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Index insurance and basis risk: A reconsideration

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ABSTRACT

Index insurance has been seen as an important tool for managing the risks faced by farmers in developing countries but uptake has been disappointingly low. Basis risk is often cited as one of the main reasons for the lack of uptake. We investigate the role of basis risk in greater depth by considering contracts that allow farmers to choose the level of the index that triggers an indemnity in addition to coverage. We show that risk averse farmers will select trigger levels to protect against catastrophic outcomes, even if downside basis risk increases. A numerical simulation model bears out our theoretical results.

1. Introduction

There is considerable interest in index insurance for agriculture, especially for use in developing countries. Risk from weather shocks is inherent in agriculture. Informal risk sharing mechanisms often fail in the face of adverse shocks affecting whole local communities. In the absence of insurance or other financial means of smoothing income, farmers typically use strategies that involve significant sacrifices in mean income to manage those risks. Those sacrifices are especially great in developing countries, where weak financial markets limit the use of savings, let alone more complex instruments like futures and options, to manage those risks (see for example Miranda and Farrin 2012).

Agricultural insurance based on external sources such as data from weather stations or satellites has been seen as an attractive way to provide farmers with protection against weather-related risk (see for example Miranda and Farrin 2012; Carter et al., 2017; Jensen and Barrett 2017; Cole and Xiong 2017). Index insurance generally is not prone to the moral hazard and adverse selection problems that are believed to limit agricultural insurance (which even in developed countries is available commercially only for hazards such as fire and hail).

Despite rosy predictions from experiments and heavily subsidized pilot programs, uptake of index insurance has been disappointingly low, especially when premiums are priced at commercial levels. One of the most commonly cited impediments to index insurance uptake is basis risk, especially the probability that farmers will suffer losses for which they will not be indemnified (Miranda and Farrin 2012; Carter et al., 2017; Jensen and Barrett 2017; Cole and Xiong 2017). Clarke (2016) provides a formal analysis of how and why downside basis risk can make the purchase of index insurance unattractive to a risk averse farmer. His analysis casts doubt on whether any improvements can increase uptake, arguing that basis risk may pose an insurmountable obstacle to designing index insurance programs that farmers will want to buy. Intuitively, index insurance lowers income in the worst states of nature (when farmers suffer losses but are not indemnified because the index does not reflect their losses) and increases it in the best states of nature (when farmers do not suffer losses but are indemnified anyway). As a result, risk averse farmers have little incentive to purchase index insurance.

This paper examines the role of basis risk in index insurance contracts more closely. In contrast to Clarke—but consistent with the design of crop insurance programs in the US, Canada, and Europe and with some recently introduced index insurance contracts in East Africa—we consider the effect of allowing farmers to choose the level of the index that triggers an indemnity in addition to the extent to which losses are indemnified. We show that the optimal choice of a trigger level may involve an increase in basis risk. Specifically, our analysis suggests that risk averse farmers prefer index insurance oriented toward catastrophic

Abbreviations: NDVI, Normalized Difference Vegetative Index.

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risk, that is, policies that indemnify losses when those losses are relatively severe, as a means of controlling premiums. That theoretical prediction is consistent with the results of experiments like that of Cole et al. (2013), which finds that farmers who received an extra payment for participating in a survey were markedly more likely to purchase rainfall insurance, Karlan et al. (2014), which find that farmers prefer insurance to other financial instruments, and Casaburi and Willis (2018) and Liu et al. (2020), which find that uptake is greater when farmers can pay premiums at harvest rather than planting time. It is similarly consistent with the evidence obtained by Chantarat et al. (2013)), Bertram-Huemmer and Kraehnert (2017), and others which indicate that index livestock insurance contracts have provided effective protection for pastoralists against catastrophic losses. It implies that observed low uptake rates are partially attributable to insurance contracts that feature higher premiums than farmers are willing or able to pay, consistent with Binswanger-Mkhize's (2012) argument that cost is a major impediment to index insurance uptake. A numerical simulation analysis indicates that allowing a choice of an index level that triggers indemnification can have large effects on coverage levels, downside basis risk, the probability of indemnification, insurance uptake, and, in some cases, premiums.

We proceed as follows. Section 2 reviews recent literature on crop insurance design and implementation. Sections 3 and 4 revisit Clarke's discrete states of nature model, allowing for a choice of a trigger index level that alters basis risk in addition to a choice of coverage level. Section 5 uses the results of numerical simulations to explore how the choice of a trigger index level affects the propensity to purchase insurance, the choice of coverage, and the level of basis risk under different assumptions about correlation between the index and individual output levels, the riskiness of output, risk aversion, and loading factors. Section 6 concludes.

2. Index insurance in principle and practice

Index insurance has been seen as a way to improve farmers' ability to manage risk, especially in developing countries. Commercial multiple peril crop and livestock insurance is generally unavailable even in developed countries due to inherent problems of moral hazard and adverse selection. Index insurance in the form of crop insurance with indemnities based on area, rather than individual yield was first proposed as a means of mitigating those problems (Halcrow 1949). The US Department of Agriculture has offered area-yield crop insurance since 1993, for example, and has since extended that form of index insurance to coverage against revenue losses.

Farmers in developing countries frequently lack adequate means of managing risk and thus often adopt risk management strategies that limit productivity. Informal risk sharing mechanisms are inadequate to cope with adverse shocks that affect large shares of local populations. Financial markets generally are poorly developed and fail to offer mechanisms for smoothing consumption over time. The ability of many farmers to diversify sources of income is often limited. This general lack of tools for risk management means that poor farmers have little incentive to adopt new practices that could increase productivity and incomes but are perceived as risky. From this perspective, index insurance is seen as an instrument for promoting development in poor rural areas (Miranda and Farrin 2012; Carter et al., 2017; Jensen and Barrett 2017; Cole and Xiong 2017).

In developing countries, there has been a great deal of interest in insurance that provides indemnities triggered by externally measured sources like satellite imagery (e.g., Normalized Difference Vegetative Index or NDVI), weather stations (e.g., number of days of drought or excessively high temperatures), and the like. Insurance based on actual loss histories is generally infeasible, even if contracts could be designed to mitigate moral hazard and adverse selection problems, due to low literacy rates that result in a lack of formal household records. Weak government capacity in developing countries also means that statistical information is poor and unreliable, if it exists at all, rendering infeasible insurance products based on indices such as area yields, which are more highly correlated with individual yields but can still be sufficiently decoupled to prevent severe moral hazard and adverse selection problems.

Pilot programs and economic experiments indicate that index insurance has significant potential to improve farmers' livelihoods. The World Bank and other entities have embraced that potential enthusiastically by funding pilot projects and providing subsidies for insurance premiums. The World Bank's Global Index Insurance facility, funded by the European Union, the governments of Germany, Japan, and the Netherlands, reports having helped fund more than 1.5 million contracts with insured value of $151 million in Sub-Saharan Africa, Asia, Latin America and the Caribbean (Global Index Insurance Fund). The World Food Program has run an index insurance program in East Africa since 2011. Other public and some private entities also offer index insurance in various countries (see for example Kilgour and McArdle 2017). Index-based livestock insurance in Africa and Central Asia has been shown to provide long-term protection to herders who have limited options for diversification or other means of buffering against extreme weather shocks (Chantarat et al., 2013; Bertram-Huemmer and Kraehnert 2017).

Despite index insurance's potential to deliver sorely needed risk management tools to farmers in a cost effective manner, it has proven difficult to devise programs that are financially sustainable. In India, the first developing country to introduce index insurance, uptake has been relatively high only because index insurance is (a) heavily subsidized and (b) mandatory for those receiving loans from financial institutions. Even so, most farmers insure only a portion of their holdings and large shares of those currently insured fail to maintain consistent coverage. In fact, uptake appears to respond to immediate past experience, increasing in years immediately following those with large payouts in the local area and falling in years immediately following those with low payouts in the local area (Clarke et al., 2012; Cole et al., 2014; Tobacman et al., 2017; Cai et al., 2020). Experience in Africa has been largely similar, with many pilot programs failing to scale up and most programs that do succeed in scaling up remaining reliant on subsidies (McIntosh et al., 2013; Karlan et al., 2014; Greatrex et al., 2015; Jensen and Barrett 2017).

