SPECIAL FEATURE

# Index insurance for pro-poor conservation of hornbills in Thailand

Sommarat Chantarat[a,1], Christopher B. Barrett[b], Tavan Janvilisri[c], Sittichai Mudsri[d], Chularat Niratisayakul[e], and Pilai Poonswad[f]

[a]Arndt-Corden Department of Economics, Crawford School of Economics and Government, Australian National University, Canberra ACT 0200, Australia; [b]Charles H. Dyson School of Applied Economics and Management and David R. Atkinson Center for a Sustainable Future, Cornell University, Ithaca, NY 14853-7801; Departments of [c]Biology and [f]Microbiology, Faculty of Science, Mahidol University, Bangkok 10400, Thailand; [d]Budo-Sungai Padi National Park, Wildlife and Plant Conservation Department, Bangkok 10900, Thailand; and [e]Biodiversity-Based Economy Development Office, Bangkok 10210, Thailand

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**This study explores the potential of index insurance as a mechanism to finance community-based biodiversity conservation in areas where a strong correlation exists between natural disaster risk, keystone species populations, and the well-being of the local population. We illustrate this potential using the case of hornbill conservation in the Budo-Sungai Padi rainforests of southern Thailand, using 16-y hornbill reproduction data and 5-y household expenditures data reflecting local economic well-being. We show that severe windstorms cause both lower household expenditures and critical nest tree losses that directly constrain nesting capacity and so reduce the number of hornbill chicks recruited in the following breeding season. Forest residents' coping strategies further disturb hornbills and their forest habitats, compounding windstorms' adverse effects on hornbills' recruitment in the following year. The strong statistical relationship between wind speed and both hornbill nest tree losses and household expenditures opens up an opportunity to design wind-based index insurance contracts that could both enhance hornbill conservation and support disaster-affected households in the region. We demonstrate how such contracts could be written and operationalized and then use simulations to show the significant promise of unique insurance-based approaches to address weather-related risk that threatens both biodiversity and poor populations.**

weather risk management | poverty | safety net | sustainable conservation

Weather risk is unavoidable. Storms, droughts, floods, and other extreme events happen and cause considerable damage. In high-income countries, insurance and related risk-transfer instruments offer at least partial protection from catastrophic losses by providing indemnity payments to finance rapid recovery. However, conventional insurance is typically unavailable in the more remote rural regions of the low-income world, where the poorest people live and the highest rates of species endemism and biodiversity are found. The high transactions costs of verifying losses and problems of moral hazard and adverse selection that arise from imperfect information concerning individuals' loss experience conspire to preempt the emergence of conventional insurance for these regions.

New initiatives in index insurance show considerable promise for filling missing risk markets in low-income countries (1). These financial instruments make indemnity payments on the basis of an index that is precise, objectively verifiable, available at low cost in near-real time, not manipulable by either party to the contract, and strongly correlated with the covariate risk being insured. Common indexes include rainfall or temperature available from meteorological stations, area average crop yields estimated from farm surveys, and crop growth models. Because it overcomes the transaction cost and information problems that bedevil conventional insurance, index insurance is especially well suited to manage weather risk and natural disasters that threaten poor populations, critical ecosystems, or both.

As the literature on poverty traps emphasizes, natural disaster risk is especially salient in the presence of tipping points below which people commonly fall into a low-level equilibrium standard of living. Insurance that protects households against losses that cast them catastrophically below that tipping point can yield handsome payoffs of higher economic growth and lower long-run poverty rates (2–4): hence the burgeoning interest in new insurance instruments to manage weather risk as a means of overcoming poverty traps (5, 6).

Natural disasters also threaten the sustainability of key natural resources (7–10). Just like the poverty traps literature in the social sciences, research on resiliency in environmental systems focuses on threshold effects and the need for timely recovery to conserve critical resources and preserve the system state (11–13). A minimum viable population size and natural habitats must be maintained to sustain species (14, 15). Current practice among conservation agencies involves time-consuming fundraising appeals to finance disaster response. In the case of endangered species with specific breeding calendars, like hornbills, delays in securing funds often delay ecological rehabilitation and can mean a breeding season is missed, with a potentially profound—even irreversible—impact on the threatened population. Effective insurance could help a conservation agency turn its relatively steady revenues (e.g., from donors or an endowment) into insurance premium payments that yield episodic indemnity payments to meet the extraordinary costs of responding effectively to events that might otherwise push the system beyond a critical threshold. Prefinancing natural disaster risk response through insurance can also ensure timely availability of adequate resources when rapid response is essential to the efficacy of rehabilitation efforts.

When an exogenous shock is strongly linked to both rural livelihoods and ecosystem dynamics, an opportunity emerges to design insurance to provide state-contingent financing of pro-poor, community-based ecological rehabilitation projects. Cash indemnity payments tied to conservation work requirements can both buffer human populations injured by natural shocks and prevent them from resorting to forest exploitation and predatory behaviors as coping strategies, instead empowering them as agents of ecological restoration. Properly designed index insurance can provide a safety net for both vulnerable households and the natural environment within which they live.

