solution) are

$$\max_{N,I} Eu(\pi) = \omega_H u\left(\pi(N, r_H) - \tau I\right) + (1-\omega_H) u\left(\pi(N, r_L) + I - \tau I\right) \tag{5}$$

$$N : \omega_H u'\left(\pi^{H*} - \tau I\right)\left(pf_N\left(N^*, r_H\right) - p_N\right) + \omega_L u'\left(\pi^{L*} + (1-\tau) I\right)\left(pf_N\left(N^*, r_L\right) - p_N\right) = 0 \tag{6}$$

$$I : \frac{u'\left(\pi^H - \tau I\right)}{u'\left(\pi^L + (1-\tau) I\right)} \geq \frac{(1-\omega_H)(1-\tau)}{\tau\omega_H} \tag{7}$$

Equation (7) implies that insurance will be demanded only if the deflated price of insurance (RHS) is lower than the marginal rate of substitution between income in the good to the bad rainfall year without insurance $u'\left(\pi^H\right)/u'\left(\pi^L\right)$.[8]

If the insurance is actuarially fair ($\tau = 1 - \omega_H$), one obtains the standard result that the risk averse producer insures fully $\left(I^* = \pi^{H*} - \pi^{L*}\right)$.[9] This results is analogous to proposition 2 in Mahul (with independent risks), where the trigger for the insurance is the maximum value of the weather variable, and the slope of the indemnity function with respect to the index equals its marginal productivity (given an input decision). When the producer is able to insure fully, equation (6) can be rewritten as

$$u'\left(\pi^{H*} - \tau I\right)\left(\omega_H pf_N\left(N^*, r_H\right) + \omega_L pf_N\left(N^*, r_L\right) - p_N\right) = 0 .$$

Thus, the choice of inputs will coincide to those of a risk neutral decision maker. Since we showed that the risk neutral producer will use less inputs that his/her risk neutral counterpart this implies that total output will increase as a result of the availability of an actuarially fair insurance. Under the assumption that the insurance is actuarially fair, and the absence of price effects (area is assumed small, relative to world production) all the welfare gains are captured by the producer. In reality, the premium rate will be above the

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[8] See Ehrlich and Becker. The condition just presented translates into $\tau \leq \frac{\omega_L u'\left(\pi^L\right)}{\omega_L u'\left(\pi^L\right) + \omega_H u'\left(\pi^H\right)}$.

[9] If the insurance is actuarially fair, the RHS of equation (7) is one, and the marginal utilities of wealth are equalized across states of the world.

actuarially fair rate, and the degree to which farmers decrease the amount of insurance purchased is determined by his/her risk preferences. In this line, a more risk averse producer will modify less his/her decision than a less risk averse. In a sense, a more risk averse will have a lower demand elasticity for the insurance. However, it can be shown, that for any given amount of insurance purchased, the amount of the input applied is higher than the optimal choice in the absence of insurance, even when the premium is not actuarially fair. To see this, subtract equation (2) from equation (6) for an arbitrary amount of insurance purchased (I), and plug the optimal solution for equation (2) (N^*).[10] After rearranging this yields

$$\begin{aligned}&\omega_H\left(pf_N\left(N^*,r_H\right)-p_N\right)\left[u'\left(\pi(N^*,r_H)-\tau I\right)-u'\left(\pi(N^*,r_H)\right)\right]\\&+\omega_L\left(pf_N\left(N^*,r_L\right)-p_N\right)\left[u'\left(\pi(N^*,r_L)+I-\tau I\right)-u'\left(\pi(N^*,r_L)\right)\right]>0\end{aligned},$$

implying that the producer should increase the amount of nitrogen applied to maximize expected utility. Hence, the introduction of insurance will result in a supply expansion in this model, even if it is not actuarially fairly priced. When the insurance market is not competitive, the rents generated by the insurance will by divided between the insurance company(ies) and the producers. The fraction of the rent captured by each sector depends on the producer's risk preferences, technologies, and the degree of market power of the insurance companies.

When actuarially fair insurance is available, the producer is able to remove all uncertainty and lock his realized income at $\omega_H\pi^H+\left(1-\omega_H\right)\pi^L$, and the value function is $u\left(\omega_H\pi^H+\left(1-\omega_H\right)\pi^L\right)$. The next section shows the impact of the introduction of a skillful and unbiased climate forecast.

