Index Insurance, Probabilistic Climate Forecasts, and Production

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Abstract

Index insurance and probabilistic seasonal forecasts are becoming available in developing countries to help farmers manage climate risks in production. Although these tools are intimately related, work has not been done to formalize the connections between them. We investigate the relationship between the risk management tools through a model of input choice under uncertainty, forecasts, and insurance. While it is possible for forecasts to undermine insurance, we find that when contracts are appropriately designed, there are important synergies between forecasts, insurance, and effective input use. Used together, these tools overcome barriers preventing the use of imperfect information in production decision making.

Keywords: basis risk, climate forecast, index insurance, input decisions, insurance, risk management.

Index Insurance, Probabilistic Climate Forecasts, and Production

Droughts and other climate-related risks have profound impacts on agricultural producers around the world. [1] These effects are particularly important in developing countries, where agriculture makes a significant contribution to gross domestic product (World Bank 2001) and insurance markets are under-developed or nonexistent. Recently, index insurance and probabilistic seasonal forecasts have become available to help farmers manage climate risks in production. Although these tools are intimately related, work has not been done to formalize the fundamental connections between them.[2]

It is well known that households facing risk with few resources are likely to remain poor or to be caught in poverty traps (see a review by Barnett, Barrett, and Skees 2007). Lack of assets and risk exposure may lead households to forego activities with high returns, perpetuating their poverty. Credit constraints and nearly nonexistent insurance markets are two (of many) important factors keeping households in traps.

Recently, innovative instruments to help farmers in developing countries manage their risks have been proposed and strongly supported by international development organizations, such as The World Bank. One avenue that is being intensely pursued is the development of index-based insurance. This is sometimes bundled with micro-credit since the decision to commit resources to production is often jointly determined by the farmer and lender. An example is the index insurance for groundnut and maize farmers in Malawi (Hess and Syroka 2005).[3] In this case, the insurance provides the risk protection required for lenders to be willing to provide the credit farmers need to be able to adopt yield- and quality-increasing seeds.

Work in the agricultural economics literature has examined the relationship between insurance and input usage for both farm-level insurance (Ramaswami 1993; Babcock and Hennessy 1996; Horowitz and Lichtenberg 1993; Smith and Goodwin 1996) and index insurance (Chambers and Quiggin 2000; Mahul 2001). In the United States, the presence of yield insurance resulted in conflicting empirical results. Horowitz and Lichtenberg estimated that farmers who purchased insurance increased nitrogen applications, whereas both Babcock and Hennessy, and Smith and Goodwin found 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.[4] 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 analyzed the effects of area-yield insurance on farmers' decisions regarding their exposure to risk. Focusing on the relationship between insurance and input use, this literature does not address interactions 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. 2001). For example, the El Niño Southern Oscillation (ENSO) phenomenon has been linked to variations of seasonal precipitation in some regions (Ropelewski and Halpert 1987). This predictability offers the potential to better manage climatic uncertainty through contingent choices of production (Hansen 2002) and insurance practices. Crop yields may therefore be affected distinctly by different ENSO phases. Despite this observation, pricing and insurance coverage usually do not respond to the ENSO information available. The financial soundness of the programs could be threatened if buyers have the option to decide when to participate.

Weather index developers routinely acknowledge that climate forecasts may undermine the financial soundness of a product by providing opportunities for inter-temporal adverse selection. However, after expressing their concern, developers typically assert that forecasts are still not a significant source of concern if contracts are sold a few months in advance, when the skill of the forecast is still low (see, e.g., Hess and Syroka 2005; World Bank 2005). Opportunities for inter-temporal adverse selection in the context of U.S. yield insurance and based on different forecasts of growing conditions for the coming season have been explored by Luo, Skees, and Marchant (1994) and Ker and McGowan (2000). The authors argue that there is enough early-season information to allow inter-temporal adverse selection. In work focusing on the actuarial stability of insurance products, insurance premiums that reflect forecast information have been mentioned as a mechanism for keeping the programs sound (Skees, Hazell, and Miranda 1999), motivating the need for research connecting forecast information, production, and insurance design.

Work in agricultural and climate science has modeled the impact of probabilistic climate forecasts on production decisions (e.g., Solow et al. 1998) but has, with few exceptions (Mjelde, Thompson, and Nixon 1996; Cabrera, Letson, and Podesta 2005), ignored the potential impact of insurance. The two exceptions just mentioned analyze the impact of several government programs (including traditional yield insurance) on the value of seasonal forecast information. Based on numerical simulations of specific situations, these studies motivate the need for work that derives the fundamental relationships underlying numerical findings.

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.

We investigate the fundamental relationship just described through the simplest possible model of input choice under uncertainty, forecasts, and index insurance. The model is highly stylized in order to represent in the most transparent way the fundamental features. We derive optimal input and insurance demand as a function of forecast quality, determine production changes with respect to the absence of forecast information and insurance, and analyze how the different tools interact.

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 to intensify production in potentially good years and thus realize higher average payoffs. We also find that the presence of skillful probabilistic forecasts may affect the demand for insurance as well as its effectiveness as a risk-reducing tool. If the value of production decisions, insurance products, and forecasts is calculated without addressing their interactions, substantial benefits may be missed.

We begin by presenting the base framework that will be used throughout the article. Probabilistic seasonal climate forecasts and index insurance with their well-known impacts on production decisions and welfare are then introduced individually in this framework in order to provide benchmarks for our findings. Next, we combine the instruments (forecasts and insurance) and analyze their joint interactions with production practices. The last section provides concluding remarks and proposes some avenues for future research.

