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Measuring the Impact of the Pet Trade on Indonesian Birds

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Abstract

The trade in wild animals involves one third of the world's bird species and thousands of other vertebrate species. While a few species are known to be imperiled as a result of the wildlife trade, the lack of field studies makes it difficult to gauge how serious a threat it is to biodiversity. We combined data on changes in bird abundances across space and time with trapper interviews to evaluate the effects of trapping wild birds for pets in Sumatra, Indonesia, an international pet trade hotspot. In southern Sumatra we analyzed bird abundance changes over time using a rare 14-year dataset of repeated bird surveys from the same extensive forest. In northern Sumatra we surveyed birds along a gradient of trapping accessibility, from the edge of roads to five km into the forest interior. We also interviewed 49 bird trappers in northern Sumatra to learn which species they target and how far they go into the forest to trap. We found that market price was a significant predictor of species declines over time in southern Sumatra, implicating the pet trade in those declines. In northern Sumatra, we found no relationship between price and change in abundance as a function of remoteness. However, high-value species were rare or absent across our surveys there. Notably, the median maximum distance trappers went into the forest each day was 5.0 km. This suggests that trapping has depleted bird populations across our remoteness gradient. Alarmingly, we found that less than half of Sumatra's remaining forests are >5km from a major road. These results indicate that trapping for the pet trade is a threat to birds in Sumatra. Given the popularity of pet birds across Southeast Asia, additional studies are urgently needed to determine the extent and magnitude of the threat posed by the pet trade.

Introduction

The trade in wild animals is worth billions of dollars annually (Wilson-Wilde 2010) and encompasses one third of the world's bird species and thousands of reptile, amphibian, mammal, and fish species (e.g. Carpenter et al. 2004; Nekaris & Jaffe 2007; Butchart 2008; Maldonado et al. 2009; Nijman & Shepherd 2010; Rosen & Smith 2010; Alves et al. 2013; Raghavan et al. 2013). A small number of species have been added to the IUCN Red List of imperiled species due to trapping for the pet trade (e.g. Spix's macaw *Cyanopsitta spixii* in South America; Bali myna *Lecopsar rothschildi* , greater slow loris *Nycticebus coucang*, and red line torpedo barb *Sahyadria denisonii* in Asia; and radiated tortoise *Astrochelys radiata* in Madagascar) (Collar et al. 1992; IUCN 2015), but they constitute severe cases involving well-studied species. Scientists have not assessed the impact of the pet trade on wild populations for the vast majority of vertebrates sold in markets.

Southeast Asia is a global hotspot for the wild bird trade; >1,000 species are sold (authors' unpubl. data) for pets, song competitions, religious animal release, traditional medicine, and food (McClure & Chaiyaphun 1971; Nash 1993; Shepherd et al. 2004; Jepson 2008; Chng et al. 2015; Harris et al. 2015; Su et al. 2015). Indonesia is the largest importer and exporter of wild birds in Asia (Nash 1993). Indonesian bird trappers use mist nets, bird lime, snares, and traps baited with decoy birds to catch target species (Shepherd et al. 2004), with mist nets becoming increasingly popular (authors' pers. obs.). The deep cultural roots of bird keeping in Indonesia have contributed to the country's active bird trade, while human population growth and the rise of bird song competitions have intensified the pressure on Indonesia's wild birds (Jepson 2010). For example, the highly prized straw-headed bulbul *Pycnonotus zeylanicus* is now extirpated in Java and Sumatra, and in steep decline in Indonesian Borneo (Shepherd et al. 2013; BirdLife International 2015; J. A. Eaton pers.

comm.). Many wild birds of multiple species sold in Javan markets are now sourced from Sumatra because trapping has depleted Javanese bird populations (Jepson & Ladle 2009; Shepherd 2012).

In Sumatra and Java, the ubiquity of trapping, including inside national parks, complicates efforts to assess the impact of the bird trade on wild populations. Possible ways forward are to (1) analyze time series of systematic survey data, which are very scarce in Indonesia, (2) study how bird abundance changes across remoteness gradients, which can serve as proxies for trapping intensity, or (3) use population models to estimate extinction risk based on an estimate of the number of birds caught and the species' life history traits. Given the lack of high quality demographic information for virtually all of Indonesia's wild bird species, we focused on the first two, field-based methods to examine the effects of trapping on bird communities in lowland and highland forests. We then related changes in bird abundance to species trait predictor variables to weigh the evidence for the relative effects of trapping, hunting, and habitat change. We also interviewed trappers to determine: (a) how far they typically travel in search of valuable birds and (b) their impressions of long-term changes in the catch rates of sought-after species. Finally, we estimated how much of Sumatra's forests may be safe from intensive trapping pressure. Given the high levels of trapping in Sumatra, we hypothesized that commercially valuable species would have declined over time and with increasing proximity to roads.

Methods

Study areas and field sampling

Way Canguk (Southern Sumatra)

We studied changes in bird abundance from 1998−2011 at the Way Canguk Research and Training Area, Bukit Barisan Selatan National Park, Lampung province, southern Sumatra (Figs. 1, 2). The Way Canguk area is one of the few remnants of lowland forest on level terrain in Sumatra (Whitten 2000; Miettinen et al. 2011). Way Canguk consists of 900 ha of lowland forest (50 m elevation, 4,000 mm annual rainfall) that includes primary forest (currently 50% of the area) and forest disturbed by fire, drought, and logging (Kinnaird & O'Brien 1998). El Niño-related drought and fires damaged approximately 165 ha of forest in 1997 and 1998 (Kinnaird & O'Brien 1998; Adeney et al. 2006). Adeney et al. (2006) studied the effects of the fires on birds from 1998−2002, and found that understory avian insectivore abundance was significantly reduced in burned areas versus unburned forest. They also found that open-field species had colonized burned areas. Way Canguk remained fire-free until 2015 , and the forest has recovered, although some exotic plants have invaded (Kinnaird & O’Brien 1998). The site has been subject to trapping for the bird trade since at least the late 1990s (O'Brien & Kinnaird 1996), and trapping has continued up to the present time despite the presence of a research station and national park staff. The most commonly used trapping methods we observed in Way Canguk were (1) attracting birds to branches covered in bird lime with a song recording or a decoy bird in a cage, (2) mist nets combined with decoys or recordings, and (3) snares for catching pheasants.

