







Collateral damage from agricultural netting to open-country bird populations in Thailand

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Abstract

Nets are used across a wide variety of food production landscapes to control avian pests typically resulting in deaths of entangled birds. However, the impact of nets on bird populations is a human-wildlife conflict that remains mostly unquantified. Here, we examined the scale of netting in the central plains of Thailand, a region dominated by ricefields, among which aquaculture ponds are increasingly interspersed. Nets/exclusion types, number of individual birds and species caught were recorded on 1312 road-survey transects (2-km length × 0.4-km width). We also interviewed 104 local farmers. The transect sampling took place in late-September 2020, and from December 2020 to April 2021. Each survey transect was visited only once. We found 1881 nets and barriers of parallel cords on 196 (15%) of the transects. Counts of nets and barriers were ~13 times higher than expected in aquaculture ponds based on their areal proportion, and vertical nets were the most commonly observed type ($n = 1299$). We documented 735 individuals of at least 45 bird species caught in the nets and parallel cords, including many species not regarded as pests. Approximately 20% of individuals caught in ricefields and 95% at aquaculture ponds were non-target bycatch. Our interviews suggested that 55% of respondents thought nets were ineffective while only 6% thought they were effective. We suggest imposing a ban on netting, considering other mitigation strategies to reduce conflicts such as promoting the use of parallel cords, and prioritizing conservation actions with community participation. Further studies should investigate the efficacy of less deleterious deterrents.

KEYWORDS

agricultural landscapes, aquaculture, central plains of Thailand, human-wildlife conflict, pest control, ricefields

1 | INTRODUCTION

Among wildlife inhabiting agricultural landscapes, birds are the most diverse group of vertebrates and provide a

variety of different ecological services beneficial to farmers (Asokan et al., 2009; Maas et al., 2016; Tschamtker et al., 2008). For example, insectivorous and predatory birds provide services in the form of pest control and such

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species often predominate in open-country agricultural landscapes like ricefields (Sundar, 2010). However, many species are also considered pests (Whelan et al., 2008). Pest bird management can be especially challenging and costly to farmers and to local economies (Anderson et al., 2013; Lindell, 2020). Various methods have been applied to deter, prevent, or kill bird pests, but there are relatively few studies on sustainable bird management strategies, and neither implementation guidelines, nor information on the effectiveness of the various deterrent practices, and their possible negative impacts on biodiversity (Lindell, 2020; Michel et al., 2020).

Netting has long been indiscriminately used in pest management across different types of production landscapes in many regions including ricefields, other field crops, orchards, and aquaculture ponds (e.g., Anderson et al., 2013; Bomford & Sinclair, 2016; Russell et al., 2012; Wang et al., 2020; Yong et al., 2022), particularly in Indo-Burma, one of the world's most important biodiversity hotspots (Hu et al., 2020; Myers et al., 2000). Netting is widely believed to be the most effective, albeit costly, method of bird control (Anderson et al., 2013; Firake et al., 2016; Lindell, 2020). Farmers use several types of nets to protect their yields from pest birds, particularly targeting granivores such as weavers *Ploceus* spp. and munias (Estrildidae) in ricefields, and piscivores, particularly cormorants (Phalacrocoracidae), in aquaculture ponds. But in some settings, netting has a strong tendency to also affect non-target bird species as bycatch Nemtzov & Olsvig-Whittaker, 2003, sometimes including globally threatened species such as the critically endangered Yellow-breasted Bunting *Emberiza aureola* (Heim et al., 2021; Upton, 2017) and the vulnerable Black-capped Kingfisher *Halcyon pileata*.

Nearly all open-country birds are potentially harmed by netting methods. According to Nemtzov and Olsvig-Whittaker (2003), birds are more likely to be killed or injured where relatively large mesh size (>5 cm) nets of thin monofilament are used. Such netting is illegal in some areas, for example, Victoria, Australia (State Government of Victoria, 2019). In many Asian countries however, including Thailand, legal interpretation regarding restrictions on netting in agricultural landscapes is ambiguous, and regulations are poorly enforced; hence netting is still widely used (e.g., Yong et al., 2022). In addition to illegal intentional captures for local consumption (e.g., Chowdhury, 2010; Kasper et al., 2020; Xayyasith et al., 2020; Zöckler et al., 2010), recreation (e.g., Chang et al., 2019), merit-making release (e.g., Gilbert et al., 2012), pets (e.g., Harris et al., 2017; Nijman et al., 2018; Wang, Shi, et al., 2021), or trafficking (e.g., Heim et al., 2021; Heinrich et al., 2020), collateral damage through the use of nets and other preventive

means is likely to be a significant threat to certain species.

The effect of netting on wild birds has scarcely been assessed and is likely underestimated. We therefore aimed to assess the scale of net-use and identify the bird species impacted by nets and other similar preventive measures. Besides standing nets which are thought to be the majority used in Thailand, these measures also include dense lines of parallel cords set horizontally above aquaculture ponds. Unlike nets, which are set deliberately to entangle birds, such cords are presumably intended to impede access by birds, although (inevitably) some birds do become entangled. However, in some cases lines of monofilament stretched across ponds are also fitted with hooks, dangling vertically, that are deliberately intended to entangle and kill birds. Such gear is mainly used for protecting yields (e.g., rice, fish, prawns, etc.), and for trapping birds either for consumption or for sale (mainly for religious or "merit" release based on a belief that the liberation of animals from captivity is a powerful means of attaining spiritual merit and advancing to a state of enlightenment; Gilbert et al., 2012).

