Conservation of avian diet specialists: lessons from brood provisioning ecology of the endangered vermivore, the Fairy Pitta (*Pitta nympha*)

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Abstract

Information on the diet of endangered species is crucial in conservation, especially for diet specialists. The Fairy Pitta, *Pitta nympha*, is classified as "vulnerable species" by IUCN. In a field-based study on the nestlings' diet and parental care, combined with the existing literature, we confirm pitta's dietary specialization as vermivory and report the effect of rain on the proportion and size of earthworms in the nestlings' diet. We use the quantitative results, along with the literature on earthworm densities, to speculate that the habitat's surface area required to supply a pair of the Fairy Pitta with earthworms for the whole breeding event approximately matches the territory (home range) size extracted from the published censuses of the Fairy Pitta. This match highlights the importance of earthworms for the population ecology of the Fairy Pitta. Finally, based on the comparison of earthworm densities in natural and anthropogenic habitats, we hypothesize that spatial mosaic of patches of natural and anthropogenic habitats, with patch sizes based on the Fairy Pitta's territory size, may mitigate the negative effects of the conversion of natural habitats to anthropogenic habitats on pitta's population.

Introduction

Unique dietary specializations have to be considered in the conservation of endangered species (e.g., fig-eating birds[1]). Diet specialization that involves feeding on earthworms (one of the prey types of vermivorous birds) is observed in a range of avian species from several families worldwide, such as pittas[2,3], antpittas (Grallariidae[4]), and thrushes (Turdidae[5–8]), including 16 species of pittas classified as "near threatened", "vulnerable" or "endangered"[3] and the "near threatened" vermivorous Amami Thrush (*Zoothera major*[5])

The Fairy Pitta, *Pitta nympha*, is one of the endangered vermivores[9]. It is a ground forager with a body length of 16-20 cm, a body weight of 67.5–155 g, and a colorful plumage[9] (Fig. 1A). It is classified as Vulnerable on the IUCN Red List of Threatened Species and as Endangered in CITES Appendix II, with the population declining as a result of deforestation and destruction of typical breeding habitats[10–12]. However, environmental changes may lead to an increase in habitats optimal for the breeding of the Fairy Pitta[13], and in some areas their breeding was reported in anthropogenic landscape[9]. The Fairy Pitta breeds in moist broadleaved evergreen forests, especially near streams and in ravines[9,11,14]. Even though it prefers areas of low urban development[15], it also breeds in scrub jungle and anthropogenic habitats such as cedar and bamboo plantations and scarcely populated wooded areas[9], which indicates that the species may be adaptable to modified forest habitats[11]. As one of the main threats is the conversion of natural habitats to anthropogenic habitats, the ability of pittas to exploit food resources in newly created habitats is important for conservation. To address this, basic information on the diet of pittas during breeding season is needed.

The main breeding range of the Fairy Pitta comprises E and SE China, S Korea (Jeju and SW Korean Peninsula), S Japan, and Taiwan[9,16,17] (Fig. 1B). Two published studies of observations at nine nests provided some basic data on parental care and nestlings' diet for the southern part of the breeding range[18,19] (Taiwan and SE China; nr 1, 2 in Fig. 1B), while the information for the northern part of the breeding range comes from only two nests studied on Jeju Island[20] (nr 3 in Fig. 1B). It has been suggested that the species' dietary specialization, vermivory, should be considered for conservation actions. However, except for the species account in BirdLife International[11], no attempt to compile all the evidence from the literature and to summarize it from the standpoint of conservation has been conducted yet. Additionally, apart from only three reports of earthworm densities in the Fairy Pitta's habitats in Korea[21,22] and Japan[23], we are not aware of broader analyses that would use the results of the nestling diet and parental provisioning studies combined with the literature on earthworm abundance to discuss its consequences for ecology and conservation of the Fairy Pitta. Basic-science of ecology often refrains from speculations that, even if approximate in nature, can be useful for conservation, while practically oriented conservationists may disregard purely basic knowledge if it is not directly linked through generalization and science-based speculations to the applied science of conservation.

The study has two aims and two parts: an analysis of field-collected data compared to basic information already published, and a set of speculative calculations, based on our data and the literature, which can be useful for conservation. The first part comprises standard statistical analyses of the new data on the nestlings' diet and parental provisioning in the northern part of the Fairy Pitta's breeding range. Here we present the diet composition of nestlings, and we determine the effect of nestlings' age, rain fall, and time of day on the composition of the food load, the proportion of earthworms, and the size of earthworms delivered to nestlings at a parental food provisioning visit. The second part is an attempt to use all currently available information to evaluate the importance of earthworms in the breeding ecology of the Fairy Pitta and to hypothesize about possible conservation implications of our results. It involves combining our data and the literature to quantitatively speculate about the hypothetical match between the pitta's breeding territory size and the surface area of breeding habitat needed to provide a sufficient number of earthworms for the whole breeding event (nestlings and parents), as well as to discuss conservation implications of the results.

Results

Standard analytical part

General diet composition and prey size

We recorded 647 prey items in total. Earthworms made up the largest proportion of the nestlings' diet (n = 547, 84.5%; Fig. 1C; Supplementary Table S2; Supplementary video). Centipedes were the next most frequent prey item (n = 34, 5.3%). The other prey categories such as caterpillars, adult beetles, insect pupae, dragonfly, arrowhead flatworms, mole crickets, moth, grasshoppers, stick insect, and snake, comprised less than 9% of all prey items (details in Supplementary Table S2). In each of the four nests, the proportion of earthworms decreased as the nestling age increased (Supplementary Table S3). The length of prey items varied from 0.49 to 15.49 cm (5.92 ± 2.68 cm, mean ± SD; n = 647; Fig. 2A). The earthworms were relatively longer (6.34 ± 2.50 cm) than most of the other prey items (3.59 ± 2.40 cm), except several long prey items comprising 6.6% of the prey items, and including snake, earthworms, and arrowhead flatworms, which were longer than 10 cm. The longest prey was a 15.5 cm long earthworm.

Provisioning of nestlings

The parents hunted one prey at a time and deposited each prey in a pile on the ground so that the bird can search for more prey. After multiple invertebrates have been collected in this manner, the bird would pick all prey items and it would fly to the nest. The birds frequently sundered prey before depositing them on the ground. We observed 233 feeding visits. There was a negative relationship between the **number of earthworms** per visit and the **average prey length** per feeding visit for visits loads that included only earthworms (Fig. 2B; Supplementary Table S4; the variable names are in **bold font** and their detailed definitions are in the Methods part 3). Only in 4.7% of visits, the food loads did not contain earthworms (NoE visit type), while the remaining 95.3% of visits (EI visit type; "**E**arthworms **I**ncluded") comprised either only-earthworms food loads (OE visit type) or a mixture of earthworms and other food items (MIX visit type). The frequency of NoE feeding visits was significantly smaller for younger nestlings (Fig. 2C; Supplementary Tables S5, S6). Among EI visits, 67.5% were of OE type, and the remaining visits were of the MIX type. The probability of MIX type was significantly smaller for younger nestlings (Fig. 2D; Supplementary Table S5). The **inter-visit interval** and the **time of day** were excluded from the best models (Supplementary Tables S4, S5).

The parents brought one to seven prey items in each visit (2.74 ± 1.30, mean ± SD, n = 233). The **number of prey items** per visit was larger for the prey loads that included earthworms (EI) than for the prey loads that did not contain earthworms (NoE; Fig. 2E; Supplementary Table S7). Analogical analysis among the visits containing earthworms (EI), showed that the **number of prey items** was larger for visits containing a mix of earthworms and other prey items (MIX) than for visits with only earthworms (OE; Fig. 2F; Supplementary Table S7).

