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Designing Catastrophe Bonds to Securitize Systemic Risks in Agriculture: The Case of Georgia Cotton

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This article makes an initial attempt to design catastrophe (CAT) bond products for agriculture and examines the potential of these instruments as mechanisms for transferring agricultural risks from insurance companies to investors/speculators in the global capital market. The case of Georgia cotton is considered as a specific example. The CAT bond contracts are based on percentage deviations of realized state average yields relative to the long-run average. The contracts are priced using historical state-level cotton yield data. The principal finding of the study is that the proposed CAT bonds demonstrate potential as risk transfer mechanisms for crop insurance companies.

Key words: CAT bonds, catastrophe bond pricing, catastrophe insurance, disaster risk, reinsurance, risk securitization

Introduction

Agricultural production is susceptible to the influence of various hazards. Farmers' unique and substantial exposure to natural disasters caused by factors such as adverse weather and disease has led to the development of various agricultural insurance products (Kramer, 1983). For crop production in the United States, insurance policies are available primarily through the federal crop insurance program. These policies cover most causes of crop loss and are sold by private insurance companies. The federal government provides premium subsidies for farmers as well as administrative and operating (A&O) cost reimbursement and subsidized reinsurance for insurance companies participating in delivery of crop insurance policies (Glauber and Collins, 2002; Glauber, 2004). Federal reinsurance, which is of main interest in the context of this article, is provided through the Standard Reinsurance Agreement (SRA) between the Federal Crop Insurance Corporation and participating companies (Glauber, 2004; Vedenov et al., 2004). The current study analyzes the potential of catastrophe (CAT) bonds as an alternative reinsurance tool for private insurance companies underwriting crop insurance.

The original motivation for federal reinsurance of crop insurance policies was the perceived inability of private insurance markets to absorb broad risk exposures over

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large geographic areas (Kramer, 1983; Glauber and Collins, 2002). This is due to the systemic (spatially correlated) nature of risks inherent in agricultural production, and thus the potential for losses of catastrophic magnitude (Miranda and Glauber, 1997). However, the establishment of the public-private crop insurance delivery system in 1980 led to additional subsidies being built into federal reinsurance provisions in order to provide incentives for private insurance companies to participate in the program (Glauber, 2004; Barnett, 2003). The SRA allows insurance companies to allocate their insurance portfolios among reinsurance funds with different levels of risk reduction. The funds are structured so that the companies both reduce risk exposure and increase expected return.[1] Such a system obviously differs from traditional market-based reinsurance contracts which typically provide risk reduction in exchange for a decrease in expected net return. The presence of heavily subsidized federal reinsurance greatly reduces market incentives for private reinsurance of crop insurance.

In recent years, a series of innovative financial instruments such as catastrophe options and catastrophe bonds (CAT bonds) have been introduced to hedge against catastrophe risks such as widespread losses due to hurricanes and/or earthquakes in heavily populated areas (Bantwal and Kunreuther, 2000; George, 1999; Froot, 1999; Hommel, 2000). Unlike traditional insurance contracts, these instruments transfer risks rather than pool them. This feature makes them attractive to insurance companies faced with a high systemic component of insurance portfolio risk that cannot be diversified away.

In particular, CAT bonds provide a mechanism that insurance or reinsurance companies can use to transfer nondiversifiable risks (e.g., due to natural disasters) to capital markets (Lewis and Davis, 1998; Jaffee and Russell, 1997). CAT bonds are usually sold to both private and public investors who are interested in adding to their portfolios instruments with returns that are uncorrelated with traditional financial instruments such as stocks and bonds. CAT bonds are similar in design to conventional bonds in that they are a loan given to the issuing firm by investors who, in return, expect payment of interest and repayment of principal at the end of an agreed period (Cummins, Lalonde, and Phillips, 2000). CAT bond investors, however, agree to forfeit the interest and/or principal under certain well-defined conditions such as an occurrence of a catastrophic event. The issuer may then utilize the proceeds from selling the bonds to offset losses caused by the event.

CAT bonds have been issued by insurance and reinsurance companies since 1996. In recent years, the uses of CAT bonds have begun to extend beyond protection against natural perils, encompassing, thus far, risk coverage against power failures, cancellation of sporting events, epidemics, and acts of terrorism (Bowers, 2004; Lee, 2004). Despite growing interest in CAT bonds in other areas of insurance, they have never been used to hedge disaster risks in agriculture. Nonetheless, based on their use in other sectors of the economy, it seems logical that CAT bonds could play a similar role in agriculture. The ability of CAT bonds to transfer the systemic component of risk to capital markets may provide the reinsurance capacity to absorb widespread losses from crop insurance, the very lack of which was the original motivation for federal provision of reinsurance.

[1] Analysis of the Standard Reinsurance Agreement and its effect on crop insurance is beyond the scope of this paper. Interested readers may refer to Glauber and Collins (2002); Glauber (2004); Mason, Hayes, and Lence (2003); and Vedenov et al. (2004) for additional information on the topic.

Private crop insurance companies could potentially use CAT bonds to shift at least part of their catastrophic agricultural risk exposure to capital markets. If so, policy makers could reconsider the motivation, nature, and extent of federal reinsurance, and thus perhaps reduce taxpayer exposure to reinsurance losses on crop insurance policies.

To the best of our knowledge, this paper represents a first attempt to design CAT bonds for transferring the systemic risk present in agricultural crop production. The results obtained for the case study of Georgia cotton demonstrate the potential for CAT bonds as a reinsurance mechanism for crop insurance companies.

The specific objectives of this study are (*a*) to introduce the concept of CAT bonds with a particular focus on hedging systemic risks in crop production, (*b*) to describe CAT bond designs and pricing mechanisms that could be used in agriculture, and (*c*) to examine the potential efficiency of CAT bonds as reinsurance vehicles for insurance companies underwriting crop insurance using the case of Georgia cotton as an empirical example.

The remainder of the paper is organized as follows. The next section provides further background information on CAT bonds. This is followed by a section that: (*a*) discusses the basic structure of a CAT bond contract, (*b*) describes the particular characteristics of the specific CAT bonds considered in this research, (*c*) presents a pricing methodology, and (*d*) describes procedures for analyzing the effectiveness of CAT bonds as hedging instruments. The results of the empirical analysis are then presented. The final section offers concluding comments and discussion of the potential role of CAT bonds as reinsurance mechanisms for crop insurance.

CAT Bonds

CAT bonds belong to a family of index-based instruments because the occurrence of the catastrophic event is usually determined based on realizations of a prespecified stochastic variable or *index*.[2] More specifically, a CAT bond purchaser typically agrees to forfeit a portion or all of the expected financial payments from the bond in the event the index exceeds a prespecified threshold.

