

Index Insurance for Pro-poor Biodiversity Conservation: The Case of Hornbills in Thailand

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Abstract

This study explores the potential of index insurance as a mechanism to finance community-based biodiversity conservation in areas where there exists a strong correlation between natural disaster risk, keystone species populations and the well-being of local population. We illustrate this potential using the case of hornbill conservation in the Budo-Sungai Padi rainforests of southern Thailand using 16 years' hornbill reproduction data and 5 years' human consumption data. We show that severe windstorms cause both lower human consumption 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 rate the following year. The strong statistical relationship between wind speed and both hornbill nest tree losses and household consumption opens up an opportunity to design wind-based index insurance contracts that could both enhance hornbill conservation and support disaster-affected human populations in the forest region. We demonstrate how such contracts could be written and operationalized, then use simulation methods to show the significant promise of novel insurance-based approaches to addresses weather-related risk that threatens both biodiversity and poor human populations.

Introduction

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 effectively 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 based on 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 indices include rainfall or temperature levels available from meteorological stations, area average crop yields estimated from farm surveys or crop growth models. Because they overcome the transactions 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 in order to conserve critical resources and preserve the system state (11-13). Current practice among conservation agencies involves time-consuming public fundraising appeals to finance disaster response. In the case of endangered species with specific breeding calendars, like hornbills, commonplace delays in securing funds often delays 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 donor agencies 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. Pre-financing 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.

This paper explores the potential of index insurance in areas where a strong correlation exists between weather risk, key biodiversity resources and rural livelihoods. We illustrate this potential using the case of hornbill conservation in the Budo-Sungai Padi (BSP) Mountains 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.

Hornbills and Rural Livelihoods in Southern Thailand

Budo-Sungai Padi National Park in southern Thailand covers mountainous tropical rainforests within man-altered habitats, rubber plantations and rice fields. The 90 km² forest area within

* (14) reports similar phenomena related to drought and ungulate conservation in the Serengeti.

BSP (Fig. S1) is home to six locally endangered and near-threatened hornbill species including White-crowned (*Berenicornis comatus*), Wreathed (*Rhyticeros undulates*), Bushy-crested (*Anorrhinus galeritus*), Great (*Buceros bicornis*), Rhinoceros (*Buceros rhinoceros*), and Helmeted (*Rhinoplax vigil*) hornbills (Fig. S2). Mean annual rainfall in these areas averaged over 2400 mm with a marked dry season from February to July and a rainy season from August to January. The rainy season often brings severe tropical storms, a 1-in-6 year event (Fig. S3).

Hornbills are recognized as keystone species for their importance regenerating the forest by dispersing seeds of their food plants (15). The uniqueness of hornbills is due to their nesting habits. 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 fundamentally on (i) the availability of suitable nest cavities that limits the number of feasible breeding pairs per nesting season (16-18) and (ii) the suitability of nesting conditions free from human disturbance so as to ensure high chick production rates for a given stock of available nest trees. The estimated 26% rate of competition among hornbills for nesting cavities in BSP (17) suggests that nest trees are fully utilized and constrain hornbill reproduction in this area.

The unique and limiting nesting habitat of natural tree cavities leaves hornbill reproduction – and thus population dynamics – vulnerable to weather shocks. According to data collected by THP from 1994-2009 (see Methods), the annual rate of nest tree loss varies between 0 – 15% (average = 3%, n=16) as a share of total nest trees available 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 of the breeding pairs 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 available at the beginning of nesting season (see Methods) – of 37% over the 16 year period. Because the availability of nesting sites currently limits population recruitment, a monotonically positive relationship has been observed between the number of new chicks recruited and the number of available nest trees. Nest tree loss thus translates directly into reduced recruitment of new chicks the following year. Extensive human disturbance, some of it induced by adverse storm-related income shocks to peoples' primary livelihood, critically impedes the hornbill chick production rate (16, 17, 24).

BSP is also home to some of Thailand's poorest subpopulations. From the biennial household socio-economic survey (1998-2006), the poverty headcount rate (US\$1.25/day/capita poverty line) in six predominantly Muslim, ethnic minority villages in Narathiwat Province ranged from 43%-89% with village-averaged real monthly per capita consumption of only \$38 over the survey period (Table S1). These populations are poor by virtually any standard. 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 number of

households relying on rice farming and other subsistence crops on agricultural lands, the vast majority of them within BSP even though the park itself was gazetted in 1999. Active Muslim separatists operating in the area since 2004 have raised serious insecurity threats to outside businesses and tourists, which in turn limits rural households' access to modern infrastructure reinforcing their heavy dependence on agriculture and forest-based livelihoods. The severe cyclone year 1998 also brought the lowest village average real monthly consumption 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, collecting forest products 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 optimal modification of unsuitable nests and replacement of irreversible nest losses using artificial nests, which have proved an effective substitute for natural nests, yielding an average 26% chick production rate per unit installed (16,17).[§] To date, THP has relied on private donations, mainly through Hornbill Family Adoption Program, to finance these community-based efforts, engaging at least 13 villages surrounding BSP. Installation of artificial nests is, however, very costly as it involves both nest materials as well as labor for installation, monitoring and regular local maintenance. The pace of fundraising thus limits the rate of restoration of nesting capacity and therefore chick recruitment in the aftermath of severe windstorm shocks.

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. These behaviors necessarily sow distrust between the conservation community and area residents. In the next section we explore the possibility of developing an insurance instrument to address windstorm shocks in a manner that might cushion both local peoples and hornbills while also transforming the relationship between humans and the park in the wake of natural disasters.

[†] Before THP was established in 1994, poaching of hornbill chicks for illegal pet trading was very common in BSP (16, 17). Poaching has subsequently fallen as THP has involved local villagers, especially known poachers, in research and conservation activities, has built local awareness of the economic value of hornbills (e.g., via employment by the program or in ecotourism) and has used community-based mechanisms to help local authorities enforce poaching laws (20, 21, 22). Today, illegal logging, forest clearance for cultivation, forest products extraction that shrink the forest habitat and deplete natural food sources are probably the key sources of human disturbance to hornbill reproduction in BSP, decreasing the suitability of nest trees and nesting conditions as well as feed availability (17, 23).

[‡] 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, wind and water damage to stored grain, and diversion of labor effort to repairing homes and local infrastructure. This 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 forestry and hunting, reflecting the local population's coping response in the aftermath of storms that disrupted primary agricultural livelihoods.