We illustrate this potential using the case of hornbill conservation in the Budo-Sungai Padi (BSP) National Park of southern Thailand, where the community-based Thailand Hornbill Project (THP) has conducted extensive studies of natural habitats and population dynamics of various species of hornbills, a keystone species in the tropical rainforests on which some of Thailand's poorest communities depend for their livelihoods.

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[1]To whom correspondence should be addressed. E-mail: sommarat.chantarat@anu.edu.au.

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## Hornbills and Rural Livelihoods in Southern Thailand

BSP National Park covers mountainous tropical rainforests severely encroached by man-altered habitats and rubber plantations. The 90-km$^2$ study area, which occupies the good forests on 190-km$^2$ Budo Mountain within BSP (Fig. S1), is home to six nationally endangered and near-threatened hornbill species including rhinoceros (*Buceros rhinoceros*), helmeted (*Rhinoplax vigil*), white-crowned (*Berenicornis comatus*), great (*Buceros bicornis*), wreathed (*Rhyticeros undulatus*), and bushy-crested (*Anorrhinus galeritus*) hornbills (Fig. S2). Annual rainfall in these areas averaged >2,400 mm with a marked dry season from February to July and a rainy season from August to January, which often brings severe tropical storms, a 1-in-6 y event (Fig. S3).

Hornbills are recognized as keystone species as they regenerate the forest by dispersing seeds of their food plants (16). They are well known for their nesting behavior. A breeding pair normally returns to or searches for a large tree cavity as a nest site. The breeding female seals herself inside the cavity, relying on her mate to supply food to her (and, later, nestlings) throughout the nesting season that starts in the driest month of February and lasts until mid-September each year (Fig. S3). Hornbill conservation in this region depends on maintaining stable rates of reproduction, which thus rely on (*i*) availability of nest cavities that limits the number of feasible breeding pairs per nesting season (17–19) and (*ii*) availability of suitable nesting conditions free from human disturbance to ensure high chick production rates for a given stock of available nest trees.

Availability of suitable nest trees is currently the key limiting factor constraining hornbill reproduction in this area (16–18). Evidence of competition for nest cavities among hornbills thus has been observed persistently from 1994 to 2009.* A monotonically positive relationship has been observed between the number of new chicks recruited and the available nest trees. Nest tree loss thus translates directly into reduced recruitment of new chicks the following year. As much as 42% of the variation in the number of chicks produced per nesting season during this 16-y period is explained by variation in available nest trees.

The nesting habitat of hornbills that rely on natural tree cavities leaves hornbill reproduction—and thus population dynamics—vulnerable to weather shocks. Data (1994–2009) obtained from the THP (*Methods*) indicate that the annual rate of nest tree loss varies between 0% and 15% (average = 3%, $n$ = 16) of total nest trees available observed at the beginning of nesting year (average = 90 trees, $n$ = 16). Nest tree breakages and/or uprooting due to erosion of the root zone from heavy rains that typically accompany severe windstorms have been the key cause of nest tree losses, accounting for 93% of total losses since 1994. The maximum nest tree loss was recorded in 1998 when tropical storm Gil hit Narathiwat, depressing nesting capacities and resulting in a 26% reduction in the estimated hornbill chicks recruited the following year. Even modest perturbations in nest tree availability in the small and closed forest habitats of BSP can therefore significantly disrupt hornbill population dynamics.

The six hornbill species in BSP maintained an average annual chick production rate—computed as the ratio of the number of chicks successfully fledged over the total nest trees at the beginning of nesting season (*Methods*)—of 37% over the 16-y period. Extensive human disturbance, some induced by adverse storm-related shocks to people's primary livelihood, is a key factor affecting the hornbill chick production rate (17, 18, 20).

BSP is also home to some of Thailand's poorest subpopulations. From the biennial household survey (1998–2006), the poverty headcount (US$1.25/d per capita poverty line) in six predominantly Muslim, ethnic minority villages in Narathiwat Province ranged from 43% to 89% with the mean village-averaged real monthly per capita expenditures of $38 ($1.27/d) over the survey period (Table S1). The livelihoods of 40–64% of these households rely mainly on rainfed agriculture and income as farm laborers. Permanent tree crops, especially rubber, predominate with a small subpopulation relying on rice farming and subsistence crops on agricultural lands, the vast majority of them within BSP, although the park was gazetted in 1999. Muslim separatists operating in the area since 2004 have raised insecurity threats to outside businesses, which in turn limits rural access to modern infrastructure, reinforcing their heavy dependence on agriculture and forest-based livelihoods. The storm in 1998 also brought the lowest mean village real monthly expenditures and the highest poverty headcount observed in the data. When storms damage their rubber trees and rice fields, BSP residents commonly turn to illegal logging, forest products extraction, and hornbill poaching† as a coping strategy.‡

