**Supplementary information: Spatial divergence in ecological responses to typhoons across a subtropical island**

Samuel R.P-J. Ross, Nicholas R. Friedman, Kenneth L. Dudley, David W. Armitage, Masashi Yoshimura, Takuma Yoshida, Marina Lašić, Robert McHenry, Evan P. Economo, Ian Donohue

Table S1. Justification behind multi-stability hypotheses tested in this study. Explanation of *a priori* hypotheses for each tested stability component, in both natural forest sites and developed (urban/agricultural) sites, for our focal acoustic indices (NDSI, NDSIBio, NDSIAnthro; see Methods) and bird species detections (*Corvus macrorhynchos*, *Horornis diphone*, *Otus elegans*). For descriptions of components and their calculation, see Table S3.

|  |  |  |
| --- | --- | --- |
| **Stability component** | **Expectation in forest sites** | **Expectation in Developed sites** |
| ***Acoustic Indices*** | | |
| **Pre-typhoon soundscape** | Forests should support more biodiversity (Itô et al., 2000), and thus should have richer biotic soundscapes (NDSI, NDSIBio; Kasten et al., 2012). | Developed sites should have fewer species (lower biophony) but more prevalent noise pollution (higher NDSIAnthro; Kasten et al., 2012). |
| **Post-typhoon soundscape** | Typhoons should reduce biophony either by direct mortality of vocalising species, or movement of species into other habitats (Wiley & Wunderle, 1993), but damage to canopy structure may produce forest gaps through which higher anthropophony can be heard (Cely, 1991). | Typhoons should also reduce biophony with species losses, but given the lower richness of developed sites, we expect a less extreme change. Similarly NDSIAnthro should not increase as much in developed sites. Overall, post-typhoon soundscapes should be less distinct between land cover types compared to pre-typhoon patterns (soundscape homogenisation). |
| **Temporal stability** | Species rich forests should produce uneven, temporally variable, biotic soundscapes (Bradfer-Lawrence et al., 2020), and NDSIAnthro should be infrequent (*i.e.*, variable). | Developed sites should have more consistent (stable) anthropophony than forests (Derryberry et al., 2020), and vocalising species are more likely to be generalists or disturbance-specialists, so should be less variable through time (Concepción et al., 2015). |
| **Resistance** | Closed canopy forests provide resistance to typhoons, buffering soundscapes in the from the immediate loud geophony (wind, rain, etc.) associated with typhoon impact (Abbas et al., 2020). | The more open habitat structure of developed sites should result in higher geophony (including low frequency sounds recognised as anthropophony) immediately following typhoons, so resistance should be lower than in forests (Raymond et al., 2020). |
| **Recovery speed** | Given the greater potential for structural change to habitat in forests, and higher potential change in species richness as a result of habitat loss, all aspects of forest soundscapes should recover more slowly (Elliott & Nino, 1960). Resistance trades off with recovery, so higher forest resistance should mean slower recovery (Patrick et al., 2022). | Less potential structural change and loss of life means developed sites are more likely to recover quickly; connected urban-ecosystems especially recover quickly after typhoons (Chang et al., 2018). Resistance trades off with recovery, so lower developed site resistance should mean faster recovery (Patrick et al., 2022). |
| **Extent of change** | Given the higher potential structural damage to forest, higher potential species losses, and expected slow recovery, the extent of change (longer-term resistance, Table S3) should be higher in forests (Wiley & Wunderle, 1993). | Given the lower potential structural habitat change, disturbance-adapted species, and expected fast recovery, extent of change should be lower in developed sites (Raymond et al., 2020). |
| **Spatial variability** | Forests should host a greater diversity of species from the regional pool, including disturbance-sensitive forest specialists (Wiley & Wunderle, 1993), so spatial variability should be lower (forest sites should have more similar soundscapes). Typhoons should homogenise forest soundscapes by removing specialists and damaging habitat structure, opening habitats to increase anthropophony; higher expected extent of change in forests should result in higher post-typhoon soundscape spatial homogenisation (Cely, 1991). | Developed sites should be more spatially variable before typhoons, as they include agricultural and urban sites (Olivier et al., 2020). Typhoons should homogenise soundscapes in space through their destructive potential, loss of any specialists etc., though the lower expected extent of change among developed sites (Raymond et al., 2020), means the effect size of the post-typhoon spatial homogenisation should be lower than among forest sites. |
| ***Species detections*** | | |
| **Pre-typhoon detections** | Total species detections should be higher in forests, driven by the forest specialist *Otus elegans* (Inoue et al., 2019). | Total species detections should be lower in developed sites than in forests, and individual species (*Horornis diphone*, *O. elegans*) should be detected less frequently, but *Corvus macrorhynchos* is a generalist well adapted to developed sites, so should not differ with land cover (Devictor et al., 2008). |
| **Post-typhoon detections** | Total species detections should decline following the typhoons, driven by the habitat specialist *O. elegans* and sensitive, small-bodied *H. diphone*, while *C. macrorhynchos* is largely unaffected (Cohen et al., 2021). The greater potential habitat loss in forests should result in a greater change in vocalisation rates in the forest than developed sites (Wiley & Wunderle, 1993). | Total species detections should decline following the typhoons, driven by the vulnerable small-bodied *H. diphone* in agricultural sites (Cohen et al., 2021). *C. macrorhynchos*, a disturbance-adapted omnivore, should be unaffected by the typhoon (Seki, 2005). The lesser expected structural habitat change should produce less severe drops in detection rates in developed sites (Wiley & Wunderle, 1993), and the change in forested sites should serve to bring detection rates closer together among habitat types (no expected post-typhoon difference in detections). |
| **Temporal stability** | Bird detections should mirror acoustic indices (Kasten et al., 2012); natural forest soundscapes should have more variable bird detections of each species, owing to high competition for acoustic space with non-focal vocalising species (Krause, 1993). | Variability of bird detections should be lower in developed sites than in forests; open habitat structure provides less attenuation of sound, and species are more likely to be generalists, with less extreme competition for acoustic space due to lower species richness (Krause, 1993). |
| **Extent of change** | Greater potential structural habitat change should produce higher extent of change values in forest for bird detections, particularly for the sensitive/specialist species *H. diphone* and *O. elegans*, which should both decline post-typhoon (Chevalier et al., 2019). *C. macrorhynchos*, a generalist, should be largely unaffected, or in some cases benefit by the creation of forest gaps increasing access to insect, small mammal, and reptilian prey (Zhang et al., 2016). | Less potential structural habitat change should result in lower extents of change for bird detections in developed sites (Wiley & Wunderle, 1993). *C. macrorhynchos*, a generalist, should be largely unaffected, while *H. diphone* should decline where present due to its reliance of bush and understorey vegetation (Chevalier et al., 2019). |
| **Spatial variability** | As with acoustic indices, typhoons should homogenise bird detections across forest sites due to changes in habitat structure, and mortality or behavioural changes of birds following typhoons (Wiley & Wunderle, 1993). The specialists, *H. diphone* and *O. elegans* should be more homogenised than *C. macrorhynchos* (Seki, 2005). The higher potential extent of change in forests should result in a greater post-typhoon spatial homogenisation among forest sites than among developed sites (Elliott & Nino, 1960). | Typhoons should homogenise bird detections across developed sites, as agricultural and urban sites become more similar following changes to habitat specialists in agricultural sites such as *H. diphone* (Olivier et al., 2020). The lower richness and lower potential extent of change (due to less structural habitat change) should result in less severe spatial homogenisation among developed sites (Elliott & Nino, 1960). The disturbance-adapted generalist, *C. macrorhynchos* should not suffer spatial homogenisation as much as the other species among developed sites (Seki, 2005). |