For visits that included only earthworms (OE), the **number of earthworms** per visit was significantly smaller during days with heavy rain than on days with light rain (Fig. 2G; Supplementary Table S8). Although the best model for the **biomass of a single earthworm** did not include the **weather category**, the second-best model (DAICc = 0.33) included a significant (p = 0.004) effect of rain: the earthworms fed to the nestlings were heavier on days with heavy rain than on days with light rain (Fig. 2H; Supplementary Table S8). The total **biomass of earthworms per visit** was not affected by the **weather category**, **inter-visit interval**, and **nestling age class** (Fig. 2I; Supplementary Table S8).

The average **inter-visit interval** was 35 ± 26 minutes (mean ± SD, n = 200). We found that the **inter-visit interval** was significantly shorter in the morning than in the remaining time of day (Supplementary Fig.

S1A; Supplementary Table S9) and significantly longer for young than for old broods (Supplementary Fig. S1B; Supplementary Table S9).

Speculative part

Number and biomass of earthworms consumed by one brood and implications for breeding territory size

As a result of approximate calculations based on our empirical data (see Methods part *5*), a brood was estimated to consume on average about 985 earthworms from hatching to fledging (range of estimates: 619-1359; Supplementary Table S10), and a nestling was estimated to consume on average about 171 earthworms from hatching to fledging (range of estimates: 83-227; Supplementary Table S10). This corresponds to about 699 g of the fresh mass of earthworms per brood (range of estimates: 398-1009g; Supplementary Table S10), and about 21 g of the fresh mass of earthworms per nestling (range of estimates: 12.2-29.0g; Supplementary Table S10).

We approximately estimated (details and assumptions in the Methods part *5*) that a pair of the Fairy Pitta and their brood might have consumed from 2844 to 5668 earthworms during a breeding event, and the estimate depends on the assumed brood size (5 or 6), and the proportion of earthworms in the parents' daily energy expenditure (a range from 30% to 70% was used; Supplementary Table S11).

For a range of epigeic earthworms' densities found in the upper soil layer in the breeding habitats of the Fairy Pitta (Fig. 3B-first column), and using the above estimates of the number of earthworms required for one breeding cycle, we calculated (see Methods part *6*) the relationship between the percentage of local earthworm density available to pittas on ground surface (horizontal axis in Fig. 3A and in 30 panels of Supplementary Fig. S2A) and the theoretically predicted surface area of a local habitat needed to provide a sufficient number of earthworms for a pair and its brood ("predicted territory" gray band in Fig. 3A and in the panels of Supplementary Fig. S2A) over a range of earthworm densities: from the smallest to the largest density of earthworms empirically detected in the territories of the Fairy Pitta (lower and upper edge of the gray band in Fig. 3A and in the panels of Supplementary Fig. S2A). Fig. 3A is an example of estimated range (gray-shaded diagonal band of "predicted territory") of the natural breeding habitat surface area (vertical axis) that is needed to provide a sufficient number of earthworms (in this case 5668 earthworms needed for a brood of 6 nestlings and 2 parents for the full breeding event assuming that earthworms constitute 70% of adult DEE; see Methods part *6*) as a function of proportion of the epigeic earthworm abundance available and detected on the surface by the foraging birds (horizontal axis; 0.1–100%), and assuming that epigeic earthworm densities vary between the smallest (0.53 individuals/m^2; blue line upper edge of the gray band) and the highest (8.67 individuals/m^2; orange line lower edge of the gray band) value detected in breeding habitats of the Fairy Pitta[21,23]. The vertical semitransparent green band indicates the range of values (0.5-5%) on the horizontal axis that is likely to occur in nature based on Duriez et al.[24]. The horizontal semitransparent purple band indicates the empirically estimated range of breeding territory size of the Fairy Pitta (10-30 ha; "observed territory"; see Methods part *7*), and the section marked with the red outline indicates where the observed territory size overlaps with the predicted area needed for a breeding event (see Methods part *8*). This panel is taken from Supplementary Fig. S2A where a full set of 30 similar panels is given representing all combinations of two brood sizes, 3 types of estimates (only needs of nestlings, needs of nestlings + provisioning parents; needs of nestlings + parents during the full breeding event), five levels of % of earthworms in the adult's DEE (see Methods part *6*).

The surface area of the overlap between the gray, green and purple bands marked with a red line polygon in Fig. 3A and with red-shaded polygons in Supplementary Fig. S2A, indicates the degree of match between the range of the theoretically predicted territory (home range area) and the range of empirically derived area ("observed" territory size). The greatest match was observed when the needs of the nestlings and parents during the whole breeding event were taken into account, while the match was the poorest when only nestling provisioning needs were considered (Fig. 3D, E; Supplementary Fig. S2B, C). The results suggest that the breeding territory area established by the Fairy Pitta may adaptively match the surface area needed to provide earthworms for the whole family during the full breeding event.

The abundance of earthworms in different habitats

Anthropogenic habitats in the Fairy Pitta's breeding range, such as plantations or secondary woodlots that provide vegetation cover under which pittas could safely forage, do not seem to harbor larger densities of earthworms than the natural-forest breeding habitats do (Fig. 3B), and data for the earthworm biomass are too scarce for reliable conclusions (Fig. 3C). On the wintering grounds (non-breeding range), however, the data including winter season (when Fairy Pitta are present on their wintering grounds) indicate that some of the anthropogenic habitats may provide better foraging opportunities for pittas than the natural habitats do (Fig. 3B, C; see also Supplementary data and Methods part *9*)

Discussion

Our results combined with the literature[20] show that the frequency of parental visits to the nest is the highest in the morning and the lowest in the middle of the day – a typical pattern for provisioning by passerine birds[25–27]. The overview of all four studies of the nestlings' diet (Table 1) suggests that pittas in the northern part of the breeding range have a lower frequency of nest visits (Table 1) and that they bring more prey items during each visit than pittas in the southern part of the breeding range (Table 1). Although earthworms form a majority of prey items in the northern and southern part, caterpillars appear to play an important role in the diet of nestlings in the southern part of the breeding range, while centipedes and probably cicada nymphs ("Homoptera larvae") seem important in the northern part of the breeding range (Table 1). In both the southern and the northern parts of the breeding range, the number of prey items per visit is larger when earthworms are included in the prey load brought to the nest (Table 1) suggesting that earthworms may be more abundant (at least in habitat patches visited by the birds) than the other prey, or that simply it is easier to pack a load of multiple earthworms than other invertebrate prey in the pitta's beak. Regardless, a visit of a parent with multiple prey items is important for the growth of nestlings, suggesting that breeding territories providing a high abundance of earthworms are better for the provisioning of nestlings. This is especially clear considering that in both the southern and the northern parts of the breeding range earthworms comprise above 70% (usually 80–90%) of the items in the diet of the Fairy Pitta's nestlings[18–20] (Table 1), with nearly 100% of diet items consisting of earthworms for the young nestlings.

As rain is known to affect earthworms' surfacing activity[28], it is not surprising that in the wetter breeding seasons the birds included more earthworms in their nestlings' diet[18]. However, the short-term effect of the heavy rain in our data resulted in a lower number of earthworms brought per visit on days with heavy rain, albeit those worms were larger. The smaller number might have been caused by heavy rain interrupting foraging trips or simply because fewer large worms can fit in the bird's beak. However, it is also possible that foraging birds may cue on the sounds of earthworms moving in the litter[8], and therefore during dry weather or under light rain (when litter produces clear sounds during earthworms' movements), the % of epigeic earthworms available to the Fairy Pitta on the surface may be larger than the % visually detectable (as assumed in Fig. 3A and Supplementary Fig. S2; vertical semitransparent green band). These auditory cues are not likely to be helpful when dead leaves on the ground are wet after heavy rain and do not produce clear sounds when worms move in the litter. The larger size of worms collected on days with heavy rain may be related to the earthworms' surfacing behavior in response to rain[29]: rain might have contributed to the increase in earthworm's body length either because a proportion of larger earthworms on the surface is larger after/during heavy rain or because a total abundance of earthworm increases and birds become more choosy picking up only the larger prey in accordance with optimal foraging theory[30–32].