As the availability of trees with suitable nesting cavities is a critical limiting factor for hornbill reproduction, THP has focused its conservation and research priorities on regular modification of unsuitable nests and occasional replacement of irreversible nest losses using artificial nests. Artificial nest installation has proved an effective approach to maintain hornbill reproduction rates as they can be installed quickly before the next breeding season and near the broken nest trees to which former breeding pairs normally return, yielding an average of 26% chick production rate per unit installed (17, 18).§ To date, THP has relied on private donations, mainly through the Hornbill Family Adoption Program (18), to finance these community-based efforts, engaging 13 villages surrounding BSP. Artificial nest installation is, however, costly as it involves both nest materials and labor for installation, monitoring, and regular local maintenance. Experience to date indicates that the pace of fundraising limits the rate of restoration of nesting capacity and therefore chick recruitment in the aftermath of severe windstorm shocks that lead to catastrophic loss of nest trees. Tropical windstorms pose a critical threat to both hornbill conservation and community livelihoods, both because of the direct disruption storms cause and because their damage often induces local villagers suffering income losses to prey on hornbills and their habitats.

## Results

The magnitude and intensity of windstorm-related shocks in each nesting year $t$ are represented by two key variables: annual maximum wind speed, $w_t$, and cumulative monthly maximum wind speed above the 30-y monthly average, $cw_t$, constructed from 1980–2009 data from the weather station closest to BSP (*Methods*). The vector of wind speed variables can thus be written as $\omega_t = (w_t, cw_t)$. Their time series are shown in Fig. 1 with mean $w_t$ of 25 knots (kn) and a maximum of 40 kn in 1989 when Typhoon Gay—the strongest storm event of the last three decades—hit peninsular Thailand. $w_t$ also captures well the other extreme storms that struck the region in 1982, 1984, 1996, and 1998. $cw_t$

*According to 1994–2009 THP data (*Methods*), intra-specific competitions were observed annually at rates from 0% to 8% (average = 4%, $n$ = 16) of total nest cavities available at the beginning of each nesting year. The cumulative frequency of nest competitions increased over time to 29% in 2009 despite growth in the number of nest trees found.

†Before THP was established in 1994, poaching of hornbill chicks for illegal pet trading was very common in BSP (17, 18). Poaching has fallen as THP has involved local villagers, especially known poachers, in research and conservation activities, has built awareness of the economic value of hornbills, and has used community-based mechanisms to help authorities enforce poaching laws (21–23). Illegal logging, forest clearance for cultivation, and forest product extraction that depletes habitat and natural food sources are the key human disturbances to hornbill reproduction in BSP today (17, 18).

‡Strong winds usually come with heavy rains, which could also disrupt rubber tapping and rice farming, due not only to direct damage to trees and paddy in fields, but also to flooding that impedes access to markets, to wind and water damage to stored grain, and to diversion of labor effort to repairing homes and local infrastructure. This result is manifest, for example, in a relatively low share of crop production in total income for the severe storm year 1998 and an unusually high share of income that year from forestry and hunting, reflecting the local population's coping response in the aftermath of storms that disrupted primary agricultural livelihoods.

§Nineteen artificial nests have been installed in BSP from 2006 to 2009, resulting in an average of five successfully fledged chicks per year. This 26% rate is slightly below the annual average 37% chick production rate in natural nest trees. Research is underway to improve the biological condition of the artificial nests to increase the nesting and breeding success rates. Several more nests have been installed and observed in 2010. The estimated annual costs of artificial nest installation are based on current projects implemented by THP, http://en.thaihornbill.org/.

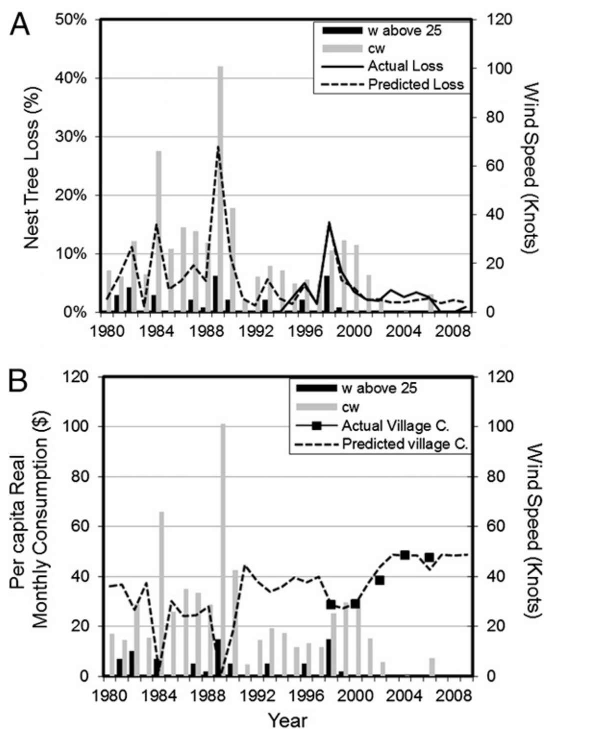


**Fig. 1.** (*A* and *B*) Relationship between wind speed variables and (*A*) nest tree loss (%) and (*B*) village-averaged monthly expenditures per capita. $w >$ 25 represents annual maximum wind speed >25 kn. Predicted values are constructed from 1980 to 2009 wind speed data on the basis of the regression results in Table 1. The actual average village expenditures data are averaged across six villages' data. The model generates implausibly low out-of-sample predictions of village expenditures levels during the bad storm years of 1984 and 1989 due to limited expenditures data in the storm years.

captures the cumulative intensity of repeated strong winds; the three-decade maximum also occurred in 1989 (Table S2).