CAT bonds were introduced in the mid-1990s in the wake of enormous losses caused by hurricane Andrew in 1992 and the Northridge earthquake in 1994 (Lewis and Davis, 1998). One of the largest ($477 million) issues was placed by United Service Automobile Association (USAA) in 1997 (Lewis and Davis, 1998; Froot, 1999). The issue was oversubscribed and generated considerable trading in secondary markets. Overall, five CAT bond issues were placed in 1997, involving $633 million in risk capital to hedge potential losses from natural perils such as hurricanes and earthquakes. The bonds were sold offshore to select groups of investors at premiums in some cases surpassing a 5% spread over LIBOR[3] (Banks, 2004; Bantwal and Kunreuther, 2000; Bossom et al., 2004). The relatively high spreads over LIBOR encompassed both the risk premium on

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[2] Other agricultural applications of index-based instruments include area yield insurance (Skees, Black, and Barnett, 1997; Baquet and Skees, 1994) and weather derivatives (Turvey, 2001; Martin, Barnett, and Coble, 2001; Vedenov and Barnett, 2004; Skees et al., 2001). At a sufficient level of abstraction, all of these instruments can be treated as contingent claims that trigger based on realizations of the underlying stochastic index.

[3] LIBOR stands for "London interbank offer rate" and represents a rate at which large banks are willing to accept deposits for a specified period of time. This rate is widely used to approximate a risk-free rate and is considered by financial institutions as the opportunity cost of capital (Hull, 2004, pp. 93–94). A rate of return on any financial instrument can be then thought of as a certain premium or spread over LIBOR.

comparably rated corporate bonds and a novelty premium. The latter reportedly compensates for ambiguity about the probability of catastrophic events that rarely occur in a given location, loss aversion which leads to subjective overvaluing of loss probabilities, and the cost of the learning curve for a complex new market (Banks, 2004; Bantwal and Kunreuther, 2000; Daneshvaran and Morden, 2004; Nell and Richter, 2004). Aside from higher rates of return, CAT bonds are attractive to investors because returns on the bonds are not correlated with that of the market portfolio (Banks, 2004).

Although still rather small compared to the corporate bond market, the CAT bond market has continued to grow since its inception. Nine issues involving \$1.22 billion in risk capital were placed in 2002, and 15 issues involving \$1.73 billion were placed in 2003 (Bossom et al., 2004; Bowers, 2004). While CAT bonds are not intended to replace reinsurance completely, they have been providing reinsurance capacity for a layer of low-probability/high-loss risk exposure. The amount of capital involved in these transactions indicates the presence of demand for these types of securities.[4] Admittedly, the rates of return required by investors in CAT bonds still remain relatively high compared to conventional reinsurance. However, the risk capital under management via CAT bonds is expected to continue trending upward as the cost of issuing CAT bonds declines with the establishment of more standardized bond structures and as the investor base expands and becomes more knowledgeable (Bowers, 2004). While not currently used in agriculture, CAT bonds could similarly provide alternative (or additional) means of reinsuring catastrophic layers of crop insurance loss risks.

Empirical Approach

Basic Structure of a CAT Bond Contract

Before discussing applications of CAT bonds to agriculture, it is instructive to consider the basic structure and terminology of a CAT bond contract. CAT bonds are typically issued by insurance companies for a predetermined period of time, e.g., one year, with a specific face value. As with traditional bonds, the company essentially borrows a certain amount (principal or face value) from investors and repays the principal plus a specified amount of interest at maturity. Unlike traditional bonds, however, the issuing company reserves the right to forfeit payment of interest and part or all of the principal if a specified triggering event occurs. The latter can be defined in a variety of ways, but usually reflects a situation in which the company experiences catastrophic losses. For example, the triggering event may be a category three or higher hurricane in a given geographic area during the bond lifetime, or a case of total insured losses of the issuing company exceeding a certain threshold.

Alternatively, the CAT bond can be structured as a zero-coupon bond that is initially sold at a discount. An investor's return is then the difference between the purchase price and the face value. The issuing company again reserves the right to forfeit payment of part or all of the face value if a predetermined triggering event occurs. The analysis presented in this paper considers such zero-coupon CAT bonds.

[4] Note that the presence of well-developed secondary markets for CAT bonds, while beneficial for price discovery, is not required in order to use CAT bonds' risk-reducing capability. As long as the issuing entity can place the issue on the primary market, it receives immediate access to the pool of contingent capital it seeks.

More formally, assume a zero-coupon CAT bond is issued at time 0 with the face value F and time to maturity T. The payoff V_T of the bond at maturity is conditional on realization of a certain index L relative to the predetermined trigger value D so that:

$$(1) \qquad V_T = \begin{cases} A \times F & \text{if } L > D \text{ (bond is triggered),} \\ F & \text{if } L \leq D \text{ (otherwise),} \end{cases}$$

where $0 \leq A < 1$ is the proportion of the face value repaid to investors. In other words, part or all of the proceeds from selling the bond are retained by the issuing company when the index L exceeds the specified trigger D; otherwise, the bond pays its face value, which includes the initial amount borrowed and a return on the investment.

For example, suppose an insurance company ABC issued a CAT bond with the face value of F = \$1,000 and maturity T of one year, and sold it at discount for \$920. The payoff of the CAT bond is conditional on total insured losses of the company (L) over one year not exceeding a preset limit of D = \$5 million.

If the total insured losses of ABC over one year were only L = \$3 million, i.e., below the trigger level of \$5 million ($L < D$), then an investor who purchased the bond for \$920 would receive the face value of \$1,000 one year later ($V_T = F$ = \$1,000), and thus realize a return of (\$1,000 - \$920)/\$920 = 8.7%. The latter can also be interpreted as a 5.5% spread over a one-year LIBOR rate of 3.2%.[5] However, if the total insured losses of ABC over the one-year period were \$6 million ($L > D$), the company would only repay a preset proportion A of the bond's face value. For example, if $A = 0.5$, the investors would receive only 50% of the face value of each CAT bond at maturity (i.e., $V_T = A \times F$ = \$500), while the company would keep the remaining \$420 from the initial proceeds and use it to offset losses.[6] Similarly, if $A = 0.25$, the investors would receive \$250 and the company would keep the remaining \$670. In the extreme case of $A = 0$, the company would keep all the proceeds from selling the bond and the investors would receive nothing at maturity.

Note that the CAT bond structure described above can offer flexible bond designs with differing triggers, rates of return, and proportions of face value repaid in case of a catastrophic event. However, all of these parameters need to be fixed in order to specify a particular bond contract.

The Proposed CAT Bond Contracts

In the absence of a traded underlying asset, insurance-linked securities have been structured to pay conditional on three types of variables—insurance industry catastrophe loss indices, insurer-specific catastrophe losses, and parametric indices based on the physical characteristics of catastrophic events. For example, Property Claim Services (PCS), an insurance industry statistical agency, defines catastrophes as losses from catastrophic perils that cause insured property damage of \$5 million or more (Cummins, Lewis, and Phillips, 1998). In agriculture, however, farmers deal with natural perils on an annual basis, and crop insurance is provided based on cropping season cycles. Therefore, it is

[5] This is the LIBOR rate as of January 1, 2005.