2 | METHODS

2.1 | Study area

The study was conducted in the central plains of Thailand (Figure 1), covering an area of ~51,643 km² (12.5° N–17.5° N, 99.5° E–101.8° E) with elevations ranging from less than 0 to ~100 m asl. The topography of the plains, especially within the southern part where elevations are at or below 5 m asl, has been greatly modified through the construction of canals, dams, and levees to promote intensive rice cultivation. Although the central plains of Thailand has been recognized as a key rice-producing area of the country since the 1870s (Round, 2008; Shahbandeh, 2021), the area still supports enormous numbers of both resident and migratory birds including threatened passerine species. It has been considered an Important Bird and Biodiversity Area (IBA) assessed by the Bird Conservation Society of Thailand in 2013 (BirdLife International, 2020).

Rice is a major crop grown on ~53% (~27,552 km²) of the total area based on land-use maps provided by the Thai Land Development Department (2020). In addition to ricefields, aquaculture ponds, especially fish and shrimp/prawn farms (covering ~6%; ~3078 km² of the area), are another habitat in which nets and other deterrents are placed to protect cultivation and aquatic livestock. Aquaculture ponds have increasingly become distributed throughout. The remaining lands (41%;

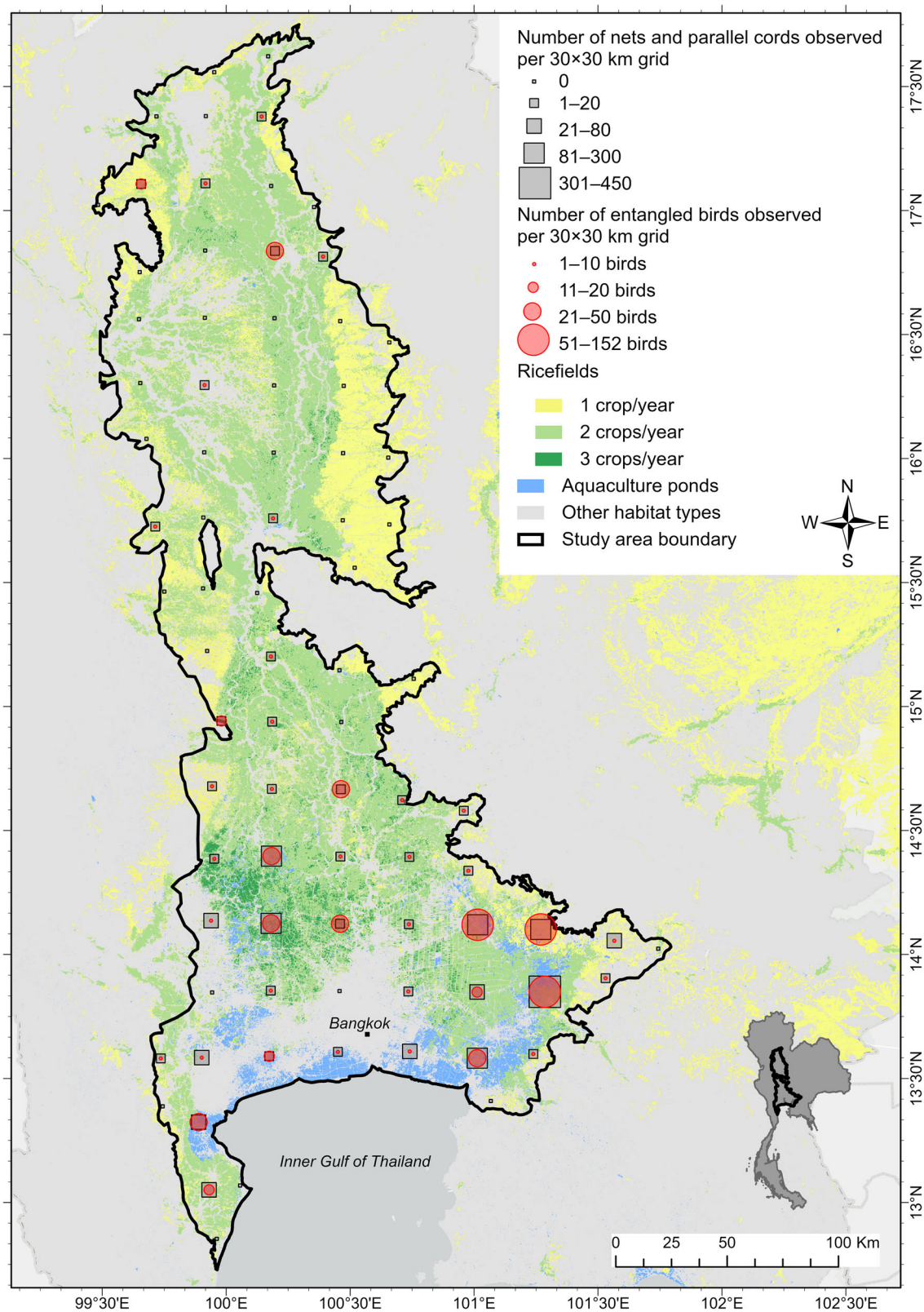


FIGURE 1 Numbers of nets and entangled birds observed from 1312 road-survey transects throughout the central plains of Thailand. Data presented at grid (30 km²) level with sizes of gray squares and red circles representing numbers of nets and parallel cords (max 450 nets/parallel cords) and entangled birds (max 152 individual birds), respectively. All data analyses were performed at the transect level (Figure S1); grid level data are presented here are only for visualization

~21,013 km²) are other habitat types (e.g., human settlements, plantations, and dryland croplands).