[§] According to (17), 19 artificial nests have been installed in BSP from 2006-2009, resulting in an average of 5 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 so as 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 the Hornbill Research Foundation, <http://en.thaihornbill.org/>.

Results

The magnitude and intensity of windstorm related shocks in each nesting year t (starting in February) are represented by two key variables: annual maximum wind speed, w_t , and cumulative monthly maximum wind speed above the 30-year monthly average, cw_t , constructed from 1980-2009 data from the weather station closest to BSP (see 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 and a maximum of 40 knots 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 captures the cumulative intensity of repeated strong winds; the three-decade maximum also occurred in 1989 (Table S2).

Severe storm events usually occur during the rainy season, right after the conclusion of that year's nesting cycle 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. The severe windstorms and storm-associated rainfall patterns also disrupt human livelihoods and consumption during and following the storms. Storm-triggered consumption shocks could further induce household anthropogenic pressure on hornbills and their habitat, further depressing chick production rate in the following breeding cycle. These interrelated nest tree, hornbill population and human consumption dynamics and the resulting dynamic impacts of storm events can be formalized as a system of equations (Methods and Fig. S4), which motivates the logic and design of our index insurance product. Those equations can be used to simulate impact of this insurance contract on the coupled dynamics of the BSP human-managed ecosystem. In order to do so, we first must establish the statistical relationship among the key variables describing this system.

Windstorm Risk, Hornbill Reproduction and Rural Consumption

Annual data on percentage nest tree loss (l_t) and hornbill chick production rate (s_t) were constructed from 1994-2009 data obtained from THP (see 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 statistically 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 ε_t^l represents risk due to other factors. If the estimated function $\hat{l}(\omega_t)$ 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 in the region.

An endogenous regime switching model was used in this estimation. This allows us to estimate two separate relationships conditional on how badly the area was hit by strong winds each year, determined by a threshold annual maximum wind speed endogenously identified using minimum sum of squared errors criterion:

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

Table 1 reports estimation results based on 16 years' annual data. The optimal $\kappa = 25$ knots, 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 ($R^2 = 90\%$, $n = 16$). Nest tree losses in the light winds regime are difficult to explain, with no statistically significant relationship between any wind speed regressor and nest tree loss and with only 52% adjusted R^2 in the regime-specific linear regression estimation. This 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 annual maximum wind speed has a very strong, statistically significant positive effect on rate of 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 effective 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 model performance evaluation. As an alternative, we compare the predicted rate of nest tree loss constructed based on historical 30-year wind speed data with the evidence from three severe storm events that hit the region since 1980. Fig. 1A shows that the predicted storm-related nest tree loss $\hat{l}(\omega_t)$ quite accurately captures these events, predicting high rates of nest tree losses in storm years – 28% in the 1989 and 12-15% in the tropical-storm years 1982, 1984 and 1998 – while predicting less than 10% losses for years without severe storms. Based on 1994-2009 rates of nest tree loss, in-sample prediction errors are less than 2% in absolute terms. Over- and under-predictions are apparent in the normal years, when wind speed is less correlated with nest tree loss, while the predicted storm-related nest tree loss explains virtually all nest tree loss during the tropical storm year of 1998. The estimated regression function $\hat{l}(\omega_t)$ therefore 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 real monthly consumption per capita in six villages collected biennially from 1998-2006 (See Methods, Table S1). A linear least squares regression that decomposes village consumption 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 on human consumption, cw_t has a strong, statistically significant negative effect on consumption. While single severe storms have 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. 1B, predicted village consumption based on wind speed explains actual consumption patterns quite well in sample; prediction errors are always less than \$5/month in absolute terms. Doubling cw_t (approximately one standard deviation above the mean) leads, on average, to a 35% reduction in village consumption.

The data strongly indicate that high winds hurt both hornbills and humans in BSP. Furthermore, because windstorms stress human 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 years of overlapping data in 1998-2006, there is a high bivariate correlation coefficient, 0.52 ($n=5$), between village average consumption, $Y_{v,t}$, and hornbill chick

production rates in the following year, $s_{t+1}(Y_{v,t}, \omega_t, \varepsilon_{t+1}^s)$. 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 hornbill chick production rate and the vector of wind speed variables in the current year according to:

$$s_{t+1}(\omega_t, \varepsilon_{t+1}^s) = s(\omega_t) + \varepsilon_{t+1}^s \quad (3)$$

The estimated effect of wind speed on chick production the following year captures the joint effects of human disturbance induced by windstorm shocks as well as non-anthropogenic 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 – which reduced hornbill chick production by 25%, on average – the regression model explains the chick production rate well, with an adjusted R^2 of 73% ($n = 16$). A very strong, statistically significantly 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 – which directly affects hornbill reproduction – and on rural livelihoods and suggest strongly 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, an annual index insurance contract can be designed based on a predicted nest tree loss index specified as a function of wind speed data observed throughout the year, $\hat{l}(\omega_t)$. We now explain how such a contract might be designed to address both conservation and poverty reduction objectives.

At the beginning of each nesting year, THP can insure any number of nest trees, T , against storm-related loss so that in a year of extreme winds, when $\hat{l}(\omega_t)$ exceeds a level specified in the contract, a year-end indemnity payout can finance community-based efforts for timely installation of artificial replacement nests prior to the start of the next nesting season. Pre-financing nest restoration program using the index insurance allows THP to replace lost nesting capacity quickly, so as to stabilize hornbill recruitment the following season. Because severe windstorms typically occur during the rainy season just prior to nesting, prompt restoration of viable nesting cavities is essential (Fig. S3). Contractually triggered indemnity payouts can significantly accelerate installation of artificial nests relative to the current practice, in which fundraising begins after storm damage has been documented.

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 $\hat{l}(\omega_t)$ relative to a contractually specified strike rate for nest tree loss (l^*) – the maximum uninsured loss, like a deductible on conventional insurance contracts – can be written as

$$\Pi(\hat{l}(\omega_t), l^*, T) = \max(\hat{l}(\omega_t) - l^*, 0) \cdot c \cdot T \quad (4)$$

where c represents nest replacement cost per tree, assumed to encompass both the artificial nest (approximately \$400) and the cost of installation and monitoring by the local community (currently about \$600 per year) (17).[§]

Table 2 analyzes wind-based index insurance for hornbill conservation at various strike levels, beyond which indemnity payments are assumed proportional to the predicted nest tree loss. 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 long-term mean (3%). This compares to 20% (13%) payout frequency for contracts with a strike level one or two standard deviations 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.