[6] Note that the issuing company may invest the initial proceeds from selling the bond in risk-free securities, e.g., Treasury bills, and accumulate additional interest over the life of the CAT bond.

hard to define agricultural catastrophes in terms of insured losses based on the PCS definition.

A different way of defining catastrophes in agriculture is presented in this study. For a given crop, it is assumed the state average yield loss (i.e., the percentage deviation of realized state average yield from its long-term average) for each year adequately represents insured losses suffered by insurance companies writing crop insurance policies in the state. Note that the choice of a triggering variable involves a tradeoff between moral hazard and basis risk (Doherty, 1997). In order to eliminate or minimize the prospects for moral hazard, a trigger related to state-level yield loss is appropriate because yield loss values depend only upon realized state average yield. Thus, there is no incentive for insurers to over-report losses in an attempt to increase recoveries. In addition, realized yield incorporates a cumulative representation of losses due to catastrophes, no matter what kinds of catastrophic events or how many of them occur during the growing season. In this regard, different yield loss thresholds could be used to define different levels of catastrophes and thus alternative triggers for CAT bonds.

The hypothetical CAT bond analyzed in this study is crop- and location-specific, with cotton as a representative crop and Georgia as the location. A specific location is necessary because different areas have different exposures to risk factors affecting crop production. Cotton was chosen for the analysis because of its importance in Georgia and its high ranking in liability among all crops insured through crop insurance programs administered by the Federal Crop Insurance Corporation (FCIC). It is assumed that a hypothetical crop insurance company ABC is the issuer of the CAT bond.

The purpose of the CAT bond is to provide protection from catastrophic losses in a given year. The proposed instruments are zero-coupon CAT bonds sold at discount. The selling price of the bonds determines the rate of return, which can be interpreted as a certain percentage spread over the LIBOR. Design aspects of the agricultural CAT bond contract in this study include the following:

- The CAT bond contracts are sold annually with a maturity of one year, and provide disaster coverage for insured losses on cotton suffered by insurance company ABC over the course of a year due to all causes.

- The payoff structure of the CAT bonds is given by equation (1). The index determining the payoff of the bond is the realized yield loss measured as a percentage deviation of realized state average yield y from the long-term average state yield $\bar{y}$:

  $$L = \frac{\max\{0, \bar{y} - y\}}{\bar{y}}.$$

  The trigger levels D are set as specified percentages of yield losses.

- The payout schedule of the CAT bond contract as a function of the percentage loss of state average yield is fixed when the contract is issued. In particular, the CAT bond contract stipulates the face value F of the bond as well as its proportion A repaid to the investor in case of default. Without loss of generality, the face value of all CAT bond contracts in this study is set to one dollar.

- Expected yield losses are derived from a probability distribution of state yields, which in turn is estimated from historical data on state average yields.

By design, if the realized state average yield does not deviate from the long-term average by more than the preset trigger percentage, the CAT bonds repay the face value at maturity. Otherwise, the CAT bonds default, paying either nothing or only a part of the face value to the investor depending on the design. For example, if the long-term average state yield is 500 lbs./acre and the trigger is set at 40%, then realized state average yields below 300 lbs./acre would trigger the CAT bonds, while realized state average yields above 300 lbs./acre would not affect the bond payoff.

Pricing Methodology of CAT Bonds

In this analysis, CAT bond prices are based on the discounted expected payoff of the bond over possible states of nature. Such an approach assumes that the triggering index underlying CAT bond contracts is characterized by a stationary distribution. Given the nature of the index used in our analysis, this appears to be an appropriate assumption as stationarity of aggregate yields around a deterministic trend is commonly accepted and documented in the agricultural economics literature (Goodwin and Ker, 1998; Ker and Goodwin, 2000; Ker and Coble, 2003; Mason, Hayes, and Lence, 2003; Schintkey, Sherrick, and Irwin, 2003; Sherrick et al., 2004).

Alternative valuation approaches are based on an assumption that the underlying index variable follows a stochastic process (e.g., option valuation models). Such models are widely used in finance literature for contracts which can be bought and sold at any point in time so that prices change on a nearly continuous basis. However, these are not applicable to our analysis since the CAT bonds are sold by the issuing company only once, and mature after a fixed period of time. Further, the value of the underlying index (state average yield) is also realized only once during the life of the contract (at harvest).[7]

The suggested approach to pricing a CAT bond involves two basic steps: (*a*) estimating the distribution of the index underlying the CAT bond contract and thus probabilities of triggering the bond, and (*b*) incorporating the estimated probabilities and the required rate of return into the bond contract price (Cummins, Lewis, and Phillips, 1998; Baryshnikov, Mayo, and Taylor, 1998; Lee and Yu, 2002).

A nonparametric technique—kernel density estimation—was used to derive the distribution of the index from historical yield data. Kernel density estimation was preferred to parametric estimation because it better preserves the information contained in the data, which could be missed by imposing a parametric structure.

Kernel density estimation constructs the probability distribution of a random variable x as a sum of specially selected functions or *kernels* of the form:

$$f(x) = \frac{1}{nH}\sum_{i=1}^{n} K\left(\frac{x - x_i}{H}\right), \tag{2}$$

where $f(x)$ is the kernel density function; $x_1, \ldots, x_n$ are observations (realizations) of the random variable x; H is a smoothing parameter called bandwidth; and $K(u)$ is the kernel

[7] One can conceivably develop a continuous valuation model for the suggested CAT bonds based on changes in yield predictions over the growing season. Such a model could be used as a pricing tool for CAT bonds traded in the secondary market. However, this would be of little interest to the issuing company that receives only the proceeds from bond placement in the primary market (see footnote 4).

(Wand and Jones, 1995). The Epanechnikov kernel, which is one of the standard kernel functions, was used to model the distribution of percentage deviations of state average yield from its long-term average.[8] The functional form for the kernel is written as:

(3)
$$K(u) = \begin{cases} \tfrac{3}{4}(1 - u^2) & |u| \le 1, \\ 0 & \text{otherwise.} \end{cases}$$

A CAT bond is valued by taking the discounted expectation of its possible payoffs under the derived distribution of realized yield losses (the triggering variable) and the required rate of return on investment. The formula for pricing a CAT bond with time to maturity T is then given as:

(4)
$$V = \mathbf{E}_{\theta,\eta}\left[V_T \exp\left(-\int_0^T r(t)\,dt \right) \right],$$

where V_T is the payoff of a CAT bond in (1), $r(t)$ is the appropriate interest rate used to discount future cash flows, and $\mathbf{E}_{\theta,\eta}$ indicates expectations with respect to two state variables. It is reasonable to assume that the state variable θ, which for the purpose of valuing catastrophe bonds essentially encompasses the term structure of interest rates, is independent of the state variable η, which pertains to catastrophe risk per se. Under this assumption, the CAT bond price becomes:

(5)
$$V = \mathbf{E}_\eta V_T \times \mathbf{E}_\theta \exp\left(-\int_0^T r(t)\,dt \right),$$

where now $\mathbf{E}_\eta V_T$ is the expected payoff of the CAT bond, and

$$\mathbf{E}_\theta \exp\left(-\int_0^T r(t)\,dt \right)$$

is the expected value of a conventional zero-coupon bond.