Inadequate design of existing insurance products is frequently cited as a major reason for low uptake and high "churn" (Miranda and Farrin 2012; Jensen and Barrett 2017; Carter et al., 2017). The most commonly cited problem with design is basis risk, in particular, the fact that there will be years in which farmers suffer losses for which they are not indemnified due to imperfect correlation between individual losses and the indexes triggering indemnities. Basis risk is an inherent feature of index insurance of any kind, since indexes are never perfectly correlated with individual experiences. Thus, there will be states of nature in which the insured suffer losses but are not indemnified against those losses (downside basis risk) as well as states of nature in which the insured receive payouts even though they have not suffered losses (upside basis risk). The presence of downside basis risk means that index insurance will perform poorly, at least from the point of view of farmers who fail to receive payments to cover their losses on some occasions. Basis risk has been shown to be quite high in a number of existing index insurance programs: Studies from the US, Argentina, Poland, the Sahel, and other locations demonstrate highly imperfect correlation between data from weather stations and remote sensing used to trigger indemnity claims and realized yields, resulting in chances in the range of 16–36% that farmers would receive no compensation on occasions when they experience significant losses (Yu et al., 2019; Smith and Watts 2019; Keller and Saitone 2022).

Basis risk also makes index insurance more difficult for poor farmers to understand. The lack of payouts to cover losses can undermine trust in insurance providers and may induce behavioral responses due to ambiguity aversion, factors that may lead farmers to drop coverage or not take it up in the first place (Carter et al., 2017). Jensen et al. (2018) provide some direct empirical evidence of the adverse effect of basis risk on index insurance uptake. Cai et al. (2020) provide experimental evidence that improvements in financial literacy can mitigate the effects of payout non-receipt, confirming the inferences about the importance of financial literacy drawn from a meta-analysis of existing implementation studies by Cole et al. (2012).

Binswanger-Mkhize (2012) takes a somewhat contrary view of the reasons for low uptake and high turnover in index insurance programs in developing countries. He argues that the need for insurance is greatest among poor farmers, as better off farmers have adequate means of managing risk through informal risk sharing mechanisms, diversification of income, or access to financial resources and thus have low demand for insurance. He cites cost and liquidity constraints as the major obstacles to uptake for poor farmers. Cole et al. (2013) provide some empirical evidence in support of this view. The high price elasticity of demand and greater responsiveness of Bangladeshi farmers' index insurance purchases to discounts compared to rebates is also consistent with this perspective (Hill et al., 2019). The apparent success of index insurance brokered through the Africa Agriculture and Climate Risk Enterprise Ltd. (ACRE) also supports this view, as ACRE is able to keep premiums low and indemnification fast by using mobile technology to process premiums and payments and by working through seed distributors, lenders, etc.

In what follows, we re-examine the role of basis risk in index insurance contract design. We consider what choices a risk averse farmer (without liquidity constraints) would make if she could select the value of the index triggering a payout in addition to the share of the loss covered, thereby affecting basis risk as well as the probability of receiving an indemnity. Such choices are characteristic of area-yield insurance programs offered in the United States, pasture index insurance programs in Spain; ACRE recently included such choices in its index insurance products in Kenya, Tanzania, and Rwanda.

3. Optimal choice of trigger level and coverage with discrete states of nature

Our analysis builds on Clarke's (2016) formulation because it distinguishes basis risk in a clear manner. Clarke analyzes the optimal choice of index insurance coverage α by a risk averse farmer with initial wealth w who suffers a loss of fixed size L with probability p. An indemnity αL is paid when the index takes on a value $I > 0$, which occurs with probability q. With probability r, the farmer will suffer losses but the index will take on a value $I = 0$, in which case no indemnity will be paid. If the farmer purchases insurance (chooses coverage $\alpha > 0$), she pays a premium αqmL, where m is a loading factor taking on a value of 1 if insurance is actuarially fair, less than one if insurance is subsidized, and greater than one if insurance is costly.

There are four discrete states of nature in this model: (1) the farmer suffers a loss and receives an indemnity (denoted *LI*), which occurs with probability p-r; (2) the farmer does not suffer a loss but receives an indemnity anyway (*0I*), which occurs with probability q+r-p; (3) the farmer does not suffer a loss and does not receive an indemnity (*00*), which occurs with probability 1-q-r; and (4) the farmer suffers a loss but does not receive an indemnity (*L0*), which occurs with probability r. These four possible states of nature and the probabilities associated with them are shown in Table 1, taken from Clarke (2016).

The farmer's expected utility is

$$EV = (p-r)V_{LI}(w-\alpha qmL-(1-\alpha)L)+(q+r-p)V_{0I}(w-\alpha qmL+\alpha L) \\ +(1-q-r)V_{00}(w-\alpha qmL)+rV_{L0}(w-\alpha qmL-L \quad (1)$$

The necessary condition defining the optimal coverage level assuming that insurance is purchased is

$$\frac{\partial EV}{\partial \alpha} = (1-qm)L\left[(p-r)V'_{LI}+(q+r-p)V'_{0I}\right]-qmL\left[(1-q-r)V'_{00}+rV'_{L0}\right]=0 \quad (2)$$

Clarke shows that it is optimal for an infinitely risk averse farmer with maximin preferences to forego the purchase of insurance (choose $\alpha = 0$). Intuitively, the farmer is worse off in the worst state of nature (*L0*) because she pays the insurance premium in addition to suffering a loss and thus prefers not to purchase insurance. More generally, Clarke argues that diminishing marginal utility implies that increases in income in the best state of nature (*0I*) cannot compensate for lower income in the worst state of nature (*L0*), so that basis risk poses a substantial obstacle to commercial success of any index insurance offering.

Now suppose that the farmer can choose the level of the index that triggers an indemnity payment in addition to choosing the level of coverage. Assume without loss of generality that the probability of receiving an indemnity is decreasing in that trigger index level and is thus $q(k)$, $q'(k) < 0$ where $k \geq 0$ denotes the trigger level of the index. In terms of concrete examples, a higher trigger level corresponds to a higher value of a drought index, a larger number of days with rainfall below (or temperature above) a critical level, a higher shortfall in area crop yield relative to the historic area average, a larger shortfall of NDVI relative to a reference value, and the like. Changing the trigger level of the index also changes the probability that the farmer suffers a loss but is not indemnified, $r(k)$. A lower probability of receiving a payment means a higher probability of not receiving a payment in the event of a loss, hence $r'(k) > 0$. For convenience, let $r'(k) = \lambda(k)q'(k)$ where $-1 < \lambda(k) < 0$ measure the change in downside basis risk (r) per unit change in the in the probability of receiving an indemnity (q). Further, the ratio $\frac{1+\lambda(k)}{\lambda(k)}$ measures the correlation between upside (+r-p) and downside (r) basis risk.

The necessary condition characterizing the choice of a trigger level k is

$$\frac{\partial EV}{\partial k} = \left[(p-r)V'_{LI}+(q+r-p)V'_{0I}+(1-q-r)V'_{00}+rV'_{L0}\right](-\alpha mL)q'(k) \\ +(V_{0I}-V_{00})q'(k)+[-V_{LI}+V_{0I}-V_{00}+V_{L0}]r'(k)\leq 0 \quad (3)$$

After substitution using $r'(k) = \lambda(k)q'(k)$, cancelling out $-q'(k) > 0$, and rearranging terms, condition (3) can be rewritten as:

$$\alpha mL\left[(p-r)V'_{LI}+(q+r-p)V'_{0I}+(1-q-r)V'_{00}+rV'_{L0}\right]\leq(1+\lambda)[V_{0I}-V_{00}] \\ -\lambda[V_{LI}-V_{L0}] \quad (4)$$

The term in the left hand side of this condition measures the loss of utility in all states of nature due to higher premium payments. The first and second terms on the right hand side represent the increases in expected utility from receiving an indemnity payment when there is no loss and when there is a loss, respectively. Thus, the non-minimal choice of a trigger level balances the change in utility from higher premium payments in all states of nature against the net change in utility from a change in basis risk. Note that it is only when this condition holds as a strict inequality for all possible values of the index that a risk averse farmer will choose the minimum value of the index as a trigger level, as Clarke's analysis assumes implicitly.[1]

We can get some additional intuition by noting that a choice of a trigger level is relevant only when a farmer chooses a positive coverage level. Substitution from the necessary condition for a positive coverage level $\alpha > 0$ and second order Taylor series approximations for V_{L0} and V_{00} around V_{LI} and V_{0I}, respectively, allow us to rewrite the necessary condition for a non-minimal choice of k as

[1] In Clarke's discrete case, the assumption of a non-minimal trigger is implied by the fact that an indemnity is paid when the index takes on a value greater than zero. In Clarke's continuous case, the indemnity equals the value of the index.

$$\left[\lambda + \frac{p-r}{q} + \frac{\alpha(1+\lambda)L\gamma_{OI}}{2}\right]V'_{OI} = \left[\lambda + \frac{p-r}{q} + \frac{\alpha\lambda L\gamma_{LI}}{2}\right]V'_{LI} \quad (5)$$

Here γ_{0I} (γ_{LI}) denotes the coefficient of absolute risk aversion in state *0I* (*LI*). Intuitively, the optimal choice of a trigger level balances the marginal utility of income in states when indemnities are received and there is no loss with the marginal utility of income in states where indemnities are received following a loss. Thus, a necessary condition for a farmer to choose a trigger level that decreases the probability of receiving an indemnity is that the corresponding decrease in the probability of receiving an indemnity when a loss is incurred (due to the increase in downside basis risk) is not too large. More formally.