Similar processes related to the importance of earthworms as a food source are likely in other species of pittas as they are vermivorous and their geographic distribution is consistent with the distribution of relatively high earthworm abundance[14,33]. For example, the Indian Pitta, *Pitta brachyura* prefers to breed in evergreen broad-leaved forests along ravines where surface living earthworms are abundant[23], and the number of nests of the Rainbow Pitta, *Pitta iris* was positively correlated with both rainfall and earthworm abundance[34]. As earthworms are the most important food source, especially for the young nestlings, it is not surprising that the Fairy Pitta appears to have developed a special behavioral adaptation for handling and carrying earthworms to the nest: earthworm sundering[35], which also occurs in other avian vermivores[2,4,6,7,35,36].

Our calculations of the surface area required to provide a breeding pair with a sufficient number of earthworms are based on multiple assumptions and therefore must be critically viewed as only very rough approximations justifiable due to the lack of better data needed for science-based conservation strategies. While we are aware of their extremely approximate nature, we believe that through similar attempts of generalizations and approximations the basic scientific knowledge may be directly useful in the applied science of conservation. Our results showed that there is a reasonable match between the surface area that contains a sufficient number of earthworms for the full breeding cycle of a pair with their brood and the empirically derived evaluations of the size of the breeding territory (in songbirds breeding territory typically provides all resources for the brood and parents) based on the literature, while the match was much less clear when only the needs of nestlings or families (parents +nestlings) during only the brood provisioning period were considered. This is consistent with the hypothesis that densities of earthworms living in the surface layer of soil in habitats surrounding pitta's nests shape the Fairy Pitta's territoriality, spacing, and population density during the breeding season.

As the transformation of natural forest habitats within the Fairy Pitta's breeding range into anthropogenic vegetation that may be potentially suitable for pitta's foraging (due to the presence of sufficient vegetation cover) leads generally to a decrease in earthworm abundance (Fig. 3C), establishing territories that contain these anthropogenic habitats may require from the birds to increase the territory size above the typical range of values, which would increase foraging costs and may have negative effects on the efficiency of provisioning of nestlings, nestlings' growth and breeding success. However, we cannot exclude that some of the anthropogenic habitats that have not been sampled for the abundance of earthworms within the breeding range of the Fairy Pitta harbor higher earthworm abundance than the natural breeding habitats as suggested by the high abundance of earthworms in bamboo plantations in the tropical non-breeding range of pitta (Fig. 3C). If this is the case, then it may explain why in Japan and Taiwan the Fairy Pitta establishes territories in or near plantations[18,23], but no data on earthworm abundance for these habitats is available. This suggests that anthropogenic transformations of natural forest habitats into plantations that harbor high densities of earthworms may hypothetically benefit breeding pittas by providing a high abundance of the crucial food resources assuming that those habitats provide enough cover for pittas to safely forage there. For example, it has been already reported that pitta parents visited anthropogenic forests of *Cryptomeria japonica* and *Chamaecyparis obtusa* more frequently because the density of earthworms was relatively high there, but they apparently required natural habitats for nest location[37] (Supplementary information Part 3; cited in BirdLife International[10]).

We therefore propose that creating a spatial mosaic of natural habitats, in which nests can be located, mixed with plantations, in which earthworm densities are high, may lead to a balance between conservation and development in which the Fairy Pitta populations survive. The spatial mosaic should take into account the breeding territory size needed to supply a breeding pair with a sufficient number of earthworms for the provisioning of the nestlings. For example, based on the literature-derived evaluations of territory size presented here (10–30 ha) such a mosaic may involve a mixture of ~10–15 ha natural woodlots with good nesting sites (e.g., forested ravines) intermixed with ~10–15 ha patches of plantations with known high densities of earthworms. As it is possible that on the wintering grounds Fairy Pittas learn that high earthworm densities occur in some specific types of plantations, the proposed mosaic landscape on breeding grounds should involve similar types of plantations. Similar reasoning may apply to the conservation of 15 other species of pittas classified as “near threatened” (7 species), “vulnerable” (6 species), or “endangered”[3] (2 species) and the “near threatened” vermivorous Amami Thrush[5] (*Zoothera major*). However, more studies have to be conducted to determine if breeding in the earthworm-rich plantations or near them is indeed caused by a high abundance of earthworms in those habitats in the breeding range of the Fairy Pitta.

In conclusion, the Fairy Pitta is a vermivorous diet specialist with specific behavioral adaptations unique to the process of provisioning altricial nestlings with earthworms. It is susceptible to among-season differences in diet due to negative effects of drought on the availability of earthworms and within-season short-term variation in the number and size of earthworms associated with the presence or absence of heavy rainfall. We have presented evidence suggesting that earthworms’ availability crucially affects the Fairy Pitta’s breeding and spacing (territory size) and that the breeding territory size corresponds to the surface area needed to supply earthworms for the whole breeding event. We propose that the negative effects of degradation and fragmentation of the Fairy Pitta’s habitats[10] may be partially mitigated by policies requiring that the natural habitat is replaced with man-made habitats that are rich in earthworms, provide appropriate vegetation cover for the foraging birds, and form a spatial mosaic with the non-transformed natural habitats, in which pittas can build their nests. We suggest that a similar approach can be used in the conservation of other endangered vermivorous birds worldwide.

Methods

We number the subsections in the “Methods” for easier cross-referencing among the Methods, Results and Supplementary Materials.

Standard analytical part

1) Ethics declarations

No animals were captured, harmed, or stressed in any way during this study. Observations of birds were conducted from a distance without disturbance in accordance with the laws of the Republic of Korea.

2) Field work

From May to July in 2012, 2013, and 2017, we (JP) studied a total of four nests of the Fairy Pitta in Namhae-gun located in the southern part of the Republic of Korea (127°54'E, 34°50'N; nr 4 in Fig. 1B), which is the northern part of the pitta’s breeding range[9] (Fig. 1B; eBird 2020). We conducted detailed observations at four nests (Supplementary Table S1). At each nest, we installed a dark-colored camouflaged tent 20 m away from the nest, and from inside of the tent we filmed and photographed visiting parents using cameras[38] (Canon 1D Mark 4, Canon 7D, Canon 500D, lens Sigma 50–500mm).

3) Variables for statistical analyses

From the videos and photos, we extracted the following variables that were used in statistical analyses:

- Nest ID: This categorical variable has four values; Nest 1, Nest 2, Nest 3, and Nest 4. Each nest ID indicates a distinct nest, but as we observed 4 nests over 3 years, it is clear that variation among nests also represents variation among years.

- Nestling age class: The age of the nestlings coded as "young" for 1–7 days old brood, and "old" for 8–13 days old brood.

- Number of prey items: Number of prey items brought by a parent in its beak at one visit (which constitutes a prey load).

- Number of earthworms: Number of earthworms brought by a parent in its beak at one visit (which constitutes a prey load).

- Time of day: This categorical variable has 3 values; morning (before 10 AM), noon (10 AM to 2 PM), and afternoon (after 2 PM).

- Prey type: 14 categories that correspond to the taxon of the identified prey (12 categories) or indicate that the prey item is unidentified: unidentified arthropods, unidentified prey (not earthworms).

- Prey length: A body length of each single prey (cm) brought to the nest. We measured the prey length in the units of beak length and recalculated it to centimeters assuming beak length of 2 cm[18]. In some cases, the length of prey or composition of the food load was not recognizable due to the light condition or prey position in the beak. This data was removed in statistical analyses regarding the length of prey. Also, we often observed visits of parents with food items (mostly earthworms) sundered into pieces. We determined the length of prey before sundering by matching the thickness, length, color, and pattern in the cross-section of sundered prey.