Preliminaries and Base Model

Consider first a competitive farmer with a single crop with yield $\left(y\right)$ dependent on the level of a controllable input (N , may be thought of as nitrogen, an improved seed, or the level of technology used), a systemic weather shock (r , hereafter rainfall) affecting all farmers in the area, and an idiosyncratic aggregate production shock (ε) as follows:

(1) $$y = f\left(N,r\right)+\varepsilon .$$

A special case of this yield function was used by Mahul.[5] It is assumed that

$f_N\left(N,r\right)=\frac{\partial f\left(N,r\right)}{\partial N}>0$, 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 value of the random variables is learned after the input has been applied. In the sections to follow, the systemic shock r is the variable on which the forecast provides information and on which the index insurance is written. For simplicity assume that rainfall can take only two values, r_h and r_l (denoting high and low or good and poor growing condition, respectively). The farmer knows that the climatological (historical) probability of observing $r = r_h$ is ω_h. The expected value of the idiosyncratic shock, which by definition is independent of the systemic shock, is assumed to be zero, and its variance is given by σ_ε^2. Both the price of the controllable input (p_N) and of the output (p) are assumed to be nonrandom, and the later price is normalized to 1 without loss of generality. Conditional on the idiosyncratic shock, and defining $\pi^o(N,r) = f(N,r) - p_N N$, profits for the farmer are given by

$$\pi|\varepsilon \quad = \begin{cases} \pi^o(N,r_h) + \varepsilon & with \quad prob = \omega_h \\ \pi^o(N,r_l) + \varepsilon & with \quad prob = \omega_l \end{cases}. \tag{2}$$

The farmer is assumed risk averse with a Bernoulli utility function given by $u(\pi)$, with $u''(\pi) < 0 < u'(\pi)$. If the farmer's choice is on the level of the input to apply, the farmer's problem is given by

$$\max_N E\hat{u}(\pi) = \omega_h \hat{u}\left(pf(N,r_h) - p_N N\right) + (1-\omega_h)\hat{u}\left(pf(N,r_l) - p_N N\right), \tag{3}$$

where as in Mahul the indirect utility function $\hat{u}(\bullet)$ is $\hat{u}(\pi^o) = Eu(\pi^o + \varepsilon)$ for all π^o. Kihlstrom, Romer, and Williams (1981) showed the indirect utility function is increasing and concave in π^o. The first-order condition for this problem is

$$E\left(\hat{u}'\left(\pi^o(N^*,r)\right)\pi_N^o(N^*,r)\right) = \frac{Cov\left(\hat{u}'\left(\pi^o(N^*,r)\right),\pi_N^o(N^*,r)\right)}{E\left(\hat{u}'\left(\pi^o(N^*,r)\right)\right)} + E\left(\pi_N^o(N^*,r)\right) = 0. \tag{4}$$

Noticing that the covariance term in the equation is negative (because of the concavity of the indirect utility function), we infer that $E\left(\pi_N^o(N^*,r)\right) > 0$. The latter implies that the farmer is engaging in self-insurance (Ehrlich and Becker 1972) and by choosing the level of inputs in this fashion he is reducing the magnitude of the loss when one occurs. In other words, the farmer would be under-applying (over-applying) inputs in good (bad) rainfall years. Furthermore, since a risk-neutral farmer maximizes expected profits by equating expected marginal profits to zero, equation (4) indicates that the risk-averse farmer applies less of the input than does a risk-neutral farmer.[6] That is, the input under consideration is risk increasing in the sense that a risk-averse farmer uses less of it than does a risk-neutral farmer (Pope and Kramer 1979), giving up some expected profits in order to reduce their variability. For future reference notice that, in the absence of insurance or seasonal forecasts, the expected level, and variability of profits are given by

(5a) $$E(\pi) = E\left(E(\pi|\varepsilon)\right) = \omega_h \pi^o\left(N^*, r_h\right) + (1-\omega_h)\pi^o\left(N^*, r_l\right)$$

and

(5b) $$Var(\pi) = E\left(Var(\pi|\varepsilon)\right) + Var\left(E(\pi|\varepsilon)\right) = \omega_h(1-\omega_h)\left(\pi^o\left(N^*, r_h\right) - \pi^o\left(N^*, r_l\right)\right)^2 + \sigma_\varepsilon^2 .$$

Forecasts without Insurance

Suppose now that a skillful probabilistic seasonal climate forecast is available before decisions over the input are made. The forecast indicates the future state of the world (high or low rainfall) for the coming season and an associated uncertainty given by the probability that the forecast is incorrect. For example, if high levels of rainfall 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 forecast is skillful if $\omega_{h|h} > \omega_h$, and $\omega_{l|l} > \omega_l$.[7] The extent to which $\omega_{i|i}$ departs from ω_i for $i = l, h$ (the "skill" of the forecast) is parameterized by s (with $\partial\omega_{i|i}(s)/\partial s > 0$) and is omitted unless specifically needed. Assume that the forecast is unbiased; that is, the frequency with which a high rainfall forecast is issued (m_h) equals that of high rainfall years (ω_h). We assume forecasts are used at least partially by stakeholders. In other words, we assume that $\omega_{h|h}$ reflects the probability stakeholders assign to a high rainfall year after a forecast for a wet year is issued (Lybbert et al. 2007). This stakeholder-assigned probability need not coincide with that assigned by the forecaster. However, a crucial assumption for the section in which forecasts and insurance are combined is that insurers and farmers interpret the forecasts as shifting the relative odds of good and bad years in the same fashion.