**Figure S1.** Ordination biplot for the land cover variables used in this study. We used unsupervised k-means clustering (optimal *k* value = 2 clusters) of a Principal Component Analysis (PCA) of land cover variables (see Methods) to automatically identify clusters of sites with similar land cover. We found a clear distinction between two clusters (red versus blue points and ellipsoids). When examining the variable loadings (land cover classes marked on PCA ordination with names and arrow length showing relative variable weights), we found that the clusters represented a clear distinction along PCA axis 1 (variance explained = 81.2%), where the 10 blue sites were primarily forest sites, while the 14 red sites with either primarily agricultural, urban, or managed grassland sites, herein collectively termed ‘developed’ sites.

**Table S2.** Automatic supervised learning bird species detection classifiers across field sites. We produced automated (supervised machine learning) species vocalisation classifiers in Kaleidoscope Pro (version 5.3.0; Wildlife Acoustics Inc., Concord, MA, USA), using training data from across a variety of sites and dates, and applying trained classifiers to the full dataset of recordings (30 Aug-04 Nov 2018) to automatically identify species detections. We assessed classifier accuracy at each site (Site name, with land use marked in brackets: FOR = forest, DEV = developed site) via visual inspection with a threshold of 15% false positives. We applied the same species-specific classifiers to each site, to prevent site-specific differences in base classifier performance (though given the challenge of applying a single classifier across 24 sites, there were several cases where classifiers did not meet our accuracy threshold (0s in columns 2-4). We achieved accurate classifiers at a range of sites for three species: the large-billed crow (*Corvus macrorhynchos*, 嘴太烏 in Japanese); the Japanese bush warbler (*Horornis diphone*, 鶯); and the Ryukyu scops-owl (*Otus elegans*, 琉球木の葉木菟). Accurate classifiers are marked with 1, indicating that we used data from that site-by-species combination for analysis (see *Analyses on automated species detections*). Note that *O. elegans* is a forest specialist, so is not expected to be found at the developed sites (we did not produce an accurate classifier at any developed sites for this species, in accordance with expectation). Classifiers were produced by S.R.P-J.R. and R.M. and accuracy was visually checked by a single observer (S.R.P-J.R.) for consistency.