Severe storms usually come during the rainy season, right after the conclusion of that year's—and before the beginning of the following year's—nesting cycle (Fig. S3). These storms cause nest tree losses observed at the end of each nesting year as well as disrupt human livelihoods during and following the storms. The interrelated nest tree, hornbill population, and human expenditures dynamics and the resulting dynamic impacts of storms can be formalized as a system of equations (*Methods* and Fig. S4), which motivates the logic and design of our index insurance.

**Windstorm Risk, Hornbill Reproduction, and Rural Expenditures.** Annual data on percentage of nest tree loss ($l_t$) and hornbill chick production rate ($s_t$) were constructed from 1994–2009 THP data (*Methods*). To identify how prominently windstorms affect nest tree loss we decompose annual rates of nest tree loss according to $l_t(\omega_t, \varepsilon_t^l) = l(\omega_t) + \varepsilon_t^l$, where $l(\cdot)$ represents the predicted relationship between an observable vector of wind variables in period $t$ and actual nest tree loss recorded at the end of that period. Thus, $l(\omega_t)$ is the covariate risk associated with observable wind variables and $\varepsilon_t^l$ represents risk due to other factors. If the estimated function $\widehat{l}(\omega_t)$ explains much of the variation in total nest tree loss, it could serve as a reasonable index on which to write a wind-based index insurance contract for hornbill nest trees.[¶]

An endogenous regime switching model was used in this estimation to allow us to estimate two separate relationships conditional on how badly the area was hit by strong winds each year, determined by a threshold $w_t$ endogenously identified using a minimum sum of squared-errors criterion:

$$l_t(\omega_t, \varepsilon_t^l) = \begin{cases} l^1(\omega_t) + \varepsilon_t^{l1}, & w_t > k \\ l^2(\omega_t) + \varepsilon_t^{l2}, & w_t \leq k. \end{cases} \quad [1]$$

Table 1 reports estimation results based on 16-y annual data. The optimal $k = 25$ kn, the long-term mean of $w_t$. The statistical model explains the annual rate of nest tree loss quite well, especially in the high wind regime ($R^2 = 90\%$, $n = 16$). In the light winds regime, the resulting insignificant relationship between any wind speed regressor and nest tree loss (with only 52% adjusted $R^2$ in the regime-specific linear regression estimation) makes intuitive sense as variation in light-to-normal wind speeds should not have a systematic effect on nest tree loss. In the high wind regime, however, $w_t$ has a very strong, statistically significant positive effect on nest tree loss. A single extremely strong windstorm generally destroys nest trees and expected losses increase at a rate that increases with storm strength above the mean. The cumulative effect of above average winds, $cw_t$, also has a statistically significant positive effect on nest tree loss.

The limited size of the hornbill reproduction sample precludes setting aside data for out-of-sample evaluation. As an alternative, we compare the predicted rate of nest tree loss constructed from 30-y historical wind speed data with the evidence from four severe storm events that hit the region since 1980. Fig. 1*A* shows that the predicted storm-related nest tree loss $\widehat{l}(\omega_t)$ quite accurately captures these events, predicting high rates of nest tree losses in storm years—28% in 1989 and 12–15% in the tropical-storm years 1982, 1984, and 1998—and predicting <10% losses for years without storms. On the basis of 1994–2009 data, in-sample prediction errors are <2% in absolute terms. Over- and underpredictions are apparent in the normal years, when wind speed is less correlated with nest tree loss, whereas the predicted storm-related nest tree loss explains virtually all nest tree loss during the storm year. The estimated relationship $\widehat{l}(\omega_t)$ thus shows promise as an index[‖] on which to write insurance contracts to preserve nesting capacity for hornbill reproduction.

Next, we verified that windstorms are likewise good predictors of adverse livelihood shocks for human populations in the region, using pseudo-panel data of village average monthly expenditures per capita in six villages collected biennially from 1998 to 2006 (*Methods* and Table S1). A linear least-squares regression that decomposes village expenditures shocks into storm-related and other stochastic shocks, $\varepsilon_{v,t}^y$,

$$Y_{v,t}(\omega_t, \varepsilon_{v,t}^y) = Y(\omega_t) + \varepsilon_{v,t}^y, \quad [2]$$

has an overall adjusted $R^2$ of 60% ($n = 30$). Although $w_t$ has no statistically significant effect, $cw_t$ has a strong, statistically significant negative effect on rural expenditures. Whereas single severe storms have a greater effect on nest trees, the cumulative intensity of severe windstorms over the course of the year causes greater damage to rural livelihoods in the forest region. As shown in Fig. 1*B*, predicted village expenditures based on wind speed explain actual expenditure patterns quite well in the sample; prediction errors are always <$5/mo in absolute terms. Doubling $cw_t$ (~1 SD above the mean) leads, on average, to a 35% reduction in village expenditures.