We computed an actuarially fair premium rate for this insurance contract, quoted as a percentage of the total replacement cost of insured nest trees, using the traditional burn rate approach based on thirty years' historical wind speed data. Table 2 shows that the fair premium rates vary from 2.9% of insured value for the highest coverage contract (with a 3% strike) down to only 0.9% for the 11% strike contract offering only catastrophic coverage. At an estimated total replacement cost of \$1,000 per insured nest tree, the total annual premium cost (\$) 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 real-time in order to update the predicted nest tree loss index, $\hat{l}(\omega_t)$, continuously. In the event of one or more extreme windstorms leading to predicted loss beyond the strike level at the end of the coverage year, the contract would trigger an indemnity payment from the insurer to the conservation project, enabling prompt replacement of lost trees with artificial nests. This contrasts sharply with prevailing practice, which requires THP to mount a time-consuming and costly appeal to finance artificial nest installation. The resulting delays can cause one or more hornbill species to miss a breeding season.

Since 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 and the chick production rate. The strong joint correlation between high winds, nest tree losses and livelihood losses permits state-conditional payments for work targeted at rehabilitating hornbill habitats in the wake of a storm event. This design uses the insurance contract to finance a safety net employment program; best practices for such programs are now well established (27).

What effects could one reasonably expect from wind-based index insurance contracts? We simulated the expected effects on hornbill populations and monthly per capita consumption levels in rural villages around the park under the 3% and 11% strike level contracts (see 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 to the no-insurance counterfactual that prevails currently. Fig. 2A plots the cumulative distribution of predicted annual hornbill population sizes in 1000 replications of 100-year 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 noticeably 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 consumption shocks. Assuming that indemnity payment per insured nest tree goes to a representative villager at the rate of \$600/year (\$50/month) – the labor share of current nest replacement costs – multiplied by the payout rate realized at the end of the insured year, Fig. 2B plots the cumulative distribution of monthly per capita consumption, again based on 1000 replications of 100-year 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. We note that these simulations do not include any induced reduction in anthropogenic pressure on hornbills caused by providing an alternative buffer for local human populations that might otherwise prey on hornbills and their natural habitats to cope with shocks. This potential indirect effect could offer additional protection to hornbill populations.

Discussion

Covariate weather risk threatens people, keystone species and the ecosystems they regulate. Index insurance, while 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 novel opportunity to use modern financial risk

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

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 exists sufficient high-quality longitudinal data on an insurable interest (e.g., nest trees, monthly consumption) and a reliable weather or other 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 new instruments must undergo rigorous ex post impact evaluation.

Methods

Data

Hornbill data from 1994-2009 were obtained from THP, which involved local communities in locating all nesting cavities, monitoring them throughout the nesting season and checking for nest tree losses immediately after rainy season, prior to the nesting season of the following year (see 16 and 17 for detailed methodology on data collection). From these data we constructed (i) percentage annual nest tree loss (l_t) by dividing total nest tree losses in nesting year t by total nest trees available at the beginning of that nesting year, and (ii) chick reproduction rate (s_t) by dividing number of chicks successfully produced during nesting year t by the total nest trees available at the beginning of that nesting year.

Household livelihood and consumption data come from the household socio-economic surveys conducted biennially by Thailand National Statistical Office, 1998-2006. A stratified two-stage sampling design is used with fifteen households randomly sampled for all the sampled villages. While sampled households are not the same each year, there are some villages with repeated surveys for every round. We used village-level measures as repeated observations, constructed as pseudo-panel data using household data from the six rural villages in Narathiwat Province with recorded surveys in all rounds. Household consumption (\$) included total cash and in-kind expenditures on food, education and health. Real household consumption was calculated using 2006 as the base year (Table S1).

Monthly maximum wind speed data (w_m) from 1980-2009 were obtained from the Narathiwat Meteorological station. We constructed two key wind variables for each nesting year t (February-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-year monthly average ($\bar{w}_m$): $cw_t = \sum_{m \in t} \max(w_m - \bar{w}_m, 0)$.

Dynamic Framework and Simulations

Hornbill population dynamics can be described by the following system of dynamic equations

$$\begin{aligned} T_{t+1} &= (1 + \bar{g} - l(\omega_t, \varepsilon_t^l)) \cdot T_t \\ R_{t+1} &= s_{t+1}(Y_{v,t}(\omega_t, \varepsilon_{v,t}^y), \omega_t, \varepsilon_{t+1}^s) \cdot \min(b\delta B_{t+1}, T_{t+1}) \end{aligned} \quad (5)$$

$$B_{t+1} = (1 - \bar{m}) \cdot B_t + R_t$$

where the total nest trees observed at the beginning of the following nesting year, T_{t+1} , evolves from T_t at a constant rate $\bar{g}$ per year adjusted by rate of nest tree losses over the current year, $l(\omega_t, \varepsilon_t^l)$ due to winds, ω_t , and other shocks, ε_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 the constant b representing average nest trees needed per potential breeding pair and δ representing the constant proportion of adult breeding pairs in the total hornbill population observed at the beginning of next year, 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 strategy 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 human consumption levels $Y_{v,t}(\omega_t, \varepsilon_{v,t}^y)$ in surrounding rural villages. Recall that human consumption is affected by storm events late in year t , as well as other shocks to consumption, $\varepsilon_{v,t}^y$. The chick production rate is also conditioned by occurrence of storm events during the current year and other stochastic shocks to chick production rate, ε_{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, $\bar{m}$.

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

$$T_{t+1}^{insured} = (1 + \bar{g} - l(\omega_t, \varepsilon_t^l)) \cdot T_t + \max(\hat{l}(\omega_t) - l^*, 0) \cdot T_t \quad (6)$$

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

$$Y_{v,t}^{insured} = Y(\omega_t, \varepsilon_{v,t}^y) + \max(\hat{l}(\omega_t) - l^*, 0) \cdot c \quad (7)$$

Fig. S4 depicts how index insurance affects these dynamics. Wind-based index insurance affects hornbill population dynamics through two paths. First, it protects the availability of nest trees necessary for hornbill reproduction in the following nesting season. Second, by buffering local consumption, it reduces human disturbance that otherwise reduces chick production the following nesting season. We evaluate the performance of this insurance product by simulating 1000 replications of 100-year time series of nest tree, hornbill populations and village consumption dynamics using the parameters in Table S3.