We quantified bird abundance at Way Canguk with 10-minute, unlimited radius visual and aural point counts in 1998−2002, 2007, and 2011 (Table S1; see Supporting Information for details). Sampling for this study was restricted to unburned forest and forest that experienced only light ground fires in 1997−1998. Light fires burned dead leaf litter and damaged saplings slightly (leaving most with green leaves); large trees were unaffected (Adeney et al. 2006). We included the lightly burned areas in our analysis so that we could increase our statistical power to detect changes in the avifauna over time.

North Sumatra

We sampled bird communities along remoteness gradients in the Tanah Karo region of North Sumatra province (Karo, Deli Serdang, Langkat, and Dairi regencies) from March to November 2013 (Fig. 1). We sampled two areas of humid montane forest, one near Mt. Sinabung in the north and another near Lake Toba in the south. These montane forests are important sources of wild birds for the Medan markets (Shepherd et al. 2004), and are therefore under heavy trapping pressure, but they also have remote areas far away from roads that may experience less trapping. In North Sumatra we encountered trappers using bamboo traps with live decoys, bird lime placed on perches near live decoys and in fruiting trees, and pheasant snares. Sampling at the northern sites was done before the 2014 eruption of Mt. Sinabung.

We sampled birds aurally by walking transects from 600−1030 AM in sunny or cloudy weather without wind or rain. Our transects were sections of forest trails that were approximately 400 m in length (along the trail) and separated by points that were spaced 300 m apart (straight line distance; Fig. 2). Transects were surveyed in March/April (n = 74), June (n = 28), and November/December (n = 54) of 2013. We used the number of minutes spent walking each transect as a measure of survey effort. Transect elevation was approximated by averaging the elevation of the points at each end of each transect. Elevations sampled ranged from 1018−1875 m (average = 1550 m) (Table S2). Approximately 92% of transects were in old-growth forests; the remaining transects were in secondary forests with large remnant trees. Open fields were not sampled. Remoteness was estimated by taking the straight-line distance from the center of the transect to the nearest major road (see Supporting Information for details). Transects ranged in remoteness from 0.1 to 4.9 km from the nearest road (average = 1.8 km). Our field sampling was done under RISTEK permit 75/SIP/FRP/SM/III/2013.

Species trait data

We related changes in abundance to species traits associated with three potential drivers of population change: the pet trade, subsistence hunting, and habitat change. We used market price as a proxy for demand for pets and, therefore, trapping pressure on a species (e.g. Crookes et al. 2005). Data on sale prices came from surveys in the four markets of Medan, North Sumatra from July-September 2012 (Harris et al. 2015). Medan has the largest and most diverse wildlife markets in Sumatra, with species coming from across the island and the rest of Indonesia (Shepherd et al. 2004; Shepherd 2006). A group of Indonesian researchers asked sellers for bird prices during the market surveys (initial asking price, not negotiated; Harris et al. 2015). This yielded multiple price estimates for most study species in the current analysis. When we had multiple prices we used the average price. . We used body size as a proxy for hunting pressure, assuming that hunters would be more likely to target large-bodied species (e.g. Cardillo et al. 2005). Body sizes were the average body mass from a global database of avian ecological traits based on the ornithological literature (see Sekercioglu et al. 2004; Sekercioglu 2012) and regularly updated with recent literature (del Hoyo et al. (1992-2009) and primary sources). We used habitat preferences as a proxy for tolerance to anthropogenic habitat disturbance, on a scale of 1 to 6. For example, species with a disturbance tolerance of 1 are found only in the interior of primary forest, species with a score of 3 are found in both primary and disturbed secondary forests, and species with a score of 6 are non-forest species. These scores were calculated by combining habitat characterizations from Wells (1999, 2007) with the expert opinion of one of the coauthors (see Supporting Information for more details).

In North Sumatra, drongos *Dicrurus* sp. and white-eyes *Zosterops* sp. were heard commonly, but we could not assign their calls to species. Because Sumatran drongo *D. sumatranus* and black-capped white-eye *Z. atricapilla* were the most commonly seen members of their respective genera in this area, we assigned the trait variables of those two species to the genus-level records.

Statistical analyses

We used hierarchical Bayesian models to simultaneously model changes in abundance over time (Way Canguk) and over space (North Sumatra) for each species, and to relate these parameters to species traits to weigh the evidence for drivers of change in abundance (Gelman et al. 2013). We limited analyses to the set of species for which we had complete data on these traits, specifically excluding species without price data (i.e., species that we did not find for sale in the Medan markets). We did not assume that species without prices were valued at $0, as prices were derived from current markets, and there are many reasons why species with non-$0 prices may not be present in current markets (due to supply or demand).

For both Way Canguk and North Sumatra, we modeled the expected change in abundance over time (or change in abundance with distance from road) for species i, $\mu_{\beta1,i}$, as a linear function of three variables representing distinct hypotheses:

$$\mu_{\beta1,i} = \alpha_0 + \alpha_1 \text{price}_i + \alpha_2 \text{disturbance tolerance}_i + \alpha_3 \text{body size}_i$$

For both sites, inference on the strength of each hypothesized driver of change was made by evaluating the sign, effect size, and 95th percentile Bayesian credible interval (BCI) of each of the slope parameters, α_1-α_3. All three variables were standardized to a standard deviation of 1 prior to modeling so that effect sizes would be directly comparable.

Although the general model structure and basis of inference is the same across the two locations, due to differences in data collection and other study-specific factors, the two models were parameterized slightly differently. For example, we controlled for transect elevation in North Sumatra in our estimates of $\mu_{\beta1,i}$ because sites there spanned a montane gradient, and bird abundance in Indonesia is related to elevation (e.g. Harris et al. 2014). We describe the overall Bayesian model structure as well as the differences between the two models in the Supporting Information.

In order to evaluate our statistical power to detect a trapping effect, we did two retrospective (a posteriori) power analyses. These analyses explored the probability of rejecting the null hypothesis that there is no relationship between market price and either temporal or spatial trends in bird abundance (H_0: $\alpha_1 = 0$), for Way Canguk and North Sumatra, respectively. In both cases, we used the posterior means for all other hyper-parameters (α_0, α_2, α_3, σ_α) and a range of values for α_1 in order to probabilistically simulate trends, $\mu_{\beta1,i}$, for each of the species in both data sets. In both cases, we simulated 5000 sets of $\mu_{\beta1,i}$ for each of 25 potential values of α_1, ranging from -0.01 to -0.25. We then ran a linear model (identical in parameterization to the formal analysis) on each simulated set of $\mu_{\beta1,i}$, looking at the proportion of simulations where H_0 would be rejected by finding a 95% confidence interval of $\alpha_1$that did not include 0.