Proposition 1. If absolute risk aversion is non-increasing, a necessary condition for a non-minimal choice of a trigger level to be optimal is $\frac{r'}{p-r} < -\frac{q'}{q}$.

(See Appendix A for proofs of all propositions.)

Intuitively, farmers face a tradeoff between the insurance premium (a reduction of income incurred with certainty) and receipt of indemnity payments in cases of loss. Since the insurance premium is based on expected indemnities, the proportional change in the probability of receiving an indemnity, q'/q, measures the impact of adjusting the trigger level on the insurance premium. The proportional change in the probability of receiving an indemnity when a loss is suffered (and in this model the size of loss is fixed), $r'/(p-r)$, measures the impact of adjusting the trigger level on receiving an indemnity in the event of a loss. Proposition 1 thus indicates that farmers are willing to decrease the probability of receiving indemnities in the event of loss if the associated decrease in premiums is sufficiently large.

In other words, this result suggests that, if offered a choice of a trigger level, a risk averse farmer may prefer to accept greater downside basis risk (a choice of k that reduces q and thus increases r) in return for a lower insurance premium and thus higher income in the worst state of nature (*L0*). In other words, basis risk may not be as much of an impediment to the purchase of index insurance as is often believed. In fact, existing contracts may offer too little basis risk in the sense that farmers place a greater value on lowering premiums than on the prospect of suffering a loss without being indemnified.

4. Impact of trigger level choice on the decision of whether to purchase insurance with discrete states of nature

As noted above, allowing agents to select a trigger level of the index gives them the ability to adjust the balance between premiums (which lower income in the worst state of nature) and indemnities (which increase income in the best state of nature). In other words, a choice of a trigger level of the index gives farmers a way to adjust their insurance coverage to fit the correlation between the index and their own individual risk of loss. As a result, the ability to choose a trigger level can mitigate disincentives for purchasing index insurance created by the presence of basis risk.

In the context of Clarke's discrete states of nature model, it is straightforward to show that allowing a choice of a trigger value makes uptake of index insurance more likely. Clarke's Theorem 3 shows that a necessary condition for positive coverage to be optimal is that the expected value of the index in case of loss, $E[\tilde{i}|\tilde{l} = L]$, exceeds the product of the loading factor and the unconditional expected value of the index, $mE[\tilde{i}]$. Proposition 1 implies that the ratio of the two, $\frac{\widetilde{E[\tilde{i}|\tilde{l}=L]}}{\widetilde{mE[\tilde{i}]}}$, is greater when a non-minimal choice of a trigger value is optimal.

Proposition 2. When absolute risk aversion is non-increasing, a non-minimal choice of a trigger level $k > 0$ increases the probability that positive coverage $\alpha^* > 0$ will be optimal.

Proposition 2 indicates allowing a choice of a trigger value of the index makes uptake of index insurance more likely whenever agents exhibit non-increasing risk aversion. It is also straightforward to show that a non-minimal choice of a trigger level means that positive coverage is also optimal for risk averse agents of any kind:

Proposition 3. If a non-minimal choice of a trigger level k is optimal, then a positive level of coverage is also optimal ($\alpha^* > 0$) for any risk-averse agent.

The ability to adjust the tradeoff between premiums and indemnities in case of loss (equivalently, upside and downside basis risk), is likely to be especially important in a developing country context. In many developing country situations, there is a great deal of heterogeneity in the correlation between the index used in the insurance contract and individual farmers' actual experiences of loss (e.g., where the index is based on readings from weather stations that are few and far between). Contracts featuring a single fixed level of the index that triggers indemnity payments may be optimal for only a small subset of farmers. Allowing farmers to choose that trigger level allows them to select a contract that optimizes the tradeoff between the insurance premium and compensation for a loss when it occurs for their own circumstances. If farmers in the insurance program catchment area are largely homogeneous in terms of the correlation between the index and the losses they experience, the choice of a trigger level may not matter; but when there is significant heterogeneity, our result suggests that offering farmers the choice of a trigger level in addition to a level of coverage could increase uptake.

Finally, Clarke's condition for positive coverage to be optimal suggests a diagnostic for index insurance contract design. The requirement that the expected value of the index in the event of loss exceed the product of the loading factor and the unconditional expected value of the index can be used to assess whether an insurance contract utilizing any specific index will not be commercially viable or, in the case of heterogeneous populations, which kinds of agents are not likely to purchase a contract based on a specific index. It is straightforward to characterize the features of an index that will never be commercially viable:

Proposition 4. It will never be optimal to purchase index insurance under any contract for which $p\text{-}r(k)\text{-}pmq(k) \leq 0$ and $1 + \lambda(k) < 1\text{-}pm$ for all feasible choices of a trigger level.

Since $\lambda(k) > -1$, it follows immediately that:

Corollary. It will never be optimal to purchase index insurance under any contract for which $p\text{-}r(0)\text{-}pmq(0) \leq 0$ and $pm > 1$.

Intuitively, the ability to adjust the level of the index that triggers an indemnity payment in addition to selecting the level of coverage gives agents a greater chance of fashioning a contract that provide them with a balance between premiums and indemnities most suitable for their own situation and attitudes toward risk. There are, however, conditions under which such an adjustment will never be possible. There are two critical factors determining whether index insurance will never be commercially viable. The first is that the expected value of the index in case of loss, $E[\tilde{i}|\tilde{l} = L]$, is less than the product of the loading factor and the unconditional expected value of the index, $mE[\tilde{i}]$, at the level of the index that gives the greatest chance of an indemnity, $q(k)$. The second is that the product of the probability of loss and the loading factor, *pm*, is too large relative to the ability to adjust downside risk relative to the probability of receiving an indemnity. The latter will always be true when the first condition holds and $pm > 1$. A straightforward implication is that policies whose costs of selling and administering index insurance policies are too high relative to loss probabilities will not be commercially viable..

Propositions 3 and 4 generalize straightforwardly to the case where losses and the index have a joint continuous distribution. As we show in Appendix B, whenever insurance is provided at commercial rates ($m > 1$), (1) an optimal choice of a positive level of coverage ($\alpha^* > 0$ implies a non-minimal choice of a trigger level *k*; and (2) farmers are more likely to purchase index insurance when they can choose both the coverage level and the level of the index that triggers indemnities. In the numerical illustration that follows, we employ such a more general continuous joint distribution of losses and the index employed by the insurer.

5. Numerical illustration: a simulation model of optimal insurance purchase with and without choice of trigger level

We illustrate how allowing a farmer to select a trigger coverage level affects the choice of a coverage level (and thus also whether to purchase insurance), basis risk, insurance premiums, and indemnities using a numerical simulation model. This section describes the parameterization of the model; the impacts of allowing a choice of trigger on insurance policy design and uptake for the cases of constant absolute and relative risk aversion; and implications of those results for the design of index insurance.

5.1. Methodology

We characterize both outcomes and the index in terms of income rather than losses. We assume that the farmer's risk preferences are characterized by constant absolute risk aversion:

$$u(\pi) = 1 - \frac{e^{-\gamma\pi}}{\gamma} \tag{6}$$

where π denotes income net of insurance premiums plus indemnities and γ is the coefficient of absolute risk aversion. As a robustness check, we also analyze the case of constant relative risk aversion with the farmer's risk preferences characterized as

$$u(\pi) = \frac{\pi^{1-\gamma} - 1}{1-\gamma} \tag{7}$$

We assume that income from farm operations (y) and the index (i) are random and jointly normal, with ρ denoting correlation between both variables and σ_y, σ_i denoting respective standard deviations[2]:

$$\begin{pmatrix} y \\ i \end{pmatrix} \sim N\left(\begin{pmatrix} 1 \\ 1 \end{pmatrix}, \begin{pmatrix} \sigma_y^2 & \rho\sigma_y\sigma_i \\ \rho\sigma_y\sigma_i & \sigma_i^2 \end{pmatrix}\right) \tag{8}$$

The farmer receives an indemnity when the index falls below the trigger level *k*. As in the preceding section, the indemnity equals the product of the coverage level α and the difference between the index and the trigger level, *i-k*. The insurance premium equals the $\alpha m \mu_i$ where *m* is a loading factor and $\mu_i = E[\widetilde{i} - k] = \int_k^I \int_0^L (i-k) \cdot f(i,l) didl$ is the average indemnity paid to the farmer.