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 is

(6) $$\max_N E\hat{u}\left(\pi^o \middle| h\right) = \omega_{h|h}\hat{u}\left(\pi^o\left(N, r_h\right)\right) + \left(1-\omega_{h|h}\right)\hat{u}\left(\pi^o\left(N, r_h\right)\right),$$

and the first-order condition for this problem is

(7) $$\omega_{h|h}\hat{u}'\left(\pi^o\left(N^{*h}, r_h\right)\right)\pi_N^o\left(N^{*h}, r_h\right) + (1-\omega_{h|h})\hat{u}\left(\pi^o\left(N^{*h}, r_l\right)\right)\pi_N^o\left(N^{*h}, r_l\right) = 0.$$

N^{*h} is the optimal amount of input 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 against the uncertainty in the forecast. From equation (7), if the forecast has no skill (i.e., $\omega_{h|h} = \omega_h$) then the farmer will apply the same amount of inputs as if the forecast is not available (compare with equation (4)). An analogous problem can be written for the case in which a low rainfall year is forecasted.

In this framework, it is straightforward to show that as the forecast becomes more skillful, the amount of inputs 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.

By the implicit function theorem, and since the second-order conditions for a maximum hold, we obtain

$$(8)\quad \operatorname{sgn}\left(\frac{\partial N^{*h}}{\partial \omega_{h|h}}\right) = \operatorname{sgn}\left(\hat{u}'\left(\pi^o\left(N^{*h}, r_h\right)\right)\pi_N^o\left(N^{*h}, r_h\right) - \hat{u}\left(\pi^o\left(N^{*h}, r_l\right)\right)\pi_N^o\left(N^{*h}, r_l\right)\right) > 0 .$$

Analogously, it can be shown that the amount of inputs applied when a low rainfall forecast is issued is lower than what is applied in the absence of a forecast, and that the difference increases with the skill of the forecast. The skillful forecast is allowing farmers to reduce the degree to which they self-insure. Increasing the skill of the forecast will reduce the uncertainty and move the amount of input application toward what would be optimal if the future state of the world was known. The ex ante amount of input applied depends on the relative probabilities and on the skill of the forecast.

In this simple scenario without price effects (see Babcock 1990), the forecast increases the farmer's welfare. The welfare change from introducing a skillful forecast is expressed in terms of the change in expected indirect utility as

$$(9)\qquad \Delta E\hat{u}\left(\pi^o, s\right) = m_h E\hat{u}\left(\pi^o \middle| h\right) + \left(1 - m_h\right) E\hat{u}\left(\pi^o \middle| l\right) - E\hat{u}\left(\pi^o\right),$$

where s is the skill of the forecast, $E\hat{u}\left(\pi^o \middle| i\right)$, $i = l, h$ denotes the expected indirect utility when a good or bad year is forecasted, respectively, and $E\hat{u}\left(\pi^o\right)$ is the expected indirect utility if the forecast is not available or is not used. Equation (9) is positive, indicating that the skillful forecast improves the farmer's welfare.[8]

Insurance without a Forecast

Suppose now that instead of a forecast, insurance (I) is available to farmers, and they must decide how much of it to buy at a price τ per unit. To allow the analysis to address basis risk, we assume that the insurance is available for the systemic shock (r) but not for the idiosyncratic shock (ε). In this case, the objective function and first-order conditions (at an interior solution) are

(10) $$\underset{N,I}{Max}\, E\hat{u}\left(\pi^{o}\right)=\omega_{h}\hat{u}\left(\pi^{o}\left(N,r_{h}\right)-\tau I\right)+(1-\omega_{h})\hat{u}\left(\pi^{o}\left(N,r_{l}\right)+(1-\tau)I\right)$$

(11) N: $$\omega_{h}\hat{u}'\left(\pi^{o}\left(N,r_{h}\right)-\tau I\right)\pi_{N}^{o}\left(N,r_{h}\right)+(1-\omega_{h})\hat{u}'\left(\pi^{o}\left(N,r_{l}\right)+(1-\tau)I\right)\pi_{N}^{o}\left(N,r_{l}\right)=0$$

(12) $$I:\frac{\hat{u}'\left(\pi^{o}\left(N,r_{h}\right)-\tau I\right)}{\hat{u}'\left(\pi^{o}\left(N,r_{l}\right)+(1-\tau)I\right)}=\frac{\left(1-\omega_{h}\right)\left(1-\tau\right)}{\tau\omega_{h}}.$$

If the insurance is actuarially fair ($\tau=1-\omega_{h}$), one obtains the standard result that the risk-averse farmer insures fully against the systematic risk; that is,

$I^{*}=\pi^{o}\left(N^{*},r_{h}\right)-\pi^{o}\left(N^{*},r_{l}\right)=f\left(N^{*},r_{h}\right)-f\left(N^{*},r_{l}\right)$. This result 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 farmer is able to insure fully (against r), equation (11) can be rewritten as

(13) $$\hat{u}'\left(\pi^{o}\left(N,r_{h}\right)-\tau I\right)\left(\omega_{h}\pi_{N}^{o}\left(N,r_{h}\right)+(1-\omega_{h})\pi_{N}^{o}\left(N,r_{l}\right)\right)=0.$$

The farmer will insure fully against the weather variable and adopt a risk-neutral attitude toward the insurable event. Thus, even though the idiosyncratic risk impacts the overall utility of the farmer, the choice of inputs will coincide with those of a risk-neutral decisionmaker. The farmer's expected level and variability of profits when actuarially fair insurance is available are given by