- Feeding visit type: In the variable **feeding visit type1**, each feeding visit was categorized according to the beak-load composition as either "No Earthworms (NoE)" or "Earthworms Included (EI)" type. In the variable **feeding visit type2**, we classified each visit in the "EI" category as either "Only Earthworms present (OE)" or "earthworms mixed with other prey types (MIX)" type.

- Average prey length: Average length of the prey items per visit (cm), which comprises the average prey length in a prey load. We added all length of prey items the parents brought at a feeding visit and divided it by their number.

- Biomass of a single earthworm (in grams of ash-free dry mass, AFDM): We calculated ash-free dry mass (AFDM) of each single earthworm brought to the nest from its estimated length using the allometric equations for Megascolecidae[39] (AFDM (g) = exp(3.19 × ln [length (mm)] - 15.85)), which is dominant in the earthworm fauna of South Korea[40,41]. Then, we estimated the fresh mass of earthworms by multiplying the ash-free dry mass (AFDM, g) by 5.7904 based on Onrust[51], which is also similar to the ~5.6 suggested by the data in Table II of Reynolds[52].

- Biomass of earthworms per visit (in grams): We calculated a sum of the biomass (estimated using the equation above) of all earthworms for a feeding visit of type OE.

- Earthworm length category: Earthworm length was categorized based on the average of all earthworms in all visits observed in those 4 nests (6.34 ± 2.50 cm). Earthworms longer than the average length were categorized as the “long” type and earthworms shorter than the average length were categorized as the “short” type.

- **Visit ID**: Each feeding visit was given a categorical value. Each visit ID indicates a distinct feeding visit across all four nests.

- Inter-visit interval: Time interval between the two consecutive feeding visits expressed in minutes; the time between the moment of leaving the nest and the moment of the subsequent arrival to the nest with food. We did not calculate the frequency of visits because our observations’ starting and ending times were usually at the moment of a visit rather than at a pre-established moment independent of the timing of visits.

- Weather category: The daily cumulative precipitation on the day of observations was categorized as “light rain” for precipitation below 4 mm or no precipitation, and as “heavy rain” for precipitation over 4 mm.

4) Statistical analyses

As often happens in reports on vulnerable or endangered species, we faced an issue of small sample sizes, which constrained the statistical analyses to simpler and more basic approaches. Nevertheless, we attempted to extract as much valuable information from our data set as possible, and we added an overview analysis of all the current knowledge on pitta’s parental provisioning and the diet of nestlings in order to generate reasonable conclusions that may be useful in the conservation of this species.

Overall analyses using contingency tables and nonparametric tests **-** For each nest, we used the Fisher exact tests to determine the effect (in a statistical sense) of **nestling age class** on the proportion (%) of earthworms in the nestlings' diet and on the proportion (%) visits with earthworms only in all visits (100% × OE/[OE + NoE + MIX]), followed by the Fisher's combined probability test using survcomp package[42].

Generalized linear and linear mixed model analyses **-** We used generalized (glmer) or linear (lmer) mixed-effects models to determine factors that affect (in the sense of statistics) the following response variables: **number of prey items**, **number of earthworms**, **biomass of a single earthworm** (Box-Cox-transformed; exponent value of 0.1), **biomass of earthworms per visit** (square-root-transformed), **average prey length** (analyzed only for the OE feeding visit type, square-root-transformed), **inter-visit interval** (square-root-transformed), **prey handling**, **feeding visit type1**, **feeding visit type2**. We used **nest ID** as a random variable. We also used **visit ID** (nested within the **nest ID**) as a random variable in the mixed models where appropriate. Additionally, in alternative analyses, we used **nest ID** as an independent variable in order to examine the robustness of our conclusions. In each analysis, we started with an initial model, generated all possible models, and chose the three best models ranked according to their AICc value using the dredge function[43]. As we deal with a small amount of data, we chose to avoid initial models that may be too complex considering available data. Therefore for each response variable, we chose only several initial independent variables (different sets for different response variables, depending on the question in mind) that were likely to affect the response variable. Also, for the same reason, we did not explore interactions between independent variables. We fully recognize the shortcomings of these analyses, but this compromise results from the paucity of data relative to the complexity of the possible full models and it guards against overparameterization. Since the inter-visit interval for the first feeding visit of each day could not be calculated, the data points for the first visit were excluded from those analyses that considered models with the inter-visit interval as a dependent or an independent variable. We tested multicollinearity between independent variables by *vif* using *car* package[44] and found no serious concerns as the VIF and $GVIF^{1/(2 \times DF)}$ were smaller than 1.15[45,46]. Normality was checked using the Shapiro-Wilk test. GLMER and LMER were conducted using lme4 package[47] and lmerTest package[48] in R version 4.0.2[49].

Speculative part

5) Summary and estimation of the number and biomass of earthworms consumed during one breeding event

Summary table based on literature **-** In order to summarize all available information on parental provisioning and diet, and in order to determine if earthworms comprise the majority of food items brought to nestlings across the breeding range of pittas, we tabularized the existing knowledge (literature plus our data) systematically to highlight common characteristics among all four studied sites (15 nests; including our data). Next, we focused on earthworms as nestling's main food resource that is crucial for breeding success.

Estimation of earthworms consumed in the observed nests during breeding season - Based on our empirical results, we approximately estimated the ash-dry and fresh biomass, as well as the number of earthworms (assuming an average earthworm size from our data) needed in one breeding event. First, in each nest for each day of video recording, we calculated the number of earthworms and the ash-free dry mass (AFDM, g) of earthworms delivered per hour. Then, we calculated the **average number/biomass of earthworms per hour** from the multiple data points (one data point per day) for each nest. This procedure of approximate calculations is justified by the relatively equal contribution of data from the separate consecutive stages of nestling development: the young, intermediate, and old age nestlings contributed approximately equally to the data set in each nest, especially in the three nests used for the final evaluation (nest 1, 3, 4; Supplementary Table S1, S10).

Next, for each nest we multiplied the **average number** (and **average biomass** in separate calculations) **of earthworms per hour** by the number of hours per day during which pitta parents provision nestlings (15 hours of daily activity of the Fairy Pitta parents between 5 AM and 8 PM; based on JP observation) and by the duration of the nestling stage (12.05 days; mean value calculated from our data) to obtain the **estimated number** (and **biomass**) **of earthworms during parental provisioning** for each nest (Supplementary Table S10). For each nest, we divided it by brood size to obtain the **estimated number** (and **biomass) of earthworms per nestling during parental provisioning**. Our estimates of the number of earthworms consumed by a brood in each nest are generally consistent with Okada's estimate of 70–80 earthworms daily[50] (Supplementary information Part 3; cited in BirdLife International[10]), which would amount to about 910-1040 earthworms during the period of parental provisioning, a number within our range of estimates (Supplementary Table S10).

Finally, we calculated the **mean estimated number** (and **biomass**) **of earthworms per nestling during parental provisioning** for all four nests (Supplementary Table S10), and also for the three nests with more reliable data (excluding nest 2 with the smallest number of days with recordings; Supplementary Table S10). We treat the means from these three well-sampled nests as the approximate estimate of the number of earthworms needed to successfully raise one nestling.

Estimation of number (and biomass) of earthworms needed for an average breeding attempt in broods of 5 and 6 nestlings - We calculated the estimated number and biomass of earthworms needed to raise a full brood by multiplying the mean number (and mean biomass in a separate calculation) per nestling from those 3 nests (nest 1, 3, 4)) by the number of nestlings in the typical brood of the Fairy Pitta (5 or 6 nestlings, separately) and we labeled the estimate as the **Number of earthworms estimate1** (separately for brood of 5 and 6 nestlings).