The data strongly indicate that high winds hurt both hornbills and humans in BSP. Furthermore, because windstorms stress hu-

[¶]Note that this index will also pick up storm-related loss of food trees that is correlated with the loss of nest trees.

[‖]Index insurance products in developing countries generally quantify insurable risks with indexes based on observed climatological data (e.g., rainfall, temperature) with indemnity payment cutoff points constructed using a generalized crop growth model or expert judgment. Thus, the true relationship between the insurable interest and the index is unknown. The approach followed here not only enables the design of an index based directly on the predictive relationship between climatological data and observed losses, but also permits ex ante assessment of the product's effectiveness that is absent from the extant index insurance literature.

**Table 1. Regression estimates of windstorm effects on nest tree loss, rural village expenditures, and hornbill chick production rate**

| | Annual nest tree loss, $l_t$ (% of nest trees) | | | | Village expenditures per capita, $Y_{v,t}$ (monthly $) | | Following year's chick production rate, $s_{t+1}$ (% of nest trees) | |
|---|---|---|---|---|---|---|---|---|
| | $w_t \geq 25$ | | $w_t < 25$ | | | | | |
| Explanatory variables | Coefficient | SE | Coefficient | SE | Coefficient | SE | Coefficient | SE |
| Maximum windspeed, $w_t$ (knots) | −0.0052*** | (0.0013) | 0.0003 | (0.0032) | −0.1250 | (0.1637) | −0.0034 | (0.4000) |
| Maximum windspeed squared, $w_t^2$ | 0.0002*** | (0.0000) | 0.0000 | (0.0002) | | | | |
| Cumulative above average maximum windspeed, $cw_t$ | 0.0017* | (0.0009) | −0.0012 | (0.0028) | −0.6697*** | (0.1442) | −0.0100*** | (0.0026) |
| Official forest clearance (=1 if yes) | | | | | | | −0.2495*** | (0.0423) |
| Constant | | | | | 50.5676*** | (4.6678) | 0.4465*** | (0.0763) |
| Observations | 16 | | | | 30 | | 16 | |
| Adjusted $R^2$ | 0.896 | | | | 0.601 | | 0.728 | |

Robust SEs are in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively. Summary statistics of the regressors are reported in Table S2. The variable official forest clearance for agriculture = 1 if such government programs were identified in BSP.

man populations, local residents intensify anthropogenic pressure on hornbill populations. We found suggestive statistical evidence that local residents cope with the adverse shock of windstorms by increasing their disturbance of hornbill nests. With 5 y of overlapping data in 1998–2006, there is a high bivariate correlation coefficient, 0.52 ($n = 5$), between real village average expenditures, $Y_{v,t}$, and hornbill chick production rates in the following year, $s_{t+1}(Y_{v,t}, \omega_t, \varepsilon^s_{t+1})$. However, with only a few observations, we could not directly estimate the induced human disturbance effect on hornbill chick production rate controlling for other factors. We instead estimated an overall predictive relationship between the following year's hornbill chick production rate and the vector of wind speed variables in the current year according to

$$s_{t+1}(\omega_t, \varepsilon^s_{t+1}) = s(\omega_t) + \varepsilon^s_{t+1}. \quad [3]$$

The estimated effect of wind speed on the following year's chick production captures the effects of human disturbance induced by windstorm shocks as well as nonanthropogenic effects associated with high winds, e.g., those due to storm-associated rainfall patterns. As shown in the rightmost columns of Table 1, controlling for the years with known official forest clearance for agriculture, the regression model explains the chick production rate well, with an adjusted $R^2$ of 73% ($n$ = 16). A strong, statistically significant negative effect of $cw_t$ suggests that a doubling in $cw_t$ results, on average, in a 54% reduction in hornbill chick production rate in the following year. Qualitative evidence suggests that a significant portion of the effect is due to storm-induced anthropogenic pressure on the hornbill population.

Our estimated results thus confirm the significant covariate effects of windstorms on overall nest tree loss and on rural livelihoods and suggest that human coping behaviors in response to severe windstorms further damage hornbill chick recruitment in the following breeding cycle.

**Wind-Based Index Insurance for Pro-poor Hornbill Conservation.** To address this covariate risk for both conservation and poverty reduction objectives, an annual index insurance contract can be designed on the basis of a predicted nest tree loss index specified as a function of wind speed observed throughout the year, $\widehat{l}(\omega_t)$. At the beginning of each nesting year, the THP can insure any number of nest trees, $T$, against storm-related loss so that in a year of extreme winds, when $\widehat{l}(\omega_t)$ exceeds a level specified in the contract, a year-end indemnity payout can finance community-based efforts for timely installation of artificial nests before the start of the next nesting season. Because windstorms typically occur during the rainy season at the end of the nesting season, pre-financing a nest restoration program using the index insurance allows the THP to replace lost nesting capacity in time to stabilize hornbill recruitment the following season (Fig. S3).