|  |  |  |  |
| --- | --- | --- | --- |
| Site name (Land use) | *Corvus macrorhynchos* | *Horornis diphone* | *Otus elegans* |
| Genka (FOR) | 1 | 0 | 0 |
| Hentona (FOR) | 1 | 1 | 1 |
| Katsuudake (FOR) | 1 | 1 | 1 |
| Kemin (FOR) | 1 | 1 | 1 |
| Manabi (FOR) | 1 | 1 | 0 |
| OIST forest (FOR) | 1 | 1 | 1 |
| OIST campus (FOR) | 1 | 1 | 0 |
| Oku (FOR) | 1 | 1 | 1 |
| Takeyanbaru (FOR) | 1 | 1 | 1 |
| Yona (FOR) | 1 | 1 | 1 |
| Chatan (DEV) | 0 | 0 | - |
| Gesashi (DEV) | 1 | 0 | - |
| Heiwa (DEV) | 0 | 1 | - |
| Kurashiki (DEV) | 1 | 1 | - |
| Nago (DEV) | 1 | 0 | - |
| Nakagusuku (DEV) | 1 | 1 | - |
| Oyama (DEV) | 0 | 0 | - |
| Sefa-utaki (DEV) | 1 | 1 | - |
| Senbaru (DEV) | 1 | 1 | - |
| Sueyoshi (DEV) | 1 | 0 | - |
| Tamagusuku (DEV) | 1 | 1 | - |
| Tounan (DEV) | 1 | 1 | - |
| Uehara (DEV) | 1 | 0 | - |
| Yacho (DEV) | 1 | 1 | - |
| Total | 21 | 17 | 7 |



**Figure S2.** Extent of change in automated bird species detections with different detection confidence thresholds. Higher thresholds of detection confidence are less conservative (*i.e*., a higher likelihood of false positives), since values represent the distance from a sound type cluster centroid to be considered for analysis, where sounds further from the cluster centroid are less likely to be the sound type of interest. Extent of change values (y-axis, see Table S3 for methods and interpretation) are shown for the three target species (*Corvus macrorhynchos* [L], *Horornis diphone*, and *Otus elegans* [R]), across the 7 forest sites at which all species were detected (site names follow Table S2). Points represent extent of change values where stars show a significant change in post-typhoon detection rates (based on z-scores from a Wilcoxon signed rank test, Table S3), while open triangles show no significant change. Generally, higher threshold values (permitting lower certainty detections) increased the magnitude of extent of change values, but rarely changed the sign or significance of values. Only in two cases, for *C. macrorhrynchos* at j) OIST forest and m) Oku forest, did the significance and sign of the relationship change; j) nonsignificant extent of change became negative and significant with higher threshold values, and m) significant positive extent of change became nonsignificant with higher threshold values. The remaining cases (N = 19) showed no change in sign or significance, so we accepted the conservative threshold of 0.5 as being representative of all threshold values.



**Figure S3.** Comparison of Biophony (NDSIBio) time series at the Manabi (FOR) field site after detrending using moving average window sizes of **a**) 3 days, **b**) 5 days, and **c**) 7 days. Red dashed lines represent the pre-disturbance baseline value (mean). Grey windows indicate the periods of typhoons Trami (29-30 Sep 2018) and Kong-Rey (04-05 Oct 2018).

****

**Figure S4.** Comparison of recovery time values for different recovery window sizes. A change in window size represents a change in the amount of time for which consecutive data points must remain within the pre-typhoon baseline mean ± 1 standard deviation. Relationships between the 24 hr window size used in our analyses (x-axis) and the 12 (top panels) or 48 hr window sizes (bottom panels) are shown for three acoustic indices: NDSI (left), NDSIBio, and NDSIAnthro (right). Note the number of data points differs particularly for the 48 hr window size, since normalised acoustic index values were found not to recover within 30 days of the typhoon when using the 48 hr window size. Results generally show a positive correlation between the chosen 24 hr window size and other window sizes, excepting NDSIAnthro with a 12 hr window size, which recovered quickly in most cases, resulting in a flat relationship.