These estimates do not include earthworms consumed by parents and therefore they underestimate the total number of earthworms needed by the whole family during parental provisioning. Hence, we calculated the theoretically predicted number of earthworms needed to fulfill the presumptive Daily Energy Expenditure (DEE) of the parents of the Fairy Pitta during the breeding event. The average mass of adult male and female Fairy Pitta is 109 g and 71.5 g respectively[53]. Assuming those sex-specific body masses, we calculated the DEE of male and female from the formula (DEE = 1092 × $BM^{0.729}$; where BM stands for body mass and DEE is expressed in kJ) derived by Kersten and Piersma[54] for wading birds similar in size to the Fairy Pitta and used in similar calculations by Onrust[51]. This is also consistent with the relationship between body weight and DEE in Goldstein[55] (see Fig. 6 there), and quite similar to the evaluation of DEE for such species similar in size to the Fairy Pitta like the starling, *Sturnus vulgaris*[56] or the dipper, *Cinclus cinclus*[57,58]. According to the calculations, a pair with the average body mass is predicted to have the DEE of about 377 kJ/day (See Supplementary Calculation File in excel format).

To express the estimated DEE in the earthworm biomass we assumed that the energy content of earthworms collected by the Fairy Pitta is 16.72 kJ per gram of earthworms (Ash free dry mass; AFDM) as measured by Yin et al.[59] in forest habitats of China. Finally, to express it in the number of earthworms we assumed that an average earthworm weighs 0.12258 g of AFDM as indicated by our data. We also took into account that in addition to the earthworms, the parent birds have a much more diverse diet than nestlings[9,10]. However, since no precise information on the proportion of earthworms in the diet of the parents is available, we conducted calculations for five different values of the contribution of earthworms to the adult's DEE: 30, 40, 50, 60, or 70% of the DEE. The resulting formula for the estimated number of earthworms eaten by a pair of Fairy Pittas during 12.05 days of parental provisioning is:

Estimated number earthworms consumed by a pair during parental provisioning = {proportion of earthworm abundance on surface [0.30-0.70] × DEE [377 kJ/day] × number of days [12.05 days)] × 2 parents] }/ 16.72 (kJ per gram AFDM of earthworms) / 0.12258 g (average earthworm weight: AFDM)]

After adding this number to the **Number of earthworms estimate_1** we obtained the **Number of earthworms estimate_2**

These estimates ignore the DEE of the pair for the nest building and incubation period. To account for those periods, we considered that incubation lasts two weeks (based on our data) and the nest building stage lasts for 10 days[60] (cited in Kim[61]). Hence the formula is the following:

Estimated number earthworms consumed by a pair during a full breeding event = {proportion of earthworm abundance on surface [0.30-0.70] × DEE [377 kJ/day] × number of days [12.05 + 14 + 10 days)] × 2 parents] }/ 16.72 (kJ per gram AFDM of earthworms) / 0.12258 g (average earthworm weight: AFDM)]

After adding this number to the **Number of earthworms estimate_1** we obtained the **Number of earthworms estimate_3**

6) Estimation of the surface area of the breeding territory that provides the number of earthworms needed for one successful breeding event ("predicted territory")

We then used the estimates of the number of earthworms needed in calculations to approximate theoretical size of the breeding home range (or breeding territory, as in the case of typical songbirds the two mostly overlap) that may provide a sufficient number of earthworms for a typical brood of pittas (and parents) assuming that densities of earthworms in the surface A0 layer of the soil follow the values found in the typical breeding habitats of the Fairy Pitta[21,23] (from the **lowest abundance** = 0.53 earthworms/m^2 to the **highest abundance** = 8.7 earthworms/m^2).

In the calculations, we considered that only a certain proportion of those epigeic earthworms can be visually detected at any point in time (and captured by pittas). As there are no empirical data concerning the proportion of surfacing earthworms in habitats of the Fairy Pitta, we calculated the predicted home range surface area for the range of the proportion of surfacing earthworms from 0.1% to 100%.

In these approximate calculations, we did not consider nuances of a possible effect of pitta's foraging on earthworm abundance during the pitta's breeding period, and we simply assumed that density of epigeic earthworms, and the proportion of them surfacing, remain stable during this time, i.e., that the reproduction and mortality roughly cancel each other and predation have minimal effect. This assumption of the stable population seems feasible to us for the purpose of our approximate calculations in this paper because the effects of "macro-predators" on earthworm abundance are usually relatively weak[62–65].

Using these values and assumptions, we estimated the home range size that would provide a sufficient number of surfacing earthworms for the nestlings during 12.05 days of parental provisioning (**Required home range area 1**), for the nestlings and parents during 12.05 days of parental provisioning (**Required**

home range area 2), or for the nestlings and parents during a full breeding event (36.05 days; **Required home range area 3**).

The lowest estimates (based on the lowest earthworm abundance known from literature) were calculated according to the following formulas (separately for broods with 5 and 6 nestlings) and correspond to the lower orange edge of the gray diagonal band in Supplementary Fig. S2A in the Supplementary Materials and in Fig. 3A (only **Required home range size 3** is shown in Fig. 3A)

Low_Required home range area 1 [m^2] = nr of earthworms needed [**Number of earthworms estimate_1**] / ((earthworm **lowest abundance** [nr/m^2]) × (0.01 × % surfacing earthworms))

Low_Required home range area 2 [m^2] = nr of earthworms needed [**Number of earthworms estimate_2**] / ((earthworm **lowest abundance** [nr/m^2]) × (0.01 × % surfacing earthworms))

Low_Required home range area 3 [m^2] = nr of earthworms needed [**Number of earthworms estimate_3**] / ((earthworm **lowest abundance** [nr/m^2]) × (0.01 × % surfacing earthworms))

The highest estimates (based on the highest earthworm abundance known from literature) were calculated according to the following formulas (separately for broods with 5 and 6 nestlings), and correspond to the upper blue edge of the gray diagonal band in Supplementary Fig. S2A in the Supplementary Materials and in Fig. 3A (only **Required home range size 3** is shown in Fig. 3A)

High_Required home range area 1 [m^2] = nr of earthworms needed [**Number of earthworms estimate_1**] / ((earthworm **highest abundance** [nr/m^2]) × (0.01 × % surfacing earthworms))

High_Required home range area 2 [m^2] = nr of earthworms needed [**Number of earthworms estimate_2**] / ((earthworm **highest abundance** [nr/m^2]) × (0.01 × % surfacing earthworms))

High_Required home range area 3 [m^2] = nr of earthworms needed [**Number of earthworms estimate_3**] / ((earthworm **highest abundance** [nr/m^2]) × (0.01 × % surfacing earthworms))

These formulas estimate the required home range as a function of the % (from 0 to 100%) of earthworm abundance that is “available” to the birds when earthworms are active on the ground surface. However, there are some indirect indications that the most likely values are within a range of several percent of the abundance of epigeic earthworms. This is based on the range of 0–2.6% of surfacing earthworms of seven epigeic species of earthworms (average: 1.4%; median: 1.3%) as measured by a human observer using a headlamp at night (calculations based on data in Table 2 of Duriez et al.[24]). It is reasonable to assume that pittas visually searching for earthworms in shadowy places in the undergrowth during the daytime may have higher efficiency than that of a human in the study[24]. Therefore, we assumed that the proportion of surfacing and visually detectable earthworms is within the range of 0.5–5% of the number of epigeic earthworms, and this is marked in the results (Fig. 3A, B; Supplementary Fig. S2A) with a green vertical band.

7) Literature-based estimations of breeding territory surface area ("observed territory")

We compared the range of the estimated *Required home range area* needed to supply sufficient food for a breeding event with the range of empirically derived breeding territory sizes of the Fairy Pitta from the literature. We used three sources to estimate the breeding territory surface area of the Fairy Pitta:

1) Observations by Okada[50] (Supplementary information Part 3; cited in Kim[66]) indicate that a breeding pair forages within 100–400 m from the nest. If the territory is circular that would amount to an estimated range of 3–50 ha, and assuming a radius of ~250 m (midrange between 100 and 400) the hypothetical circular territory would have a size of about 20 ha.