As the central plains of Thailand are a large expanse of open-country habitats (including grasslands, wetlands, and scrublands) that have been extensively converted into agricultural lands to produce food, as in many other habitable lands worldwide (Yao et al., 2017), cultivation methods, and how farmers protect their crops and livestock, have considerable impact in either sustaining biodiversity and ecosystem functions (Hendershot et al., 2020) or in affecting them deleteriously.

2.2 | Netting and trapping surveys

We conducted surveys of nets, parallel cords, traps (i.e., snares and hanging hooks), or other gear set to trap or deter birds using 1312 road-survey transects (2 km length × 0.4 km width). The transect sampling took place in late-September 2020, and from December 2020 to April 2021. Each survey transect was visited only once by car at a speed of 10 km/h or ~15–20 min/survey transect. As

this study was part of an ongoing project focusing on open-country bird populations, each net survey transect started at a bird survey point that we randomly located in a 30 km² grid overlaid on the study area. Within each grid cell, 30 survey points were randomly located at least 1-km apart, and accessible by secondary and tertiary roads. The total number of survey points varied with proportion of urban area and orchards which were considered to be unsuitable habitats. Survey points were removed if the area within a 300-m radius contained >50% urban cover. Locations at least 2 km apart were then selected for net surveys (Figure S1). The numbers of nets, traps, and deterrents that could potentially entangle birds were grouped into four types: (1) vertical nets, (2) net enclosures, (3) parallel cords; usually suspended above aquaculture ponds at short intervals over entire ponds, and (4) others (all methods in this category are intended to catch and kill birds); for example, horizontal cords set, at intervals, with vertical dangling hooks or snares (Figure 2). Colors and mesh sizes of nets/cords were noted. A single unit of vertical net was typically ~10 m long × ~5 m in height, while net enclosures,

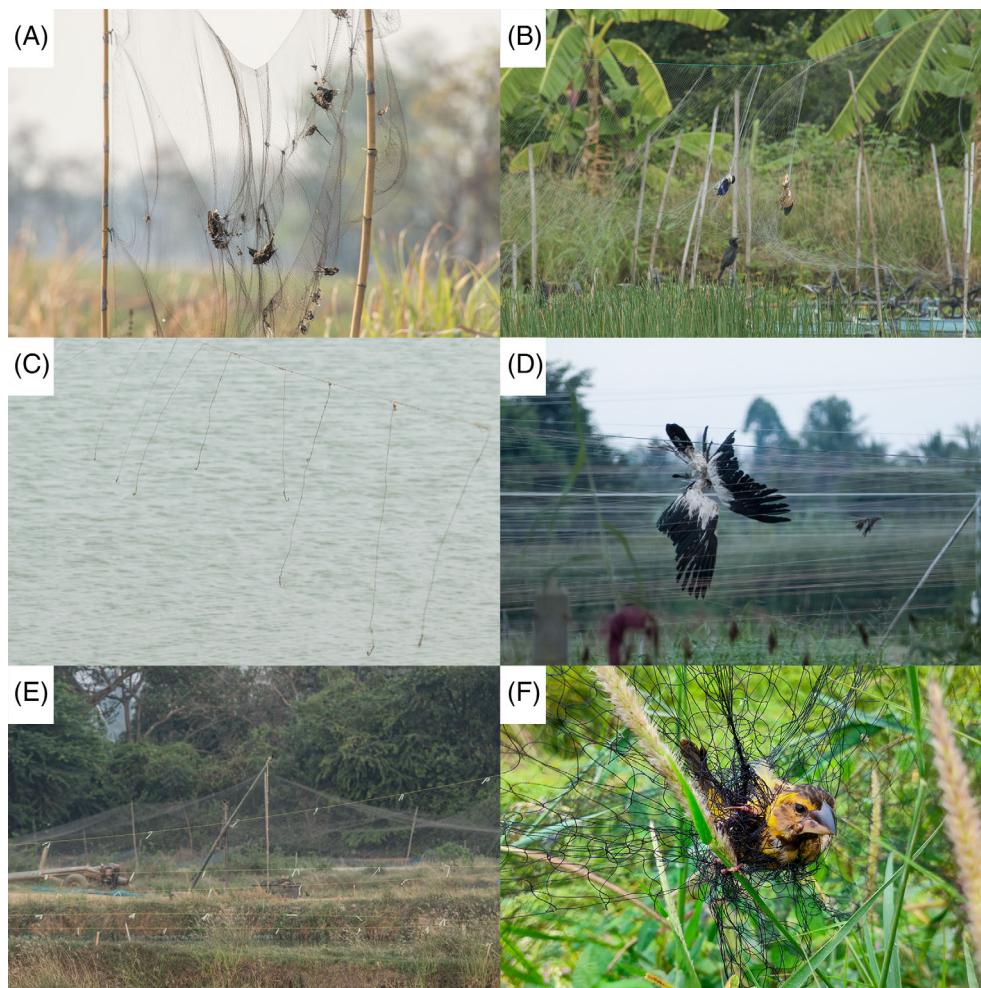


FIGURE 2 Examples of major net types found within the study area: Vertical nets of black nylon (a), and transparent nylon (b); hooks attached to cords (c), and parallel cords set above aquaculture ponds (d); ponds with a net enclosure (e); and a globally near-threatened Asian Golden weaver entangled in a vertical net in a ricefield (f)

parallel cords, and others were counted as the number of ponds or fields in which they were present. All dead, injured, or entangled birds observed within nets/gear were counted and identified to the lowest taxonomic rank possible. The gear may either be set year-round or during temporary periods depending on their main purpose. Within the rice fields, the gear was set mostly during the rice ripening phase which typically takes place in March–May and September–December for double-cropped rice, and in November–December for single-crop rice. Use in aquacultural areas depended on the size or age of the farmed fish/aquaculture stocks.