**Table S3**. Components of ecological stability measured in this study, methods of their measurement and interpretation. Stability components (see also Figure 2) were calculated separately for time series of acoustic indices and bird species detections, based largely on methods adapted from Hillebrand *et al.* (2018) and White *et al.* (2020). Following calculation, all stability measures were normalised to 0-1 (see Methods) and then temporal variability was converted to temporal stability as 1 values, and recovery time to recovery speed in the same way. This was done so that all stability measures have high values which represent higher stability (except for extent of change which retains a sign positive/negative element to express the direction of change).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Stability component** | **Time window of measurement** | **Method of measurement:**  ***acoustic indices*** | **Method of measurement:**  ***species detections*** | **Interpretation** |
| **Pre-typhoon mean** | 30 days pre-typhoon | Mean acoustic index value across the 30-day detrended time series. | Mean number of daily species detections across the 30-day time series. | Higher values correspond to higher acoustic index values (a proxy for biodiversity for NDSI and NDSIBio or higher human noise for NDSIAnthro) or species detections. |
| **Post-typhoon mean** | 30 days post- typhoon | Same as above. | Same as above. | Same as above. |
| **Temporal stability** | 30 days pre- typhoon | 1 coefficient of variation (that is, standard deviation/mean) among acoustic index values across the 30-day detrended time series from the pre-typhoon period. | 1 coefficient of variation (that is, standard deviation / mean) among daily species detections across the 30-day time series from the pre-typhoon period. | Higher values correspond to lower variability through time (higher stability). |
| **Resistance** | 2 days post- typhoon | Maximum absolute difference in acoustic index values from pre-typhoon mean in the 48 hours following the 2nd typhoon. | - | Values represent log response ratios, where zero equates to complete resistance (no change), and more extreme positive or negative values represent lower resistance through over- or underperformance, respectively (Hillebrand et al., 2018). |
| **Recovery speed** | 30 days post- typhoon | 1 *recovery time*, calculated as the time taken (in hours) for acoustic index values to return to baseline (that is, mean ± 95% confidence interval of 30-day pre-typhoon detrended time series) and stay within this range for 24 consecutive hours, starting from the point of maximum displacement (the resistance point; (Garnier et al., 2017; White et al., 2020). | - | Higher values indicate shorter recovery time (higher stability). |
| **Extent of change** | 30 days pre- versus post- typhoon | *z*-score calculated based on a Wilcoxon signed rank test (*wilcox.test* function in *R* *stats* package; R Core Team 2021) comparing detrended acoustic index values from the 30 days before versus after the typhoons. | *z*-scores comparing daily species detections for the 30 days before versus after the typhoons. | Values represent effect sizes, where more extreme positive or negative values represent lower stability (that is, a larger post-disturbance increase or decrease, respectively). Where extent of change values ± 95% C.I.s do not span zero, this represents a significant (*p* < 0.05) post-disturbance change. Though conceptually similar to resistance, extent of change represents longer-term change relative to resistance—an important distinction given the need to combine instantaneous measures of stability with longer-term metrics to reveal stability responses through time (Yang et al., 2019). |
| **Spatial variability** | One value per day (entire time series) | Coefficient of variation (standard deviation/mean) among field sites in daily mean acoustic index values on each date (Donohue et al., 2013). | Coefficient of variation among field sites in daily species detections on each date. | Higher values represent higher variability in space, which is stabilising as spatial variability represents asynchronous biomass fluxes within or among species, in turn providing spatial insurance through patch dynamics (Leibold et al., 2004; Loreau et al., 2003). |