We compare two types of insurance contract. Both feature contracts in which payouts occur when the index falls below a certain trigger level, so that the index is inversely correlated with losses as in existing area-yield and NDVI-based contracts. One corresponds to the situation Clarke analyzes in which the farmer is assumed to choose coverage α only and the trigger level *k* is given and equal to 1 (so that the farmer receives an indemnity whenever the index falls below average).[3] In the other, the farmer is assumed to choose coverage α and the level of the index level *k* that triggers an indemnity to maximize expected utility subject to the constraints $0 \leq \alpha \leq 1$ and $0 \leq k \leq 1$. This second scenario allows the farmer to choose policies oriented toward more catastrophic coverage, i.e., indemnities paid out only when farm income falls well below average.

We conduct these comparisons over a range of levels of risk aversion, insurance premium loading factors, and characterizations of the joint distribution of farm income and the index. Specifically, we analyze the model for three levels of risk aversion ($\gamma = \{1,3,5\}$ for constant absolute risk aversion and $\gamma = \{1,2,3,5\}$ for constant relative risk aversion) and loading factors over a range that covers subsidized premiums and loading factors commonly observed in developing countries ($m = \{0.8, 1.0, 1.2, 1.4, 1.6, 1.8\}$) (see for example the literature cited in Clarke 2016). We assume that the standard deviations of *y* and *i* are equal and vary them over a range characteristic of African maize yields {0.3, 0.4, 0.5, 0.6, 0.7} (Shi and Tao 2014). We follow Carter et al. (2016) in assuming a positive correlation between individual idiosyncratic yield and the index.[4] The correlation coefficient ρ is varied over the same range of values as the standard deviations.

We analyze utility maximizing choices of the trigger level k^* and loss coverage α^* under the two types of insurance contracts for all possible combinations of parameter values, a total of 540 scenarios for each contract or 1080 scenarios in all. In each scenario, we conduct Monte Carlo simulations with 1000 draws from the joint distribution of farm income and the index (*y* and *i*). For computational ease we draw from separate marginal distributions of farm income and the index linked by copula, a procedure that avoids some of the difficulties involved in drawing from joint distributions while retaining a great deal of flexibility in defining how correlations between two random variables vary (Anderson et al., 2009). Copulas have been used extensively in the insurance literature, including crop insurance (Mendes and Souza 2004, Goodwin and Hungerford, 2015). We calculate optimal outcomes for each scenario, giving us a data set containing 1080 observations.

5.2. Results and discussion

Our theoretical analysis indicates that risk averse farmers may want to orient insurance coverage toward greater indemnification of more catastrophic risk and are thus more likely to purchase index insurance that pays indemnities in fewer states of nature. As a result, they may be willing to accept greater basis risk in return for lower premiums in all states of nature. In terms of our simulation model, a contract that does not allow the choice of a trigger level pays an indemnity whenever the index falls below average. Our theoretical analysis indicates that farmers may prefer a contract that pays an indemnity only when the index falls well below average as a means of controlling premium costs—even if

[2] We set the mean of income from farm operations *y* to 3 in the case of constant relative risk aversion to ensure positive expected utility.

[3] Our simulation uses a scaling analogous to that used in area-yield or area-revenue insurance contracts, which happens to be the reverse of that used in preceding theoretical analysis. Following Clarke, our theoretical analysis specifies a lower support of the index equal to 0 whereas our simulations assume an upper support of the index equal to one. Our theoretical analysis assumes that a higher trigger level yields a lower probability of receiving an indemnity whereas our simulation assumes that higher trigger level yields a lower probability of receiving an indemnity.

[4] Carter et al. (2016) argue that the divergence between individual idiosyncratic yields and the index is greatest when yields are closest to the mean and smallest when yield losses are close to absolute. That argument implies a positive correlation between the two.

that choice involves greater (downside) basis risk. As a result, allowing farmers to select the level of the index that triggers an indemnity payment should increase uptake.

Put in terms of our numerical simulations, our theoretical analysis suggests that allowing a risk averse farmer to choose the level of the index that triggers an indemnity payment should result in a higher optimal choice of coverage, a lower probability that a loss is indemnified, a lower insurance premium, and, as a result, a higher probability of purchasing insurance. Downside basis risk should be higher as well.

Figs. 1 and 2 summarize the results of these numerical simulations graphically for constant absolute and relative risk aversion, respectively. Panels A–F of each figure show respectively how the trigger, coverage, premium, downside basis risk, probability of indemnification, and probability of insurance uptake each varies with the level of risk aversion, the correlation between the index and realized loss, and the insurance load factor. In all cases except insurance uptake, the shaded area around the smoothed line shows variations in outcomes due factors not held constant. In the case of risk aversion, for example, risk aversion is held constant at each level while the correlation between the index and realized loss, the load factor, and the standard deviations of crop yield and the index are all allowed to vary. The probability of insurance uptake is calculated as the share of simulation results with a positive insurance premium at each level of risk aversion or correlation between the index and realized loss or load factor.

Fig. 1.A and 2.A illustrate the effect of allowing farmers to choose the level of the index that triggers indemnification. In the absence of such a choice, the contract specifies indemnification when the index falls below 100% of the average. The optimal choice of a trigger is substantially lower than the average: In some cases, it is optimal to select a trigger corresponding to extreme shortfalls, as little as 40% of that average in the constant absolute risk aversion case and 20% in the constant relative risk aversion case. The shortfall decreases as risk aversion and the correlation between the index and realized loss each increase. It increases as the load factor increases: The trigger falls from 100% of the average value of the index when insurance is heavily subsidized (a load factor of 0.8) to roughly 20–40% of the average value of the index when the load factor reaches 1.8. This latter result suggests that the choice of a trigger is especially important for commercially provided insurance policies.

Fig. 1.B and 2.B illustrate the effects of trigger choice on the choice of coverage. Unless premiums are heavily subsidized (a load factor of 0.8), the optimal choice of coverage is always greater when farmers are allowed to choose the level of the index that triggers indemnification. The difference in coverage decreases as risk aversion increases. It increases as the loading factor increases: At a loading factor of 1.8, coverage with an endogenous trigger is roughly twice that with a trigger fixed at the index average in the constant absolute risk aversion case and five times that in the constant relative risk aversion case.

Fig 1.C and 2.C illustrate the effects of trigger choice on the insurance premium. Unless premiums are heavily subsidized, it is optimal to select trigger and coverage levels that lower premiums, albeit modestly. The reduction in premiums due to an endogenous trigger increases as risk aversion, the correlation between the index and realized loss, and the loading factor all increase. The differences in the premium are relative modest in the constant absolute risk aversion case and nearly non-existent in the constant relative risk aversion case, suggesting that the ability to control cost may be more important than whether significant cost savings are realized.

Fig 1.D and 2.D illustrate the effects of trigger choice on downside basis risk, that is, the probability that a loss is incurred without indemnification. Consistent with the predictions of the theoretical analysis, a choice of the trigger level makes it optimal to incur greater—not less—downside basis risk. The difference is substantial: The level of downside basis risk with an endogenous trigger can be three times or more that incurred when the trigger is fixed at 100% of the index average. The difference in downside basis risk between a fixed and endogenous trigger decreases as both risk aversion and the correlation between the index and realized loss increase. That difference is negligible when premiums are heavily subsidized but increases rapidly as the load factor increases, suggesting that farmers are willing to incur greater basis risk with commercial insurance products compared to subsidized programs.

Fig 1.E and 2.E illustrate the effects of trigger choice on the probability of indemnification. Consistent with the predictions of the theoretical analysis, allowing farmers to choose the level of the index that triggers indemnification leads them to tailor policies to cover catastrophic losses: The probability of indemnification is substantially lower with an endogenous trigger than with a trigger set at 100% of the index average. The difference between the indemnification probability with an endogenous versus a fixed trigger is decreasing in risk aversion and the correlation between the index and realized loss and but increasing in the load factor. At a loading factor of 1.8, for instance, the probability of indemnification with an endogenous trigger is only about a sixth to a quarter that with a trigger fixed at the index average.

Finally, Fig 1.F and 2.F illustrate the effects of trigger choice on insurance uptake. Consistent with the predictions of the theoretical analysis, the overall probability that a farmer purchases index insurance is substantially higher with an endogenous trigger that with a trigger fixed at 100% of the index average. The difference in insurance uptake decreases as risk aversion increases but remains roughly constant as the correlation between the index and realized loss increases. Also consistent with the theoretical analysis, there is no difference in the probability of insurance uptake when premiums are actuarially fair or heavily subsidized; but that difference increases markedly as the load factor rises, indicating that uptake is much more sensitive to an endogenous trigger choice for commercial insurance products. At a loading factor of 1.8, for instance, the probability of uptake is about 30 percentage points higher with an endogenous trigger than with a trigger fixed at the index average.