The total indemnity payment the insurance company pays at the end of each insured nesting year $t$ conditional on the predicted nest tree loss index $\widehat{l}(\omega_t)$ relative to a contractually specified strike rate ($l^*$)—the maximum uninsured loss, like a deductible on conventional insurance contracts—can be written as

$$\Pi\left(\widehat{l}(\omega_t), l^*, T\right) = \max\left(\widehat{l}(\omega_t) - l^*, 0\right) \cdot c \cdot T, \quad [4]$$

where $c$ is the replacement cost per nest tree, encompassing both the artificial nest (∼$400) and the cost of installation and monitoring by the local community (∼$600/y) (18).

Table 2 analyzes wind-based index insurance for hornbill conservation at various strike levels. The lowest strike contract necessarily provides greater compensation in the event of predicted nest tree loss, with 47% frequency of payout for a contract that pays out whenever predicted loss exceeds the 16-y mean (3%). This result compares to 20% (13%) payout frequency for contracts with a strike level 1 or 2 SD above the mean, 7% and 11%, respectively. Using 1994–2009 data, we computed the in-sample frequency when the index would have correctly triggered an indemnity payment (i.e., when both predicted and actual losses either exceeded or fell below the strike level). The probability of a correct trigger decision increases in the contract strike level, reflecting greater focus on covariate, catastrophic shocks, from 87.5% accuracy for the 3% contract up to 100% correct predictions for the contracts.

Table 2 presents actuarially fair premium rates for this insurance (quoted as a percentage of the total replacement cost of insured nest trees) computed by the traditional burn rate approach based on 30-y historical wind speed data. The fair premium rates vary from 2.9% for the highest-coverage contract (with a 3% strike) down to 0.9% for the 11% strike contract offering only catastrophic coverage. At an estimated replacement cost of $1,000 per insured nest tree, the annual premium per insured nest tree would be $29, $15, and $9 for the 3%, 7%, and 11% strike contracts, respectively, before any commercial loadings are added by a local underwriter or international reinsurer.

These wind-based index insurance contracts could be used to finance timely community-based hornbill conservation programs in BSP. At the beginning of each year, the THP could approach key donors to pay the premium for an insurance contract on the number of trees it determined is essential to insure against collapse of hornbill reproduction. Note that it would not insure specific trees, just a count, enabling it to ensure some minimum nesting capacity the following year. This expense would be stable and low. Wind data would be monitored in real time to update the predicted nest tree loss index continuously. In the event of extreme winds leading to predicted loss beyond the strike level, the contract would trigger an indemnity payment from the insurer to the conservation project, enabling prompt replacement of lost trees with artificial nests, repair of damaged cavities, or alteration of unused existing cavities to make them hornbill friendly. The conservation project would have the flexibility to respond as it deems most appropriate, potentially prioritizing among species and interventions. Contractually triggered in-

**Table 2. Wind-based index insurance for hornbill conservation**

| Strike ($I^*$), % | Frequency of indemnity payment: $P_r(I(\omega_t) > I^*)$, % | Frequency of correct indemnity trigger decision, % | Fair annual premium rate, % replacement cost of insured nest tree | Annual premium ($) per insured nest tree (at $c$ = $1,000 per tree) |
|---|---|---|---|---|
| 3 | 46.7 | 87.5 | 2.9 | $29.0 |
| 7 | 20.0 | 93.8 | 1.5 | $15.0 |
| 11 | 13.3 | 100.0 | 0.9 | $9.0 |

Strike levels are set at the 16-y mean (3%), 1 (7%), and 2 (11%) SD above 16-y mean (3%) actual rates of nest tree losses, respectively.

demnity payouts can significantly accelerate restoration of nesting capacities relative to the prevailing practice, in which time-consuming fundraising begins after storm damage. The resulting delays can cause species to miss a breeding season.

Because most replacement costs pay for local labor to install and monitor the artificial nests, the indemnity payments would effectively finance a cash-for-conservation work scheme to buffer rural villagers' incomes against storm damages. In this way, the index insurance could reverse the prevailing effect of windstorms on human pressure on hornbills. Rather than relying on illegal logging, forest product extraction, or poaching as de facto natural insurance with which to cope with storm shocks, local populations would instead receive cash payments for work to restore hornbill nesting capacity. The strong joint relationship between windstorms, nest trees, and local livelihood losses permits state-conditional payments for work targeted at rehabilitating hornbill habitats in the wake of a storm event. This design uses an insurance contract to finance a safety net employment program. The pro-poor efficacy of and best practices for such programs are now well established (24).