**Table S4**. Summary of typhoon, land cover, and species identity effects on each response variable. We tested the effects of time period (Pre-typhoon = the 30-day period before typhoon Trami, Post-typhoon = the 30-day period after typhoon Kong-Rey), land cover (Forest = 10 forest sites, Developed = 14 developed sites described by k-means clustering; Fig. S1), and their interaction (For/Pre = forest sites pre-typhoon, For/Post = forest sites post-typhoon, Dev/Pre = developed sites pre-typhoon, Dev/Post = developed sites post-typhoon) on three acoustic indices (NDSI, Biophony [NDSIBio] and Anthropophony [NDSIAnthro]), and the summed bird detections of three species, as well as their individual detections (Corvus = *Corvus macrorhynchos*, Horornis = *Horornis diphone*, Otus = *Otus elegans*). We also tested for interactions between species and land use (Corv/For = *C. macrorhynchos* in forest, Corv/Dev = *C. macrorhynchos* in developed sites, Horo/For = *H. diphone* in forest, Horo/Dev = *H. diphone* in developed sites, Otus/For = *O. elegans* in forest) and species and time period (Corv/Pre = *C. macrorhynchos* pre-typhoon, Corv/Post = *C. macrorhynchos* post-typhoon, Horo/Pre = *H. diphone* pre-typhoon, Horo/Post = *H. diphone* post-typhoon, Otus/Pre = *O. elegans* pre-typhoon, Otus/Post = *O. elegans* post-typhoon). Numbers in brackets represent 95% confidence intervals (5th percentile-95th percentile) of the boostrapped mean distributions. Significant contrasts (*p* < 0.05 based on non-overlapping 95% confidence intervals of bootstrap mean distributions, see Methods) are marked with vertical arrows, showing an increase (↑) or decrease (↓) relative to other groups. Where pairwise comparisons, are not explicit (‘vs’) contrasts show relevant group-levels (e.g., Corv ↑vs Horo = *C. macrorhynchos* increases relative to *H. diphone*, but not compared to the other species, *O. elegans*). To aid interpretation, the Figure column shows the relevant figure visualising each result.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Response variable** | **Stability component** | **Predictor variable** | **Figure** | **Mean bootstrap 95%**  **confidence intervals** | **Significant contrast(s)** |
| **Acoustic Indices** | |  |  |  |  |
| NDSI | Mean | Time period | 3a | Pre-typhoon (0.766–0.852), Post-typhoon (0.678–0.784) | - |
|  | Pre-typhoon | Land cover | S5a | Forest (0.803–0.890),  Developed (0.716–0.845) | - |
|  | Post-typhoon |  | S5b | Forest (0.722–0.836),  Developed (0.619–0.775) | - |
|  | Temporal stability |  | S5c | Forest (0.468–0.632),  Developed (0.420–0.610) | - |
|  | Resistance |  | S5d | Forest (0.557–0.746),  Developed (0.557–0.780) | - |
|  | Recovery speed |  | S5e | Forest (0.755–0.874,  Developed (0.629–0.835) | - |
|  | Extent of change |  | S5f | Forest (-0.104 – -0.038),  Developed (-0.138 – -0.054) | - |
|  | Spatial variability | Time period | 4a | Pre-typhoon (0.170–0.171),  Post-typhoon (0.236–0.24) | Post ↑ |
|  |  | Land cover | 4b | Forest (0.126–0.128),  Developed (0.239–0.241) | Dev ↑ |
|  |  | Land cover x time period | 4c | For/Pre (0.108–0.109),  For/Post (0.143–0.147),  Dev/Pre (0.203–0.204),  Dev/Post (0.275–0.278) | Dev/Post ↑vs Dev/Pre ↑vs For/Post ↑vs For/Pre |
| NDSIBio | Mean | Time period | 3b | Pre-typhoon (0.460–0.514), Post-typhoon (0.428–0.518) | - |
|  | Pre-typhoon | Land cover | S6a | Forest (0.493–0.530),  Developed (0.426–0.512) | - |
|  | Post-typhoon |  | S6b | Forest (0.441–0.543),  Developed (0.392–0.525) | - |
|  | Temporal stability |  | S6c | Forest (0.405–0.566),  Developed (0.364–0.589) | - |
|  | Resistance |  | S6d | Forest (0.519–0.762),  Developed (0.417–0.701) | - |
|  | Recovery speed |  | S6e | Forest (0.882–0.951),  Developed (0.601–0.838) | Dev ↓ |
|  | Extent of change |  | S6f | Forest (-0.070 – 0.027),  Developed (-0.065 – 0.039) | - |
|  | Spatial variability | Time period | 4d | Pre-typhoon (0.193–0.194),  Post-typhoon (0.318–0.321) | Post ↑ |
|  |  | Land cover | 4e | Forest (0.175–0.18),  Developed (0.299–0.303) | Dev ↑ |
|  |  | Land cover x time period | 4f | For/Pre (0.113–0.115),  For/Post (0.239–0.244),  Dev/Pre (0.236–0.237),  Dev/Post (0.363–0.367) | Dev/Post ↑vs For/Post ↑vs Dev/Pre ↑vs For/Pre |
| NDSIAnthro | Mean | Time period | 3c | Pre-typhoon (0.287–0.410), Post-typhoon (0.415–0.549) | Post ↑ |
|  | Pre-typhoon | Land cover | S7a | Forest (0.224–0.363),  Developed (0.300–0.478) | - |
|  | Post-typhoon |  | S7b | Forest (0.340–0.486),  Developed (0.435–0.628) | - |
|  | Temporal stability |  | S7c | Forest (0.339–0.572),  Developed (0.527–0.685) | - |
|  | Resistance |  | S7d | Forest (0.491–0.720),  Developed (0.459–0.704) | - |
|  | Recovery speed |  | S7e | Forest (0.717–0.792),  Developed (0.446–0.680) | Dev ↓ |
|  | Extent of change |  | S7f | Forest (0.070–0.183),  Developed (0.095–0.222) | - |
|  | Spatial variability | Time period | 4g | Pre-typhoon (0.616–0.63),  Post-typhoon (0.482–0.496) | Post ↓ |
|  |  | Land cover | 4h | Forest (0.49–0.501),  Developed (0.532–0.542) | Dev ↑ |
|  |  | Land cover x time period | 4i | For/Pre (0.579–0.594),  For/Post (0.400–0.410),  Dev/Pre (0.599–0.613),  Dev/Post (0.463–0.474) | Dev/Pre ↑vs For/Pre ↑vs Dev/Post ↑vs For/Post |
| **Species detections** | |  |  |  |  |
| Total | Mean | Time period | 5a | Pre-typhoon (32.0–61.0),  Post-typhoon (16.6–37.2) | - |
|  | Pre-typhoon | Species | 6a | Corvus (45.0–94.9),  Horornis (11.2–23.0),  Otus (11.1–94.0) | Corv ↑vs Horo |
|  | Post-typhoon |  | 6b | Corvus (32.4–70.1),  Horornis (1.28–3.01),  Otus (7.48–18.9) | Corv ↑vs Otus ↑vs Horo |
|  | Temporal Stability |  | 6c | Corvus (0.355–0.493),  Horornis (0.489–0.630),  Otus (0.155–0.304) | Otus ↓ |
|  | Extent of change |  | 6d | Corvus (-26.7 – 1.46),  Horornis (-17.9 – -7.82),  Otus (-53.3 – -1.00) | - |
|  | Spatial variability | Time period | 7a | Pre-typhoon (1.85–2.20),  Post-typhoon (2.17–2.51) | - |
|  |  | Land cover | 7b | Forest (1.61–1.76),  Developed (1.53–1.70) | - |
|  |  | Land cover x time period | 7c | For/Pre (1.37–1.57),  For/Post (1.80–1.99),  Dev/Pre (1.48–1.65),  Dev/Post (1.53–1.83) | For/Post ↑vs For/Pre & Dev/Pre |
|  |  | Species | 7d | Corvus (1.29–1.41),  Horornis (1.79–2.10),  Otus (3.23–3.48) | Otus ↑vs Horo ↑vs Corv |
|  |  | Species x  land cover | 7e | Corv/For (1.25–1.42),  Corv/Dev (1.25–1.37),  Horo/For (1.48–1.75),  Horo/Dev (1.85–2.10),  Otus/For (2.10–2.28) | Otus/For ↑vs Horo/Dev ↑vs Horo/For ↑vs Corv/For & Corv/Dev |
|  |  | Species x  time period | 7f | Corv/Pre (1.22–1.37),  Corv/Post (1.29–1.45),  Horo/Pre (1.37–1.56),  Horo/Post (2.05–2.50),  Otus/Pre (3.11–3.49),  Otus/Post (3.21–3.53) | Otus/For & Otus/Dev ↑vs Horo/Dev ↑vs Horo/For & Corv/For & Corv/Dev |
| *Corvus*  *macrorhynchos* | Mean | Time period | 5b | Pre-typhoon (44.3–94.7),  Post-typhoon (32.5–70.3) | - |
|  | Pre-typhoon | Land cover | S8a | Forest (40.2–99.1),  Developed (31.7–110.1) | - |
|  | Post-typhoon |  | S8b | Forest (23.4–85.6),  Developed (29.4–73.5) | - |
|  | Temporal stability |  | S8c | Forest (0.323–0.517),  Developed (0.328–0.527) | - |
|  | Extent of change |  | S8d | Forest (-30.6 – 7.28),  Developed (-35.3 – 5.66) | - |
| *Horornis diphone* | Mean | Time period | 5c | Pre-typhoon (11.1–22.8),  Post-typhoon (1.3–3.0) | Post ↓ |
|  | Pre-typhoon | Land cover | S9a | Forest (9.23–23.9),  Developed (8.73–27.2) | - |
|  | Post-typhoon |  | S9b | Forest (0.844–3.078),  Developed (1.16–3.75) | - |
|  | Temporal stability |  | S9c | Forest (0.545–0.664),  Developed (0.374–0.632) | - |
|  | Extent of change |  | S9d | Forest (-19.9 – -6.78),  Developed (-20.8 – -5.25) | - |
| *Otus elegans* | Mean | Time period | 5d | Pre-typhoon (11.4–93.5),  Post-typhoon (7.6–18.8) | - |