5.3. Uptake in a heterogeneous population

The preceding section considers how an endogenous trigger might affect uptake of insurance by an individual farmer. Earlier, we speculated that allowing farmers to choose the level of the index that triggers indemnities might be especially effective in increasing uptake in heterogeneous populations, in particular, populations that differ in terms of the accuracy of the index, as measured by the correlation between the index and realized losses. This section uses our numerical model to investigate that conjecture. We examine three different scenarios in which the correlation between the index and realized losses varies within a population. We construct the first scenario using data from the Spanish pasture insurance program ("Seguro de compensacion por perdida de pastos"), which offers a form of area-yield insurance. The correlation between average pasture biomass in a county, as measured by NDVI, and pasture biomass in an individual pixel within that county is extremely high: Almost 70% of pixels have a correlation with the county average of 0.8 for an overall average correlation of 0.72 (Table 2).[5] The second scenario exemplifies a polar opposite case in which the index performs quite poorly. We construct this scenario by inverting the Spanish pasture insurance program data, so that almost

[5] The distribution of correlations between the index and realized losses in the Spanish case is not unusual, at least for area-yield type insurance programs. For example, correlations between NDVI-estimated biomass at the state and county levels in Nigeria and Burkina Faso have distributions almost identical to that of the Spanish case.

70% of the population has a correlation of 0.3. The overall average correlation in this scenario is 0.38, squarely within the range estimated for pasturage insurance programs worldwide (Yu et al., 2019; Smith and Watts 2019; Keller and Saitone 2022). The third scenario is intermediate between these two extremes. For this scenario, we assume a uniform distribution between 0.3 and 0.8, for an overall average correlation of 0.55.

As we surmised, allowing farmers to choose the level of the index that triggers indemnities results in greater uptake in the overall population (Table 2). The increase in uptake is especially noteworthy under constant relative risk aversion, where uptake in the population with a fixed trigger is low, on the order of 45–60%.[6] Allowing an endogenous choice of trigger increases population uptake by 12–18 percentage points, a relative increase of roughly 30%. In this case, increases in uptake are of roughly the same magnitude in both absolute and percentage terms under all three scenarios. The increase in population uptake is smaller but still significant under constant absolute risk aversion, amounting to 5–13 percentage points or 5–19%. In this case, the increase in uptake is especially pronounced in the case where the index is poorly correlated with realized losses (the inverse Spanish pasture insurance case). Taken together, these results thus suggest that allowing farmers to tailor their choice of a trigger to their individual circumstances has the greatest potential to increase index insurance uptake in situations where the index performs relatively poorly.

5.4. Summary

Overall, our simulation results indicate that farmers are more likely to purchase insurance policies that offer more complete reimbursement when catastrophic losses occur.[7] Further, they are willing to accept greater basis risk as a result, indicating a willingness to trade off greater downside basis risk—and less frequent indemnification—for greater coverage at lower premiums. Like our theoretical analysis, our simulation results suggest that basis risk is not as much of an impediment to index insurance uptake as has been assumed to date. Instead, our results indicate that risk averse farmers are mainly interested in protection against catastrophic outcomes. Further, our results are consistent with Binswanger-Mkhize's (2012) argument that cost is a major obstacle to index insurance uptake, especially among poor farmers in developing countries. While our simulations do not include liquidity constraints or wealth effects, they do point to a fundamental problem with index insurance. Index insurance can magnify the disparities between good and bad states of nature since premiums are incurred in states of nature characterized by un-indemnified losses while indemnities are received in some states of nature where no losses occur. Allowing farmers to choose the level of the index that triggers indemnity payments reduces that disparity. Premiums are lower because indemnities are paid less often; income when losses are indemnified is higher because coverage is greater; and indemnities are received less often when no losses occur.

One especially noteworthy aspect of these simulation results is that the ability to choose the level of the index that triggers indemnification has the greatest impacts when insurance is provided at commercially viable rates, that is, for policies with load factors greater than one. The ability to choose a trigger in addition to a coverage level gives farmers a way to customize the tradeoff between indemnification and premiums to suit their individual circumstances to a degree that choosing coverage alone cannot accomplish. Our simulation results suggest that the ability to make that tradeoff is of greater importance when premiums reflect the full cost of servicing insurance policies, that is, when insurance is provided at commercially viable rates. When insurance is heavily subsidized or even provided at actuarially fair premiums, our simulation results indicate no difference in uptake between fixed and endogenous triggers: In our simulations, it is always optimal to purchase insurance when loading factors are actuarially fair or subsidized. Uptake with a trigger fixed at the index average drops rapidly as the loading factor increases above 1.0 while uptake with an endogenous trigger drops much more slowly. These results thus suggest a new, hitherto unexplored reason for low uptake of commercially provided index insurance policies that looked very promising in pilot studies: As the cost of insurance rises, uptake becomes sensitive to cost; an endogenous trigger offers the ability to control cost by tailoring policies toward greater coverage in more catastrophic states of nature.

6. Conclusion

Index insurance has been seen as an important tool for managing the risks faced by farmers in developing countries, but uptake of index insurance has been disappointingly low. One of the most commonly cited impediments to index insurance uptake is basis risk, especially on the downside (i.e., the probability that farmers will suffer losses for which they will not be indemnified). It has been argued that such downside basis risk may pose an insurmountable obstacle to designing index insurance programs that risk averse farmers will want to buy because it increases the disparity between good and bad states of nature (see for example Miranda and Farrin 2012; Clarke 2016; Carter et al., 2017; Jensen and Barrett 2017).

Previous analyses of the effects of basis risk have considered only its impact when farmers can only choose coverage levels. This paper considers the effect of allowing farmers to choose the level of the index that triggers an indemnity in addition to coverage. We show theoretically that risk averse farmers prefer index insurance oriented toward catastrophic risk as a means of lowering premiums, even at the cost of increasing downside basis risk. A numerical simulation model illustrates the effects of choosing a trigger index level on the probability of purchasing insurance, coverage, premiums, downside basis risk, the probability of indemnification for loss, and indemnity payments. Our findings suggest that allowing farmers to choose a level of the index that triggers indemnity payments as well as the level of coverage could help increase uptake by making index insurance more affordable. Utility maximizing choices of the index level that triggers indemnity payments result in insurance policies that provide greater coverage but only in situations where shortfalls in income are more catastrophic. Premiums are lower because indemnities are paid less often, even though those indemnities are larger when they are paid out. A consequence of that shift toward more catastrophic risk is that basis risk increases.

Overall, our findings lend support to Binswanger-Mkhize's (2012) argument that cost is a more important impediment to crop insurance uptake than basis risk. Our findings also offer an alternative explanation of Karlan et al.'s (2014) finding that Ghanaian farmers prefer insurance to other financial instruments, in that farmers may be more interested in protection against exceptionally bad harvests than in financial stability more generally.

Our arguments speak to the financial rather than the behavioral impacts of basis risk: We consider the optimal choices of a utility-

[6] Our estimates of uptake are higher than we would expect to observe in practice due to the fact that we average across load factors as well as risk preferences and yield variability levels. As Fig. 1.F and 2.F indicate, uptake is lower when insurance is provided at commercially viable rates.

[7] Chantarat et al. (2013) similarly find that index insurance for pastoralists in northern Kenya performs best when triggered by catastrophic losses. In their analysis, though, choosing a trigger level for payouts corresponding to catastrophic losses also reduces basis risk.

maximizing risk averse agent who faces no liquidity constraints and we do not consider wealth. Basis risk can also have behavioral effects, however. It has been observed in India that insurance uptake increases in years immediately following those in which insurance payouts are received in a community and fall in years immediately following those in which no insurance payouts were received, suggesting highly myopic evaluations of the benefits and costs of purchasing insurance (Clarke et al., 2012; Cole et al., 2014; Tobacman et al., 2017; Cai et al., 2020). Insurance policies oriented toward more catastrophic coverage feature less frequent payouts and are thus likely to magnify any such behavioral effects. Empirical testing in the field should help distinguish the relative strengths of these financial and behavioral effects. The recent introduction of choices in trigger level by ACRE in East Africa would seem to provide a good context for such empirical testing.

Author statement

Erik Lichtenberg: Conceptualization, methodology, formal analysis, programming, visualization, writing—original draft formulation, review & editing. Eva Iglesias Martinez: Conceptualization, methodology, formal analysis, programming, visualization, writing—original draft formulation, review & editing.

Declaration of competing interest

None.

Data availability

No data was used for the research described in the article.

Appendix A. Proofs of Propositions 1-4

Proposition 1. If absolute risk aversion is non-increasing, a necessary condition for a non-minimal choice of a trigger level to be optimal is $\frac{r'}{p-r} < -\frac{q'}{q}$.