Note that the pricing formula (5) essentially separates the risk of default due to occurrence of a catastrophic event from the risk of default due to all other factors. Models of default risk of conventional securities are well developed in finance theory (Bluhm, Overbeck, and Wagner, 2003). Since the primary goal of this paper is to evaluate efficiency of CAT bonds in managing catastrophic risks in agriculture, we do not explicitly include such a model in our study. Instead, we rely on the efficient market hypothesis which implies that the risk of default can be incorporated into the bond price through an appropriate rate of return used to discount future cash flows. In particular, the risk of insurance company ABC defaulting on repayment of the bond's face value at maturity due to factors other than a catastrophic event can be incorporated into the pricing model (5) by setting the discount rate $r(t)$ equal to the rate of return required by investors in conventional zero-coupon bonds of comparable risk (e.g., bonds with the same maturity issued by companies with the same bond rating as our hypothetical company ABC).

It is relatively easy to obtain an analytical pricing formula for a conventional zero-coupon bond under the assumption of a constant interest rate $r(t) \equiv r$. In this case, the

[8] The Epanechnikov kernel was chosen in particular because it has finite support. This is an important requirement in modeling distributions of random variables such as yields which are known to have a limited range of possible values.

solution $B(0, T)$ is found by discounting the face value of the bond at the appropriate discount rate for the time period T, i.e.,

$$\mathbf{E}_\theta \exp\left(-\int_0^T r dt\right) = B(0, T) = \exp(-rT).$$

Using (1), the expected payoff of the CAT bond can be written as:

$$\mathbf{E}_\eta V_T = F \times \Pr\{L \leq D\} + A \times F \times \Pr\{L > D\},$$

where $\Pr\{L \leq D\}$ is the probability of the realized yield loss less than or equal to the trigger level D, and $\Pr\{L > D\}$ is the probability of the opposite event.

Thus, the general pricing formula for CAT bonds can be given by:

$$\text{(6)} \qquad V = B(0, T) \times \left[F \times \Pr\{L \leq D\} + A \times F \times \Pr\{L > D\}\right].$$

In other words, the price of the CAT bond can be represented as the product of the price of a conventional zero-coupon bond and the expected payoff from the CAT bond.

The pricing model (6) assumes that the financial market is liquid and there are no arbitrage opportunities. The price of a specific CAT bond depends on the parameters of the bond (face value F, trigger level D, and proportion A of face value repaid in case of a catastrophic event) as well as the selected discount rate and the probability distribution of the triggering index. The analysis presented later in the paper uses various combinations of these factors.

Hedging Analysis

All of the CAT bonds used in this analysis are priced to be actuarially fair, i.e., selling the bonds does not change the expected return of the issuing company ABC regardless of bond face value and the number of bonds issued. Thus, the impact of issuing CAT bonds on ABC's financial situation is analyzed by focusing on the resulting reduction in variance of net returns. Specifically, it is assumed that the ABC company is risk averse and would prefer lower variability of returns.

Since the rate of return expressed as percentage of retained premiums is simply equal to one minus the loss ratio, the company's objective can be formulated as minimization of the variance of its loss ratio where the loss ratio is calculated net of CAT bond revenues and costs. Similar approaches have been used in previous studies where risk management tools were assumed to be actuarially fair (Miranda, 1991; Smith, Chouinard, and Baquet, 1994; Barnett et al., 2005). An alternative approach may involve maximization of expected utility. However, this criterion is not used in our analysis since it is more suitable for instruments that affect both the mean and variance of returns. Further, the expected utility criterion requires an additional assumption about the utility function itself.

To model the insurer's loss ratio and hedging strategy, let X be total losses of insurance company ABC in its crop insurance line of business before issuing CAT bonds, let P be total premiums of crop insurance company ABC in its crop insurance line of business, let $\tilde{L}$ be total losses of crop insurance company ABC in its crop insurance line of business after issuing CAT bonds, and let Y be the insurer's net gain or loss from selling a single CAT bond. Note that the latter depends on whether the CAT bond is triggered, and is determined as:

$$Y = V - V_T = \begin{cases} V - A \times F, & \text{bond is triggered,} \\ V - F, & \text{otherwise,} \end{cases}$$

where V is the bond's selling price (6), and V_T is the bond's payoff at maturity as defined in (1).

Company ABC's loss ratio before issuing the CAT bond can be defined as:

$$LR_B = \frac{X}{P}.$$

Assuming the insurance company ABC issues a certain number N of CAT bond contracts, its total losses after issuing the bonds can be determined as:

$$\tilde{L} = X - NY + C,$$

where C is the fixed cost of issuing CAT bonds. The company's loss ratio after issuing CAT bonds can then be expressed as:

$$LR = \frac{\tilde{L}}{P} = \frac{X}{P} - \frac{NY}{P} + \frac{C}{P}.$$

The optimal hedging strategy can now be derived by minimizing the variance of the loss ratio given by:

$$\text{(7)} \qquad \mathrm{Var}(LR) = \mathrm{Var}\left(\frac{X}{P}\right) + N^2\mathrm{Var}\left(\frac{Y}{P}\right) - 2N\mathrm{Cov}\left(\frac{X}{P}, \frac{Y}{P}\right),$$

where Var(X/P) is the variance of the insurer's loss ratio before issuing CAT bonds, Var(Y/P) is the variance of the ratio of net gain/loss from issuing CAT bonds and the insurance premiums, and Cov(X/P, Y/P) is the covariance between the two. Differentiating (7) with respect to N and solving the first-order conditions results in the optimal number of contracts:

$$\text{(8)} \qquad N^* = \frac{\mathrm{Cov}\left(\frac{X}{P}, \frac{Y}{P}\right)}{\mathrm{Var}\left(\frac{Y}{P}\right)}.$$

Thus, in order to calculate N^*, it is necessary to compute the variance of the ratio of net gains/losses from issuing the CAT bond to the total premiums, Var(Y/P), and the covariance between it and the loss ratio before issuing the bonds, Cov(X/P, Y/P). The distribution of loss ratio X/P can be estimated based on historical loss ratio data. The distribution of net gains/losses Y, and hence the variance of the ratio Y/P, can be estimated based on the payout structure of the CAT bonds described in (1) for given parameters of the contract. However, this is not enough to calculate Cov(X/P, Y/P) analytically because a joint distribution of two variables cannot be reconstructed based on two marginal distributions alone. Instead, the covariance must be determined empirically based on historical data on losses and the derived distribution of the triggering index.

Data

Since the payoff of the proposed CAT bond depends on the level of realized yield losses for Georgia cotton, the distribution of yield losses is necessary for correct bond pricing. This can be derived from historical yield data. In addition, data on premiums and indemnities associated with underwriting cotton insurance in the state of Georgia are required for evaluation of CAT bond performance in hedging catastrophic risks.