2.3 | Land-use mapping

A land-use map based on Landsat-8 and THEOS satellite images provided by the Thai Land Development Department (2020) combined with our field survey, was reclassified into three major land-use types based on the focal habitats in which we observed most of the nets (including other deterrents and trapping gear): (1) ricefields, (2) aquaculture ponds, and (3) other, for example, human settlements, plantations, and dryland croplands. Rice intensification level was also included in the final map based on the annual number of crop cycles per year during 2015–2019. The study area was mostly attributed to only one intensification category—two crops/year. The data, provided by Geo-Informatics and Space Technology Development Agency (GISTDA), were taken from the Terra and Aqua MODIS (Moderate Resolution Imaging Spectroradiometer) satellites. All map preparations were performed using ArcGIS Pro 2.6.0.

2.4 | Local perspectives survey

Because improved understanding of local people's attitudes is central to achieving coexistence with wildlife and is a key consideration in engaging relevant stakeholders (König et al., 2020; Pejchar et al., 2018; Shapiro et al., 2020), we also conducted interviews with local farmers to obtain data on their perspectives and knowledge regarding the effects of their preventative agricultural practices.

Local perspectives related to the need, the relative utility, and related questions regarding the use of nets and other deterrents were obtained from 104 interviewees who had lived in the study area for at least 5 years regardless of their land ownership status. We focused primarily on rice farmers and aquaculture farmers because their yields were potentially affected by bird pests. Brief information on our project background, objectives, scope

of questions were provided to interviewees before the interview was conducted by RA in Thai language. The interviews were conducted under the condition of anonymity, verbal consent acceptance, and respondent's right to not answer some questions and to stop an interview at any time were stressed. To increase confidentiality and privacy protection, interviews were not recorded. Interviews took approximately 10–20 min each. This included other questions regarding land-use change and agricultural practices related to our ongoing project focusing on the impact of these factors on the open-country bird community. Respondents were asked how they protected their crops and fish/shrimp stocks and whether they had ever used nets or seen people use nets to capture birds in the surrounding area within the past 5 years (2015–2020). We asked what the main purpose of using nets, traps, or net-like deterrents was, and what they did with the entangled birds (see survey questionnaire in Table S1, approved by the Human Ethics Committee of King Mongkut's University of Technology Thonburi [KMUTT-IRB-COE-2021-124]). During these conversations, but not as part of the formal questionnaire, we often asked questions about which birds the interviewees perceived as pests and the level of damage they believed these birds caused. The perceived pest level to crops/stocks (high, moderate, low, and no) was then assigned using informal judgments made by the investigators based on bird foraging guilds, the investigators' direct observations, and interview respondents' perceptions. Because aquaculture ponds made up a much smaller proportion in the study area than did ricefields, this resulted in interview data associated with the former habitat being somewhat scant. In total, we interviewed 104 respondents (81 men and 23 women) in the study area, of whom 84.6% were rice farmers, 5.8% were aquaculture farmers and 9.6% had some other occupation. Interview results were analyzed using descriptive statistics to assess broad patterns in the data because our main objective was to use the interviews as a source of supporting information regarding local people's perspectives.

2.5 | Data analysis

2.5.1 | Number of nets/deterrents found in different habitat types

To determine if there were significant differences in the relative numbers of nets and parallel cords placed in the three main habitat types of the study area (ricefield, aquaculture pond, and other), we compared the overall numbers based on the proportion of each habitat type covered by sampling transects using a G-test of goodness-

TABLE 1 Types of nets/parallel cords and the number of entangled birds observed in different habitat types based on 1312 survey transects located throughout the central plains of Thailand

Habitat	Gear type	Number of transects with detections	Number of observed gear	Number of entangled birds
Aquaculture pond (105.56 km ²) ^a	Net enclosure	17	27	52
	Vertical net	73	1158	417
	Parallel cords	132	520	56
	Other	6	30	21
Ricefield (768.37 km ²) ^a	Net enclosure	2	3	0
	Vertical net	41	123	165
	Other	2	2	1
Other (602.90 km ²) ^a	Vertical net	10	18	23
Total			1881	735

Note: Net enclosures: Fields or ponds of size $\sim 10 \times 10 \text{ m}^2$ covered by a net; vertical nets: One net unit was defined as $\sim 10 \text{ m}$ in length $\times 5 \text{ m}$ in width, usually made from black nylon (mesh size 3–5 cm) or transparent nylon (mesh size $\sim 14 \text{ cm}$); parallel cords usually suspended above aquaculture ponds at ~ 20 – 30 cm intervals over the entire bed; other net types: for example, loops attached to poles, parallel cords with fishing hooks or loops attached, and hanging snares.