Proof. Rearranging equation (5), we have

$$\left[\lambda + \frac{p-r}{q}\right]\left[V'_{LI} - V'_{OI}\right] = \frac{\alpha L \gamma_{OI}}{2} V'_{OI} + \frac{\alpha\lambda L}{2}\left[\gamma_{OI} V'_{OI} - \gamma_{LI} V'_{LI}\right] > 0$$

The second term on the right hand side of the equality is positive because $\gamma_{OI} \le \gamma_{LI}$ under non-increasing absolute risk aversion, because $V'_{OI} < V'_{LI}$ due to diminishing marginal utility of income, and because $\lambda < 0$. Thus, equation (5) implies that $\lambda + \frac{p-r}{q} > 0$ is necessary for a non-minimal choice of the trigger level k. Rearranging using the definition of λ gives the result.

Proposition 2. When absolute risk aversion is non-increasing, a non-minimal choice of a trigger level $k > 0$ increases the probability that positive coverage $\alpha^* > 0$ will be optimal.

Proof. Clarke's Theorem 3 shows that a necessary condition for the optimal choice of coverage to be positive is $r < p(1-qm)$ or $\frac{p-r}{pqm} > 1$. The derivative of the ratio on the left hand side of the inequality can be expressed as $-\frac{q'}{pqm}\left[\frac{r'}{q'} + \frac{p-r}{q}\right] = -\frac{q'}{pqm}\left[\lambda + \frac{p-r}{q}\right]$, which is positive when a non-minimal choice of a trigger level is optimal under the conditions of Proposition 1. A choice of the trigger level k greater than the minimum (implicitly assumed by Clarke) thus makes it more likely that the inequality $\frac{p-r}{pqm} > 1$ holds and thus that a positive level of coverage ($\alpha^* > 0$) will be optimal.

Proposition 3. If a non-minimal choice of a trigger level k is optimal, then a positive level of coverage is also optimal ($\alpha^* > 0$).

Proof. Suppose that condition (4) holds with equality, so that an interior solution for the trigger level k is optimal:

$$\alpha m L\left[(p-r)V'_{LI} + (q+r-p)V'_{0I} + (1-q-r)V'_{00} + rV'_{L0}\right] = (1+\lambda)[V_{0I} - V_{00}] - \lambda[V_{LI} - V_{L0}]$$

The right hand side of the equality is positive since $\lambda < 0$, $1+\lambda > 0$ by construction and $V_{0I} - V_{00}$, $V_{LI} - V_{L0} > 0$ by diminishing marginal utility. The term in square brackets on the left hand side of the equation is also positive. Since m and L are both positive, a necessary condition for the equality to hold is $\alpha^* > 0$.

Proposition 4. It will never be optimal to purchase index insurance under any contract for which $p\text{-}r(k)\text{-}pmq(k) \le 0$ and $1+\lambda(k) < 1\text{-}pm$ for all feasible choices of a trigger level.

Proof. An alternative formulation for the necessary condition for the optimal choice of coverage to be positive from Clarke's Theorem 3 is $p–r–pqm > 0$. If $p\text{-}r(0)\text{-}pmq(k) \le 0$, then the optimal choice of coverage is zero. The left hand side of the inequality is decreasing in k if $-r' - pmq' < 0$ or, rearranging, $\left[\frac{r'}{q'} + pm\right](-q') < 0$, which holds for all feasible k when $1+\lambda(k) < 1\text{-}pm$.

Appendix B. Generalization to Continuous States of Nature

More generally, consider the effect of trigger level choice on the decision to purchase index insurance when losses (and the index) are continuous rather than discrete. As in the discrete case, we build on Clarke's analysis. In the continuous case Clarke analysis, losses *l* and the index *i* are both continuous and random with a joint distribution *f(i,l)* and respective supports *[0,L]* and *[0,I]*. In contrast with the preceding section, a higher value of the index represents worse growing conditions. We consider insurance contracts that pay indemnities when the index rises above a trigger level *k* and pay indemnities equal to *i-k*, the difference between the observed level of the index and the trigger level. (The analysis is almost identical if the insurance contract pays an indemnity equal to the index only when the index exceeds a trigger level, as in Clarke.) Following Clarke, let

$$\mu_i = E[\tilde{i} - k] = \int_k^I \int_0^L (i-k)\cdot f(i,l)didl$$

denote the unconditional expected indemnity and

$$\mu_i(l) = E[\tilde{i} - k | \tilde{l} = l] = \int_k^I (i-k)\cdot f(i,l)di$$

denote the expected claim conditional on a loss of size *l*. As in the previous sections, a higher value of *k* represents a decrease in the probability of receiving an indemnity (in the terminology of the preceding section, a lower value of *q*).

Expected utility in the continuous case is

$$EV = \int_0^L \left[\int_k^I f(i,l)u\left(w - l + \alpha\left(i - k - m\mu_i(k)\right)\right)di + \int_0^k f(i,l)u(w - l - \alpha m\mu_i(k)\,)di \right] dl$$

The first order condition characterizing a positive coverage level $\alpha > 0$ is

$$\int_0^L \int_k^I f(i,l)u^{'}\left(w - l + \alpha\left(i - k - m\mu_i(k)\right)\right)\cdot\left(1 - k\right)didl - \int_0^L \int_0^I f(i,l)u^{'}\left(w - l + \alpha\left(i - k - m\mu_i(k)\right)\right)\cdot m\mu_i(k)didl = 0$$

The optimal level of coverage is chosen to equate expected utility in states of nature where indemnities are paid with the loss in expected utility from paying the premium in all states of nature.

The first order condition characterizing a non-miminal trigger value k is

$$\int_0^L \int_k^I f(i,l)u^{'}\left(w - l + \alpha\left(i - k - m\mu_i(k)\right)\right)\cdot\alpha\left(1 - m\frac{\partial\mu_i(k)}{\partial k}\right)didl + \int_0^L \int_0^k f(i,l)u^{'}\left(w - l + \alpha\left(-k - m\mu_i(k)\right)\right)\cdot\alpha m\frac{\partial\mu_i(k)}{\partial k}didl = 0$$

or

$$\int_0^L \int_k^I f(i,l)u^{'}\left(w - l + \alpha\left(i - k - m\mu_i(k)\right)\right)\cdot\alpha\left(1 - m\right)didl = \int_0^L \int_0^k f(i,l)u^{'}\left(w - l + \alpha\left(i - k - m\mu_i(k)\right)\right)\cdot\alpha mdidl$$

The second equality follows from the fact that $\frac{\partial\mu_i(k=0)}{\partial k} = \int_0^L \int_0^I -f(i,l)didl = -1$. The optimal choice of a trigger level of the index equalizes expected marginal utility in states of nature where indemnities are paid with expected marginal utility in states of nature where indemnities are not paid.

Generalizing Proposition 3 to the case where losses and the index follow a continuous joint distribution is straightforward.

Proposition B1. If a positive level of coverage is optimal ($\alpha^* > 0$), then a non-minimal interior choice of a trigger level k is also optimal whenever insurance is provided at commercial rates ($m > 1$).

Proof The derivative of expected utility with respect to the trigger value k evaluated at $k = 0$ is

$$\frac{\partial EV}{\partial k} = \int_0^L \left[\int_0^I f(i,l)u^{'}(w - l + \alpha(i - k - m\mu_i(k))\,)(-\alpha)(1 - m)di \right] dl$$

It is positive for all $m > 1$, indicating that expected utility is increasing at $k = 0$ and thus that $k^* > 0$ is optimal whenever $\alpha^* > 0$ is optimal.

It is also readily apparent from the proof that:

Corollary. If insurance premiums are subsidized or actuarially fair, then the optimal trigger level is zero.

Intuitively, actuarially fair or subsidized premiums mean that agents will want to be as fully insured as possible. Setting the trigger level at its minimum possible value achieves that end.

It is also straightforward to generalize Proposition 4 to the case of continuously jointly distributed loss and the index. Clarke shows that a risk averse farmer will not purchase insurance (the optimal level of coverage will be α = 0) in the continuous case if

$$\Psi \equiv \int_0^L u'(w-l)\left[\int_k^I f(i,l)(i-k-m\mu_i)di - \int_0^k f(i,l)m\mu_i di\right]dl \le 0$$

Now consider the effect of choosing a trigger index level k on the likelihood that the optimal level of coverage is zero. Differentiating and simplifying, we find:

$$\frac{d\Psi}{dk} = u'(w-l)\int_0^L\int_k^I f(i,l)(m-1)didl$$

which is positive for all $m > 1$. Concavity implies that $\partial EV/\partial\alpha$ is (weakly) decreasing in α, which implies that raising the trigger index level k makes it more likely that a risk averse farmer will choose to purchase insurance (i.e., makes it more likely that the level of coverage will be positive, α > 0) when premiums are commercially priced. Summing up, we have:

Proposition B2. Allowing farmers to choose both coverage and the level of the index that triggers indemnities makes uptake of index insurance more likely when premiums are commercially priced.