(14a) $$E\left(\pi_{I}\right)=\omega_{h}\left(\pi^{o}\left(N^{*I},r_{h}\right)-\tau I^{*}\right)+(1-\omega_{h})\left(\pi^{o}\left(N^{*I},r_{l}\right)+(1-\tau)I^{*}\right)=\omega_{h}\pi^{o}\left(N^{*I},r_{h}\right)+(1-\omega_{h})\pi^{o}\left(N^{*I},r_{l}\right)$$

and

(14b) $$Var\left(\pi_I\right) = E\left(Var\left(\pi_I \left|\varepsilon\right.\right)\right) + Var\left(E\left(\pi_I \left|\varepsilon\right.\right)\right) = \sigma_\varepsilon^2 .$$

Since insured farmers will replicate the risk-neutral expected profit-maximizing solution, expected profits and output increase in the presence of actuarially fair insurance relative to the uninsured case (i.e., $E\left(\pi_I\right) > E\left(\pi\right)$). Although profit variability is reduced, equation (14b) indicates that some basis risk remains for farmers even when they are fully insured against the systemic shock. The effectiveness of the insurance in reducing risks is, as expected, dependent on the relative contribution of the systemic and idiosyncratic shocks to profit variability. Under the assumption that the insurance is actuarially fair, and in the absence of price effects (area is assumed small, relative to world production), all the welfare gains are captured by the farmer.

In reality, and since insurers have to cover administrative expenses and obtain reasonable returns, the premium rate will be above the actuarially fair rate, and the degree to which farmers decrease the amount of insurance purchased is determined by their risk preferences. 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 (4) from equation (11) for an arbitrary amount of insurance purchased (I), and plug in the optimal solution for equation (4).[9] After rearranging, this yields

(15) $$\begin{aligned} &\omega_h \pi_N^o\left(N, r_h\right)\left[\hat{u}'\left(\pi^o(N^*, r_h) - \tau I\right) - \hat{u}'\left(\pi^o(N^*, r_h)\right)\right] \\ &+\omega_l \pi_N^o\left(N, r_l\right)\left[\hat{u}'\left(\pi^o(N^*, r_l) + I - \tau I\right) - \hat{u}'\left(\pi^o(N^*, r_l)\right)\right] > 0 , \end{aligned}$$

implying that the farmer should increase the amount of inputs applied to maximize expected utility. Hence, the introduction of insurance will result in a supply expansion in this model, even if it is priced higher than actuarially fair.

Combining the Forecast with Insurance

The impacts of the interaction between forecasts and insurance depend critically on the timing of the forecast information, insurance, and input decisions. To illustrate clearly the fundamental features of each situation, in this section we address several different timing constraints. We begin with a farmer who has little flexibility, who must commit to exogenously determined production practices prior to the forecast information and insurance decision. We then model a farmer who is flexible in production decisions but must commit to an insurance purchase prior to the forecast availability. Finally, we address the most flexible case in which a farmer simultaneously makes insurance and production decisions after the forecast becomes available.

Effects of a Skillful Forecast on Insurance Purchases with Fixed N

In this section, we consider a farmer who is constrained to commit to production decisions before forecasts and insurance become available. For the particular case in which there is no forecast skill available prior to the insurance purchase decision, the problem for the farmer is

(16) $$\max_I E\hat{u}\left(\pi^o\right) = \omega_h \hat{u}\left(\pi^o\left(N, r_h\right) - \tau I\right) + (1-\omega_h)\hat{u}\left(\pi^o\left(N, r_l\right) + (1-\tau)I\right),$$

and the necessary condition for an interior solution is

(17) $$-\omega_h \hat{u}'\left(\pi^o\left(N, r_h\right) - \tau I\right)\tau + \left(1-\omega_h\right)\hat{u}'\left(\pi^o\left(N, r_l\right) + \left(1-\tau\right)I\right)\left(1-\tau\right) = 0 .$$

This is a particular case of the situation encountered in the previous section. If the premium rate is actuarially fair, the farmer will again insure fully against systemic risk, setting $I^* = \pi^o(N, r_h) - \pi^o(N, r_l)$.

If skillful seasonal forecasts are released before the closing date for the insurance purchase, the premium rates must be modified to reflect the climate information available for the insurance to be financially sustainable. If premium 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, undermining the financial soundness of the product. Hence, if the insurance decision is made after the forecast is available, the problem is state contingent. When a good year is forecasted, the actuarially fair rate becomes lower (from $\tau = \omega_l$ to $\tau_1 = \omega_{l|h}$) and the farmer's problem and first-order condition (for an interior solution) are

(18) $$\max_I E\hat{u}(\pi^o | h) = \omega_{h|h}\hat{u}(\pi^o(N, r_h) - \tau_1 I) + (1 - \omega_{h|h})\hat{u}(\pi^o(N, r_h) + (1 - \tau_1)I)$$

(19) $$\frac{\hat{u}'(\pi^o(N, r_h) - \tau_1 I)}{\hat{u}'(\pi^o(N, r_l) + (1 - \tau_1) I)} = \frac{\omega_{l|h}}{\omega_{h|h}} \frac{(1 - \tau_1)}{\tau_1}.$$

Since the insurance is actuarially fair, the farmer will insure fully against the systemic risk setting $I^* = \pi^o(N, r_h) - \pi^o(N, r_l) = \pi^o_h - \pi^o_l$. Further, if inputs cannot be changed, the insurance purchase depends neither on whether the forecast is for a good or bad year nor on its skill. Hence, 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 solved and the farmer will insure fully against the systemic risk.