Official yield data were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA/NASS). The annual cotton yield data cover the period between 1900 and 2002. However, because of major changes in federal commodity programs (Becker, 1999), only data for 1974 to 2002 were used. Insured loss data including dollar values of premiums and liabilities were obtained from USDA's Risk Management Agency (RMA). Although these data span the period from 1948 to 2002, only data from 1974 to 2002 were used to match the corresponding yield data.

Raw yield data cannot be used when modeling distributions of yield losses because changes in technology generally foster higher yields over time. The commonly used approach in the agricultural economics literature is to assume that the yield data can be divided into two components: the central tendency (trend) and the deviation from central tendency (Goodwin and Ker, 1998; Ker and Goodwin, 2000; Ker and Coble, 2003; Mason, Hayes, and Lence, 2003; Schintkey, Sherrick, and Irwin, 2003; Sherrick et al., 2004; Skees, Black, and Barnett, 1997). Central tendency captures the effects of technology change, while deviations from central tendency reflect natural risks including risks of catastrophic events. It is the deviations from the central tendency that are then used to estimate the kernel density function (2) of the stationary distribution of the triggering index.

In this analysis, we follow the detrending approach used by Skees, Black, and Barnett (1997) for GRP contracts. They analyzed several detrending procedures including ARIMA models, robust double exponential smoothing, and spline regression, and concluded that piece-wise linear (spline) detrending is a pragmatic, intuitive approach, which is robust across a variety of crops.

The spline regression procedure involves fitting a series of linear regressions representing different time segments and piecing the estimated relationships together into a spline function. The general form of the estimated relationship can be specified as:

$$\ln(y_t) = a_0 + b_0 t + b_1\left[(t - t_1)\delta_1\right] + b_2\left[(t - t_2)\delta_2\right] + \ldots + b_n\left[(t - t_n)\delta_n\right] + u, \tag{9}$$

where $\ln(y_t)$ is the natural logarithm of the yield observed in year t; t_i, $i = 1, \ldots, n$, are the knots of the spline regression (i.e., the points at which the slope of the spline function changes); and δ_i, $i = 1, \ldots, n$, are dummy variables equal to 1 for all observations such that $t_i \le t$, and 0 otherwise.

Based on equation (9), the realized percentage losses of state average yield L_t can be computed as:

(10) $$L_t = \frac{\hat{y}_t - y_t}{\hat{y}_t} = 1 - \frac{y_t}{\hat{y}_t} = 1 - \exp(\hat{u}_t),$$

where $\hat{y}_t$ are the trends fitted in (9), and $\hat{u}_t$ are the corresponding residual terms.[9] The calculated realizations (10) of the percentage losses of state average yield (triggering index) can then be used to estimate the kernel density function in (2). Specific implementation details of both detrending and kernel density estimation procedures are discussed in the next section.

Historical premium and loss data also have to be adjusted to reflect nonstochastic changes over time. For example, global or local climate changes may increase or decrease the chances of loss for the insurance company; changes in the insurance portfolio may affect amounts of premiums and associated liabilities, etc. In addition, premiums and losses are expressed in nominal terms and thus are affected by inflation. However, the ratios of premiums to liabilities (premium rates) and indemnities to premiums (loss ratios) are free of these problems. Therefore, historical premium rates and loss ratios are assumed to correctly represent corresponding distributions. The historical premiums can then be adjusted to their 2002 equivalents based on crop insurance program liabilities (as reported by the FCIC) for Georgia cotton in that year[10] so that

$$P_t^{02} = P_t \frac{\Lambda_{02}}{\Lambda_t},$$

where P_t^{02} are the 2002 equivalents of total FCIC premiums from cotton in Georgia in year t, P_t are the actual (historical) total FCIC premiums from cotton in Georgia in year t, Λ_{02} are total FCIC liabilities for cotton in Georgia in year 2002, and Λ_t are total FCIC liabilities for cotton in Georgia in year t.

Empirical Results

Detrending and Index Density Estimation

Estimation of the yield trend model (9) in a general form is a rather complicated procedure. However, if the number and locations of knots are fixed, the model in (9) becomes linear and can be easily estimated by OLS. For purposes of this analysis, the number and locations of knots were determined in the following way. First, we estimated all possible models with one knot and selected the best model based on an adjusted R^2 criterion. Two additional goodness-of-fit criteria—F-statistics and the Akaike information criterion (Greene, 2003)—were also calculated in each case and yielded model rankings consistent with the adjusted R^2 criterion. In the same way, the best models were determined for two-, three-, and four-knot splines. These four best models were then compared. The one-knot spline model resulted in a negatively sloped trend for the second linear segment of the spline (most recent years), which contradicts the assumption that the trend is driven by improvements in technology. The two-knot model

[9] "Negative" losses in (10) correspond to situations when the realized state average yields are above long-term average and are of no consequence to the CAT bond issuer. However, it is important to preserve those observations for correct estimation of the distribution function of the trigger variable presented in the next section.

[10] The year 2002 was chosen as a benchmark, since it was the most recent year for which data were available.

had knots at years 4 and 11 and resulted in a better fit than the one-knot spline. Three- and four-knot splines provided no real improvement in goodness-of-fit over the two-knot spline model. Both of them also had clusters of adjacent knots (i.e., changes of slope in two or more consecutive years), which was an indication of overfitting.[11]

Therefore, the piece-wise linear trend with two knots was used for the subsequent analysis. The fitted trend function is:

$$\ln(\hat{y}_t) = \underset{(0.000)}{6.4178} - \underset{(0.029)}{0.1750t} + \underset{(0.005)}{0.2825(t-4)\delta_1} - \underset{(0.001)}{0.1073(t-11)\delta_2},$$

where $t_1 = 4$ and $t_2 = 11$ are the knots of the spline; δ_i, $i = 1, 2$, are dummy variables equal to 1 for $t_i \leq t$ and zero otherwise. The p-values of estimated coefficients are given in parentheses. The model has an adjusted R^2 of 0.54, and all coefficients are significant at the 95% confidence level. Logarithms of observed and fitted yields are shown in figure 1. The model tracks the data well, provides a reasonably good fit, and reflects the general tendency of cotton yield in Georgia. The realized yield losses for each year were computed based on the estimated trend according to (10).

After detrending the yield data, the next step was to estimate the probability density function (2) of the trigger index using the Epanechnikov kernel (3). This process also required choosing an appropriate bandwidth H. Various methods are available for bandwidth selection (Wand and Jones, 1995). For this study, we used the least-squares cross-validation method[12] which resulted in the bandwidth $H = 0.20882$. The estimated kernel density of percentage yield losses is shown in figure 2.

Numerical integration was used to compute probabilities of triggering CAT bonds for given trigger values based on the estimated density function. For example, with 40%, 35%, and 30% triggers, the probabilities of a CAT bond being triggered are 2.2%, 3.85%, and 6.1%, respectively. The general tendency is that the higher the trigger level, the lower the probability the bond is triggered, and vice versa.