^aTotal area of each habitat type covered by the sampling transects, assuming a 200-m buffer width around each transect.

of-fit with a William's correction (Woolf, 1957) in package “DescTools” (Signorell et al., 2022), with the null hypothesis that the number of nets/deterrents in each habitat would be proportional to the area of each habitat. We created a buffer of 200-m distance surrounding each survey transect to calculate the area covered by the sampling transects. In total, the surveys covered an area of $\sim 1477 \text{ km}^2$, of which 52% and 7% were covered by ricefields and aquaculture ponds, respectively (Table 1).

We assessed whether the spatial distribution of nets and parallel cords observed was significantly spatially clustered in the study area using the “Spatial Autocorrelation Analysis (Global Moran's I)” toolbox in ArcGIS. Then, the “High/Low Clustering Analysis (Getis-Ord General G)” toolbox was used to identify whether high or low values were clustered in the area. A positive z -score value in the High/Low Clustering Analysis would indicate that high values in the dataset were clustered in the study area, whereas a negative z -score value would indicate that low values were clustered in the study area. Both analyses were performed in ArcGIS Pro 2.6.0.

2.5.2 | Number of entangled birds in different gear types and habitats

We developed a model to compare the numbers of entangled birds in different gear types (i.e., vertical nets, parallel cords, net enclosures, and others) observed in different habitats (i.e., ricefields, aquaculture ponds, and other habitats). In total, there were eight sample groups observed (Table 1), but only three sampled groups were of sufficient quantity for analysis (>30 transects with

gear): (1) parallel cords in aquaculture ponds, (2) vertical nets in aquaculture ponds, and (3) vertical nets in ricefields.

Prior to analysis, we assessed the data for outliers. Outliers were defined by a graphical boxplot of the number of entangled birds in each sampled group. We compared the effect of outliers by fitting the models with both the full dataset and with the outliers removed. When predicted values from the models were significantly different, the outliers were excluded. Prior to developing models, we also generated boxplots to visualize the patterns of entangled birds in gear of different colors and mesh sizes. However, there were no clear patterns, so we did not include color and mesh size in the models (Cumming & Finch, 2005). Poisson regression and negative binomial regression models were assessed (package “glmmTMB”; Brooks et al., 2017) and checked for assumptions violations, zero-inflation, and overdispersion (package “DHARMA”; Hartig, 2022).

Based on the above tests, the final models we ran used a negative binomial distribution, and numbers of observed gear were set as a model offset. The response variable was the number of entangled birds observed in each sampled habitat-by-gear group from each transect. We then used Akaike's Information Criterion adjusted for small sample size (AICc) for model selection by comparing fitted models with null models (Burnham & Anderson, 2004). The average number of entangled birds from each sampled group was calculated by back-transforming the beta coefficients gathered from the best-fitted models using an exponential function. All analyses throughout this study were performed at the transect level in R 4.1.0. (R Core Team, 2021).