When a forecast for a good year is issued, profits equal $\pi_h^* | \varepsilon = \pi_h^o - \tau_1 \left(\pi_h^o - \pi_l^o \right) + \varepsilon$, across realizations of the insured variable and thus $E(\pi_h^*) = \pi_h^o - \tau_1 \left(\pi_h^o - \pi_l^o \right)$ and $Var\left(\pi_h^* \right) = \sigma_\varepsilon^2$. If the forecast is for a poor year, profits equal $\pi_l^* | \varepsilon = \pi_h^o - \tau_2 \left(\pi_h^o - \pi_l^o \right) + \varepsilon$ across realization of *r*, expected profits are $E(\pi_l^*) = \pi_h^o - \tau_2 \left(\pi_h^o - \pi_l^o \right)$, and $Var\left(\pi_l^* \right) = \sigma_\varepsilon^2$. Since the forecast is unbiased and the insurance is actuarially fair we have $E(\pi^* | \varepsilon) = \omega_h \pi_h^o + (1-\omega_h) \pi_l^o + \varepsilon$, and $E(\pi^*) = \omega_h \pi_h^o + (1-\omega_h) \pi_l^o$.

Notice that expected profits change across realizations of the forecast. The difference is given by $E(\pi_h^*) - E(\pi_l^*) = \left(\tau_2 - \tau_1 \right) \left(\pi_h^o - \pi_l^o \right)$. Since the insurance is actuarially fair, $\tau_2 = \omega_{l|l}$ and $\tau_1 = \omega_{l|h}$, indicating that as the skill of the forecast increases, so does the difference in expected profits across forecasts. The resulting profit variability is

(20) $Var\left(\pi^* \right) = E\left(Var(\pi^* | \varepsilon) \right) + Var\left(E(\pi^* | \varepsilon) \right) = \omega_h (1-\omega_h) \left[\left(\tau_2 - \tau_1 \right) \left(\pi_h^o - \pi_l^o \right) \right]^2 + \sigma_\varepsilon^2$.

Equation (20) indicates that the existence of a skillful forecast that is issued before purchases of the insurance are made increases the variability of profits when compared to the no-forecast situation. In the absence of the forecast (or when the forecast has no skill), we have $\tau = \tau_1 = \tau_2$ and thus the farmer will only face the idiosyncratic risk (compare with equation (14b)). As a skillful forecast is introduced, the difference $\tau_2 - \tau_1$ increases, undermining the effectiveness of the insurance to provide protection against the insurable risk. In the limit, with a perfect forecast, we have $\tau_1 = \omega_{l|h} = 0$ and $\tau_2 = \omega_{l|l} = 1$ yielding the same variance of profits as the uninsured case (equation (5b)) for a fixed N.

In summary, since the forecast is assumed to be unbiased and available to both parties, the ex ante expected profit in this scenario equals the amount that would occur in the absence of a forecast.[10] If the insurance is actuarially fair, the risk-neutral insurance company is indifferent between the pre/post forecast contracts, as long as the prices reflect the information available. However, the farmer's expected profit varies across forecasts and the variability of that profit increases when the forecast is available. In this case in which the farmer does not modify production practices in response to the forecast, pricing the insurance using the information will reduce the utility of the farmer because of the greater exposure to risk. Hence, the presence of a forecast undermines the effectiveness of the insurance as a risk-mitigation mechanism in this situation and reduces welfare.

Effects of a Skillful Forecast on Production Decisions with Pre-Purchased Insurance

We previously analyzed the effect of insurance on input decisions when no skillful forecasts are available. Now we analyze how farmers change their production practices in response to forecast information, after they have already committed to a fixed level of insurance.[11] In this situation, the farmer's problem and first-order conditions for a forecast for a good crop season are given by

$$(21)\qquad \max_N E\hat{u}\left(\pi^o \middle| h\right) = \omega_{h|h}\hat{u}\left(\pi^o\left(N,r_h\right)-\tau_1 I\right)+(1-\omega_{h|h})\hat{u}\left(\pi^o\left(N,r_l\right)+(1-\tau_1)I\right)$$

$$(22)\quad \omega_{h|h}\hat{u}'\left(\pi^o\left(N,r_h\right)-\tau_1 I\right)\pi_N^o\left(N,r_h\right)+(1-\omega_{h|h})\hat{u}'\left(\pi^o\left(N,r_l\right)+(1-\tau_1)I\right)\pi_N^o\left(N,r_l\right)=0\,.$$

In the absence of insurance, we showed (equation (8)) that a skillful forecast for a good year will increase the input level used by the farmer (relative to climatology or no-skill forecast). Equation (22) can be used to show that when insurance is introduced, the farmer will increase input usage further. Using the implicit function theorem, we obtain

$$(23)\quad \operatorname{sgn}\left(\frac{\partial N^{*h}}{\partial I}\right)=\operatorname{sgn}\left(-\omega_{h|h}\hat{u}''\left(\pi^{oh}\right)\tau_1\pi_N^o\left(N^{*h},r_h\right)+(1-\omega_{h|h})\hat{u}''\left(\pi^{ol}\right)(1-\tau_1)\pi_N^o\left(N^{*h},r_l\right)\right)>0\,,$$

where $\pi^{oh} = \pi^{o}\left(N^{*h}, r_h\right) - \tau_1 I$ and $\pi^{ol} = \pi^{o}\left(N^{*h}, r_l\right) + (1-\tau_1)I$. Hence, insurance increases input applications beyond the raise indicated by the forecast alone. The insurance allows the farmer to take more risk in the presence of forecast uncertainty, increasing input levels. When a good year is forecast, both instruments provide incentives for the farmer to apply an amount of inputs more similar to what would be applied if it were known with certainty that a good year was coming.

In a forecast for a bad year, the problem is analogous to the difference that the forecast reduces input use. However, as in the case when the high forecast is issued, the farmer will increase the amount of inputs because of insurance (i.e., $\partial N^{*l} / \partial I > 0$), as the farmer can utilize insurance instead of managing risk through reduced input use. This has the effect of dampening the reaction to an imperfect low rainfall forecast, allowing the farmer to profit when the low rainfall forecast is wrong.