CAT Bond Pricing

Prices of CAT bonds were calculated using pricing formula (6) and the estimated distribution function of the triggering index for various combinations of bond parameters. The specific parameter values were chosen so as to cover a reasonable range for each parameter.

The index (percentage yield loss) is, by definition, confined to the range between 0% and 100%. However, values greater than 50% were not observed in the sample. Therefore, eight triggers were used in the analysis ranging from 15% to 50% in increments of 5%. Values of parameter A are limited to the range between 0 (bond repaying 0% of stated face value when a triggering event occurs) and 1 (bond repaying 100% of stated face value when a triggering event occurs). Of course, setting A equal to, or close to, one

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[11] Note that detrending is not intended to fit the absolute best possible piece-wise linear function to the observed data. In the extreme, the best fit is, of course, a piece-wise linear function that simply connects the observations by linear segments, i.e., a function with the number of knots equal to the number of observations. Such a "trend," however, would result in zero residuals, which defies the purpose of extracting the stationary distribution from the detrended data.

[12] Bandwidths obtained using alternative selection methods were also calculated and used to price CAT bonds. The results were similar to those presented here, and therefore are not reported.

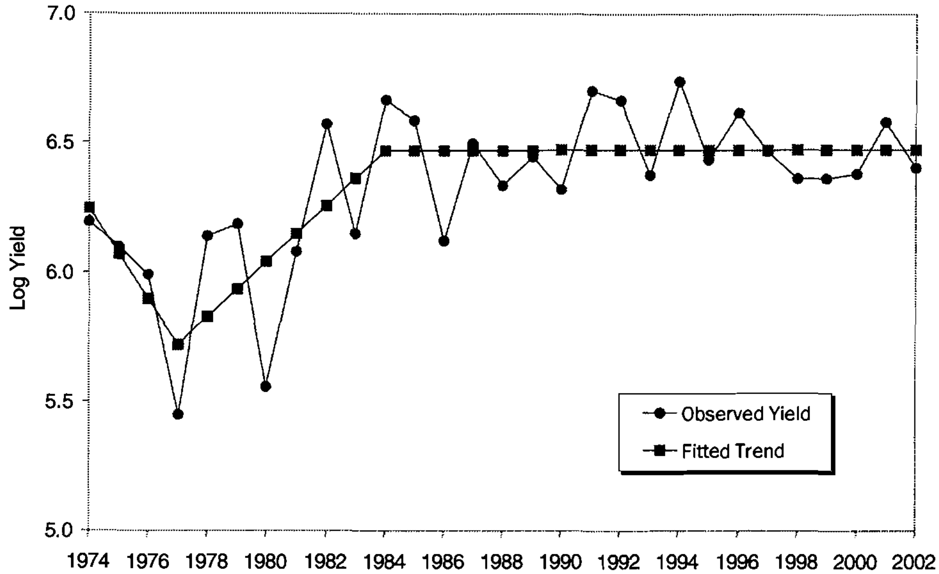

Figure 1. Historical yields and fitted trend for Georgia cotton

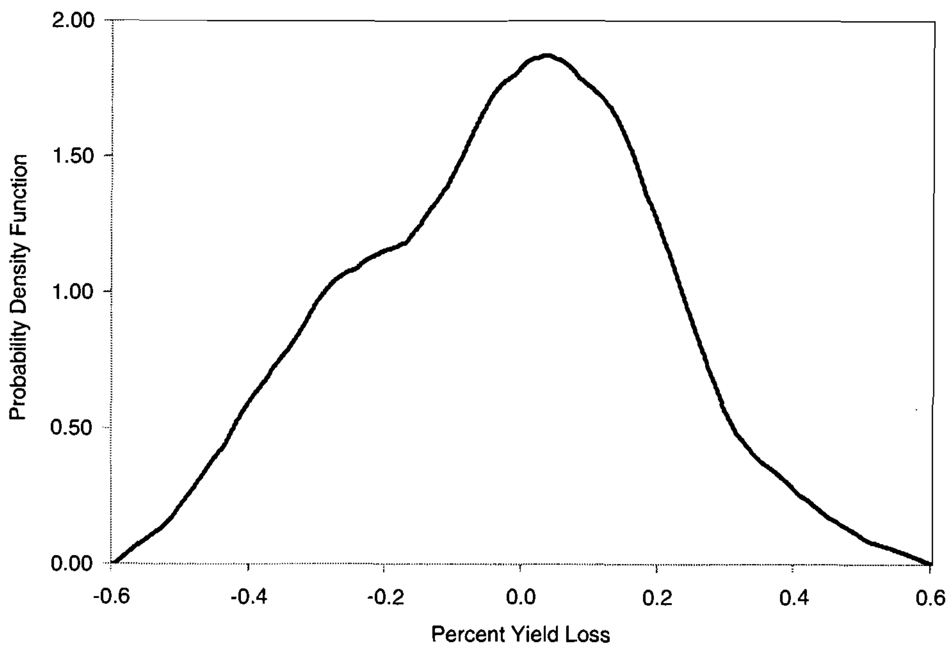

Figure 2. Probability density function of percentage yield losses estimated using the Epanechnikov kernel

Table 1. CAT Bond Prices for Different Bond Parameters

Required Return	A	Trigger 15%	20%	25%	30%	35%	40%	45%	50%
7.5%	0.0	0.7210	0.7874	0.8370	0.8711	0.8920	0.9073	0.9176	0.9236
	0.3	0.7830	0.8295	0.8643	0.8881	0.9027	0.9134	0.9206	0.9248
	0.5	0.8244	0.8576	0.8824	0.8994	0.9099	0.9175	0.9226	0.9257
10.0%	0.0	0.7032	0.7680	0.8164	0.8496	0.8700	0.8849	0.8949	0.9008
	0.3	0.7637	0.8090	0.8429	0.8662	0.8804	0.8909	0.8979	0.9020
	0.5	0.8040	0.8364	0.8606	0.8772	0.8874	0.8949	0.8999	0.9028
12.5%	0.0	0.6858	0.7490	0.7962	0.8286	0.8485	0.8630	0.8728	0.8785
	0.3	0.7448	0.7891	0.8221	0.8448	0.8587	0.8689	0.8757	0.8797
	0.5	0.7842	0.8158	0.8394	0.8556	0.8655	0.8728	0.8777	0.8805

Notes: The trigger is measured as percentage loss of state average yield for cotton. A is the proportion of the face value repaid to investors if the bond is triggered. Prices are computed based on Epanechnikov kernel density estimation.

defies the purpose of the CAT bond, as the company simply repays all or almost all of investors' money regardless of whether or not the triggering event occurs. Therefore, the values of parameter A were set to 0, 0.3, and 0.5, which correspond to bonds repaying 0%, 30%, and 50% of the stated face value, respectively, when a triggering event occurs. Finally, the required rates of return were set at 7.5%, 10%, and 12.5%. For the LIBOR rate of 3.2% (see footnote 5), this translates into risk premiums between 4.3% and 9.3%. While there are no natural limits on the values of the required return, it seems this range of risk premiums is sufficiently representative of spreads required by investors in existing CAT bonds (Jaffee and Russell, 1997; Froot, 1999).