Combining the Insurance and Climate Forecast

Abstract first from production decisions, that is, only insurance purchase decisions are made. In this case the farmer obtains high profits π^H with probability ω_H, and low profits π^L with the complementary probability. If there is no forecast available, or if it is released after the insurance purchase decision is made, the problem for the farmer is

[10] In essence we are subtracting zero from equation (6) evaluated at the amount of nitrogen that would be chosen if no insurance was available (or purchased).

$$\max_{I} Eu(\pi) = \omega_{H} u\left(\pi^{H} - \tau I\right) + \left(1-\omega_{H}\right) u\left(\pi^{L} + I - \tau I\right).$$

The necessary condition for an interior solution is

$$-\omega_{H} u'\left(\pi^{H} - \tau I\right)\tau + \left(1-\omega_{H}\right) u'\left(\pi^{L} + \left(1-\tau\right) I\right)\left(1-\tau\right) = 0.$$

If the premium rate is actuarially fair (i.e. $\tau = \omega_L I$), the producer will insure fully setting $I^* = \pi^H - \pi^L$, and income is locked across state of the world at the expected value of wealth $\omega_H \pi^H + (1-\omega_H)\pi^L$.

Assume next that advances in climate science allow for skillful forecast to be released before the closing date for the insurance purchase. If the insurance is going to be financially sustainable, the premium rates need to be modified to reflect the climate information available. If premiums rates do not reflect the information, and buyers have the ability to process the forecast, the latter will insure at higher (lower) rates when a bad (good) year is forecasted, rendering the product unsustainable. Insurers, who are more likely to have access and capabilities to understand the forecasts, can not afford to ignore it if they believe potential insurance buyers will use it in their decisions. This is especially true for index insurance, which has been touted as a tool that could be used to anybody to hedge risks (Skees et al.). For this type of products it is likely that some potential buyers have access to the information and adversely select, making the provision of index insurance commercially unviable. It is possible that the insurance company has access to and better capabilities to interpret the forecast than farmers. If the insurance company uses the forecast to modify premium rates and this is not interpreted by farmers as a signal that the odds for the good and bad years have changed, the effectiveness of the insurance as a risk management tool will be undermined. The farmer will perceive the insurance to be relatively cheap (expensive) when a good (year) is forecasted and buy more (less) of it. In this line, farmers will end up with lower levels of insurance when it is needed the most. Another problem with this is the fact that farmers may see the insurance company as merely trying to extract rents after observing a varying premium when they do not perceive a change in the risks. We do not deal with this problem here, but it may be wise for insurance companies that need to adjust premiums following a forecast to clearly convey the forecast information to farmers.

If the insurance decision is made after the forecast is released, and both parties use it, the problem will be state contingent. When a good year is forecasted, the actuarially fair rate is lowered from $\tau = \omega_L$ to $\tau_1 = \omega_{L|H}$ and the farmer's problem and first order conditions are

$$\max_I Eu\left(\pi \middle| H\right) = \omega_{H|H} u\left(\pi^H - \tau_1 I\right) + \left(1 - \omega_{H|H}\right) u\left(\pi^L + \left(1 - \tau_1\right) I\right)$$

$$\frac{u'\left(\pi^H - \tau_1 I\right)}{u'\left(\pi^L + \left(1 - \tau_1\right) I\right)} = \frac{\omega_{L|H}}{\omega_{H|H}} \frac{\left(1 - \tau_1\right)}{\tau_1} = 0 .$$

Since the insurance is actuarially fair, the producer will again insure fully setting $I^* = \pi^H - \pi^L$, and hence realized wealth is fixed at $\pi_H^* = \pi^H - \tau_1 \left(\pi^H - \pi^L\right)$.

If a bad year is forecasted, and the premium rates reflect it (defining $\tau_2 = \omega_{L|L} > \omega_L > \tau_1$), an analogous problem can be written yielding that the producer will insure fully and be able to lock his/her realized income at $\pi_L^* = \pi^H - \tau_2 \left(\pi^H - \pi^L\right)$.

Since the forecast is assumed to the unbiased, the ex-ante expected wealth in this scenario equals that that would result in the absence of a forecast,[11] however the farmer is no longer able to lock his/her income across forecasts. Hence, to the extent that the farmer is unable to modify his/her production practices in response to the forecast, the existence of the information will harm the farmer, unless he/she is able to purchase the insurance before the forecast is released.[12] The effect is magnified in the case discussed above when the premium rate is modified by the insurance company following a forecast that does not shift the farmer's belief with regards to the probabilities of experiencing a bad year. In that case, expected profits are the same as in the two scenarios just discussed, but the farmer is not able to stabilize his/her income even within a given forecast. The insurance company will be indifferent (if risk neutral and charging actuarially fair premiums) between all scenarios.