What effects could one reasonably expect from wind-based index insurance contracts? We simulated the expected effects on hornbill populations and monthly per capita expenditure levels in rural villages around the park under the 3% and 11% strike level contracts (*Methods*). Assuming installed artificial nests offer perfect substitutions for actual nest trees, we found that insurance would significantly stabilize and increase hornbill populations and also reduce rural poverty compared with the no-insurance counterfactual that prevails currently. Fig. 2*A* plots the cumulative distribution of predicted annual hornbill population sizes in 1,000 replications of 100-y simulations. The 3% strike contract reduces the estimated probability of population collapse below its initial size of 1,096 birds, from 80% without insurance to just 60%. This index insurance also drives to zero the probability of the population falling below 75% of the initial size, a 20% probability event in the absence of insurance. Conservation performance varies with contract specifications. The higher-cost 3% strike contract notably outperforms the lower-cost 11% strike one.

Because most of the indemnity payments would finance cash-for-conservation work programs, they would underwrite a partial safety net** for participating rural villagers who likewise suffer storm-related expenditures shocks. Labor costs account for ~60% of current nest replacement costs, so ~$600/y ($50/mo) would flow to villagers for each indemnity payment per insured nest tree, multiplied by the payout rate realized at the end of the insured year. Fig. 2*B* plots the cumulative distribution of monthly per capita expenditures, again on the basis of 1,000 replications of 100-y simulations. The 3% strike contract would reduce the frequency of extreme poverty by 20%. Because wind shocks have a demonstrable adverse effect on livelihoods in this region, partial safety nets triggered by windstorms and tied to rehabilitation of hornbill nest trees can serve reasonably effectively as a pro-poor, pro-environment safety net. These simulations do not include any induced reduction in anthropogenic pressure on hornbills caused by providing an alternative buffer for local populations that might otherwise prey on hornbills and their habitats to cope with shocks. This potential indirect effect could offer additional protection to hornbill populations.

**Although windstorm variables jointly affect both nest tree and rural livelihood losses, the windstorm risk captured by the predicted nest tree loss index would not perfectly capture windstorm risk on rural livelihood losses.

## Discussion

Covariate weather risk threatens people, keystone species, and the ecosystems they regulate. Index insurance, although no panacea, is one promising means of managing that risk. By providing prompt compensation in the event of catastrophic windstorm shocks, the index insurance we propose would enable the conservation project to finance community-based nest restoration programs to rapidly restore nesting capacity necessary for hornbill reproduction, provide disaster support to storm-affected rural villagers, and thereby potentially reduce human disruption of hornbill reproduction. Index insurance offers a unique opportunity to use modern financial risk-transfer mechanisms to finance cash-for-conservation work programs that could accelerate ecological recovery while simultaneously buffering vulnerable human populations.

The potential applicability of the index insurance ideas developed here extends well beyond southern Thailand and hornbills to other keystone species and conservation contexts where both people and biodiversity are threatened by a common, measurable shock. Wherever there exist sufficient high-quality longitudinal data on an insurable interest (e.g., nest trees, household expenditures) and a reliable weather or covariate risk variable that is cost-effectively and objectively measured in near real time, similar index insurance products can be designed and tested using the methodologies developed here. Once implemented, these instruments must undergo rigorous ex post impact evaluation.

## Methods

**Data.** Hornbill data from 1994 to 2009 were obtained from the THP, which involved local communities in locating all available nesting cavities†† in the study area, monitoring them throughout the nesting season for evidence of competition and nestlings and checking for nest tree losses after the rainy season, before the nesting season of the following year (see refs. 17 and 18 for detailed methodology). From these data we constructed (*i*) the percentage of annual nest tree loss ($l_t$) by dividing total nest tree losses in nesting year $t$ by total nest trees available observed at the beginning of that nesting year and (*ii*) chick reproduction rate ($s_t$) by dividing the number of chicks successfully produced during nesting year $t$ by the total nest trees available observed at the beginning of that nesting year.

Household data come from the socio-economic surveys conducted biennially by the Thailand National Statistical Office, 1998–2006. A stratified two-stage sampling design is used with 15 households randomly sampled for all of the sampled villages. We used village-level measures as repeated observations, constructed as pseudopanel data using household data from the six rural villages in Narathiwat Province with surveys in all rounds. Household expenditures (dollars) included total cash and in-kind expenditures on food, education, and health. Real household expenditures were calculated using 2006 as the base year (Table S1).

Monthly maximum wind speed data ($w_m$) from 1980 to 2009 were obtained from the Narathiwat Meteorological station. We constructed two key wind variables for each nesting year $t$ (February to January) as (*i*) annual maximum wind speed $w_t = \max_{m \in t}(w_m)$, and (*ii*) cumulative monthly maximum wind speed above the 30-y monthly average, $(\bar{w}_m)$, $cw_t = \sum_{m \in t} \max(w_m - \bar{w}_m, 0)$. See Dataset S1 for necessary data we used.

††The number of available nest trees represents the total observed in the 90-km$^2$ study on Budo Mountain alone by the research team at the beginning of each nesting year. These numbers thus inevitably understate the actual number of nest trees available in BSP as the total nest trees found depends on the skill and size of the research team. Also, as reflected in Fig. S1, other mixed forest and plantation areas exist in the part but outside the study area that could potentially offer hornbill habitat, where nest trees were not counted.