Mean, standard deviation (S.D.), and 95% credible intervals of the posterior distribution for parameters included in each best-fitting model.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Data** | **Response variable** | **Model Parameter** | **Mean** | **S.D.** | **2.5% C.I.** | **97.5% C.I.** |
| **Acoustic Indices** |  |  |  |  |  |
| NDSI | **Mean** | **Intercept** | **1.45** | **0.23** | **0.99** | **1.92** |
|  |  | LandDev | 0.37 | 0.36 | -0.35 | 1.09 |
|  |  | **TyphoonPost** | **-0.52** | **0.13** | **-0.78** | **-0.26** |
|  |  | LandDev:TyphoonPost | 0.06 | 0.21 | -0.36 | 0.48 |
|  | Temporal Variability | Intercept | -0.16 | 0.39 | -0.93 | 0.62 |
|  | LandDev | 0.36 | 0.59 | -0.80 | 1.53 |
|  | TyphoonPost | -0.10 | 0.40 | -0.91 | 0.69 |
|  | LandDev:TyphoonPost | -0.22 | 0.80 | -1.82 | 1.38 |
|  | Resistance | Intercept | 0.66 | 0.48 | -0.29 | 1.63 |
|  |  | LandDev | 0.04 | 0.77 | -1.51 | 1.55 |
|  | Recovery Time | Intercept | 0.94 | 0.52 | -0.08 | 1.97 |
|  |  | LandDev | 0.66 | 0.89 | -1.10 | 2.43 |
|  | Spatial Variability  [Across all sites] | Intercept |  |  |  |  |
|  |  | TyphoonPost |  |  |  |  |
|  | Spatial Variability [Forest vs Developed] | Intercept |  |  |  |  |
|  |  | LandDev |  |  |  |  |
|  |  | TyphoonPost |  |  |  |  |
|  |  | LandDev:TyphoonPost |  |  |  |  |
| NDSIBio | Mean | Intercept | -0.12 | 0.14 | -0.39 | 0.16 |
|  |  | LandDev | 0.16 | 0.22 | -0.26 | 0.59 |
|  |  | TyphoonPost | -0.06 | 0.13 | -0.31 | 0.19 |
|  |  | LandDev:TyphoonPost | -0.02 | 0.20 | -0.41 | 0.37 |
|  | Temporal Variability | Intercept | -0.33 | 0.41 | -1.15 | 0.49 |
|  | LandDev | 0.26 | 0.61 | -0.96 | 1.46 |
|  | TyphoonPost | 0.40 | 0.54 | -0.67 | 1.48 |
|  | LandDev:TyphoonPost | -0.10 | 1.00 | -2.09 | 1.89 |
|  | Resistance | Intercept | 0.10 | 0.55 | -0.98 | 1.20 |
|  |  | LandDev | 0.57 | 0.89 | -1.17 | 2.34 |
|  | Recovery Time | Intercept | 0.91 | 0.59 | -0.26 | 2.08 |
|  |  | LandDev | 1.62 | 0.96 | -0.25 | 3.54 |
|  | Spatial Variability |  |  |  |  |  |
| NDSIAnthro | **Mean** | Intercept | -0.51 | 0.26 | -1.01 | 0.00 |
|  |  | LandDev | -0.44 | 0.40 | -1.23 | 0.34 |
|  |  | **TyphoonPost** | **0.68** | **0.17** | **0.34** | **1.00** |
|  |  | LandDev:TyphoonPost | -0.12 | 0.26 | -0.62 | 0.40 |
|  | Temporal Variability | Intercept | 0.48 | 0.28 | -0.07 | 1.04 |
|  | LandDev | -0.98 | 0.72 | -2.42 | 0.46 |
|  | TyphoonPost | -0.73 | 0.45 | -1.62 | 0.16 |
|  | LandDev:TyphoonPost | 0.34 | 0.95 | -1.55 | 2.24 |
|  | Resistance | Intercept | 0.20 | 0.48 | -0.73 | 1.15 |
|  |  | LandDev | 0.30 | 0.77 | -1.21 | 1.84 |
|  | Recovery Time | Intercept | 0.04 | 0.53 | -1.01 | 1.07 |
|  |  | LandDev | 1.11 | 0.64 | -0.15 | 2.40 |
|  | Spatial Variability |  |  |  |  |  |
| **Species detections** |  |  |  |  |  |  |
|  | Mean Daily Detections | Intercept |  |  |  |  |
|  |  | LandDev |  |  |  |  |
|  |  | TyphoonPost |  |  |  |  |
|  |  | LandDev:TyphoonPost |  |  |  |  |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  | Temporal Variability |  |  |  |  |  |
|  | Spatial Variability |  |  |  |  |  |