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[11] To see this note that $E\pi^* = m_H \left(\pi^H - \tau_1 I^*\right) + \left(1 - m_H\right)\left(\pi^H - \tau_2 I^*\right) = \pi^H - I^* \left(m_H \tau_1 + m_L \tau_2\right)$.
Using the assumption that the forecast is unbiased yields $m_H \tau_1 + m_L \tau_2 = m_L$.

[12] Note also that we assumed thus far in this section that farmers cannot modify their input choices following the forecast. If they can adjust management practices, the forecast may allow them to obtain higher expected profits, and then it is a trade-off between risks and returns whose net balance will depend on risk preferences.

In this scenario, it is optimal for farmers to buy the insurance before the forecast is released and insurance companies adjust their premiums accordingly. As such, there would be no need to close the sales period beforehand. But the advocated measure (of closing sales period before forecast is released would obviously be needed when the premium cannot be adjusted guided by the forecast. In fact, the analysis indicates that from a welfare standpoint the sales period should be opened before climate information becomes available.

Suppose next, that the insurance purchase decision has to be made before any skillful forecast is available. The insurance is thus priced used climatology probabilities. In this case the producer faces a two stage problem. In the first stage, the producer chooses how much insurance to buy, and then he/she needs to choose how much of the input to use. If the latter decision needs to be made before the forecast is released, the producer is simultaneously choosing both variables. This case boils down to the model presented in equation (5), and the forecast has no value when producers cannot adjust their decision in response to the received information. If the choice of how much input to use is made after the forecast is available, there is a two stage optimization process. In the first stage, the amount of insurance is decided. Then the forecast is released and producers make their input decisions. Finally nature decides the state of the world. We use backward induction to solve the problem.

For the second stage, after the forecast is released, the problem of the producer is to choose the amount of nitrogen to use. The objective and first order conditions when a good year is forecasted are

$$\begin{aligned}\max_{N} Eu\left(\pi \middle| H\right) &= \omega_{H|H} u\left(pf\left(N, r_H\right) - p_N N - \tau I\right) \\ &+ \left(1-\omega_{H|H}\right) u\left(pf\left(N, r_L\right) - p_N N + \left(1-\tau\right) I\right)\end{aligned} \tag{8}$$

$$\begin{aligned}&\omega_{H|H} u'\left(pf\left(N^{*H}, r_H\right) - p_N N^{*H} - \tau I\right)\left(pf_N\left(N^{*H}, r_H\right) - p_N\right) + \\ &\left(1-\omega_{H|H}\right) u'\left(pf\left(N^{*H}, r_L\right) - p_N N^{*H} + \left(1-\tau\right) I\right)\left(pf_N\left(N^{*H}, r_L\right) - p_N\right) = 0\end{aligned} \tag{9}$$

Equation (9) reveals that even in the presence of insurance, the producers will choose to self-insure against the possibility of an erroneous forecast.[13] The amount of nitrogen is

[13] Unless of course the producer is fully insured through market insurance. This can only occur for one of the possible realizations of the forecast.

too low (high) compared to the profit maximizing level in the good (bad) year. To investigate how the choice of the input is affected to the amount of insurance previously purchased, we need to sign $\partial N^{*H}/\partial I$. Using again the implicit function theorem, the sign of $\partial N^{*H}/\partial I$ is the same as that of the partial derivative of equation (9) with respect to the amount of insurance available. This derivative is

$$-\omega_{H|H}u_H''(\cdot)\left(pf_N\left(N^{*H},r_H\right)-p_N\right)\tau+\left(1-\omega_{H|H}\right)u_L''(\cdot)\left(pf_N\left(N^{*H},r_L\right)-p_N\right)\left(1-\tau\right)>0 .(10)$$

The inequality is obtained because the self-insurance decision implies that producer's marginal valuation of the input exceeds (is lower than) the price of the input in a good (bad) year and because the producers are risk averse.