2) Based on an overview of Japanese papers (Supplementary information Part 3), Kim[66] suggested about five pairs per square kilometer, which indicates a home range size of maximally about 20 ha (corresponding to r = 253 m of a hypothetical circular territory).

3) Finally, we used calculations based on transects from Chinese forests[19]. We chose 2 transects in Nonggang and 3 transects from Mulun areas in Table 1 in Jiang et al.[19] because only those transects contained Fairy Pittas. Each transect was 200 m wide and their lengths were 2.3 km, 1.9 km and 4.6 km, 4.7 km, 5.7 km for Nonggang and Mulun respectively, and the number of individuals detected was 2, 2 and 4, 6, 2 for Nonggang and Mulun respectively[19]. Separately for each transect, we calculated the estimated territory area (in songbirds this usually corresponds to the home range) of a pair of Fairy Pittas according to the formulas:

Territory area estimate 1 = surface area of the transect / (nr of individuals recorded / 2)

Territory area estimate 2 = surface area of the transect / (nr of individuals recorded)

We then calculated the average value of estimate 1 (22.6 ha) and the average value of estimate 2 (45.3 ha). If these estimates are correct, the breeding territory size of the Fairy Pitta is estimated at 22.6–45.3 ha, which corresponds to r_1 = 268 m and r_2 = 380 m for a radius of a theoretical circular territory of the respective surface area. In this case of playback transects, both estimates assume that all birds were paired. The *Territory area estimate 2* assumes that only males, and all males, responded to the playbacks used on transects. The *Territory area estimate 1* assumes that all individuals, males, and females, responded as long as they were present within the 200 m wide band of the transect. In reality, it is likely that only some males and females responded and that the females were less responsive than males to a playback of a territorial call[67], leading to underestimation of the number of pairs and overestimation of the territory size. It is possible that the breeding territories were not adjacent to each other and that areas of unoccupied habitat separated them leading to overestimation of the territory size. But, if some of the detected pairs have territories that extended beyond the surface area of the transect (i.e., more than 100 m away from the transect route) then the estimates may underestimate the true home range size.

In summary, the three estimates of territory area overlapped to a large extent. Taking into account these estimates and considerations associated with each of them, we decided to use in the comparisons the **estimated territory area range** of 10-30 ha, which is marked as a horizontal semitransparent purple band in Fig. 3 and Supplementary Fig. S2.

8) Degree of overlap between predicted and observed territory size

Separately for the **Required home range area 1, 2 and 3** (as defined in the Methods part *6*), we determined the **degree of overlap** (marked with red line polygon in Fig. 3A and with red shaded polygons in Fig. S2A) between the theoretically predicted (Methods part *6*) and the observed territory area (estimated territory area range; Methods part *7*) within the range of 0.5–5% of the number of epigeic earthworms (Methods part *6*) assumed to be available to the birds. We measured the surface area (nr of pixels) of the overlapping region using ImageJ (version 1.53e). Then, we calculated the relative overlap by dividing the surface area (nr of pixels) of each measured overlap by the surface area (nr of pixels) of the theoretically maximal overlap possible between the gray band of predicted territory area and the purple band of empirically derived territory area ("observed territory") within the green vertical band of 0.5–5% of the number of epigeic earthworms assumed to be available to the birds. The outcomes of these calculations are presented in Fig. 3D, E and Supplementary Fig. S2B, C.

9) Literature-based summary of earthworm abundances in habitats suitable for foraging by the Fairy Pitta

From the literature, we have extracted information about earthworm abundance in natural habitats used by the Fairy Pitta for breeding, as well as other habitats in the pitta's breeding range that may provide vegetation cover and therefore potentially may provide foraging opportunities for the Fairy Pitta (e.g., various types of plantations and cultivated forests and tree/shrub stands). Additionally, we also collected similar information from the literature on earthworm densities in the typical natural forests, as well as other habitats (usually of anthropogenic origin) that may provide vegetation cover and foraging opportunities for pittas in their wintering range. We represented this data graphically, without any statistical testing of differences among habitats, because our goal is to use these data in generally discussing conservation implications of the dietary specialization of the Fairy Pitta (see Supplementary data for detailed results of this literature review), and because the methods differed among studies (the soil depth sampled ranged from 10 cm to 50 cm) leading to a heterogeneous set of data for which formal statistical analysis is not advisable.

Data Availability

The datasets generated and analyzed during this study are available from the JP on reasonable request.

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Declarations

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Author contributions

Conceptualization: J.P., S.I.L., P.G.J.; Data curation: J.P.; Formal analysis: all authors; Funding acquisition: S.I.L., P.G.J.; Investigation: J.P.; Methodology: J.P.; Project administration: S.I.L., P.G.J.; Supervision: S.I.L., P.G.J.; Validation: S.I.L., P.G.J.; Visualization: J.P., W.K., S.I.L., P.G.J.; Writing – Original Draft: P.J.; Writing – Review & Editing: all authors

Competing interests

The authors declare no competing interests.

Supplementary Information

Supplementary information.

Supplementary data.

Supplementary video: Feeding process of the Fairy Pitta. A parent with a full load of earthworms arrives at the nest entrance and is feeding the nestlings inside of the nest.

Tables

Table 1. Summary of available quantitative evidence on the parental provisioning and diet of the Fairy Pitta's nestlings. Summary of available quantitative evidence on the diet of the Fairy Pitta's nestlings. The table includes information from southern locations[18,19] and northern locations[20] (this paper is included here). YES or NO or *na* (data not available to evaluate the statement). * - estimate indirectly from the data on the number of prey items per visit, and the number of prey items per hour ([*] for Taiwan the % apparently represents the % of visits in which an item was present rather than the actual % among all food items even though the Table 2 caption in Lin et al.[18] confusingly suggests otherwise; the total number of items is not specified in the paper) [&] - (data from 2 nests pooled; % for only 2 taxa given).

Variables measured in a field study	Southern locations		Northern locations		Summary
	Taiwan[*]	South China	Jeju Island	Namhae-gun	
GENERAL INFORMATION:					
1) Breeding habitat	Bamboo plantations and secondary broadleaf forests	Limestone forests	Subtropical evergreen forests	Evergreen forests	Primary, secondary broadleaved forests and bamboo plantations.
2) Number of nests with diet studied / nr of food items (for Taiwan nr of items is not specified)	8 / > 1062[*]	1 / 354	2 / 826	4 / 647	15 nests / > 2800 items from 4 study locations
3) Clutch size (range) / brood size (range)	3-5 / 3-5	5-6 / 4-5	? / ?	5-6 / 5-6	3-6 / 3-6
FEEDING TRIPS TO PROVISION NESTLINGS:					
4) Number of visits per hour / (for old nestlings) [mean ± SD]	2-7 / (5-7) [??]	?? / (??) [3.9 ± 1.5]	?? / (??) [2.8* ± ?]	0.8-3.0 / (1.3-2.9) [1.7 ± 0.6]	Range: 1-7 per hour Mean: 1.7-3.9 per hour
5) Increase in visit frequency with nestlings' age	YES	YES	*na*	YES	YES
6) Effect of time of day on visit frequency: highest in the morning, lowest near noon	*na*	*na*	YES	YES	YES
7) Number of prey items per visit [mode, mean ± SD]	1, 1.8 ± 0.39	2, 2.05 ± 0.87	3, 3.0 ± 1.38	2, 2.74 ± 1.30	Mode: 1-3 per visit Mean: 1.8-3.0 per visit
8) Number of prey items higher in loads with earthworms	YES	*na*	YES	YES	YES
9) Parents sunder earthworms before carrying them to the nest	*na*	*na*	*na*	YES	YES
DIET COMPOSITION:					
10) If prevalence of earthworms	YES	YES	YES	YES	YES
11) Average % earthworms	73[*]	91.2	81.7	86	Typically, 80%-90%
12) Second/third/fourth most common prey taxon	caterpillars / beetles / vertebrates	Mantodea / caterpillars / Orthopterida	Homoptera larvae / ? / ?[&]	Centipedes / Orthopterida / beetles	Varies by location
13) Occasional presence of vertebrates in diet	YES	NO	NO	YES	Varies by location
14) Effect of rain on earthworms in the diet	YES, Between years	*na*	*na*	YES, Within a breeding season	YES
15) Decrease of % earthworms for older nestlings	YES[*]	*na*	*na*	YES	YES
16) Larger % of visits with earthworms for younger nestlings	YES[*]	*na*	*na*	YES	YES
PREY SIZE:					
17) Length of prey items [mode, mean ± SD], cm	4, 6.4 ± 0.55	*na*	*na*, 5.7 ± 2.85	5, 5.92 ± 2.68	Mode: 4-5 Mean: 5.7-6.4
18) Length of earthworms	*na*	*na*	Size class: 5-6, 6.8 ± 2.39	Size class: 4-6, 6.34 ± 2.50	Most common: 4-6 Mean: 6.3-6.8