The intuition underlying this result remains as in the discrete case: risk averse agents are willing to accept a greater chance of not being indemnified in the case of loss in return for lower premiums in all states of nature. A higher trigger level is attractive (up to a point) because it reduces the disparity between good and bad states of nature. In practical terms, risk averse farmers are more likely to purchase index insurance that pays indemnities in fewer states of nature, i.e., index insurance geared toward protection against catastrophic losses rather than a broader range of risks. When premiums are actuarially fair or subsidized, however, risk averse farmers will want to fully insure whenever they purchase insurance, so that trading off higher basis risk for lower premiums is not an option.

Table 1
States of Nature and Their Associated Probabilities

	Index = 0	Index = I	Row Total
Loss = 0	1-q-r	q+r-p	1-p
Loss = L	r	p-r	p
Column Total	1-q	q	1

Table 2
Impact of Endogenous Trigger Choice on Insurance Uptake in Heterogeneous Populations

Correlation between index and yield	Spanish satellite data	Uniform	Inverse Spanish satellite data
0.3	0.08	0.17	0.68
0.4	0.02	0.17	0.13
0.5	0.02	0.17	0.07
0.6	0.07	0.17	0.02
0.7	0.13	0.17	0.02
0.8	0.68	0.17	0.08
Average	0.72	0.55	0.38
Population-Level Uptake under Constant Absolute Risk Aversion			
Endogenous Trigger	0.97	0.91	0.86
Fixed Trigger	0.89	0.86	0.73
Population-Level Uptake under Constant Relative Risk Aversion			
Endogenous Trigger	0.80	0.70	0.57
Fixed Trigger	0.62	0.53	0.45

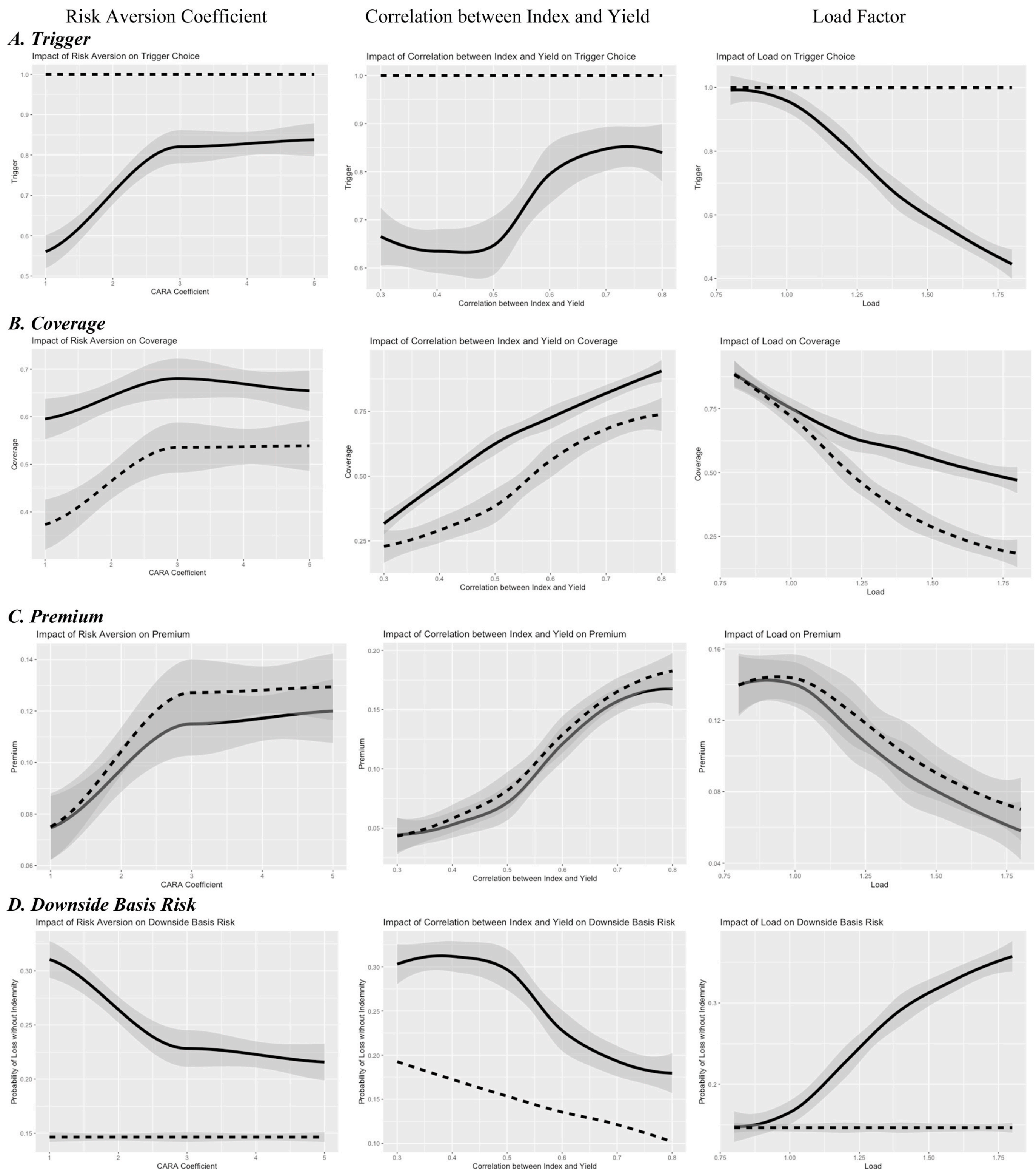

Fig. 1. Impact of Endogenous Trigger on Insurance Contract Choices, Constant Absolute Risk AversionContract choice outcomes with endogenous (fixed) trigger indicated by solid (dashed) lines. Shaded areas indicate variations in outcomes due to variations in standard deviations of loss and index, risk aversion, load factor, and correlation between index and loss.
Source: Authors' calculation

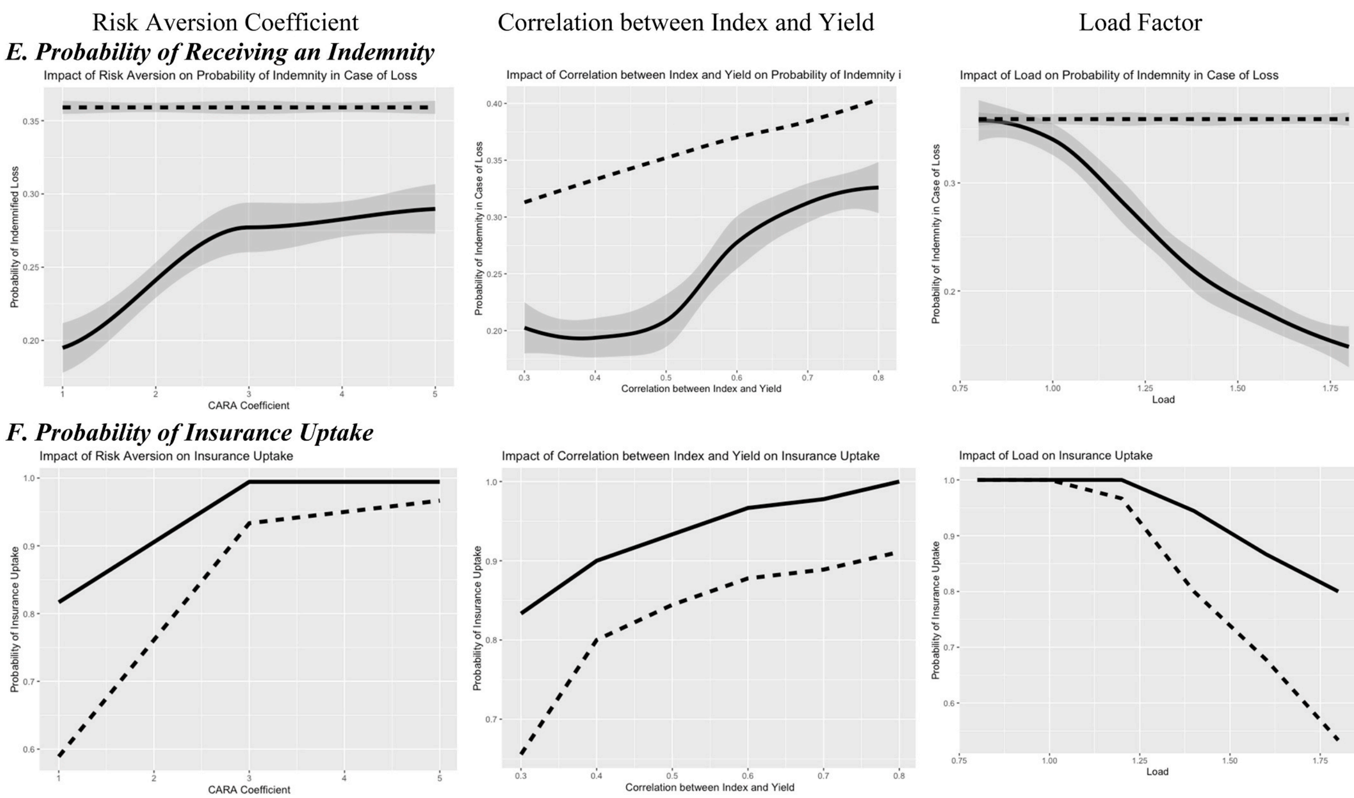

Fig. 1. (*continued*).