Acknowledgements

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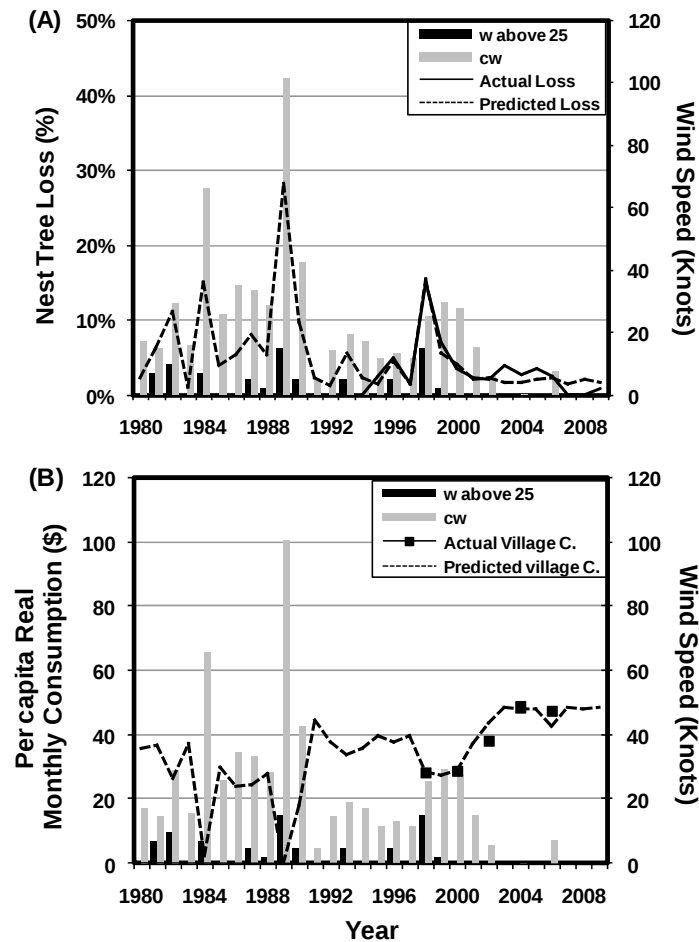


Figure 1: Relationship between wind speed variables and (A) Nest tree loss (%) and (B) Village-averaged monthly consumption per capita. w above 25 represents annual maximum wind speed above 25 knots. Predicted values are constructed from 1980-2009 wind speed data based on the regression results in Table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

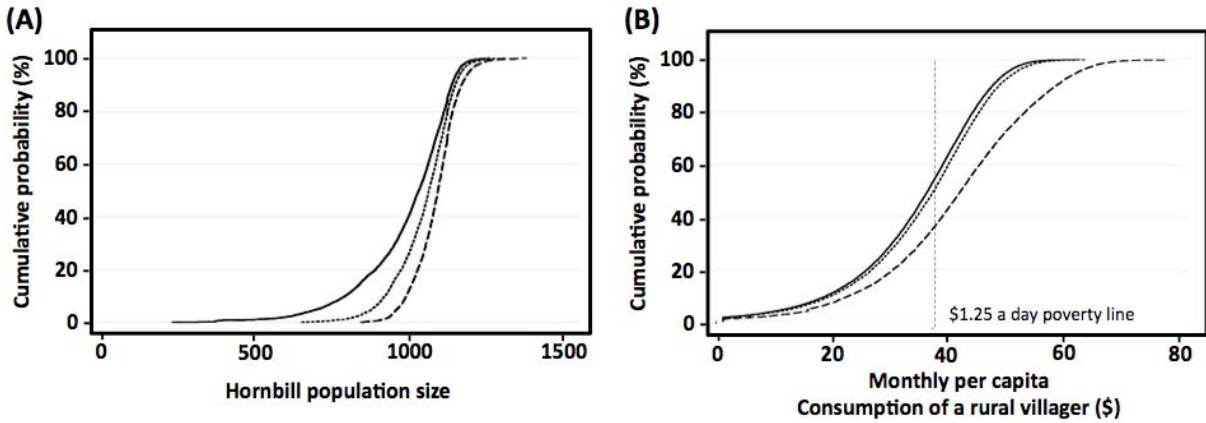


Figure 2: Effects of Wind-Based Index Insurance on Hornbill Population and Rural Livelihood. Panels (A) and (B) represent cumulative distributions of hornbill population size and per capita monthly consumption of rural households, who participates in the hornbill conservation project, respectively, observed annually from 1000 simulated replications of 100-year 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.

Table 1: Regression Estimates of Windstorm Effects on Nest Tree Loss, Rural Village Consumption and Hornbill Chick Production Rate

Explanatory Variables	Annual nest tree loss (l_t) (% of nest trees)				Village consumption per capita ($Y_{v,t}$) (monthly \$)		Following year's chick production rate (s_{t+1}) (% of nest trees)	
	$w_t \geq 25$		$w_t < 25$					
	Coef.	SE	Coef.	SE	Coef.	SE	Coef.	SE
Max windspeed, w_t (knots)	-0.0052***	(0.0013)	0.0003	(0.0032)	-0.1250	(0.1637)	-0.0034	(0.4000)
Max windspeed squared, w_t^2	0.0002***	(0.0000)	0.0000	(0.0002)				
Cum.abv.avg.max 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

Notes: Robust standard errors 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.

Table 2: Wind-based Index Insurance for Hornbill Conservation

Strike (l^*)	Frequency of indemnity payment: $Pr(l(\omega_t) > l^*)$	Frequency of correct indemnity trigger decision	Fair annual premium rate (% replacement cost insured nest tree)	Annual premium (\$) per insured nest tree (at $c = \$1000$ 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

Note: Strike levels are set at the mean (3%), one (7%) and two (11%) standard deviations above mean actual rates of nest tree losses, respectively.