**Figure S5.** Comparison of NDSI stability between land cover types. Comparison of Normalised Difference Soundscape index stability for the 10 forest sites (circles and green colours) and the 14 developed sites (triangles and grey colours) across both the pre- and post-typhoon periods. We compared several dimensions of stability (see Table S3 for methods and interpretation): a) the pre-typhoon mean, b) the post-typhoon mean, c) the temporal stability, d) short-term resistance to typhoons, e) recovery speed, and f) longer-term resistance, *i.e.*, extent of change (star points = significant site-level post-typhoon increase [above zero] or decrease [below zero], open triangles = no significant change). Results from bootstrapping means with replacement 10,000 times are shown as histograms of bootstrapped 95% confidence intervals. Nonoverlapping histograms represent significant pairwise group mean differences at the *p* = 0.05 level. Significant (*p* < 0.05) pairwise contrasts are denoted with lowercase letters.



**Figure S6.** Comparison of Biophony (NDSIBio) stability between land cover types. Figure legend follows Figure S5, but for the NDSIBio acoustic index.



**Figure S7.** Comparison of Anthropophony (NDSIAnthro) stability between land cover types. Figure legend follows Figure S5, but for the NDSIAnthro acoustic index.



**Figure S8.** Comparison of *Corvus macrorhynchos* detection stability between land cover types. Comparison between the 10 forest sites (circles and green colours) and the 14 developed sites (triangles and grey colours) across both the pre- and post-typhoon periods. We compared several dimensions of stability (see Table S3 for methods and interpretation): a) the pre-typhoon mean, b) the post-typhoon mean, c) the temporal stability, and d) the extent of change (star points = significant site-level post-typhoon increase [above zero] or decrease [below zero], open triangles = no significant change). Results from bootstrapping means with replacement 10,000 times are shown as histograms of bootstrapped 95% confidence intervals. Nonoverlapping histograms represent significant pairwise group mean differences at the *p* = 0.05 level. Significant (*p* < 0.05) pairwise contrasts are denoted with lowercase letters.

****

**Figure S9.** *Horornis diphone* detection stability versus land cover. Figure legend follows Figure S8, but for automated species detections of *Horornis diphone*.

**Supplementary references**

Abbas, S., Nichol, J. E., Fischer, G. A., Wong, M. S., & Irteza, S. M. (2020). Impact assessment of a super-typhoon on Hong Kong’s secondary vegetation and recommendations for restoration of resilience in the forest succession. *Agricultural and Forest Meteorology*, *280*, 107784.

Bradfer-Lawrence, T., Bunnefeld, N., Gardner, N., Willis, S. G., & Dent, D. H. (2020). Rapid assessment of avian species richness and abundance using acoustic indices. *Ecological Indicators*, *115*, 106400

Cely, J. E. (1991). Wildlife Effects of Hurricane Hugo. *Journal of Coastal Research*, 319–326.

Chang, C. T., Vadeboncoeur, M. A., & Lin, T. C. (2018). Resistance and resilience of social-ecological systems to recurrent typhoon disturbance on a subtropical island: Taiwan. *Ecosphere*, *9*.

Chevalier, M., Lindström, Å., Pärt, T., & Knape, J. (2019). Changes in forest bird abundance, community structure and composition following a hurricane in Sweden. *Ecography*, *42*, 1862–1873.

Cohen, J. M., Fink, D., & Zuckerberg, B. (2021). Extreme winter weather disrupts bird occurrence and abundance patterns at geographic scales. *Ecography*, 1–13.

Concepción, E. D., Moretti, M., Altermatt, F., Nobis, M. P., & Obrist, M. K. (2015). Impacts of urbanisation on biodiversity: The role of species mobility, degree of specialisation and spatial scale. *Oikos*, *124*, 1571–1582.