[size class, mean ± SD], cm					
19) Larger earthworms in loads with fewer items	*na*	*na*	*na*	YES	YES

Figures

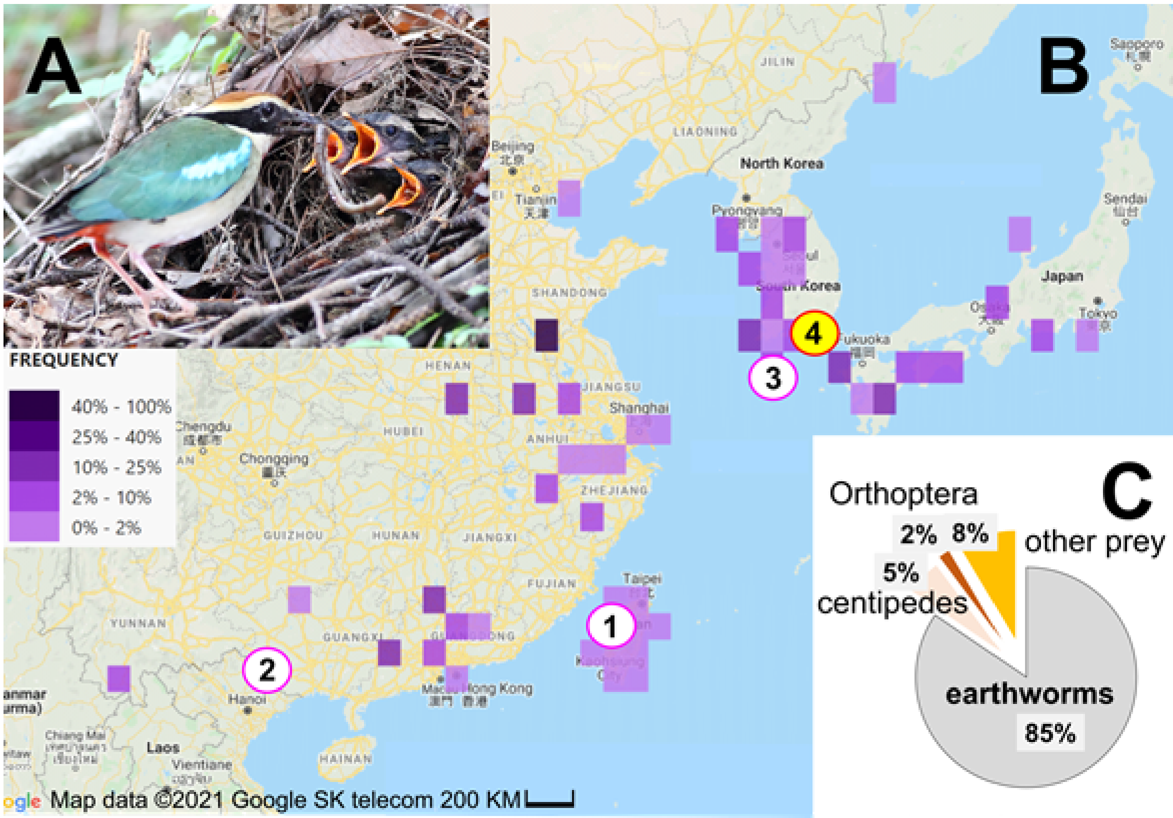

Figure 1

Study subject, study area, and diet composition. (A) - the Fairy Pitta parent sitting on the entrance of the nest with nestlings begging for food; (B) - the geographic distribution of Fairy Pitta's observations during the breeding season (based on eBird 2020 accessed 1 June 2020), and the location of our study site (red circle nr 4, filled yellow in) relative to other sites (nr 1, 2, 3) from which data on nestlings' diet and parental care are available in the literature (pink circles, filled white): (1) – Linnei, Taiwan[18], (2) – Noongang, China[19], (3) – Jeju, Korea[20]; (C) – diet composition at our study site based on total n = 647 prey items (details in Supplementary Table S2). Photo in A by JP.