Supporting Materials

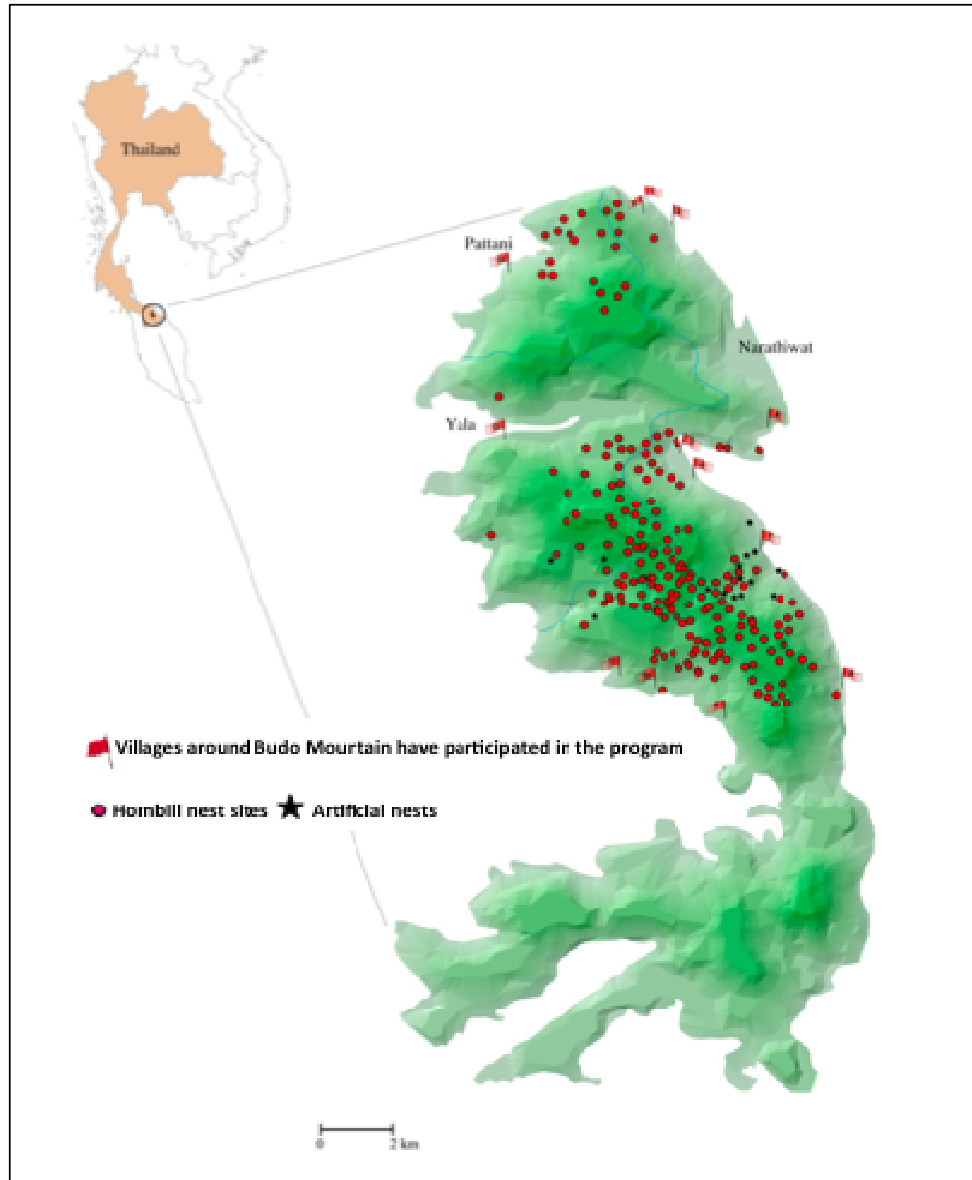
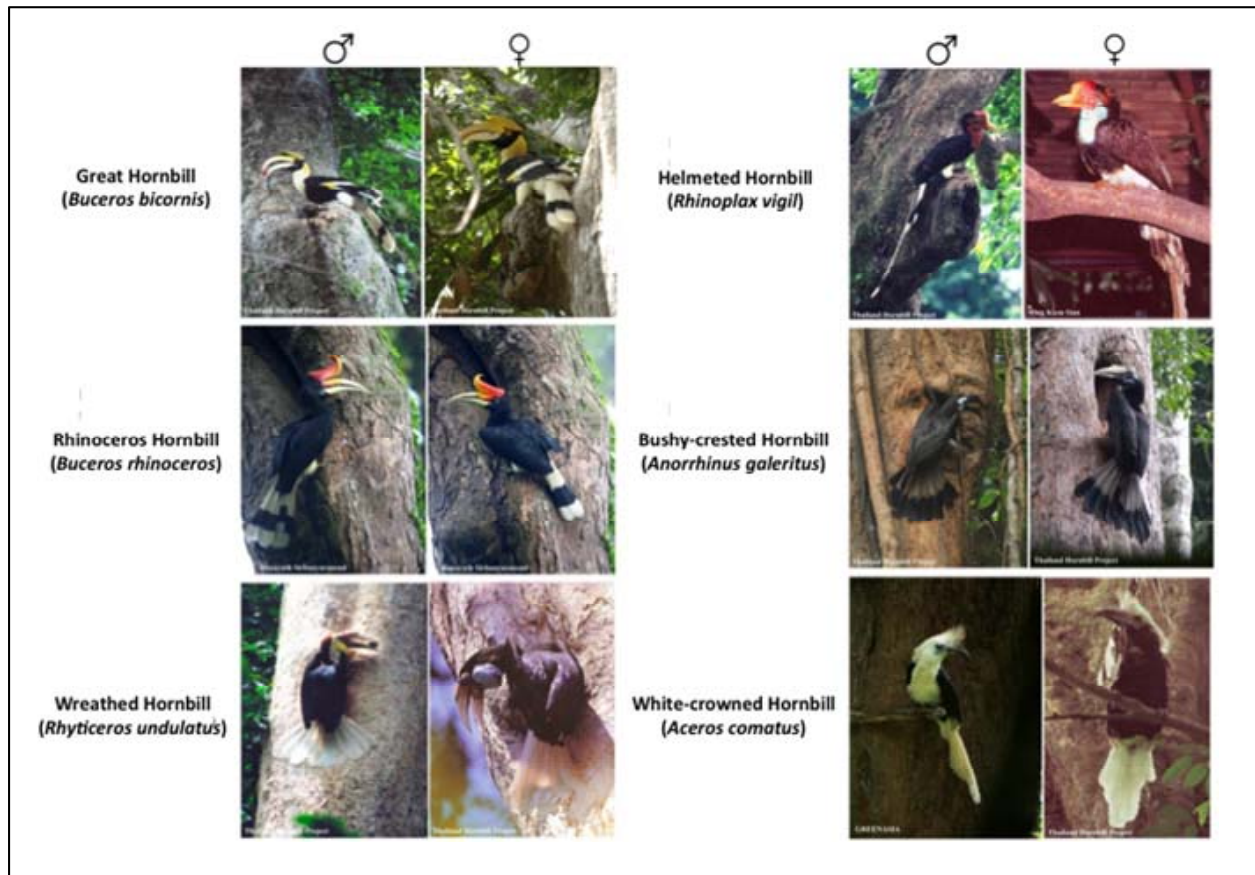


Figure S1: Study Area in Budo Sungai Padi Mountain (90 km²), Southern Thailand.