Choice of Both Insurance and Input Purchases in the Presence of a Skillful Forecast

To analyze the full interaction between the risk management tools and production decisions, we now allow farmers to choose both the level of the controllable input and the insurance purchase after observing the skillful forecast. The sequence in this case is as follows. First, the forecast is delivered. Farmers choose their insurance and production practices next. Finally, the systemic and idiosyncratic shocks are observed. Since the forecast is released before farmers make their decisions, we have a state contingent problem. The objective and first-order conditions when a good year is forecasted are

(24) $$\max_{I,N} E\hat{u}\left(\pi^{o} \middle| h\right) = \omega_{h|h}\hat{u}\left(\pi^{o}\left(N, r_h\right) - \tau_1 I\right) + (1-\omega_{h|h})\hat{u}\left(\pi^{o}\left(N, r_l\right) + (1-\tau_1)I\right)$$

(25) $$N:\ \omega_{h|h}\hat{u}'\left(\pi^{o}\left(N, r_h\right) - \tau_1 I\right)\pi^{o}_{N}\left(N, r_h\right) + (1-\omega_{h|h})\hat{u}'\left(\pi^{o}\left(N, r_l\right) + (1-\tau_1)I\right)\pi^{o}_{N}\left(N, r_l\right) = 0$$

(26) I: $-\omega_{h|h}\hat{u}'\left(\pi^{o}\left(N,r_{h}\right)-\tau_{1}I\right)\tau_{1}+(1-\omega_{h|h})\hat{u}'\left(\pi^{o}\left(N,r_{l}\right)+(1-\tau_{1})I\right)(1-\tau_{1})=0$.

Since the insurance is actuarially fair, we know that $I^{*}=\pi^{o}\left(N^{*h},r_{h}\right)-\pi^{o}\left(N^{*h},r_{l}\right)=f\left(N^{*h},r_{h}\right)-f\left(N^{*h},r_{l}\right)$. Using this result, the first-order conditions evaluated at the optimum are written

(27) N: $\hat{u}'\left(\pi^{o}\left(N^{*h},r_{h}\right)-\tau_{1}I^{*}\right)\left(\omega_{h|h}\pi_{N}^{o}\left(N^{*h},r_{h}\right)+(1-\omega_{h|h})\pi_{N}^{o}\left(N^{*h},r_{l}\right)\right)=0$

(28) I: $\omega_{h|h}(1-\omega_{h|h})\left(\hat{u}'\left(\pi^{o}\left(N,r_{l}\right)+(1-\tau_{1})I\right)-\hat{u}'\left(\pi^{o}\left(N,r_{h}\right)-\tau_{1}I\right)\right)=0$

Equation (27) indicates that in the presence of a state-dependent, actuarially fair insurance, the risk-neutral solution is replicated. Although the existence of the idiosyncratic risk imposes utility penalties, the presence of market insurance eliminated the incentive for farmers to self-insure against the possibility of errors in the forecast. Thus, the amount of inputs applied will maximize expected profits. To investigate how the farmer's decisions are affected by the skill of the forecast, we need to sign $\partial I^{*h}/\partial\omega_{h|h}$, and $\partial N^{*h}/\partial\omega_{h|h}$. For the effect of the forecast skill on the insurance purchase decision, comparative statics on the system given by (27) and (28) indicate that

(29) $$\frac{\partial I^{*h}}{\partial\omega_{h|h}}=\left(f_{N}\left(N^{*h},r_{h}\right)-f_{N}\left(N^{*h},r_{l}\right)\right)\frac{\partial N^{*h}}{\partial\omega_{h|h}}.$$

Since we assumed that the marginal productivity of N is higher in good years, increasing the skill of the forecast will move input applications and insurance purchases in the same direction. The effect of the skill of the forecast on the optimal nitrogen application is given by

(30) $$\frac{\partial N^{*h}}{\partial \omega_{h|h}} = -\frac{E\left(\hat{u}''\left(\pi^{*}|h\right)\right)E\left(\hat{u}_{N\omega_{h|h}}\left(\pi^{*}|h\right)\right)}{H} =$$

$$-\frac{1}{H}\left\{\begin{aligned}&\left(\omega_{h|h}(1-\omega_{h|h})\left(\hat{u}''\left(\pi^{o}\left(N,r_l\right)+(1-\tau_1)I\right)(1-\tau_1)+\hat{u}''\left(\pi^{o}\left(N,r_h\right)-\tau_1 I\right)\tau_1\right)\right)\\&*\left(\hat{u}'\left(\pi^{o}\left(N,r_h\right)-\tau_1 I\right)\left(\pi_N^{o}\left(N^{*h},r_h\right)-\pi_N^{o}\left(N^{*h},r_l\right)\right)\right)\end{aligned}\right\},$$

where H is the determinant of the Hessian of the problem (positive by second-order sufficient conditions (SOSC) for a maximum). $E\left(\hat{u}''\left(\pi^{*}|h\right)\right)$ is negative by SOSC. The second term in the numerator is positive by technology assumptions, and thus $\frac{\partial N^{*h}}{\partial \omega_{h|h}} > 0$ and $\frac{\partial I^{*h}}{\partial \omega_{h|h}} > 0$. Analogous analysis and previous results indicate that the farmer will purchase less insurance and use less inputs when the forecast indicates the growing conditions are likely to be poor (see the appendix).

The previous comparative statics exercise reveals that, counter to intuition, when the skillful forecast indicates a good (poor) year is likely, the farmer will purchase more (less) of an insurance of actuarially fair price. The expected change in overall insurance purchases brought about by a forecast of increasing skill depends on the relative adjustment induced by each kind of forecast (good versus poor growing conditions) and the natural frequency of each event. However, this indicates that despite reducing uncertainty about future growing conditions, it is plausible that more skillful forecasts induce more insurance purchases.