Derryberry, E. P., Phillips, J. N., Derryberry, G. E., Blum, M. J., & Luther, D. (2020). Singing in a silent spring: Birds respond to a half-century soundscape reversion during the COVID-19 shutdown. *Science*, *370*, 575–579.

Devictor, V., Julliard, R., & Jiguet, F. (2008). Distribution of specialist and generalist species along spatial gradients of habitat disturbance and fragmentation. *Oikos*, *117*, 507–514.

Donohue, I., Petchey, O. L., Montoya, J. M., Jackson, A. L., Mcnally, L., Viana, M., Healy, K., Lurgi, M., O’Connor, N. E., & Emmerson, M. C. (2013). On the dimensionality of ecological stability. *Ecology Letters*, *16*, 421–429.

Elliott, J. C., & Nino, Y. (1960). Okinawa’s Dry Typhoons. *American Midland Naturalist*, *63*, 211–211.

Garnier, A., Pennekamp, F., Lemoine, M., & Petchey, O. L. (2017). Temporal scale dependent interactions between multiple environmental disturbances in microcosm ecosystems. *Global Change Biology*, *23*, 5237–5248.

Hillebrand, H., Langenheder, S., Lebret, K., Lindström, E., Östman, Ö., & Striebel, M. (2018). Decomposing multiple dimensions of stability in global change experiments. *Ecology Letters*, *21*, 21–30.

Inoue, T., Matsumoto, M., Yoshida, T., & Washitani, I. (2019). Spatial patterns of the Ryukyu Scops Owl’s Otus elegans breeding success and forest landscape factors on Amami-Ōshima island. *Japanese Journal of Ornithology*, *68*, 19–28.

Itô, Y., Miyagi, K., & Ota, H. (2000). Imminent extinction crisis among the endemic species of the forests of Yanbaru, Okinawa, Japan. *Oryx*, *34*, 305–316.

Kasten, E. P., Gage, S. H., Fox, J., & Joo, W. (2012). The remote environmental assessment laboratory’s acoustic library: An archive for studying soundscape ecology. *Ecological Informatics*, *12*, 50–67.

Krause, B. (1993). The niche hypothesis: A virtual symphony of animal sounds, the origins of musical expression and the health of habitats. *The Soundscape Newsletter*, *6*, 6–10.

Leibold, M. A., Holyoak, M., Mouquet, N., Amarasekare, P., Chase, J. M., Hoopes, M. F., Holt, R. D., Shurin, J. B., Law, R., Tilman, D., Loreau, M., & Gonzalez, A. (2004). The metacommunity concept: A framework for multi-scale community ecology. *Ecology Letters*, *7*, 601–613.

Loreau, M., Mouquet, N., Gonzalez, A., & Mooney, H. A. (2003). *Biodiversity as spatial insurance in heterogeneous landscapes*.

Olivier, T., Thébault, E., Elias, M., Fontaine, B., & Fontaine, C. (2020). Urbanization and agricultural intensification destabilize animal communities differently than diversity loss. *Nature Communications*, *2020*, 1–9.

Patrick, C. J., Kominoski, J. S., McDowell, W. H., Branoff, B., Lagomasino, D., Leon, M., Hensel, E., Hensel, M. J. S., Strickland, B. A., Aide, T. M., Armitage, A., Campos-Cerqueira, M., Congdon, V. M., Crowl, T. A., Devlin, D. J., Douglas, S., Erisman, B. E., Feagin, R. A., Geist, S. J., … Zou, X. (2022). A general pattern of trade-offs between ecosystem resistance and resilience to tropical cyclones. *Science Advances*, *8*, eabl9155.

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>.

Raymond, C., Horton, R. M., Zscheischler, J., Martius, O., AghaKouchak, A., Balch, J., Bowen, S. G., Camargo, S. J., Hess, J., Kornhuber, K., Oppenheimer, M., Ruane, A. C., Wahl, T., & White, K. (2020). Understanding and managing connected extreme events. *Nature Climate Change*, *10*, 611–621.

Seki, S.-I. (2005). The effects of a typhoon (9918 Bart, 1999) on the bird community in a warm temperate forest, Southern Japan. *Ornithological Science*, *4*, 117–128.

White, L., O’Connor, N. E., Yang, Q., Emmerson, M. C., & Donohue, I. (2020). Individual species provide multifaceted contributions to the stability of ecosystems. *Nature Ecology and Evolution*, *1*.

Wiley, J. W., & Wunderle, J. M. (1993). The effects of hurricanes on birds, with special reference to Caribbean islands. *Bird Conservation International*, *3*, 319–349.

Yang, Q., Fowler, M. S., Jackson, A. L., & Donohue, I. (2019). The predictability of ecological stability in a noisy world. *Nature Ecology and Evolution*, *3*, 31–33.

Zhang, Q., Hong, Y., Zou, F., Zhang, M., Lee, T. M., Song, X., & Rao, J. (2016). Avian responses to an extreme ice storm are determined by a combination of functional traits, behavioural adaptations and habitat modifications. *Scientific Reports*, *6*, 22344.