The map, provided by Thailand Hornbill Project, shows available of nest trees and artificial nests observed at the beginning of 2009 in the study area in Budo Sungai Padi National Park (6°0'–40'N and 101°30'–55'E) located mainly in Narathiwat province.



Hornbill Species	Avg. Body mass (g) male/female	Avg. Breeding Cycle (day)	Status of Species	
			National	Global
Great (<i>Buceros bicornis</i>)	2950/2180	112	Near threatened	Near threatened
Rhinoceros (<i>Buceros rhinoceros</i>)	2580/2180	118	Endangered	Near threatened
Helmeted (<i>Rhinoplax vigil</i>)	2500/-	154	Endangered	Near threatened
Wreathed (<i>Rhyticeros undulates</i>)	2515/1950	123	Near threatened	Least concern
Bushy-crested (<i>Anorrhinus galeritus</i>)	1172/-	95	Near threatened	Least concern
White-crowned (<i>Berenicornis Comatus</i>)	-/1470	99	Vulnerable	Near threatened

Figure S2: Six Hornbill Species Found in Budo Sungai Padi National Park.

Sources: (28)-(31).

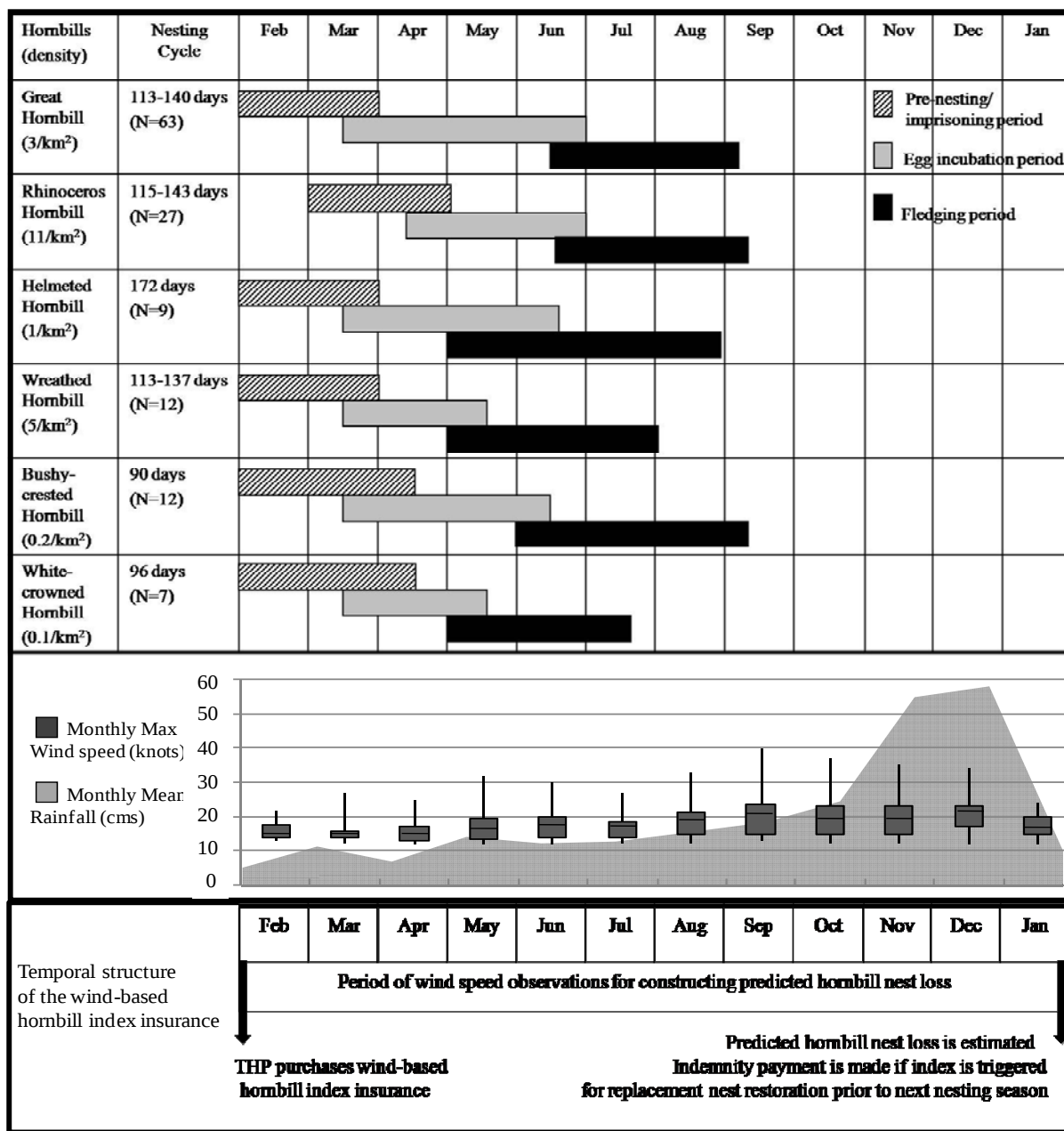


Figure S3: Summary of Nesting Cycles, Density of Hornbills, Weather Seasonality in Budo Sungai Padi National Park and Temporal Structure of Wind-based Index Insurance for Hornbill Conservation. Nesting cycle patterns for the six hornbill species are constructed based on (15, 16, 17, 32, 33). Hornbill population densities are estimated from point count surveys using the Distance 5.0 software (34). The 120 points were located on 12 transects within the study area. Observers walked along the transects, stayed at each point for 5 minutes, counted and recorded sighting or vocal detection along with angle from observer to the bird(s) and distance between observer and bird(s). The counts had been made between 2004-2006 by repeating in 3 breeding seasons for 5 replicates, and 5 in 3 non-breeding seasons, accounting cumulatively for a total of 1200 efforts/points. Long-term average maximum wind speed and monthly rainfall are constructed from 30-year historical data (1980-2009) from Narathiwat Meteorological Station. There are two main sources of strong winds that strike southern peninsular in Narathiwat Province during the sensitive monsoon seasons: the southwest and northeast winds from the Pacific and Indian oceans, respectively.