Trapper interviews

Between March and July 2013 we interviewed 49 bird trappers in 21 villages in the Karo, Deli Serdang, and Langkat regencies of North Sumatra province. Trappers ranged in age from 24 to 61 years (average 39 years; see Supporting Information for more details; interview methods were approved by the XXX University Institutional Review Board for Human Subjects research; XXX URL). We asked trappers which species they seek, how much time they spend trapping them, and how much area they cover when looking for birds each day. We used these data to (1) approximate the proportion of Sumatra's forests that is out of reach of the average bird trapper, and (2) look at changes in catch of sought-after species over time.

For the first analysis, we asked each trapper to specify how many kilometers they covered each day in search of birds in order to approximate how far from villages or roads trappers go to catch birds. Based on their reported distances and our own observations of trapping in the field (e.g. bird snares, perches with bird lime remnants), we estimated the percentage of Sumatra's forests that were out of reach of an average trapper. We did this by comparing the area of mature forest (lowland, montane, peat swamp, and mangroves) (Miettinen et al. 2011) near primary roads (Peta Dasar Indonesia road layers; see Supporting Information) and away from roads in ArcGIS v. 10 (ESRI, Redlands, CA). Given that our database included only relatively major roads, our estimate of "safe" habitat is necessarily a conservative one.

For the second analysis, we asked all 49 trappers to rank bird species based on their perceptions of the birds' sensitivity to trapping (i.e. vulnerability to population decline from trapping). We asked trappers to consider whether a particular species is easy to deplete based on how easy a species is to catch and the ability of the species' population to recover from exploitation. We then analyzed the cases of the four most vulnerable species that occur (or

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once occurred) in the montane forests we sampled in North Sumatra to see if the time spent searching for and catching these species had changed over time. To gather data on these temporal trends we did in-depth interviews with seven experienced trappers (mean of 15 years trapping). We began this section of the questionnaire by showing the trappers photos of 54 regularly traded species (selected by reviewing the native birds that are most commonly traded in Medan (Shepherd et al. 2004; Harris et al. 2015)). When a trapper acknowledged catching the species in the photograph we asked him (all trappers were men) how long he spends searching for each species, how many he catches per day, and how these variables have changed over time. We used Gaussian mixed-effect models to test for statistical relationships between year and amount of time spent trapping, and year and the number of birds caught in the 'lme4' package in R (Bates et al. 2014; R Development Core Team 2015). We coded each trapper as a random intercept because trappers differed in their habits, and their responses cannot be considered independent. We used Nakagawa and Schielzeth's (2013) method of calculating marginal and conditional R^2 of the mixed models.

Results

Bird abundance

We recorded 154 species in Way Canguk, 78 of which had non-zero prices and were included in the analysis (we refer to these 78 species as "traded birds"). Based on posterior means of annual trends in abundance, 33 species of traded birds showed temporal trends in abundance (95% BCI for trends that did not include 0). Of these species, 23 increased over time, while ten decreased (Table S3). There was a significant relationship between current market price and the trends of species over time, with species with higher prices more likely to decline over time (95% BCI on α_1: -0.10 to -0.03). This effect size indicates that given a market price increase of c. $50 (527,706 Indonesian Rupiah), the log-change in abundance per year decreases by 0.03 to 0.10. Thus, above a market price of 500,000 Indonesian Rupiah (c. $50 US), species were more likely to have declined from 1998 to 2011 than increased (Fig. 3). Abundance trends of trapped birds at Way Canguk also showed the effects of forest succession, with forest-dwelling species that are intolerant of disturbance increasing over time (95% BCI on α_2: -0.10 to -0.03; Table 1; Fig. 3). The standardized effect size of price and habitat preference was approximately equal. There was no consistent evidence for a relationship between body size and population trend (a weak negative relationship, 95% BCI on α_3: -0.05 to 0.02).

In North Sumatra we recorded 70 bird species, of which 27 were bought and sold in markets ("traded species") and thus were used in the analysis. We found no significant relationships between price, disturbance tolerance, or body size and bird abundance along the remoteness gradients (all 95% BCI overlapped zero; Table 1; Fig. 4). There was a non-significant trend of larger bodied species being commoner away from roads (95% BCI: -0.07 to 0.23). One species was clearly more common away from roads: the bronze-tailed peacock-pheasant *Polyplectron chalcurum*, which is hunted regularly (Table S4). Although true relationships between abundance and remoteness were uncertain in nearly all cases, parameter means indicated that most traded species (21 of 27 species, or 78%; Table S4) were more common at greater distances from roads.

Both abundance models showed strong posterior predictive abilities, indicating good model fit (Table S5; Figs. S1, S2; see Supporting Information for details), but the data provided relatively low power to reject the null hypothesis that there is no relationship between market price and either spatial or temporal trends in bird abundance. For Way Canguk, where our empirical findings rejected the null hypothesis, a standardized effect size for α_1 would need to be at least -0.13 to reject the null hypothesis 80% of the time. Our empirical finding for Way Canguk was an effect size of -0.064, at which point simulations rejected the null hypothesis only 31.8% of the time (Fig. S5). In North Sumatra, where our empirical findings did not reject the null hypothesis, a standardized effect size for α_1 would need to be -0.20 or more extreme in order to reject the null hypothesis 80% of the time. Our empirical finding for North Sumatra was an effect size of -0.090, at which point simulations rejected the null hypothesis only 24% of the time (Fig. S6). The lower power for North Sumatra can be attributed to the lower number of traded species providing inference on trends.

Trapper interviews and spatial analysis

The median maximum distance covered by trappers in search of birds was 5 km (mean 7.7 km; n = 25 trappers who provided distance estimates). We also observed evidence of trapping (man-made perches with bird lime remnants) up to 4.9 km from the nearest road. Our spatial analysis found that 47.6% of Sumatra's remaining mature forests are within 5 km of a major road (Fig. 5).