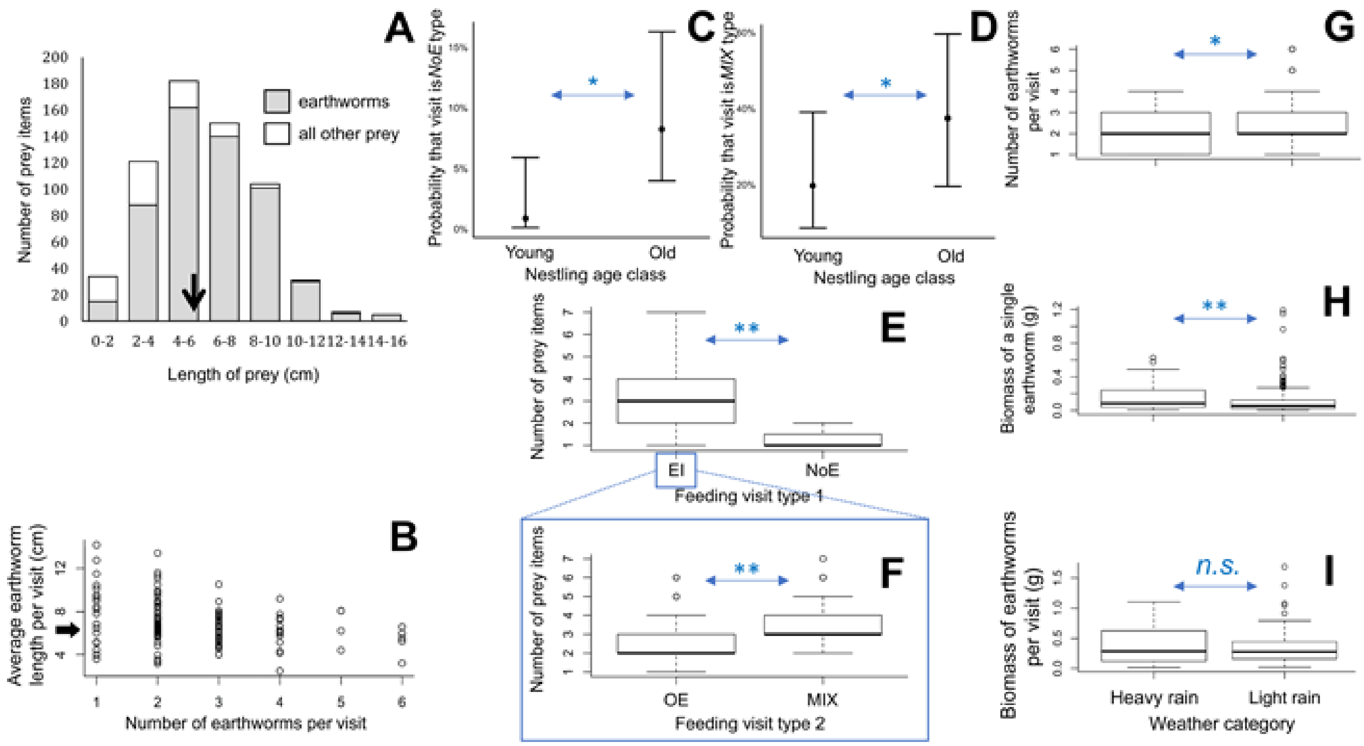

Figure 2

Factors affecting the earthworms brought to nestlings by parents. (A) - the distribution of **prey length** including earthworms (n = 647; black arrow indicates the average length for all the prey items: 5.92 cm); (B) – The relationship between the number and average length of earthworms in a food load per visit (*average length* = -0.09 * *number of earthworms + 2.84*; *p* = 0.001), an arrow indicates the average length of earthworms (6.34 cm); (C) - the effect of **nestling age class** on the probability that the load brought to the nest does not contain earthworms (**feeding visit type1**: NoE); (D) - the effect of **nestling age class** on the probability that among the loads with earthworms the load also contains other prey items (**feeding visit type2**: MIX); (E) – the effect of the **feeding visit type1** on the **number of prey items** in a load brought during a visit; (F) - the effect of the **feeding visit type2** on the **number of prey items** in a load brought during a visit; (G) - the effect of **weather category** on the **number of earthworms** per visit; (H) – the effect of the **weather category** on the ash-free dry **biomass of a single earthworm**; (I) – the effect of **weather category** on the ash-free dry **biomass of earthworms per visit**. A horizontal thick line indicates the median, the box indicates the 1st (lower) and 3rd (upper) quartiles, the error bars indicate the 1.5 interquartile range, the extra data points are outliers defined as data points that are located outside the 1.5 * the interquartile range (for E, F, G, H, I). * indicates $p < 0.05$; ** indicates $p < 0.005$. Details of statistical analyses are shown in Supplementary tables: Table S4 (for B), Table S5 (for C, D), Table S7 (for E, F), and Table S8 (for G, H, I).

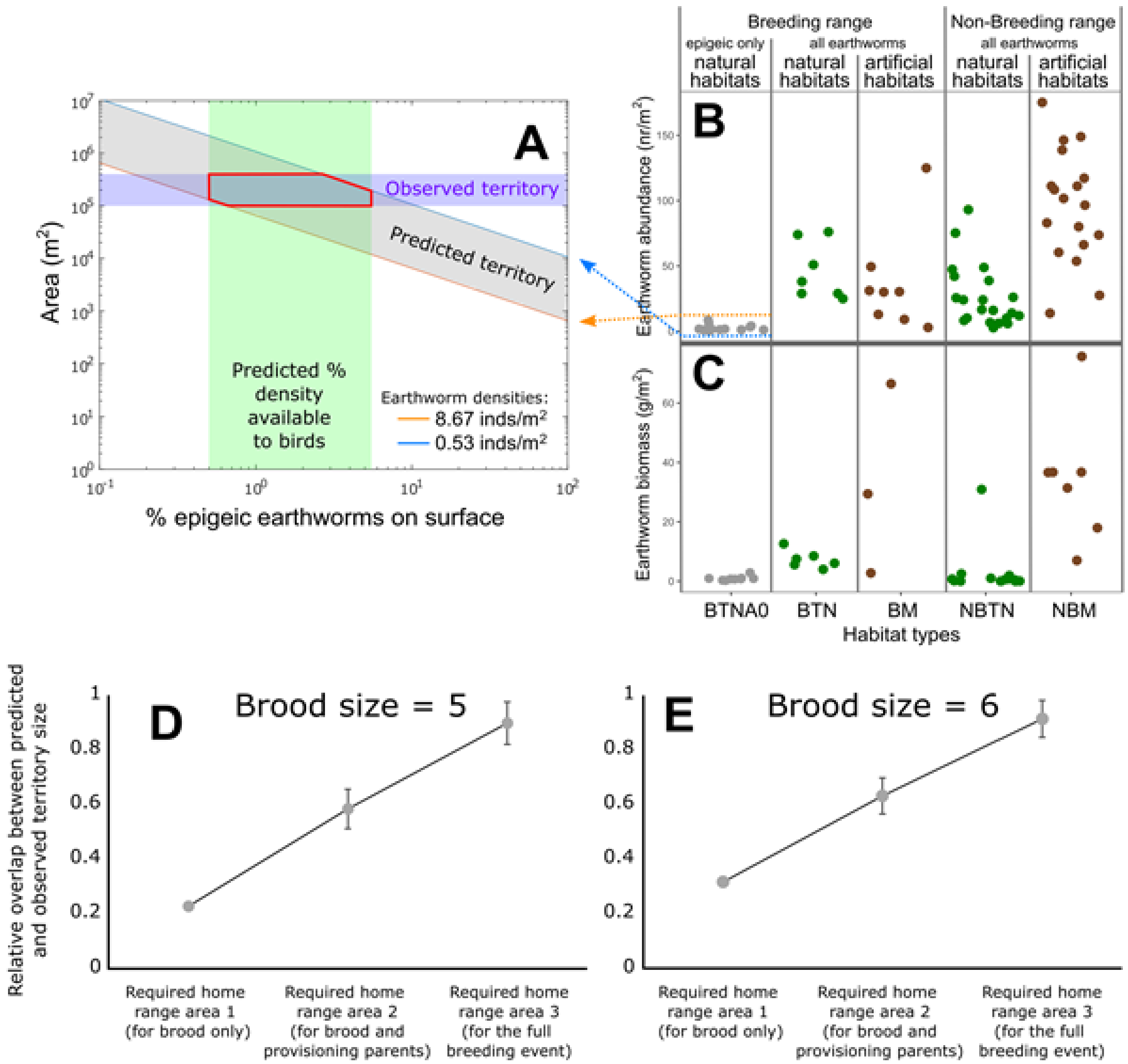

Figure 3

Connections between earthworm densities and pitta's breeding territory size. (A) – An example of the estimated range (gray-shaded diagonal band of "predicted territory") of the habitat surface area (vertical axis) that is needed to provide a sufficient number of earthworms as a function of the proportion of the epigeic earthworm abundance available to the foraging birds (horizontal axis; 0.1–100%), and assuming that epigeic earthworm densities vary between the smallest (blue line upper edge of the gray band) and the highest (orange line lower edge of the gray band) value detected in breeding habitats of the Fairy Pitta[21,23]. The vertical semitransparent green band indicates the range of values (0.5-5%) on the horizontal axis that is likely to occur in nature. The section marked with the red outline indicates the degree of overlap between the predicted (gray band "predicted territory") and the observed (purple horizontal "observed territory" band) area. (B, C) – earthworm densities (number of individuals/m^2; in B), and biomass (g of ash-free dry weight/m^2 in C) from the literature for several types of habitats: **BTNA0** – Breeding range, Typical Natural habitats, soil layer A0 only; **BTN** – **B**reeding range, **T**ypical **N**atural habitats; **BM** – **B**reeding range, **M**odified habitats that may provide sufficient vegetation cover for Pittas to safely forage there; **NBTN** – Non-Breeding range, Typical Natural habitats; **NBM** – **N**on-**B**reeding range, **M**odified habitats that may provide sufficient vegetation cover for Pittas to safely forage there. Except for **BTNA0**, the sampling was conducted from the soil surface to a variable soil depth that is clearly deeper than the A0 layer. (D, E) –the overlap between predicted and observed territory size range for different estimates of area needed for a breeding event; each estimate is an average (± SD) from n = 5 estimates for 5 different proportions (30%, 40%, 50%, 60%, 70%) of earthworms in adult's DEE. The Y-axis indicates the degree of overlap (range: 0–1), and the relative values are shown by setting the theoretical maximum overlap value to 1. See Methods parts *6*–*9* and Supplementary Fig. S2 for more details.

Supplementary Files

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