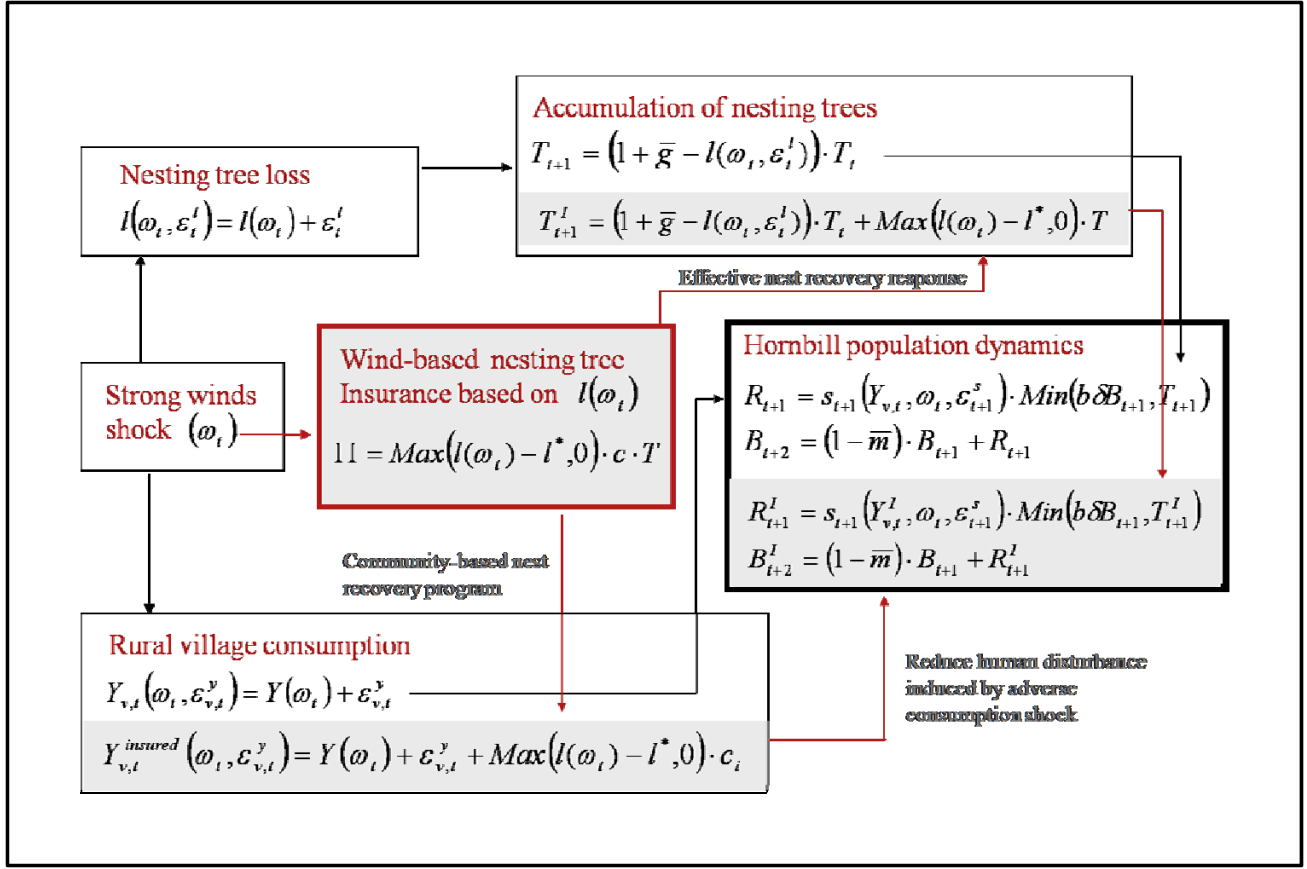


Figure S4: Schematic of How Wind Based Index Insurance Alters Hornbill Population Dynamics. Strong wind shocks (center left) initiate reactions both through nest tree losses (upper left) and reduced human consumption in villages within the forest region (lower left). Wind-based index insurance (center) alters population dynamics as reflected in the shaded portions of boxes, showing restoration of nesting capacity (the second term in the shaded option in the upper right box) and indemnity payments (at least partially) passed through to villagers (the second term in the shaded option in the lower left box). This dynamic framework implies that wind-based index insurance positively affects hornbill population dynamics through two different paths (both shown in the last two terms in the shaded option in center right box). First, it directly protects the nesting capacity necessary for hornbill reproduction in the following nesting season (in the second term on the right hand side of the third shaded equation in center right box). Second, by buffering local consumption, it reduces human disturbance that otherwise reduces hornbill chick production rate in the following nesting season (in the first term on the right hand side of the third shaded equation in center right box)

Table S1: Summary Statistics of Household Livelihoods in Rural Villages of Narathiwat

<i>Livelihood Variables</i>	1998	2000	2002	2004	2006	Average
Real Monthly consumption per capita (\$)	\$28	\$29	\$38	\$48	\$46	\$38
Monthly economic income per capita (\$)	\$34	\$24	\$31	\$50	\$58	\$39
Poverty headcount (\$1.25/day poverty line)	89%	85%	70%	43%	45%	66%
Poverty gap (\$1.25/day poverty line)	30%	30%	24%	12%	12%	22%
<i>Main livelihood (% of village households)</i>						
Farm operation (own or rented land)	31%	34%	13%	12%	21%	22%
On-farm laborer	32%	30%	27%	35%	20%	29%
Off-farm laborer	0%	0%	10%	13%	12%	7%
Salaried employment	19%	17%	26%	28%	30%	24%
Entrepreneur	11%	10%	15%	7%	12%	11%
Economically inactive	7%	9%	9%	5%	6%	7%
<i>Main agricultural production (% of households with main livelihood in agriculture; both farm operator and laborer)</i>						
Fruit, permanent crops and shrub crops	68%	73%	52%	57%	78%	66%
Rice farming	12%	6%	23%	11%	8%	12%
Other crop farm and vegetable	11%	9%	12%	14%	5%	10%
Livestock and other animal productions	4%	7%	7%	11%	3%	6%
Fishery, forestry and hunting	5%	5%	6%	7%	9%	6%
<i>Income share (% of total economic income)</i>						
Crop production (rice, all crops and vegetables)	46%	54%	36%	38%	34%	42%
Livestock	11%	10%	5%	7%	4%	7%
Fishery, forestry and hunting	8%	5%	3%	3%	4%	5%
Other non-farm income	35%	31%	56%	52%	58%	46%