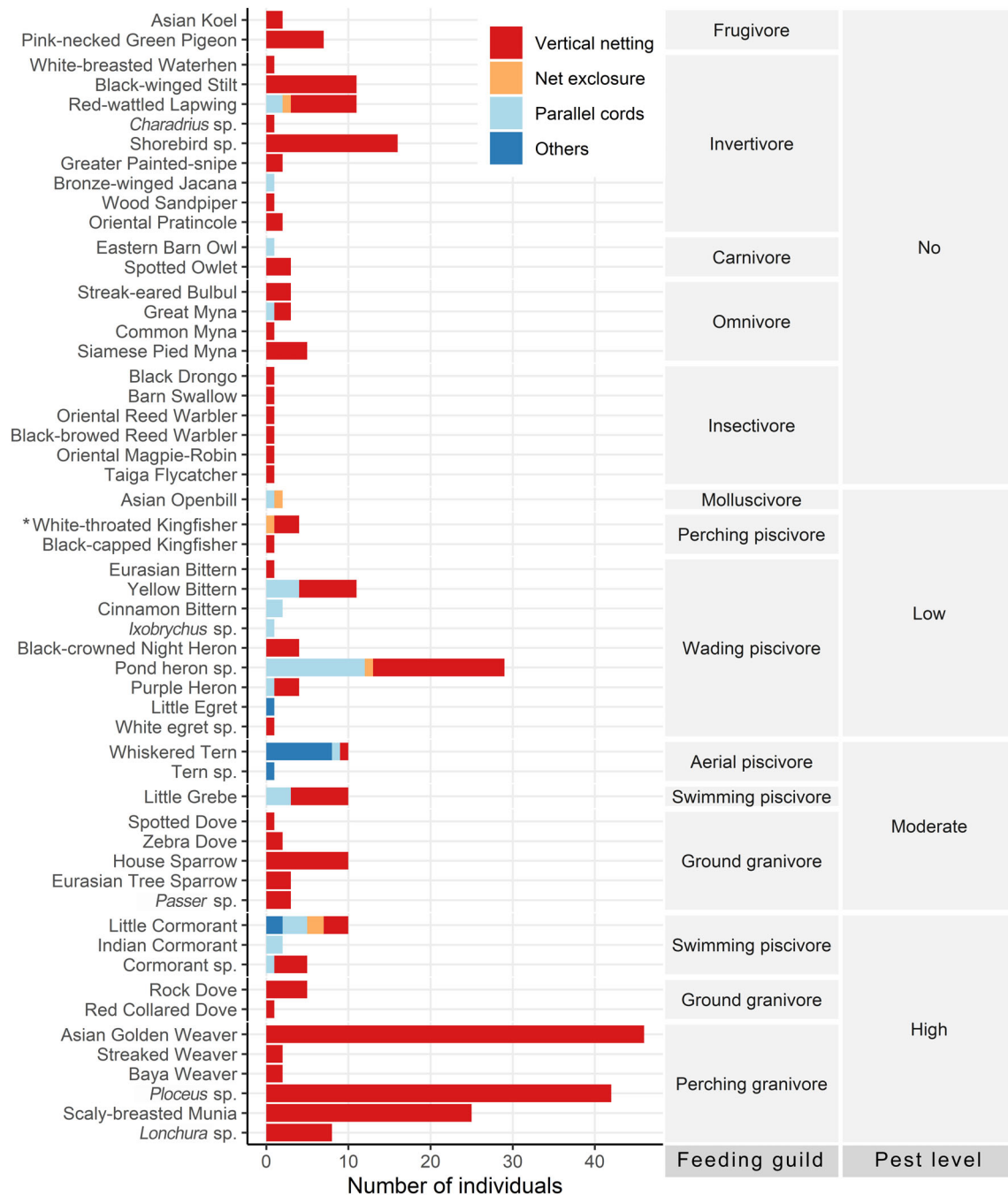


FIGURE 3 List of species and number of individual birds entangled in different gear types found in the central plains of Thailand. Species were grouped into their specific feeding guilds. Only individual birds/carcasses identified to species, genus, or group (e.g., shorebirds) were plotted. The perceived pest level to crops/stocks (high, moderate, low, and no) was assigned using informal judgments made by the investigators based on bird foraging guilds, the investigators' direct observations, and interview respondents' perceptions. * Although the White-throated Kingfisher is known to take most prey, terrestrial or aquatic, that it can subdue (Asokan et al., 2009; Wells, 1999), we categorized it as a perching piscivorous species because fish likely comprise a major part of its diet

3 | RESULTS

3.1 | Netting and trapping

We found 1881 nets and parallel cords on 196 of the survey transects (Figure S1), the highest count was from

aquaculture ponds ($n = 1735$) followed by ricefields ($n = 128$) and other habitats (i.e., croplands, human settlements, reedbeds; $n = 18$), respectively (Table 1). Vertical nets were the most frequently observed in the study area ($n = 1299$), followed by parallel cords ($n = 520$) which were found only in aquaculture sites, while net

Model	β	SE	Lower 95%	Upper 95%	p
Intercept	-0.646	0.213	-1.063	-0.229	.002
Parallel cords	-1.279	0.305	-1.877	-0.681	>.001
Vertical net (rice field)	1.114	0.349	0.429	1.798	.001

TABLE 2 Estimated coefficients (β), standard errors (SE), and 95% confidence intervals from negative binomial models of the average number of entangled birds in different sampled groups: (1) parallel cords in aquaculture ponds, (2) vertical nets in aquaculture ponds (intercept), and (3) vertical nets in ricefields. AICc = 743; the null model has a Δ AICc of 40.3.

enclosures ($n = 30$) were found in both ricefields and aquaculture areas, and the other net types ($n = 32$) included loops attached to poles, cords with fishing hooks or loops attached, and hanging snares (Figure 2 and Table 1). Vertical nets were of two types: black nylon (mesh size of 3–5 cm) and transparent nylon/monofilament (mesh size of 10–18 cm). Vertical nets were mostly found in ricefields and aquaculture ponds but rarely in the “other” habitat category. The numbers of observed nets and parallel cords were significantly different from the expected values based on the land-use area proportion covered by our transects ($G = 8288.5$, $df = 2$, $p < .001$), with the observed numbers in aquaculture ponds ~13 times higher than the expected value based on area size. We found a significantly clustered pattern of nets (including parallel cords and other gear) ($z = 16.426$, $p < .0001$), with gear per transect significantly clustered ($z = 16.456$, $p < .0001$; Figures 1 and S1) in the southern part of the study area where there are more aquaculture ponds.

A total of 735 individuals of at least 45 species were identified, with the near-threatened Asian Golden Weaver *Ploceus hypoxanthus* ($n = 46$ individuals) and pond-heron *Ardeola* sp. ($n = 29$) being the most frequently caught (Figure 2 and Table S2). Other bird species captured included 23 species of insectivores and nocturnal raptors that are unlikely to feed on either crops or aquatic livestock, with roughly 20% of individuals caught in ricefields and approximately 95% of the individuals in aquaculture ponds being non-target bycatch (Figure 3 and Table S2). Among different sampled groups, the average number of entangled birds was significantly higher in vertical nets in ricefields (5.81 birds/net) than those in vertical nets in aquaculture ponds (0.52 birds/net) and parallel cords in aquaculture ponds (0.15 birds/ponds; Table 2). For aquaculture ponds, the average number of entangled birds in vertical nets was also significantly higher than in parallel cords (Table 2).