Trappers caught 51 bird species and ranked the following species as especially sensitive to trapping (i.e., vulnerable to population decline, in descending order from extremely sensitive to highly sensitive): white-rumped shama *Copsychus malabaricus*, oriental magpie robin *C. saularis*, common green magpie *Cissa chinensis*, silver-eared mesia *Leiothrix argentauris*, Sumatran laughingthrush *Garrulax bicolor*, and chestnut-capped laughingthrush *G. mitratus*. Based on our field work and the trapper interviews, four of these species occur or once occurred (before heavy trapping) in the montane forests we sampled in North Sumatra: silver-eared mesia, common green magpie, and Sumatran and chestnut-capped laughingthrushes.

In-depth interviews revealed that experienced trappers are now expending more time searching for all four sensitive species than they used to in the 1970s and 1980s (Fig. S3; Table S6). Furthermore, daily catches of silver-eared mesia (which was once caught in large numbers) have fallen to nearly zero birds taken per day (only one trapper reported catching this species in 2013), and catches of the other three species showed non-significant negative trends (Fig. S4; Table S6). We did not observe silver-eared mesias or Sumatran laughingthrushes on any of our surveys.

Discussion

The most-frequently cited threats to Southeast Asian birds are habitat loss and hunting for food (BirdLife International 2008; Wilcove et al. 2013). Here we present multiple lines of evidence that indicate trapping for the pet trade is causing declines in populations of multiple Sumatran birds. In Way Canguk (southern Sumatra) we found a strong negative relationship between market price and population trend, which suggests that trapping is contributing to the decadal-scale declines of multiple species.

Tolerance to anthropogenic habitat disturbance was also a significant predictor of change in bird abundance in Way Canguk, where forest-dependent species tended to increase over time, while open-field species decreased. We attribute these changes to recovery of the forest after the 1997/1998 fires. It is also possible that trapping contributed to declines in sought-after open-country species (e.g. bar-winged prinia *Prinia familiaris*); the relative importance of trapping and habitat change were probably related to the species' market value and life history. Furthermore, some forest dwelling species that are heavily trapped declined significantly (e.g. white-rumped shama *Copsychus malabaricus* and blue-crowned hanging-parrot *Loriculus galgulus*), which implicates trapping. The declines of sought-after species, regardless of habitat preferences, indicate that changes in the avifauna at Way Canguk did not result only from forest regeneration. And the lack of a relationship between body size and change in abundance suggests that hunting for food is unlikely to be driving bird declines in the area. Future research could use population models to delve into the life history drivers underlying the population trends we observed, perhaps by using demographic data from related, well-known species as a proxy for Sumatra's poorly known species (e.g. Brook et al. 2002). A demographic modeling framework could then be used to test future conservation scenarios (e.g. increased enforcement or increased demand for certain species).

In North Sumatra, there were no clear relationships between any of our predictor variables and changes in abundance along the remoteness gradient. The lack of a price relationship could indicate that trapping is not affecting bird populations in the area. However, we posit that trapping has already depleted the bird community within all of the forests we surveyed, and we were thus unable to detect a price effect. Our reasons for this conclusion are four-fold. First, trapping occurs regularly out to 5 km in our study area (based on trapper interviews and direct observations during our surveys). Second, 21 of our 27 study species, all of which are traded, had positive (albeit weak) relationships between distance from road and abundance. Third, two of the most coveted species—silver-eared mesia and Sumatran laughingthrush—were once caught in large numbers in our study area (up to 30 birds/day) according to trapper interviews, but are now caught rarely. Finally, we did not encounter either of these two species in our field surveys.

Our interview results indicate that trappers are spending more time searching for prized species in North Sumatra than they used to. Despite this increase in effort, the current catch of silver-eared mesia is near zero, and catches of the other three sensitive species are either stable or decreasing over time. This apparent decrease in catch per unit effort (for some species at least) is indicative of overexpoitation (Baum et al. 2003; McNamara et al. 2015), which further supports the argument that bird populations have been affected by trapping in all of our field sites in North Sumatra. Indeed, our results indicate that the bird trade may be so pervasive in parts of Indonesia that ecologists and managers need to be alert to shifting baseline syndromes caused by trapping (Papworth et al. 2009). If we had not found out that trappers seek birds at least 5 km inside the forest, and that the catch of sensitive species had decreased over time, we might have concluded that bird populations were unaffected by trapping in North Sumatra. Additionally, our trapper interview data could be subject to the shifting baseline syndrome because trapping has gone on for so long in Sumatra. For example, van Marle and Voous noted that the common hill myna *Gracula religiosa* was already in decline from trapping by 1988 (van Marle and Voous 1988).

By 2010, only 30% of Sumatra's original forest cover remained (Margono et al. 2012). This alone constitutes a threat to many birds. However, our finding that 47.5% of the remaining forests are within 5 km of a major road, combined with the trapping impacts we detected, suggest that some of Sumatra's birds are in far greater danger than habitat-loss statistics alone would suggest. In fact, the actual extent of trapping in Sumatra's forests is likely to be higher than we found, as our road datasets exclude most small roads, which provide trappers with access to forest birds. In addition, tropical forest fires are much more likely to occur near roads (Adeney et al. 2009), and Indonesian fires threaten biodiversity and contribute to climate change (Adeney et al. 2006; Lohman et al. 2007). Predicted increases in road development in tropical countries (Laurance et al. 2014) raise the alarming prospect that both trappers' access to forests and fire risk will continue to increase in the future.

Of course, our results must be interpreted cautiously. First, we cannot eliminate the possibility that birds are declining for reasons unrelated to trapping (or hunting or habitat loss), and that their growing scarcity is driving up their prices in the markets. We also assumed that price was an adequate proxy of demand for the various uses of wild birds in

Indonesia and, therefore, of trapping pressure. In addition, we assumed that bird-trapper behavior in North Sumatra is reflective of trappers across Sumatra. Our historical trapper interview data might be subject to a retrospective bias that could over-estimate bird declines (e.g. O'Donnell et al. 2010). Lastly, our data provided relatively low power to detect a trapping effect in either dataset.

Despite these caveats, our results highlight the urgent need for increased enforcement of trapping regulations in Indonesian protected areas.. The trappers we interviewed readily stated that they often caught birds in national parks and that they rarely or never encountered park rangers.