Equation (10) indicates that insurance and a forecast for a good year reinforce each other in the decision of how much input to apply. The insurance allows the producer to take more risk in the presence of forecast uncertainty by applying larger amounts nitrogen. When a good year is forecasted, both instruments provide incentives for the producer to apply an amount of nitrogen more in-line with what would be applied if it were known with certainty that a good year was coming. In essence, the insurance is allowing the producer to "go for it" when a high forecast is issued.

The previous result of insurance and forecast working in the same direction is not observed however when a bad year is forecasted. In a bad year forecast the problem and first order conditions are

$$\begin{aligned}&\max_N Eu\left(\pi\,|L\right)=\omega_{H|L}u\left(pf\left(N,r_H\right)-p_NN-\tau I\right)\\&+\omega_{L|L}u\left(pf\left(N,r_L\right)-p_NN+\left(1-\tau\right)I\right)\end{aligned}$$

$$\begin{aligned}&\omega_{H|L}u'\left(pf\left(N^{*L},r_H\right)-p_NN^{*L}-\tau I\right)\left(pf_N\left(N^{*L},r_H\right)-p_N\right)+\\&\omega_{L|L}u'\left(pf\left(N^{*L},r_L\right)-p_NN^{*L}+\left(1-\tau\right)I\right)\left(pf_N\left(N^{*L},r_L\right)-p_N\right)=0\end{aligned}.$$

As in the case when the high forecast is issued, the producer will increase the amount of nitrogen used when more insurance was purchased in the previous period (i.e. $\partial N^{*L}/\partial I>0$). We showed before that a skillful low forecast will lead to lower amounts of nitrogen applied compared to the no forecast case. The presence of insurance will work in the opposite direction. The intuition is that the insurance is protecting the producer in the case the forecast is right, and hence allows that producer to take more chances and try to capture part of the gains that would be available if the forecast is wrong. How the amount of nitrogen applied compares to the case where no forecast and no insurance are available depends on the amount of insurance purchased in the previous period and the skill of the forecast.

Armed with the rules of the second period problem, the first period objective function can be written as

$$\max_I Eu(\pi) = m_H\left(\omega_{H|H}u\left(pf\left(N^{*H},r_H\right)-p_N N^{*H}-\tau I\right)+\omega_{L|H}u\left(pf\left(N^{*H},r_L\right)-p_N N^{*H}+(1-\tau)I\right)\right)$$
$$+(1-m_H)\left(\omega_{H|L}u\left(pf\left(N^{*L},r_H\right)-p_N N^{*L}-\tau I\right)+\omega_{L|L}u\left(pf\left(N^{*L},r_L\right)-p_N N^{*L}+(1-\tau)I\right)\right)$$

Here, N^{*i}, $i=L,H$ are the optimal solution for the second stage problem after a low or high forecast are released respectively. They are both functions of I. The first order condition for this problem is

$$\begin{aligned} &m_H\left(\frac{\partial Eu(\pi|H)}{\partial N^{*H}}\frac{\partial N^{*H}}{\partial I}+\frac{\partial Eu(\pi|H)}{\partial I}\right)+m_L\left(\frac{\partial Eu(\pi|L)}{\partial N^{*L}}\frac{\partial N^{*L}}{\partial I}+\frac{\partial Eu(\pi|L)}{\partial I}\right)= \\ &m_H\frac{\partial Eu(\pi|H)}{\partial I}+m_L\frac{\partial Eu(\pi|L)}{\partial I}=0 \end{aligned}. \quad (11)$$

Equation (11) is

$$m_H\left\{\omega_{H|H}u'\left(pf\left(N^{*H},r_H\right)-p_N N^{*H}-\tau I\right)\tau+\omega_{L|H}u'\left(pf\left(N^{*H},r_L\right)-p_N N^{*H}+(1-\tau)I\right)(1-\tau)\right\}$$
$$m_L\left\{-\omega_{H|L}u'\left(pf\left(N^{*L},r_H\right)-p_N N^{*L}-\tau I\right)\tau+\omega_{L|L}u'\left(pf\left(N^{*L},r_L\right)-p_N N^{*L}+(1-\tau)I\right)(1-\tau)\right\}=0$$