In the case in which the farmer can both purchase forecast-priced insurance and adjust input use after the forecast is available, the basic relationship between the forecast and insurance becomes clear: instead of the insurance protecting the farmer from climate risk, it protects the farmer from forecast error.

The farmer is able to remove uncertainty from forecast error and improve utility by operating at the expected profit-maximizing input level instead of self-insuring with less aggressive changes in input. When a good year is forecast, the farmer can intensify to the expected profit-maximizing level, and when a bad year is forecast the farmer can prevent losses through the efficient level of input reduction while still maintaining inputs at a level that maximizes expected profits by taking into account the chance that a good year may still occur. Ex ante expected profits and the variability of these profits when both insurance and forecast are allowed to interact with the farmer's input decisions are given by

(31a) $$E\left(\pi^*\right) = \omega_h\left(\pi^o\left(N^{*h}, r_h\right) - \tau_1 I^{*h}\right) + \left(1-\omega_h\right)\left(\pi^o\left(N^{*l}, r_h\right) - \tau_2 I^{*l}\right)$$

and

(31b) $$Var\left(\pi^*\right) = \omega_h(1-\omega_h)\left(E\left(\pi_h^*\right) - E\left(\pi_l^*\right)\right)^2 + \sigma_\varepsilon^2,$$

where we used the assumptions that the insurance is actuarially fair, and that the forecast is unbiased $\left(m_h = \omega_h\right)$. $E\left(\pi_i^*\right)$ denotes expected profits for an $i = h, l$ forecast. The actuarially fair insurance will lead farmers to maximize expected profits, and the skill of the forecast allows farmers to make better-informed decisions. Thus, expected profits increase when both the insurance and a skillful forecast are available. However, the introduction of a forecast comes at the cost of increasing profit variability. If the forecast has no skill, we showed before that the farmer will not adjust input usage, and thus expected profits are invariant to the information released. In this situation, the insurance is able to remove the systemic risk (first term in equation (31b)). If the skill of the forecast creates a wedge between expected profits obtained under different forecasts, the ex ante variance of profits increases and the effectiveness of the insurance to manage variability is reduced. Counter to intuition, the variability of profits when both risk management tools are available can be higher than when none is available. This can be seen by comparing equations (31b) and (5b). Whenever expected profits under different forecasts differ more than the profit difference in the base case, variability will be increased.

In this case, with a perfect forecast, there is no role for insurance, while insurance is completely relied upon when the forecast has no skill. The difference is that the forecast directly allows improved input application that leads to increased yields and increased profits, while the insurance does not directly increase profits, but allows the farmer to behave less conservatively. Thus, with insurance and a forecast, the farmer can have increased variability because of the potential to produce more in good years. However, to the extent that bad years are perfectly forecast, the farmer must face the full brunt of the drought, albeit with full information for optimal input use.

Since insurance plays different roles when priced using climatology or the forecast, it is worthwhile to offer both pre-and post-forecast policies, pre-forecast to protect against climatology and post-forecast to protect against forecast error. The relative value of the pre- versus post-forecast depends on the skill of the forecast and the farmer’s flexibility in making changes in order to use effectively the forecast information in production to increase profits in good years and reduce damages in bad years.

Conclusions

The failure of the development of commercially viable traditional crop insurance products and innovations in financial markets has fed a renewed interest in the search for alternatives to help farmers 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 farmers to intensify their operations and invest in higher returns but in riskier activities. This is touted as key in helping farmers in developing countries escape poverty traps.

A substantial 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. Since previous literature has said little about the interaction between insurance, in particular index insurance, and climate forecasts, we have formalized and studied the basic relationship between forecasts, insurance, and production decisions through a theoretical model.

Understanding this relationship is becoming increasingly important, as climate scientists have made remarkable progress at forecasting rainfall and temperature deviations from long-term seasonal averages months in advance. Further, improved models and techniques are appearing at an accelerated pace, increasing the number of situations in which forecasts and insurance interact in the real world. As such, the interactions between the two risk management instruments (climate forecast and index insurance) need to be better understood in order to take advantage of emerging opportunities and/or avoid situations with the capacity to threaten the effectiveness and survival of existing index insurance mechanisms to alleviate poverty.

Insurance (in the absence of moral hazard effects) will induce farmers to use more of a risk-increasing input. 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 inputs applied. If a bad year is forecasted, the forecast induces farmers to reduce inputs while the insurance allows the farmers to maintain inputs at higher levels than without insurance. Additionally, we find that if an actuarially fair insurance is available, and the farmer's profits are not sufficiently responsive to the input mix, the introduction of a climate forecast harms the farmer if the premiums reflect the forecast (even if they are actuarially fair). Hence, a necessary condition for farmers to prefer a state-contingent, commercially viable insurance product is that farmers can increase their profits by taking the forecast information into account. Perhaps surprisingly, we find that forecast information may induce farmers to buy more insurance even as it reduces risk. The intuition is that the forecast may widen the wedge between optimized profits among states of the world.

Since insurance priced using climatological probabilities protects against the climate and insurance priced on forecast probabilities protects against forecast error, farmer preferences for climatological- versus forecast-based insurance mirror the value of the forecast information in production. It is likely that both products could be useful, particularly when farms are heterogeneous, especially in the rates at which they are willing to trade expected levels by variability in profits. Insurance demand for pre- and post-forecast products may allow market valuations of forecast information. Insurance prices may communicate forecast information when farmers do not have direct access to the forecast. Studies exploring the potential of insurance prices as aggregators of forecast information would be valuable.