Note: Data are derived from the household socio-economic surveys conducted biennially by Thailand National Statistical Office, from 1998-2006, in every Province of Thailand. A stratified two-stage sampling design is used with fifteen households randomly sampled for all the sampled villages. While sampled households are not the same each year, there are some villages with repeated surveys for every round. Thus, we used village-level measures as repeated observations to construct pseudo-panel data from the six rural villages in Narathiwat Province with recorded surveys in all rounds. Summary statistics were thus averaged across these six villages. Household consumption (\$) includes total cash and in-kind expenditures on food, education and health. Real household consumption was calculated using 2006 as the base year. Household economic income (\$) includes cash and in-kind income from all sources, unpaid food, goods and services and remittances. Using with international standard \$1.25/day poverty line, poverty headcount measures the percentage of sampled households with economic income below that poverty line. Poverty gap measures the mean distance below the poverty line as a proportion of the poverty line, where the mean is taken over all sampled households, counting the non-poor as having zero poverty gap. Main livelihood and agricultural production represent the percentage of households with a majority of members engaged in these activities.

Table S2: Summary Statistics of Hornbill Reproduction and Weather Variables

Variables	Mean	SD	Minimum	Maximum	Obs.
Total nest tree availability (trees)	90	30	37	122	16
Annual nest tree loss (%)	3%	4%	0%	15%	16
Annual chick production (% of nest trees)	37%	12%	22%	57%	16
Official forest clearance for agri.(=1 if yes)	0.19	0.40	0.00	1.00	16
Maximum windspeed, w_t (knots)	25	7	15	40	30
Cumulative above average monthly maximum windspeed, cw_t (knots)	20	21	0	101	30

Table S3: Summary Statistics of Simulation Parameters

<i>Hornbill population dynamics</i>	<i>Parameter</i>
Adult mortality rate (%) (m)*	2%
Breeding adult male/female in total population (%) (δ)	30%
Nest trees needed per potential breeding pair (trees) (b)	0.13
Initial hornbill population size for the 6 species (B_0)	1096
<i>Nest tree dynamics</i>	<i>Parameter</i>
Initial nest tree availability (trees) (T_0)	90
Maximum nesting capacity, i.e., maximum available nest tree (trees)	150
Annual growth rate of nest tree (%) (g)	5%
<i>Wind based index insurance (at fair premium rate)</i>	<i>Contract Parameter</i>
Replacement cost per unit of insured nest tree (\$) (c)	\$1,000
Indemnity payments that go to a participating villager (\$) (c_i)	\$50/month (\$600/12)
Total number of insured nest tree per nesting year t (trees)	T_t
<i>Wind storm and non-wind storm related risk</i>	<i>Empirical distribution (Mean, SD, Min, Max)</i>
Max windspeed (knots), w_t	Log Normal (25.0, 6.6, 1.0, 51.0)
Cumulative above average monthly max windspeed (knots), cw_t	Extreme Value (19.6, 16.9, 0, 160.0)
Nest tree loss not explained by wind (%), ε_t^l	Normal (0%, 1%, -2%, 2%)
Chick production not explained by lagged windstorm (% nest tree), ε_t^s	Normal (0%, 5%, -7%, 11%)
Village consumption not explained by wind storm (\$), ε_t^y	Normal (0, 7.3, -27.6, 26.4)
<i>Predicted nest tree loss, chick production and village consumption</i>	<i>Statistics (Mean, SD, Min, Max)</i>
Predicted nest tree loss index (%), $l_t(\omega_t)$	(5%, 6%, 10%, 28%)
Predicted chick production (% of nest trees), $s_{t+1}(\omega_t, \varepsilon_{t+1}^s)$	(37%, 10%, 20%, 51%)
Predicted real per capita monthly consumption (\$), $Y_t(\omega_t, \varepsilon_t^y)$	(35.1, 12.7, 0, 73.6)

Note: The initial hornbill population size is based on the estimated population density from surveys conducted during 2004-2006 based on point count surveys using the Distance 5.0 software (34). Total density of all the 6 species of 20.3 birds per km² (Fig. S2) are multiplied by 60% of 90 km² studied area to represent total population size. 60% was chosen to correct for the potential overestimation of estimated population density as sighting data were insufficient to fit detection function due to smaller number of survey points that could be established within small studied area. Mean number of available nest trees was used as an initial nest tree availability, while maximum number of nest trees plus one standard deviation was used as a maximum nesting capacity. To the best of our knowledge, (15) is the only study that conducts a population analysis using simulation based on a six year study of Red-knobbed and Sulawesi Tarictic Hornbills in lowland rainforest in Sumatra, Indonesia, for life history parameters, demography and reproduction statistics (35,36). Without empirical data on adult mortality, they assume the mortality schedule that would maintain an expected net population growth rate of zero, following the observation that hornbill density in the study area has changed little in 20 years (37). Our assumptions for m and δ thus follow (15) and so $m = E(\text{total chicks reproduced/year})/1096$. Assumptions for b, B_0, T_0 and g are based on the observed reproduction data (1994-2009). Nest trees needed per potential breeding pair (b) can be calculated as $b = E(\text{total nests used by a pair each year})/(0.3 \times 1096)$. A fixed annual growth rate of nest trees can be calculated as $g = E(\text{annual nest losses} (\%))$. The distributions of wind storm and non-wind storm risk are estimated as best-fit distributions of the observed historical series, estimated with their original covariance structures (omitted here but available on request from the lead author) using @Risk program with chi-square fitness criteria.

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