If the forecast has no skill, the problem is the same as under no forecast, and the amount of insurance purchased will be the same as under the objective equation (5) i.e. $I^*=\pi\left(N^*,r_H\right)-\pi\left(N^*,r_L\right)$. If the forecast is perfect, the producer will fully insure (remember that the insurance decision and pricing is made before the forecast is released) at the level $I^{*F}=\pi\left(N^{*H},r_H\right)-\pi\left(N^{*L},r_L\right)$. Contrary to expectations, it is possible that more insurance is purchased when a more skillful forecast is available. Comparing the amount of insurance purchased under both scenarios, the producer will purchase more insurance when a perfect forecast is available than without the forecast (even when the premium rates are the same under both scenarios), when the profit differential (between good and bad states of the world) under the forecast is greater than when the forecast is not available. Alternatively, the forecast will induce the producer (ceteris paribus) to buy more insurance whenever the gains obtained when the good state of the world is forecasted exceed gains for a forecasted bad year, both compared against the no forecast scenario. That is, the forecast will induce producers to buy more insurance whenever

$$\Delta I^* = I^{*F} - I^* = \left(\pi\left(N^{*H}, r_H\right) - \pi\left(N^{*L}, r_L\right)\right) - \left(\pi\left(N^*, r_H\right) - \pi\left(N^*, r_L\right)\right) = \left(\pi\left(N^{*H}, r_H\right) - \pi\left(N^*, r_H\right)\right) - \left(\pi\left(N^{*L}, r_L\right) - \pi\left(N^*, r_L\right)\right) > 0,$$

which is entirely plausible.

Conclusions

Agricultural producer around the globe face a variety of risks, including those related to price, production, market, technology, and policies. The focus of this article is on a particular kind of production risks, namely climate risks. The failure of the development of commercially viable traditional crop insurance products and innovations in financial markers has fed a renewed interest in the search for alternatives to help producers in developing countries manage their risk exposure. Salient among these is the proposal of several index insurance schemes against weather events (World Bank, 2005). Among the basic tenets are that the presence of insurance allows producers to intensify their operations and invest in higher returns but riskier activities. Also, insurance will reduce the risks of default and hence may induce creditors to offer loans at affordable rates. The two factors combined are touted as key to help producers in developing countries escape poverty traps.

A great amount of effort has been devoted to the study of the interaction between insurance (in particular traditional yield insurance) and input decisions. Work has also explored the relationship between climate forecasts and input usage. Much less is known about the interaction between insurance, in particular index insurance, and climate forecasts. Few articles have explored the interaction between climate forecast, input usage, and insurance. These studies, which relied on numerical simulations, were focused on determining the value of improved climate forecast. This paper contributes to our understanding of the fundamental interactions between index insurance, climate forecasts, and input decisions.

Our main findings are that insurance and skillful climate forecast may have synergistic or antagonistic effects on the input decisions by producers. Insurance (in the absence of moral hazard effects) will induce producers to use more of a risk increasing input such as nitrogen. The presence of a skillful probabilistic climate forecast may result in a net increase or decrease of inputs used. When a good year is forecasted, both the forecast and insurance act to increase the amount of nitrogen applied. If a bad year is forecasted, both institutions work in opposite direction. Additionally, we find that if an actuarially fair insurance is available, and producer's profits are not sufficiently responsive to the input mix, the introduction of a climate forecast harms the producer if the premiums reflect the forecast (even if they are actuarially fair). The intuition is that producers are able to lock their income at the expected wealth when the insurance parameters do not depend on the forecast, whereas the state contingent premium prevents producers from doing that. Hence, a necessary condition for producers to prefer a state contingent commercially viable insurance product is that producers can increase their profits by taking account the forecast information. Perhaps surprisingly, we find that forecast information may induce producers to buy more insurance. The intuition is that the forecast may widen the wedge between optimized profits among states of the world.

Observation of insurance transactions may provide information on forecast value. Alternately, insurance prices may provide a mechanism to effectively communicate forecast information when farmers do not have direct access to forecast, which may occur in a developing country with limited communications infrastructure. Future work addressing these issues may be worthwhile.

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Appendix.