Finally, implementation of forecast-contingent insurance policies will require non-trivial innovation, as current insurance regulations and financing methodologies are not necessarily well suited to quickly fluctuating premiums, value at risk, and market size. Because an insurance policy typically does not include the option for resale at a market price, the pricing of information cannot directly rely on market movements. For insurance, it is likely that information pricing will be explicitly engineered into the products offered. Future work addressing these issues may be worthwhile.

Since insurance providers must typically reinsure their risks, the forecast-dependent price fluctuations of global weather derivative markets will lead to variations in reinsurance costs that must somehow be managed. Retail products that adjust based on the forecast could be one alternative that insurers have to address this problem. Future work will need to address both the technical issues of appropriately translating forecast information into an unbiased insurance as well as the financial and implementation issues of how to build a product that can be marketed and financed by an insurance company, that meets the demands of clients, and that falls within the allowable legal framework of insurance. One ENSO-based strategy might be to charge a non-varying premium for a base liability calculated for an unfavorable ENSO phase and to increase the liability covered at no cost when the forecast is favorable. These changes might be financed by the insurer through purchases of ENSO derivatives or related products.

Footnotes

[1] Since there is a large body of literature on the role of risk in agriculture (see, e.g., Just and Pope 2002; Moschini and Hennessy 2001) it is worthwhile to note that there are several sources of risk that are relevant from the farm'ers perspective, including production, price, technological, and policy uncertainties. Since our focus is on climate risks, a case of production uncertainty, we will assume that prices are non-random.

[2] It is particularly important to understand this relationship in the case of index insurance because insurance does not include an option common to weather derivatives, the option to perform repeatedly marginal transactions in a dynamic market. Therefore, instead of relying on market-based updates for optimal use of information, mechanisms to incorporate the information must be built directly into the contracts.

[3] Another well-known example is the Indian experience with rainfall insurance. A program by The World Bank in collaboration with a microfinance institution (BASIX) and an insurance company (ICICI Lombard), served 230 farmers in 2003 and expanded rapidly to serve over 20,000 farmers by 2004 (World Bank 2005).

[4] Moral hazard effects would induce an insured farmer to use less of the input work in the opposite direction than the risk reduction effect.

[5] The function used by Mahul is $y = g(N)r + h(N) + \varepsilon$.

[6] The same result for the case of two controllable inputs was obtained by Ratti and Ullah (1976), 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.

[7] A perfect forecast would entail $\omega_{i|i} = 1$ for $i = l, h$.

[8] A proof is available from the authors upon request.

[9] Thus, we are subtracting zero from equation (11).

[10] To see this, note that $E\pi^* = m_h\left(\pi_h^o - \tau_1 I^*\right) + \left(1 - m_h\right)\left(\pi_h^o - \tau_2 I^*\right) = \pi_h^o - I^*\left(m_h\tau_1 + m_l\tau_2\right)$.

Using the assumption that the forecast is unbiased, $E\pi^* = \omega_h\pi_h^o + (1 - \omega_h)\pi_l^o$.

[11] This may be the case when farmers can only buy a fixed amount of insurance or no insurance is available at all.

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Appendix

Proof of: $\partial I^{*l}/\partial \omega_{l|l} < 0$ and $\partial N^{*l}/\partial \omega_{l|l} < 0$. The objective function and associated first-order conditions for a farmer when a forecast for poor growing conditions is issued are

(A1) $$\max_{I,N} E\hat{u}\left(\pi^o \middle| l\right) = (1-\omega_{l|l})\hat{u}\left(\pi^o\left(N, r_h\right) - \tau_2 I\right) + \omega_{l|l}\hat{u}\left(\pi^o\left(N, r_l\right) + (1-\tau_2)I\right)$$

(A2) $$N\text{: } \hat{u}'\left(\pi^o\left(N^{*l}, r_h\right) - \tau_2 I^{*l}\right)\left((1-\omega_{l|l})\pi_N^o\left(N^{*l}, r_h\right) + \omega_{l|l}\pi_N^o\left(N^{*l}, r_l\right)\right) = 0$$

(A3) $$I\text{: } \omega_{l|l}(1-\omega_{l|l})\left(\hat{u}'\left(\pi^o\left(N^{*l}, r_l\right) + (1-\tau_2)I^{*l}\right) - \hat{u}'\left(\pi^o\left(N^{*l}, r_h\right) - \tau_2 I^{*l}\right)\right) = 0.$$

Comparative statics indicate that $\frac{\partial I^{*l}}{\partial \omega_{l|l}} = \frac{\partial I^{*l}}{\partial N^{*l}} \frac{\partial N^{*l}}{\partial \omega_{l|l}}$. Since

$\frac{\partial I^{*l}}{\partial N^{*l}} = \left(f_N\left(N^{*l}, r_h\right) - f_N\left(N^{*l}, r_l\right)\right) > 0$, then $\operatorname{sgn}\left(\partial I^{*l}/\partial \omega_{l|l}\right) = \operatorname{sgn}\left(\partial N^{*l}/\partial \omega_{l|l}\right)$. Using

(A4) $$\frac{\partial N^{*l}}{\partial \omega_{l|l}} = -H^{-1}\left(E\left(\hat{u}''\left(\pi^* \middle| l\right)\right)\hat{u}'\left(\pi^o\left(N, r_h\right) - \tau_2 I^{*l}\right)\left(f_N\left(N^{*l}, r_l\right) - f_N\left(N^{*l}, r_h\right)\right)\right) < 0,$$

we conclude that the farmer will optimally reduce input and insurance purchases when poor growing conditions are forecasted with any skill.