The calculated prices of CAT bonds for various values of the parameters are summarized in table 1. Note that the total return realized by investors when the bond is not triggered is always higher than the required return used in computing the bond price. The difference between the two is an additional premium associated with the catastrophic risk.[13] As a consequence, for a given value of parameter A and required return, CAT bond prices decrease with the trigger values, since a lower trigger means that the bond is more easily triggered and thus is more risky.[14] Similarly, other things equal, as the value of parameter A increases so does the CAT bond price. Since a larger proportion of the face value is repaid if the bond triggers, the risk of loss is lower and the bond price is higher regardless of the specific trigger level. Finally, it can be seen that, other things equal, bond prices decrease as the required rates of return increase and vice versa, which is a standard result of finance theory.

[13] For example, an investor who purchased a bond with the required return of 7.5%, trigger of 30%, and $A = 0$ for \$0.8711 (table 1), and received \$1 face value one year later, would realize a total return of 13.8% (compounded continuously). Assuming a LIBOR rate of 3.2% (as of January 1, 2005), this can be interpreted as a 3.2% risk-free return plus a 4.3% premium associated with the risk of default for any reason other than a catastrophic event, and an additional 6.3% premium associated with the catastrophic risk inherent in the bond.

[14] Recall that for a zero-coupon bond, a lower price means a higher return and vice versa.

Table 2. Optimal Number of CAT Bonds for Different Bond Parameters

Required Return	A	Trigger 15%	20%	25%	30%	35%	40%
7.5%	0.0	11,517,390	12,134,830	15,743,770	15,720,110	15,953,690	0
	0.3	16,450,810	17,394,890	21,834,940	21,877,580	22,278,960	0
	0.5	22,975,760	24,402,190	29,248,670	29,357,760	30,024,520	0
10.0%	0.0	11,518,320	12,163,220	15,441,110	15,445,300	15,706,260	0
	0.3	16,428,930	17,425,130	21,145,010	21,201,300	21,650,290	0
	0.5	22,864,810	24,378,030	27,772,750	27,805,380	28,536,670	0
12.5%	0.0	11,514,080	12,183,490	15,131,300	15,147,010	15,430,080	0
	0.3	16,389,800	17,429,890	20,439,850	20,470,120	20,952,540	0
	0.5	22,703,600	24,280,980	26,287,590	26,168,690	26,930,010	0

Notes: The trigger is measured as percentage loss of state average yield for cotton. A is the proportion of the face value repaid to investors if the bond is triggered. Prices are computed based on Epanechnikov kernel density estimation.

Hedging Analysis

In order to find the optimal number of $1 CAT bond contracts for a specific crop, equation (8) is employed. As indicated previously, the joint density of the two variables—loss ratios and gains from issuing CAT bonds—cannot be derived analytically. However, the correlation coefficient for the two variables can be computed empirically using historical data. More specifically, it is assumed that our hypothetical insurance company ABC issued one-year zero-coupon CAT bonds each year from 1974 to 2002. Payout information can then be generated based on the specified payout structure (1) of the CAT bonds and yield loss information from past years. We were unable to obtain crop insurance premium and loss data by individual insurance company; thus, for purposes of this study, ABC is assumed to underwrite all cotton crop insurance policies in Georgia. Therefore, the loss ratio for ABC each year is the same as that for all cotton crop insurance policies sold in Georgia.

The optimal number of contracts that ABC must issue to minimize the variance of its loss ratio was computed for required returns of 7.5%, 10%, and 12.5%; values of parameter A of 0, 0.3, and 0.5; and trigger values ranging from 15% to 40%. The results are summarized in table 2. As can be seen, for a given trigger level, the optimal number of CAT bonds increases with the portion A of face value repaid to investors. Since higher values of A mean less capital retained in case of a catastrophic event, the bond issuer needs to issue more bonds to hedge the same amount of risk. Similarly, for a given A, the optimal number of CAT bonds increases when the trigger increases from 15% to 35%. This is true because the loss, and thus the number of bonds needed to compensate for the loss, is cumulative moving from lower to higher trigger levels. The results also show that beyond the 40% level, the optimal number of bonds falls to zero. The risk of state-average yield losses in excess of 40% is insufficient to warrant issuance of CAT bonds given the historical data series for cotton yield. Finally, as required rates of return increase from 7.5% to 12.5%, all else equal, the optimal number of bonds decreases.

Higher required returns mean that the bonds have to be sold at a deeper discount, i.e., they are more costly to the issuer.

Since the objective of insurer ABC is to minimize the variance of the loss ratio, it is important to observe the variance reduction of the loss ratio given that the company issues the optimal number of CAT bonds. Different scenarios were considered with the parameter A equal to 0 and 0.5, trigger levels set at 15% and 35%, and required returns again set at 7.5%, 10%, and 12.5%. The variance reduction has been calculated as the difference between the variance of the loss ratio the company would have without issuing the CAT bonds and the variance of the loss ratio (7) with the optimal number of CAT bond contracts issued (expressed as a percentage of the former). Table 3 illustrates the potential effectiveness of issuing CAT bonds.

While there seems to be a slight decrease in CAT bond risk-reducing effectiveness at higher required returns, the differences are not meaningful. In other words, company ABC can still benefit from issuing CAT bonds even if it is forced to build higher rates of return into the bond price (e.g., due to lower credit risk ratings). Also, there seems to be no advantage to varying the proportion A of the face value repaid if the bond is triggered. Therefore, ABC can issue CAT bonds with higher values of A, thus making them more attractive to investors.[15] However, the reduction in the variance of the loss ratio is shown to vary substantially across trigger levels, all else equal. The general trend is decreasing variance reduction, but not monotonically, as trigger level rises.

Thus far, the optimal number of CAT bonds for different contract parameters has been determined using full in-sample information. In reality, the performance of CAT bonds in risk reduction is measured in an out-of-sample environment. For example, company ABC may determine the number of bonds to sell this year based on the data from previous years. Consequently, out-of-sample analysis is important to verify the relevance and plausibility of the in-sample results.

In order to perform the out-of-sample analysis, we divided the full sample of 29 observations into two subsamples of 15 and 14 observations, respectively. The years for each subsample were chosen randomly.[16] The first subsample was then used to price the bonds and determine the optimal number of contracts to issue, while the second was used to perform the hedging analysis. This procedure was then repeated five times and the results averaged. The same methodology used for pricing and hedging in the in-sample analysis was employed for the out-of-sample analysis. Similarly, the values of bond parameters in table 3 were also used for the out-of-sample analysis. The corresponding reduction in loss ratio variance is reported in table 4.

The out-of-sample results in table 4 are similar to the in-sample results in table 3. Once again, both the required return and parameter A appear to have little to no impact on variance reduction of the loss ratio. However, variance reduction changes substantially with the trigger level, as was the case in-sample.