3.2 | Local perspectives

In total, 25 respondents had used gear (either vertical nets or parallel cords) for the purpose of either protecting their crops/stocks (84%), to catch birds for food or sale (12%) or

to keep as pets (4%). Only 11 respondents (6 rice farmers and 5 aquaculture farmers) said they were still using gear against weavers *Ploceus* spp. and cormorants *Microcarbo niger/Phalacrocorax fuscicollis*. These two groups of species were regarded as the primary “pests” for rice and aquaculture farmers, respectively. However, 55% thought nets were ineffective; only 6% thought they were effective, particularly the parallel cords, which they estimated secured >50% of their production. Twenty-nine percent of respondents said they were aware of ongoing use of vertical nets (77% of netting/hunting activities), as well as shooting of birds (33%), and snaring in conjunction with playback or decoys (7%). They also stated that people from local villages tended to not catch many birds, while people from outside caught birds in a much greater quantity. For example, Lesser Whistling-duck *Dendrocygna javanica*, also considered a pest by rice farmers, is often targeted for bushmeat. Farmers told us that in the past (~ > 10 years ago), bird trappers were common and they typically trapped weavers to sell for religious merit release activities. Farmers sometimes were paid by bird trappers to set up nets on their lands, but these activities had decreased currently because of increased ecological awareness of local people and more effective law enforcement.

4 | DISCUSSION

While netting has long been used to catch birds for multiple purposes (e.g., trapping for consumption and protecting food resources), we provide one of the first assessments of the effects of netting for protection of agricultural products in Asia on wild birds. The broad-scale, systematic coverage carried out in this study provides a better understanding of the scale of netting used across the central plains of Thailand where rice cultivation is the major agricultural land-use. Our finding aligns with Yong et al. (2021) in that vertical nets and improvised fishing nets, which are extensively used in ricefields and aquaculture areas for both hunting and product protection, are a substantial threat in the East Asian Flyway. Our research also suggests that >80% of nets were used for product protection, especially in aquaculture ponds.

4.1 | Netting and effects on birds

A significant proportion of birds caught in gear, especially at aquaculture ponds, were non-target bycatch, and it was common for rice farmers to refer to nets as both ineffective and expensive. Many of our interviewees seemed to view the ecological services provided by birds as trivial and were unaware of the presence of species of conservation concern. In our study area, we observed over 30 bird species of conservation concern (Bird Conservation Society of Thailand Records Committee, 2020; IUCN, 2021). While fortunately only two species of conservation concern globally were observed in the nets/gear, many entangled species (Figure 3 and Table S2) likely play an important role in pest control. For instance, both White-throated Kingfisher *Halcyon smyrnensis* and Black Drongo *Dicrurus macrocercus* have diets of >80% arthropods (Asokan et al., 2009); Spotted Owlet *Athene brama* and Eastern Barn Owl *Tyto javanica* are major predators of murids (Labuschagne et al., 2016; Vanitha et al., 2014); Asian Openbill *Anastomus oscitans* is specialized in feeding on aquatic snails including the invasive Golden Apple Snail *Pomacea canaliculata* which is a significant pest in ricefields in central Thailand (Sawangproh, 2021). Although the globally near-threatened Asian Golden Weaver was the only species of global conservation concern entangled in the nets, one of our interviewees informed us that globally critically endangered Yellow-breasted Buntings were also sporadically caught in his nets used for rice protection. Additionally, during our survey session, Wrinkle-lipped Bat (*Chaerephon plicatus*), which plays an important role in controlling populations of a major rice pest, White-backed Planthopper (*Sogatella furcifera*), was also found dead in a vertical net (see observation details in Limparungpatthanakij, 2020). According to Wanger et al. (2014), this particular bat species may prevent national rice losses of almost 2900 tons per year, which translates into an economic value of more than 1.2 million USD. Considering the potential negative impacts of netting on biodiversity, nets, as presently deployed, appear to be an ineffective solution for bird pest control in both ricefields and aquaculture ponds.

Results from this study could be helpful in raising awareness regarding open-country bird conservation and the negative impacts of bird-exclusion netting. Informing people regarding the status of key populations or ecological services provided via pest control might raise awareness and could reduce the intensity of the agricultural netting used. Globally threatened species observed in the area, for example, Greater Spotted Eagle (*Clanga clanga*), Eastern Imperial Eagle (*Aquila heliaca*), Manchurian Reed Warbler (*Acrocephalus tangorum*), and Yellow-breasted Bunting could also be regarded as flagship

species to promote conservation (Heim et al., 2021). These species forage in ricefields and can potentially be entangled in nets/gear.

4.2 | Net characteristics

The characteristics of the nets are also likely important as most of the entanglements were recorded in vertical nets (~80%). These nets were mostly made of transparent monofilament fishing nets and, to a lesser extent, black nylon. Both net types were also used for illegal hunting (Datta, 2021; Harris et al., 2017). Transparent fishing nets (i.e., drift nets) are banned in international waters and in many countries (European Commission, 1991, 2014; Halliday et al., 2001). Although we were unable to find parallel studies conducted in ricefields elsewhere, a study in an aquaculture landscape in Israel found that vertical nets were harmful to a wide range of birds (Nemtsov & Olsvig-Whittaker, 2003). They specified that birds were more likely to become entangled and die in thin, colorless, or light-colored netting with large mesh size. Monofilament fishing nets are therefore thought to be especially dangerous, and most nets used in aquaculture ponds in our study were of this type. Moreover, although we did not conduct surveys in other systems such as orchards and flower farms in Thailand, the vertical nets used (mostly large mesh size mist-nets and improvised fishing nets, similar to those found in our study) are still used in these lands against birds and fruit bats (e.g., in longan *Dimocarpus longan*, mango *Mangifera* sp., and durian *Durio* sp. orchards; N. Panitvong 2021, personal communication; R. Angkaew 2021, personal observation) and are likely used commonly throughout Asia (Gallo-Cajiao et al., 2020; Yong et al., 2021). Multiple studies in orchards, vineyards, and flower farms from the United States and Australia have advocated that small-mesh netting is a very effective method of deterrent if the cost of purchase, installment, and maintenance are not considered (Anderson et al., 2013; Bomford & Sinclair, 2016; Lindell, 2020). More importantly, nets in those studies were mostly legally compliant with small mesh sizes, for example, $\leq 5\text{--}25$ mm at full stretch (Rigden et al., 2008; State Government of Victoria, 2019), which appear to be less harmful to biodiversity.