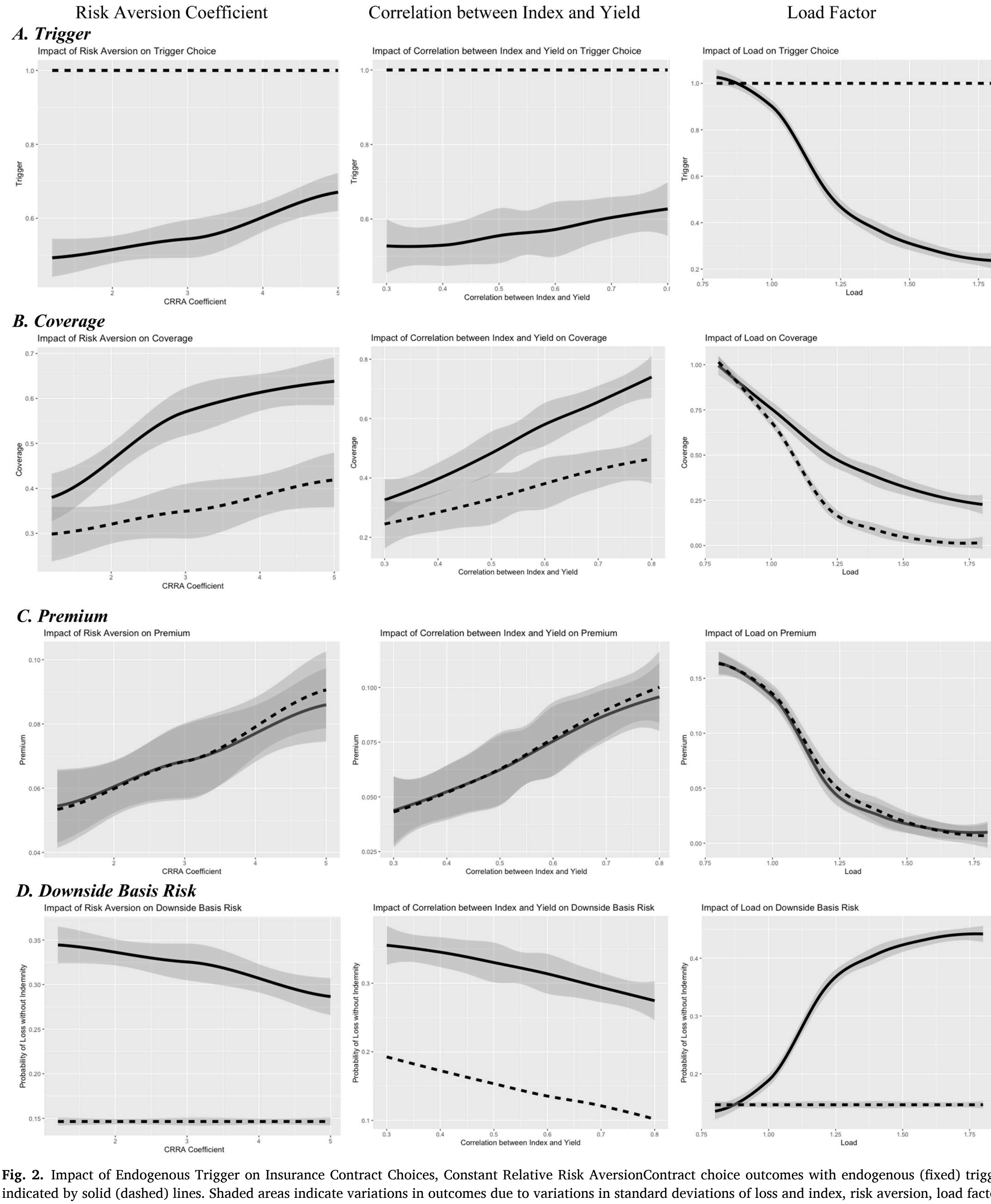

Fig. 2. Impact of Endogenous Trigger on Insurance Contract Choices, Constant Relative Risk AversionContract choice outcomes with endogenous (fixed) trigger indicated by solid (dashed) lines. Shaded areas indicate variations in outcomes due to variations in standard deviations of loss and index, risk aversion, load factor, and correlation between index and loss.
Source: Authors' calculations

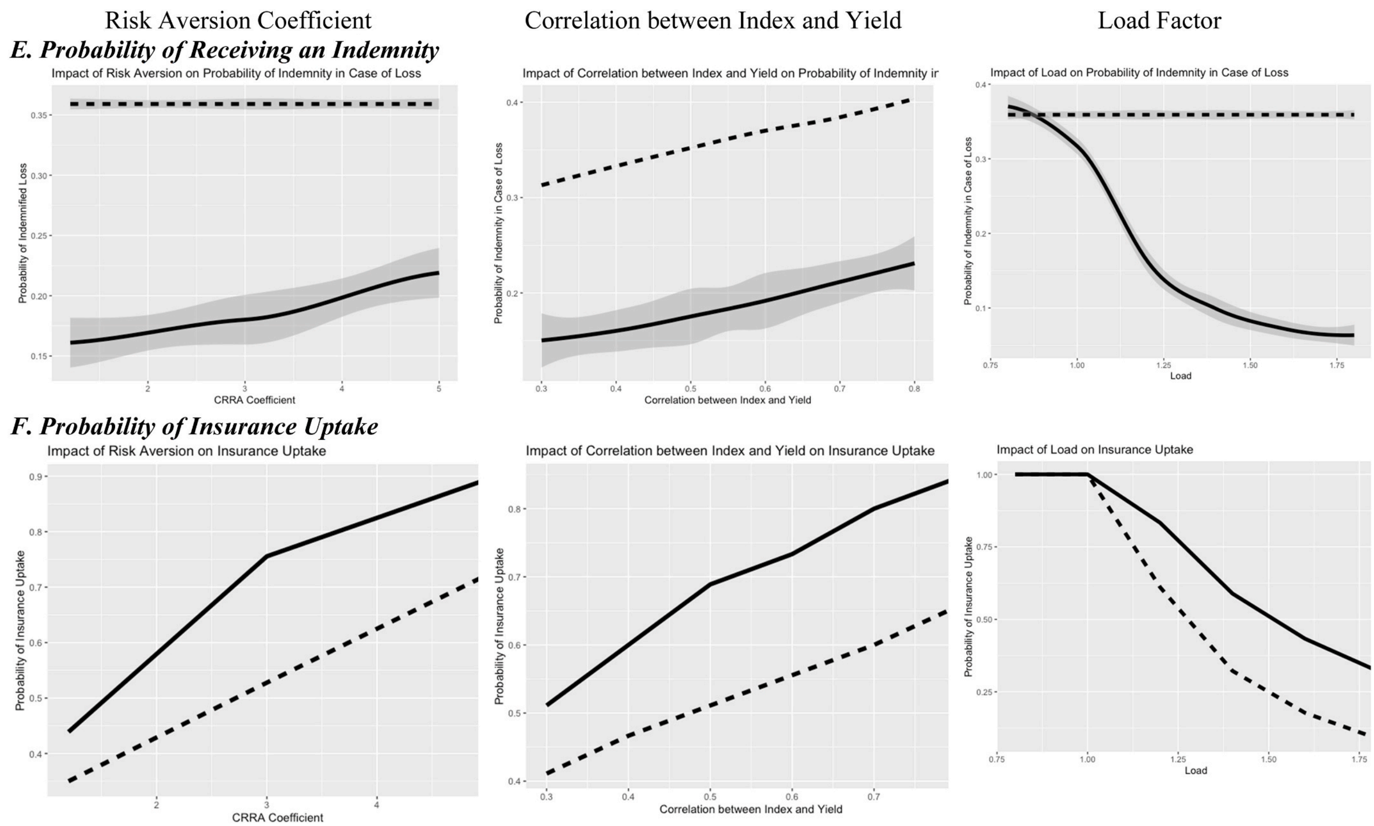

Fig. 2. (*continued*).

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