Trapping for the pet trade occurs around the globe and involves many taxonomic groups (Schlaepfer et al. 2005; BirdLife International 2008; Nijman 2010; Rhyne et al. 2012; Bush et al. 2014). Our results suggest that, in Sumatra at least, trapping can have substantial effects on wild bird populations beyond the handful of species already recognized as imperiled by it. Unlike habitat loss, the impact of the pet trade cannot be seen via remote sensing; nor is it visible through casual fieldwork. But a growing body of evidence suggests the pet trade now poses a major, quiet threat to biodiversity in Indonesia and perhaps across Southeast Asia. We fervently hope more conservation scientists will turn their attention to the pet trade in order to understand just how widespread and serious a threat it is.

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Supporting Information

Supporting methods (details on bird sampling, remoteness estimation, trapper interviews, and statistical analysis), supporting code (JAGS Bayesian modeling code for Way Canguk and North Sumatra), Table S1 (sampling localities in Way Canguk), Table S2 (sampling localities in North Sumatra), Table S3 (species-specific parameter estimates, Way Canguk), Table S4 (species-specific parameter estimates, North Sumatra), Table S5 (variance parameters from Bayesian models), Table S6 (statistical tests of the changes in hours walked by trappers in search of sensitive species and numbers of birds trapped per day), Fig. S1 (goodness-of-fit plots for Bayesian models, Way Canguk), Fig. S2 (goodness-of-fit plots for Bayesian models, North Sumatra), Fig. S3 (number of birds caught per day by trappers when searching sensitive species), Fig. S4 (time spent by trappers searching for sensitive species), Fig. S5 (power analysis for Way Canguk), and Fig. S6 (power analysis for North Sumatra) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

Literature Cited

Adeney JM, Christensen NL, Pimm SL. 2009. Reserves protect against deforestation fires in the Amazon. PLOS ONE **4:**e5014.

Adeney JM, Ginsberg JR, Russell GJ, Kinnaird MF. 2006. Effects of an ENSO-related fire on birds of a lowland tropical forest in Sumatra. Animal Conservation **9:**292-301.

Alves RRN, de Farias Lima JR, Araujo HFP. 2013. The live bird trade in Brazil and its conservation implications: an overview. Bird Conservation International **23:**53-65.

Bates D, Maechler M, Bolker B, Walker S. 2014. lme4: Linear mixed-effects models using Eigen and S4. R package version1.1-7.

Baum JK, Myers RA, Kehler DG, Worm B, Harley SJ, Doherty PA. 2003. Collapse and conservation of shark populations in the Northwest Atlantic. Science **299:**389-392.

BirdLife International 2008. State of the world's birds: indicators for our changing world. BirdLife International, Cambridge, UK.

BirdLife International. 2015. BirdLife International data zone. http://www.birdlife.org/datazone.html. Viewed 1 February 2015.

Brook BW, Burgman MA, Akcakaya HR, O'Grady JJ, Frankham R. 2002. Critiques of PVA ask the wrong questions: throwing the heuristic baby out with the numerical bath water. Conservation Biology 16:262-263.

Bush ER, Baker SE, Macdonald DW. 2014. Global trade in exotic pets 2006–2012. Conservation Biology **28:**663-676.

Butchart SHM. 2008. Red List Indices to measure the sustainability of species use and impacts of invasive alien species. Bird Conservation International **18:**S245-S262.

Cardillo M, Mace GM, Jones KE, Bielby J, Bininda-Emonds ORP, Sechrest W, Orme CDL, Purvis A. 2005. Multiple causes of high extinction risk in large mammal species. Science **309:**1239-1241.

Carpenter AI, Rowcliffe JM, Watkinson AR. 2004. The dynamics of the global trade in chameleons. Biological Conservation **120:**291-301.

Chng SCL, Eaton JA, Krishnasamy K, Shepherd, CR Nijman V. 2015. In the market for extinction: an inventory of Jakarta's bird markets. Petaling Jaya, Selangor, Malaysia: TRAFFIC.

Collar N, Gonzaga L, Krabbe N, Madroño Nieto A, Naranjo L, Parker III T, Wege D. 1992. Threatened Birds of the Americas: The ICBP/IUCN Red Data Book. International Council for Bird Preservation, Cambridge, UK.

Crookes D, Ankudey N, Milner-Gulland EJ. 2005. The value of a long-term bushmeat market dataset as an indicator of system dynamics. Environmental Conservation **32:**333-339.

del Hoyo J, Elliot A, Sargatal J, Christie DA. 1992-2009. Handbook of the birds of the world. Vols. 1-14. Lynx Edicions, Barcelona.

Gelman A, Carlin JB, Stern HS, Dunson DB, Vehtari A, Rubin DB. 2013. Bayesian data analysis. CRC Press, Boca Raton, FL, USA.

Harris JBC, Green JMH, Prawiradilaga DM, Giam X, Giyanto, Hikmatullah D, Putra CA, Wilcove DS. 2015. Using market data and expert opinion to identify overexploited species in the wild bird trade. Biological Conservation **187:**51-60.

Harris JBC, Putra DD, Gregory SD, Brook BW, Prawiradilaga DM, Sodhi NS, Wei D, Fordham DA. 2014. Rapid deforestation threatens mid-elevational endemic birds but climate change is most important at higher elevations. Diversity and Distributions **20:**773-785.

IUCN. 2015. IUCN Red List of Threatened Species. Version 2015.1. World Conservation Union, Gland, Switzerland and Cambridge, UK.

Jepson P. 2008. Orange-headed Thrush *Zoothera citrina* and the avian X-factor. Birding Asia **9:**58-60.

Jepson P. 2010. Towards an Indonesian bird conservation ethos: reflections from a study of bird-keeping in the cites of Java and Bali. Ethno-ornithology: birds, indigenous peoples, culture and society. Earthscan, London.

Jepson P, Ladle RJ. 2009. Governing bird-keeping in Java and Bali: evidence from a household survey. Oryx **43:**364-374.

Kinnaird MF, O'Brien TG. 1998. Ecological effects of wildfire on lowland rainforest in Sumatra. Conservation Biology **12:**954-956.

Laurance WF, Clements GR, Sloan S, O'Connell CS, Mueller ND, Goosem M, Venter O, Edwards DP, Phalan B, Balmford A. 2014. A global strategy for road building. Nature **513:**229-232.

Lohman DJ, Bickford D, Sodhi NS. 2007. The burning issue. Science **316:**376.