Parallel cords were the second most frequently found gear in the study area, and our results showed a significantly smaller number of entangled birds in parallel cord devices than in vertical nets. All aquaculture pond owners interviewed ($n = 5$) believed that parallel cords were effective in deterring fish-eating birds. This aligns with recommendations from the INTERCAFE Cormorant Management Toolbox for European countries (Russell et al., 2012), which

suggested that the deployment of parallel cords could substantially reduce cormorant impacts on fish, and provide a cheaper and less destructive alternative to netting. Parallel cords can be most safely used when warning tapes, colored “flags,” reflective tape, or CD discs are attached. These all readily enhance the visibility of wires/cords and reduce injuries to cormorants and other birds (Russell et al., 2012). Further studies should investigate the optimum setting specifications (e.g., spacing between cords, with flags vs. without flags, materials, colors, and costs) that are appropriate to specific sites/environments.

4.3 | Human–wildlife conflict resolution

Conflict resolution in this situation involves assessment of the tradeoffs of various alternatives available to deter pest species from aquaculture ponds and ricefields. Our assessment suggests that the current netting strategy is detrimental to non-target bird and mammal species while also being ineffective at protecting crops. Therefore, we propose that nets and monofilament nets should be banned for use as deterrents to reduce effects on non-target species. Our study shows that the use of netting appears to be fairly localized (the southern part of our study area; Figures 1 and S1) suggesting that targeted outreach to farmers in selected regions may help reduce this problem. However, socially acceptable alternatives are not currently in use or available for farmers. It is therefore important to consider other mitigation strategies for human–wildlife conflicts that might have fewer negative tradeoffs, such as promoting the use of parallel cords and offering incentives for aquaculture farmers, habitat modification (e.g., reduce potential breeding habitat for feral Rock Doves *Columba livia*) and crop intensification controls to manipulate behavior of conflict-causing species (Horgan & Kudavidanage, 2020), decoy-crops and scare devices (Linz et al., 2011), and/or provide habitats for predator species which deter pest birds (Lindell, 2020), and study pest activity patterns to plan for the setting of proper deterrent devices at optimal times (Malmqvist et al., 2018). Further studies should investigate the efficacy of less deleterious, but low-cost alternatives that are practical for farmers.

We further suggest that agricultural netting is a particular threat because in Thailand and elsewhere, open country habitats, including grasslands, are scarcely represented inside the (mainly forested) protected area networks, but open-country habitats that are utilized for agricultural purposes are an important reservoir of lowland biodiversity (Finch et al., 2019). The survival of many species is dependent on these remnants of unprotected natural and abandoned lands that exist in a mosaic

within agricultural landscapes (Hendershot et al., 2020; Wang, Li, et al., 2021). Private protected areas or public-private partnership schemes that safeguard lowland open-country habitats might offer an additional solution for long-term conservation (Palfrey et al., 2021).

The scale of netting and the impact on multiple species was high in our study, and we urge researchers to examine the impacts of similar netting practices in other agricultural countries. However, in the meantime, law enforcement needs to be more effective; information booklets in collaboration with government agencies and other local non-governmental conservation bodies as well as outreach activities with local communities are essential to provide a much more holistic understanding of the threat from these netting activities. Finally, conservation actions with community participation (Chapman et al., 2019; He et al., 2020; Shrestha, 2013), and testing of their efficacy should be prioritized (Christie et al., 2021; Dickman, 2010).

AUTHOR CONTRIBUTIONS

All authors designed the project. Rongrong Angkaew and Wich'yanan Limparungpathanakij performed the fieldwork. Rongrong Angkaew analyzed the data, interpreted the results, and wrote the original draft with inputs from all authors. The final manuscript was reviewed and approved by all authors.

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CONFLICTS OF INTEREST

The authors declare no potential conflict of interests.

DATA AVAILABILITY STATEMENT

The data is part of the Ph.D. thesis of RA and will be available online at the Conservation Ecology Program, King Mongkut's University of Technology Thonburi

website at <https://cons-ecol-kmutt.weebly.com/> once the thesis has been completed. Also, photos taken on observations of birds entangled in nets is currently being collected as a part of ongoing project; “Tangled & Trapped”; on [iNaturalist.org](https://www.inaturalist.org). We encourage readers to participate in this project by submitting observations of dead, injured, or entangled animals netted, trapped or caught in similar deterrents for non-scientific purposes. Details: <https://www.inaturalist.org/projects/tangled-trapped>

ETHICS STATEMENT

Research was conducted under permission from the Department of National Park, Wildlife and Plant Conservation, Thailand (project code: 6411704) and has been approved by the Institutional Animal Care and Use Committee of the King Mongkut's University of Technology Thonburi (KMUTT-IACUC-2021/002). Human dimension survey questionnaire was approved by the human ethics committee of the King Mongkut's University of Technology Thonburi (KMUTT-IRB-COE-2021-124).


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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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