Proof that $N^* < N^{*N}$

Plug the risk neutral solution N^{*N} into equation (2) and it by the positive number $u'\left(pf\left(N^{*N},r_H\right)-p_N N^{*N}\right)$ to obtain

$$\omega_H\left(pf_N\left(N^*,r_H\right)-p_N\right)+\left(1-\omega_H\right)\frac{u'\left(pf\left(N^{*N},r_L\right)-p_N N^{*N}\right)}{u'\left(pf\left(N^{*N},r_H\right)-p_N N^{*N}\right)}\left(pf_N\left(N^{*N},r_L\right)-p_N\right),$$

and subtract the first order condition for the risk neutral problem evaluated at $N = N^{*N}$ (which is zero) to obtain

$$\left(1-\omega_H\right)\left(pf_N\left(N^{*N},r_L\right)-p_N\right)\left(\frac{u'\left(pf\left(N^{*N},r_L\right)-p_N N^{*N}\right)}{u'\left(pf\left(N^{*N},r_H\right)-p_N N^{*N}\right)}-1\right)\leq 0.$$

The ratio of marginal utilities is at least one since profits increase with the amount of rainfall and hence the last term is positive. From the first order condition of the risk neutral producer, marginal profits for the low rainfall year are negative, and thus the overall equation is negative. This shows that in order to maximize expected utility of profits, a risk averse producer will choose a lower level of inputs that his/her risk neutral counterpart.

Alternatively, the proof can be expressed in a way that makes it clear that the result is not dependent on having only two states of the world. The first order condition for the risk averse producer can be written as $E_r\left(u'(pf(r,N^*)-p_N)(pf_N(r,N^*)-p_N)\right)=0$ or

$pE_r\left(f_N(r,N^*)\right)+\dfrac{Cov\left(u'(pf(r,N^*)-p_N),f_N(r,N^*)\right)}{E_r\left(u'(pf(r,N^*)-p_N)\right)}=p_N$. Since $u''<0$, and

$f_{Nr}(r,N)>0$, the covariance term is negative indicating that $pE_r\left(f_N(r,N^*)\right)>p_N$. The risk neutral producer will choose N^{*N} such that $pE_r\left(f_N(r,N^{*N})\right)=p_N$ and hence (by the assumption that $f_{NN}(r,N)<0$), $N^{*N}>N^*$.

Proof of $\Delta Eu\left(\pi,s\right)\geq 0$.

$Eu(\pi)$ is unaffected by the skill of the forecast, and hence we focus on the expected utility in the presence of a forecast. The value function for producer in this case is

$$\begin{aligned} Eu(\pi,s) &= m_H\left\{\omega_{H|H}u\left(pf\left(N_H^*,r_H\right)-p_N N_H^*\right)+\left(1-\omega_{H|H}\right)u\left(pf\left(N_H^*,r_L\right)-p_N N_H^*\right)\right\} \\ &\left(1-m_H\right)\left\{\omega_{H|L}u\left(pf\left(N_L^*,r_H\right)-p_N N_L^*\right)+\left(1-\omega_{H|L}\right)u\left(pf\left(N_L^*,r_L\right)-p_N N_L^*\right)\right\} \end{aligned},$$

and by the envelope theorem,

$$\begin{aligned} \frac{\partial Eu(\pi,s)}{\partial s} &= m_H\left\{\frac{\partial\omega_{H|H}}{\partial s}\left(u\left(pf\left(N_H^*,r_H\right)-p_N N_H^*\right)-u\left(pf\left(N_H^*,r_L\right)-p_N N_H^*\right)\right)\right\} \\ &\left(1-m_H\right)\left\{\frac{\partial\omega_{H|L}}{\partial s}\left(u\left(pf\left(N_L^*,r_H\right)-p_N N_L^*\right)-u\left(pf\left(N_L^*,r_L\right)-p_N N_L^*\right)\right)\right\} \end{aligned}.$$

Noting that $\frac{\partial\omega_{H|H}}{\partial s}=-\frac{\partial\omega_{H|L}}{\partial s}$, the previous equation can be rewritten as

$$\frac{\partial Eu(\pi,s)}{\partial s}=\frac{\partial\omega_{H|H}}{\partial s}\left\{\begin{array}{l} m_H u\left(pf\left(N_H^*,r_H\right)-p_N N_H^*\right)+\left(1-m_H\right)u\left(pf\left(N_L^*,r_L\right)-p_N N_L^*\right) \\ -\left(m_H u\left(pf\left(N_H^*,r_L\right)-p_N N_H^*\right)+\left(1-m_H\right)u\left(pf\left(N_L^*,r_H\right)-p_N N_L^*\right)\right) \end{array}\right\}\geq 0$$

The inequality follows because improved skill translates into $\frac{\partial\omega_{H|H}}{\partial s}>0$, and the term in braces is the difference in expected utility of profits for the case where the forecast is correct and that resulting when the forecast turns out to be wrong.