Maldonado AM, Nijman V, Bearder SK. 2009. Trade in night monkeys *Aotus* spp. in the Brazil-Colombia-Peru tri-border area: international wildlife trade regulations are ineffectively enforced. Endangered Species Research **9:**143-149.

Margono BA, Turubanova S, Zhuravleva I, Potapov P, Tyukavina A, Baccini A, Goetz S, Hansen MC. 2012. Mapping and monitoring deforestation and forest degradation in Sumatra (Indonesia) using Landsat time series data sets from 1990 to 2010. Environmental Research Letters **7:**034010.

van Marle JG, Voous KH. 1988. The birds of Sumatra: an annotated check-list. British Ornithologists' Union.

McClure HE, Chaiyaphun S. 1971. The sale of birds at the Bangkok "Sunday market" Thailand. Natural History Bulletin of the Siam Society **24:**41-78.

McNamara J, Kusimi JM, Rowcliffe JM, Cowlishaw G, Brenyah A, Milner-Gulland EJ. 2015. Long-term spatio-temporal changes in a West African bushmeat trade system. Conservation Biology**:** in press.

Miettinen J, Shi C, Liew SC. 2011. Deforestation rates in insular Southeast Asia between 2000 and 2010. Global Change Biology **17:**2261-2270.

Nakagawa S, Schielzeth H. 2013. A general and simple method for obtaining R^2 from generalized linear mixed-effects models. Methods in Ecology and Evolution **4:**133-142.

Nash SV. 1993. The trade in Southeast Asian non-CITES birds. TRAFFIC Southeast Asia, Cambridge, UK.

Nekaris K, Jaffe S. 2007. Unexpected diversity of slow lorises (*Nycticebus* spp.) within the Javan pet trade: implications for slow loris taxonomy. Contributions to Zoology **76:**187-196.

Nijman V. 2010. An overview of international wildlife trade from Southeast Asia. Biodiversity and Conservation **19:**1101-1114.

Nijman V, Shepherd CR. 2010. The role of Asia in the global trade in CITES II-listed poison arrow frogs: hopping from Kazakhstan to Lebanon to Thailand and beyond. Biodiversity and Conservation **19:**1963-1970.

O'Brien TG, Kinnaird MF. 1996. Birds and mammals of the Bukit Barisan Selatan National Park, Sumatra, Indonesia. Oryx **30:**207-217.

O’Donnell KP, Pajaro MG, Vincent ACJ. 2010. How does the accuracy of fisher knowledge affect seahorse conservation status? Animal Conservation **13:**526-533.

Papworth S, Rist J, Coad L, Milner-Gulland EJ. 2009. Evidence for shifting baseline syndrome in conservation. Conservation Letters **2:**93-100.

R Development Core Team 2015. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.

Raghavan R, Dahanukar N, Tlusty MF, Rhyne AL, Kumar K, K, Molur S, Rosser A. 2013. Uncovering an obscure trade: threatened freshwater fishes and the aquarium pet markets. Biological Conservation **164:**158-169.

Rhyne AL, Tlusty MF, Schofield PJ, Kaufman L, Morris JA, Jr., Bruckner AW. 2012. Revealing the appetite of the marine aquarium fish trade: the volume and biodiversity of fish imported into the United States. PLOS ONE **7:**e35808.

Rosen GE, Smith KF. 2010. Summarizing the evidence on the international trade in illegal wildlife. EcoHealth **7:**24-32.

Schlaepfer MA, Hoover C, Dodd CK. 2005. Challenges in evaluating the impact of the trade in amphibians and reptiles on wild populations. BioScience **55:**256-264.

Sekercioglu CH. 2012. Bird functional diversity and ecosystem services in tropical forests, agroforests and agricultural areas. Journal of Ornithology **153:**153-161.

Sekercioglu CH, Daily GC, Ehrlich PR. 2004. Ecosystem consequences of bird declines. Proceedings of the National Academy of Sciences of the United States of America **101:**18042-18047.

Shepherd CR. 2006. The bird trade in Medan, north Sumatra: an overview. Birding Asia **5:**16-24.

Shepherd CR. 2012. The owl trade in Jakarta, Indonesia: a spot check on the largest bird markets. Birding Asia **18:**58-59.

Shepherd CR, Shepherd LA, Foley K-E. 2013. Straw-headed bulbul *Pycnonotus zeylanicus*: legal protection and enforcement action in Malaysia. Birding Asia **19:**92-94.

Shepherd CR, Sukumaran J, Wich SA. 2004. Open season: an analysis of the pet trade in Medan, Sumatra 1997-2001. TRAFFIC Southeast Asia, Petaling Jaya, Selangor, Malaysia.

Su S, Cassey P, Vall-llosera M, Blackburn TM. 2015. Going cheap: determinants of bird price in the Taiwanese pet market. PLOS ONE **10:**e0127482.

Wells DR. 1999, 2007. The birds of the Thai-Malay peninsula, volumes 1, 2. Academic press and Christopher Helm, San Diego, CA, USA and London, UK.

Whitten T. 2000. The ecology of Sumatra. Tuttle Publishing.

Wilcove DS, Giam X, Edwards DP, Fisher B, Koh LP. 2013. Navjot's nightmare revisited: logging, agriculture, and biodiversity in Southeast Asia. Trends in Ecology & Evolution **28:**531-540.

Wilson-Wilde L. 2010. Wildlife crime: a global problem. Forensic science, medicine, and pathology **6:**221-222.

Table 1. Estimates of relative effects of price, disturbance tolerance, and body size (alpha parameters) on changes in bird communities (A) over time in Way Canguk, Sumatra and (B) along remoteness gradients in North Sumatra.

Parameter*	Mean (95% credible interval)	SD
A. Way Canguk (lowland forest, southern Sumatra)		
Intercept	0.256 (0.149 to 0.367)	0.056
Price	-0.064 (-0.103 to -0.026)	0.02
Disturbance	-0.063 (-0.101 to -0.028)	0.019
Body size	-0.013 (-0.048 to 0.021)	0.017
B. North Sumatra (montane forest)		
Intercept	0.052 (-0.071 to 0.168)	0.06
Price	-0.090 (-0.288 to 0.084)	0.092
Disturbance	-0.070 (-0.244 to 0.103)	0.088
Body size	0.083 (-0.066 to 0.231)	0.076

*Bold names show parameters whose credible intervals around the coefficient estimates do not cross zero.