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[15] The assumption here is that a bond which promises to repay at least 50% of face value if triggered is perceived as less risky, and hence more attractive than a bond which repays nothing if triggered.

[16] While it is common to divide the sample by chronological order (i.e., use the first m observations for estimation, and the last n for analysis), this is not the best approach for the purposes of this study. In particular, the yield series often include streaks of relatively good or relatively bad years (figure 1). If, for example, a subsample used for pricing had a high incidence of above-average yields, the risk of triggering the bond would be underestimated. At the same time, the subsample used to evaluate CAT bond efficiency would have a high incidence of below-average yields, and thus overestimate the risk-reducing capabilities of the bonds. Randomization of samples somewhat mitigates this effect and allows for more realistic analysis.

Table 3. In-Sample Reduction in Variance of the Loss Ratios

Required Return	Contract ($A = 0$, $D = 35\%$)	($A = 0$, $D = 15\%$)	($A = 0.5$, $D = 35\%$)	($A = 0.5$, $D = 15\%$)
7.5%	28.5%	56.6%	26.3%	56.0%
10.0%	27.9%	56.5%	24.7%	55.6%
12.5%	27.2%	56.4%	23.0%	54.9%

Notes: The trigger D is measured as percentage loss of state average yield for cotton. A is the proportion of the face value repaid to investors if the bond is triggered.

Table 4. Out-of-Sample Reduction in Variance of the Loss Ratios

Required Return	Contract ($A = 0$, $D = 35\%$)	($A = 0$, $D = 15\%$)	($A = 0.5$, $D = 35\%$)	($A = 0.5$, $D = 15\%$)
7.5%	12.8%	51.8%	13.0%	52.0%
10.0%	13.5%	51.9%	12.0%	51.9%
12.5%	13.5%	52.0%	10.9%	51.6%

Notes: The trigger D is measured as percentage loss of state average yield for cotton. A is the proportion of the face value repaid to investors if the bond is triggered.

Summary and Conclusions

CAT bonds have been used since 1996 by insurance companies to hedge catastrophic risk exposure. The introduction of CAT bonds has been driven both by the dramatic increase in catastrophe losses over the last decade and by insufficient capacity of conventional reinsurance markets for financing losses from catastrophes. However, CAT bonds have never been used in the field of agriculture. This research is an attempt to design a series of CAT bonds for cotton in Georgia using the state-level average yield as a trigger. Different CAT bond contracts with different parameters were designed and priced. Hedging analysis was conducted to evaluate risk-reduction capabilities of CAT bonds. While some details of the design and pricing methodology relate to previous studies on index instruments (Skees, Black, and Barnett, 1997) and estimation of yield distributions (Ker and Goodwin, 2000; Ker and Coble, 2003), the paper contributes to the literature by analyzing an entirely new class of index insurance instruments for risk management in agriculture and evaluating their effectiveness in the context of reinsurance rather than primary insurance instruments.[17]

The instruments designed in this study are zero-coupon CAT bonds priced so as to provide a certain required rate of return plus an additional risk premium. The required rate of return, which can be interpreted as a certain spread over the LIBOR, compensates the bondholder for the time value of money and the risk of default due to reasons other than occurrence of a catastrophic event. The additional premium compensates the bondholder for bearing the catastrophic risk.

[17] Primary insurance instruments are contracts purchased by individual producers to hedge their crop production risk.

The triggers of the CAT bond contracts are specified as certain levels of yield loss measured as percentage deviations of realized state average yield from its long-term average. Once the realized yield loss exceeds the trigger, the CAT bonds default, paying either nothing or a preset proportion of the face value to the investor, depending on design.

Computation of CAT bond prices involves estimation of the probability distribution of the index variable, i.e., the realized yield losses. The realized yield losses were calculated based on spline detrending of historical yield data. The probability density function was then estimated empirically using a kernel density estimator with the Epanechnikov kernel and an appropriate bandwidth. The procedure captures the basic structure of the yield data and generates accurate probabilities of triggering CAT bonds.

Findings of the study reveal that CAT bond prices increase with the trigger and proportion A of the face value paid to investors, since increases in either parameter reduce catastrophic risk exposure and thus associated risk premium. Hedging performance as measured by reduction in the variance of the issuer's loss ratio is also affected by the parameters of the bond. The principal finding of the study is that for the case of Georgia cotton, CAT bonds proved to be fairly effective in hedging catastrophic risk exposure. In particular, when issued optimally, CAT bonds reduced the variance of the loss ratio of a hypothetical insurance company by as much as 56%.

While CAT bonds performed fairly well even at lower trigger levels (i.e., in the range of noncatastrophic losses), it should be noted that the results of the hedging analysis were obtained under an assumption that a single crop insurance company underwrites all cotton insurance policies in the state. In reality, crop insurance policies are underwritten by more than one company, and a single company may only serve a portion of the state. In such situations, CAT bonds with triggers tied to realized state-level yields may not be as effective in reducing variability of the total loss ratio due to basis risk. However, such CAT bonds should retain their risk-reducing capabilities at higher trigger levels—i.e., in the case of catastrophic events for which they are designed in the first place. Indeed, extremely low state-level yields are usually caused by spatially correlated events that simultaneously affect many areas. In practice, a hedging analysis similar to the one presented in this paper can be conducted and the feasibility of CAT bonds can be ascertained for individual cases given availability of necessary data.

For the case considered, this study presents evidence that CAT bonds may be used to reduce an insurance company's exposure to systemic risks present in a portfolio of crop insurance policies, and thus may have the potential to be used as agricultural risk transfer mechanisms. The primary application of CAT bonds can be seen as a reinsurance mechanism for insurance companies underwriting crop insurance.

Practical adoption of CAT bonds in agriculture would likely require changes in the existing federal program that reinsures crop insurance policies. Otherwise, there is little to no market incentive for participating insurance companies to seek alternative means of risk transfer. Unfortunately, direct comparison of CAT bonds to existing federal reinsurance is extremely difficult because one cannot meaningfully disentangle the risk-reduction aspects of federal reinsurance from the implicit subsidies built into the system. Evaluation of CAT bonds in hypothetical "what if" scenarios with reduced or eliminated federal reinsurance would depend critically on the assumptions underlying such scenarios. Furthermore, the analysis would also have to account for changes in the behavior of insurance companies in response to changes in federal reinsurance provisions. Such an analysis goes beyond the scope of this article, but may be an area for future research.

Regardless, the findings of this analysis suggest CAT bonds may be a viable instrument for transferring systemic agricultural production risks. To the extent these findings can be generalized to other crops and regions (an important empirical question), they challenge the primary rationalization for federal reinsurance of crop insurance policies—i.e., that private markets lack an ability to absorb the extreme systemic risks present in agriculture. While the current structure of federal reinsurance provisions reflects a variety of public policy objectives, these findings suggest that policy makers could reconsider the nature and extent of federal reinsurance, and thus perhaps reduce taxpayer exposure to reinsurance losses on crop insurance policies.

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