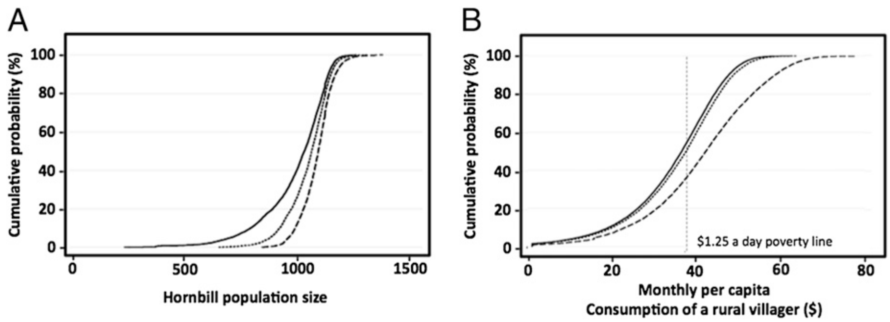


**Fig. 2.** Effects of wind-based index insurance on hornbill population and rural livelihood. (*A* and *B*) Cumulative distributions of hornbill population size and per capita monthly expenditures of rural households, who participates in the hornbill conservation project, respectively, observed annually from 1,000 simulated replications of 100-y population and livelihood dynamics under scenarios simulated with and without index insurance products. The solid lines represent cumulative distributions without insurance. The dotted and dashed lines represent the cumulative distributions under wind-based index insurance with 11% and 3% strike levels, respectively.

**Dynamic Framework and Simulations.** Hornbill population dynamics can be described by the following system of dynamic equations,

$$\begin{aligned} T_{t+1} &= (1+g-l(\omega_t,\varepsilon_t^l))\cdot T_t \\ R_{t+1} &= S_{t+1}(Y_{v,t}(\omega_t,\varepsilon_{v,t}^y),\omega_t,\varepsilon_{t+1}^s)\cdot \min(b\delta B_{t+1},T_{t+1}) \\ B_{t+1} &= (1-m)\cdot B_t + R_t, \end{aligned} \qquad [5]$$

where the total number of nest trees observed at the beginning of the following nesting year, $T_{t+1}$, evolves from $T_t$ at a constant rate $g$ per year adjusted by rate of nest tree losses over the current year, $l(\omega_t,\varepsilon_t^l)$ due to winds, $\omega_t$, and other shocks, $\varepsilon_t^l$. $T_{t+1}$ directly conditions total new chick recruitment into the population during the following year, $R_{t+1}$, which is a product of the chick production rate in the following breeding cycle, $s_{t+1}(Y_{v,t},\omega_t,\varepsilon_{t+1}^s)$, and the number of nest trees available for the following year's breeding pairs.

With $b$ representing average nest trees needed per potential breeding pair and $\delta$ representing the constant proportion of adult breeding pairs in the population, $B_{t+1}$, $T_{t+1}$ thus serves as a potential limiting factor that conditions hornbill reproduction in the following year when populations are large relative to suitable habitat, as is currently true of BSP. If hornbill populations were to crash such that nest tree availability was no longer limiting, a hornbill conservation based on restoration of nest trees, as is true of this index insurance idea, would likely become less effective.

The chick production rate for the following breeding cycle, $s_{t+1}(Y_{v,t},\omega_t,\varepsilon_{t+1}^s)$, is itself affected by human disturbance induced by current expenditure levels $Y_{v,t}(\omega_t,\varepsilon_{v,t}^y)$ in rural villages. Recall that human expenditures are affected by storm events late in year $t$, as well as other shocks to expenditures, $\varepsilon_{v,t}^Y$. The chick production rate is also conditioned by occurrence of storm events during the current year and other stochastic shocks to chick production rate, $\varepsilon_{t+1}^s$, in the following year. The total new chick recruitment into the population during the following year, $R_{t+1}$, then enters directly into hornbill population dynamics by adding to the total hornbill population after netting out a constant adult mortality rate, $m$.

Assuming artificial nests perfectly substitute for natural nests, nest tree dynamics with insurance coverage for all of the nest trees available at the beginning of each year can be written as

$$T_{t+1}^{\text{insured}} = (1+g-l(\omega_t,\varepsilon_t^l))\cdot T_t + \max(\widehat{l}(\omega_t)-l^*,0)\cdot T_t. \qquad [6]$$

Assuming that the labor cost share (60%) of any indemnity payment goes to a representative villager ($c$), the average monthly expenditures stream with insurance can be written as

$$Y_{v,t}^{\text{insured}} = Y(\omega_t,\varepsilon_{v,t}^y) + \max(\widehat{l}(\omega_t)-l^*,0)\cdot c. \qquad [7]$$

Fig. S4 depicts how index insurance affects these dynamics. We evaluate the performance of this insurance product by simulating 1,000 replications of 100-y time series of nest tree, hornbill populations, and village expenditures dynamics using the parameters in Table S3.

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