Figure 1. Overall locations of sampling sites within Sumatra (bottom left), detailed locations of sampling sites in North Sumatra (main panel), and an example North Sumatra sampling transect (bottom right). Land cover data come from Miettinen et al. (2011). The black triangle shows Mt. Sinabung.

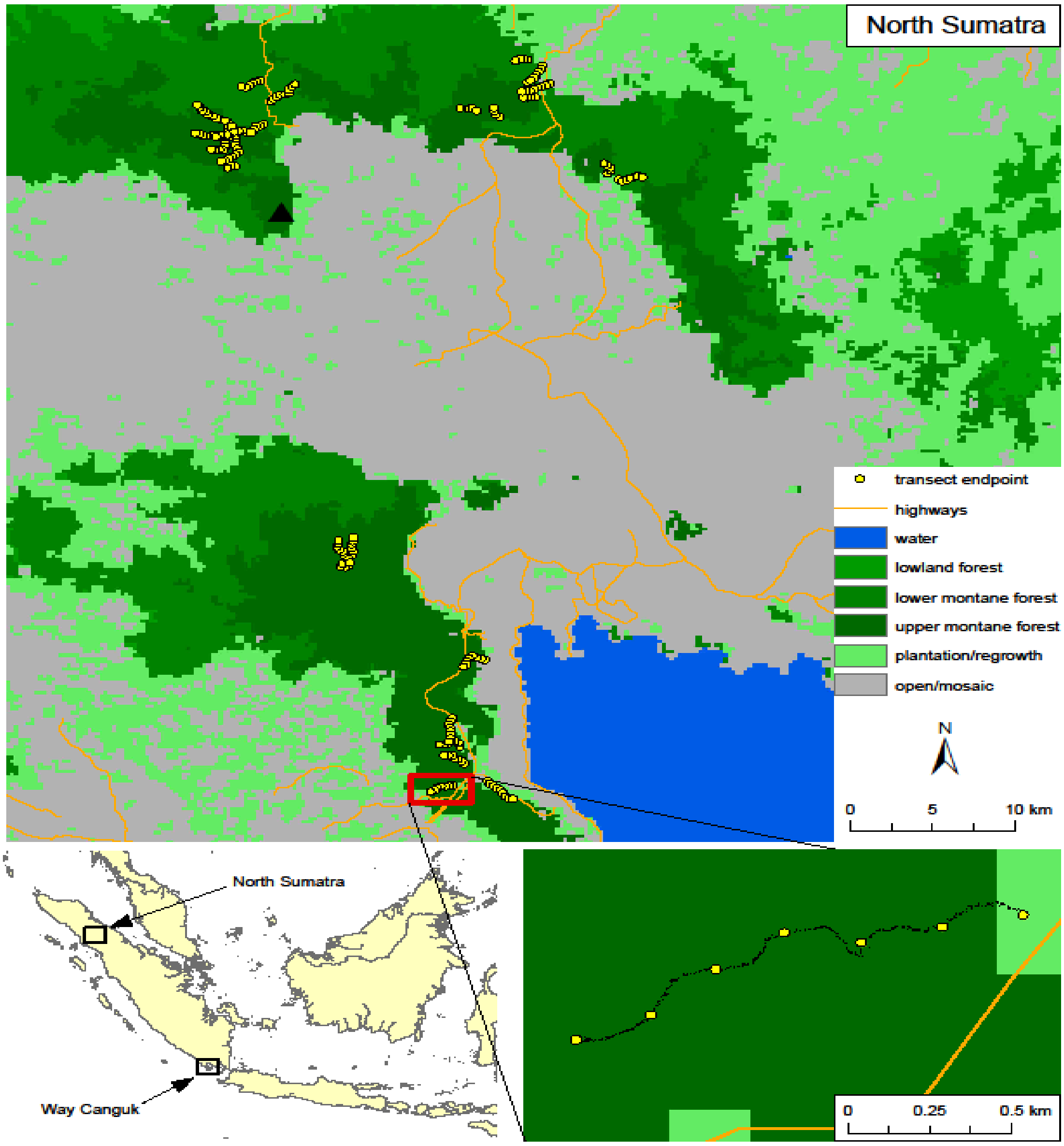

Figure 2. Location of sampling sites at Way Canguk, Bukit Barisan Selatan National Park, Sumatra. Land cover data come from Miettinen et al. (2011).

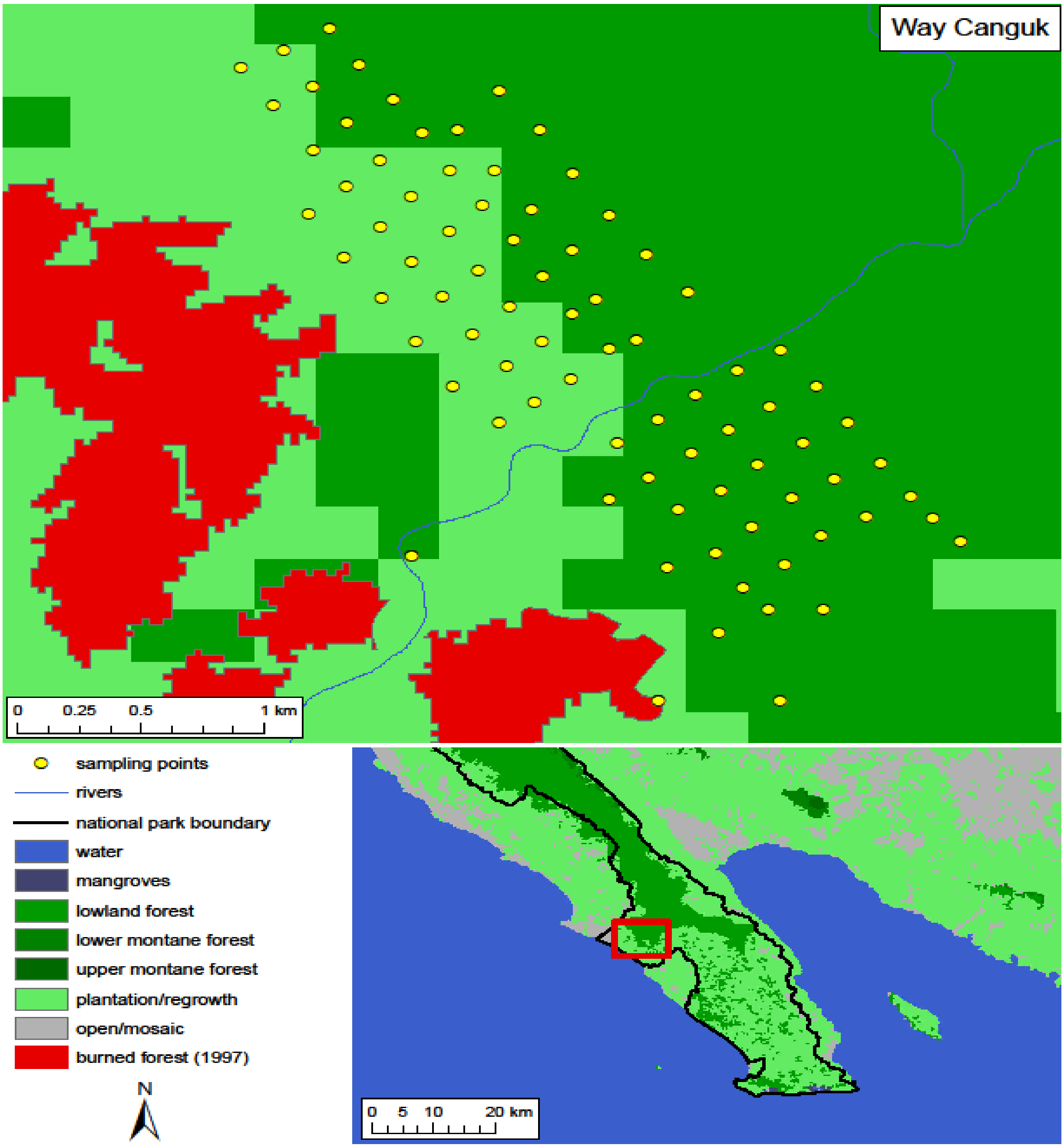

Figure 3. Plots of the relationships between price, disturbance tolerance, and body size and changes in bird abundance over time in Way Canguk, Sumatra. Asterisks show significant relationships.

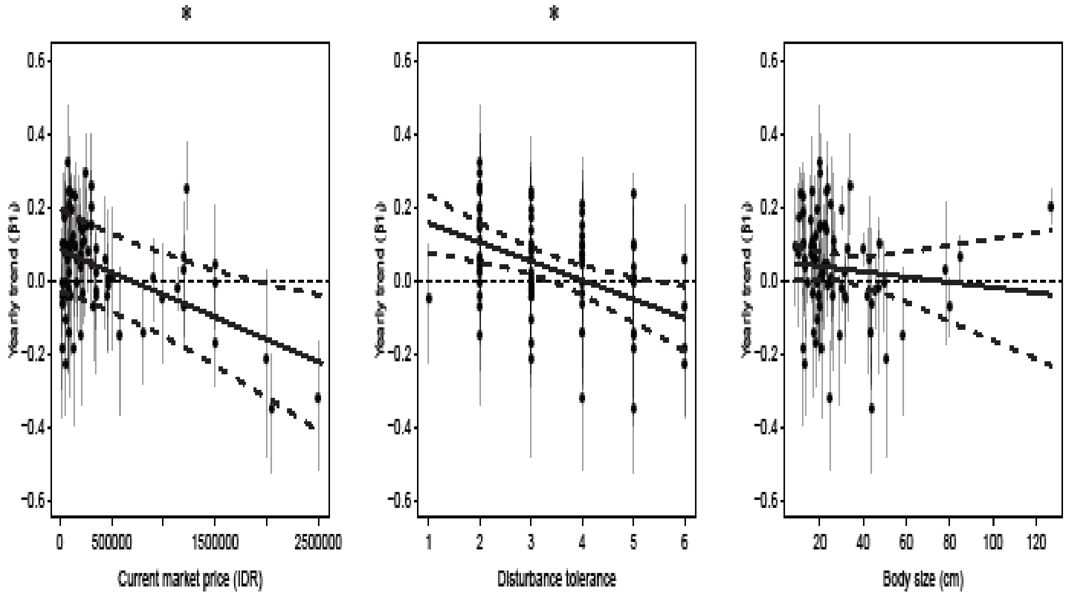

Figure 4. Plots of the relationships between price, disturbance tolerance, and body size and changes in bird abundance along remoteness gradients in North Sumatra. There were no significant relationships.

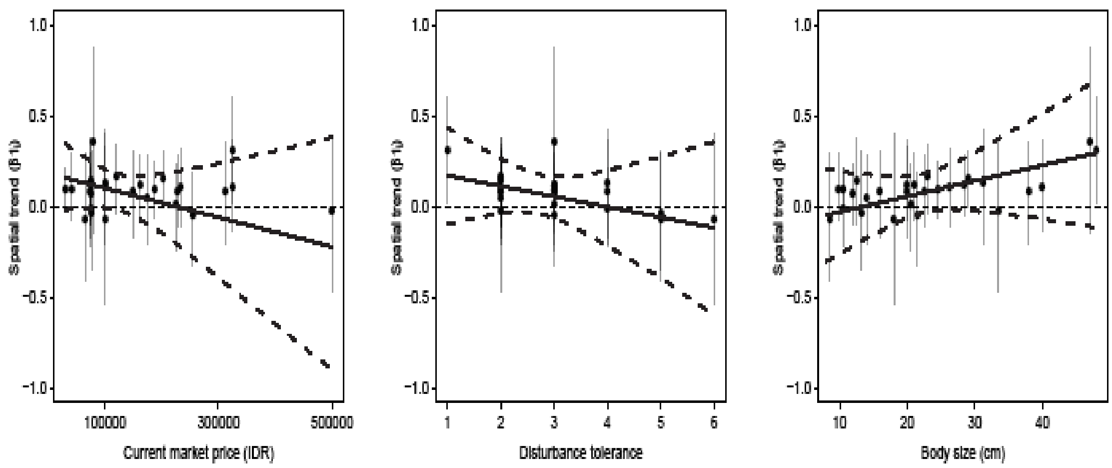

Figure 5. Sumatran forest cover in 2010. Green areas show forests that are greater than 5 km from a road (110,647 km^2 in area); pink areas show forests that are within 5 km of a road (52,622 km^2).