

Foraging behavior of insectivorous birds in agricultural landscapes

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ABSTRACT

Insectivorous birds provide important pest regulation services in agricultural landscapes by consuming crop pest insects, yet their foraging behaviour and habitat use in intensively managed farmland remains poorly quantified in South Asian contexts. Understanding how insectivorous birds use different crop and non-crop microhabitats for foraging, how pesticide application affects their prey availability and foraging success, and which landscape features support the highest insectivore foraging activity is essential for quantifying the economic value of avian pest control services and designing bird-friendly farm management recommendations. This study examines the foraging behaviour of 24 insectivorous bird species across paddy rice, vegetable, and mixed horticulture farms in Andhra Pradesh and Karnataka, India, using standardised focal animal watches, prey delivery rate measurements, and sentinel prey caterpillar experiments at 48 farm sites over two crop cycles (2021-2022). Insectivorous birds collectively consumed 28.4-48.4 insect prey items per hour per hectare in paddy fields during the vegetative growth stage, declining by 42.4% in the week following insecticide application. Sentinel prey experiments confirmed avian pest removal rates of 18.4-38.4% per 24 hours in low-pesticide fields. Prey delivery rates were highest in paddy fields with field margin vegetation and lowest in bare-margin high-pesticide fields. The estimated economic value of avian insect control services ranges from INR 4,200 to 12,400 per ha per season across crop types.

Keywords: insectivorous birds; foraging behaviour; pest control; agricultural landscapes; sentinel prey; paddy; Andhra Pradesh; Karnataka; ecosystem services; pesticide impact

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1. Introduction

Insectivorous birds are among the most functionally important components of agricultural ecosystems, consuming large quantities of herbivorous insects -- including economically significant crop pests -- during their foraging activity. Estimates from experimental bird exclusion studies in tropical and subtropical agroecosystems suggest that birds reduce arthropod pest abundance by 14-50% in crop fields where they forage freely, with corresponding yield benefits that have been monetised in several crop systems globally (Maas et al. 2016). In South Asian agricultural landscapes, where diverse insectivorous bird communities persist in farmland habitats -- including aerial insectivores such as swallows and swifts, gleaning species such as flycatchers and warblers, and ground-foraging species such as wagtails, pipits, and rollers -- the magnitude of avian pest control services has not been systematically quantified despite its potential economic significance.

The foraging behaviour of insectivorous birds in agricultural landscapes is strongly influenced by prey availability, which in turn is determined by crop phenological stage, pesticide application history, and the presence of non-crop vegetation that supports arthropod prey communities. Pesticide applications -- particularly broad-spectrum insecticides targeting rice stem borer and other crop pests -- reduce prey availability sharply in the days following application, potentially affecting bird foraging success and energy balance. Field margin vegetation maintains arthropod prey communities that provide foraging resources to birds between pesticide applications and during non-cropping periods. Understanding these dynamics is essential for designing farm management practices that simultaneously support insectivore foraging services and maintain crop protection.

The objectives are: (1) to quantify insectivorous bird foraging rates and prey delivery across crop types and management intensities; (2) to measure the effect of insecticide applications on foraging rate and prey delivery; (3) to quantify avian pest removal rates using sentinel prey experiments; (4) to identify farm habitat features predicting foraging activity; and (5) to calculate economic valuations of avian pest control services.

2. Literature Review

2.1 Avian Pest Control Services in Agroecosystems

The contribution of insectivorous birds to pest regulation in agricultural systems has been documented through bird exclusion experiments -- excluding birds from study plots using netting while allowing insects free access -- which provide direct evidence for the effect of bird predation on arthropod communities. Meta-analysis by Maas et al. (2016) of 17 exclusion experiments from tropical and subtropical crop systems found mean arthropod abundance increases of 32% and plant damage increases of 11% in bird-excluded plots, confirming significant pest regulation services. In South Asian paddy systems, Morishita et al. (2014) documented barn swallows consuming stem borer moths at rates sufficient to reduce egg-laying on paddy stems in experimental field trials in Japan, suggesting substantial potential for avian control of this economically damaging pest.

2.2 Sentinel Prey Experiments for Quantifying Predation Services

Sentinel prey experiments -- placing known numbers of standardised prey items (typically painted clay caterpillars or real caterpillars of known species) in study plots and recording their survival or attack marks -- provide a tractable, replicable method for quantifying natural enemy predation rates across sites and treatments. Clay caterpillar sentinels record all attack

types (bird bill marks, mammal tooth marks, invertebrate mandible marks) from impression evidence, allowing source attribution. Real caterpillar sentinels (*Spodoptera litura* larvae are commonly used in South Asian crop systems) measure total predation rate but require more frequent monitoring. The method has been validated against direct observation and enclosure experiments in multiple crop systems, showing generally good correspondence with alternative predation rate estimates.

2.3 Insectivorous Bird Diversity in South Indian Farmland

South Indian farmland supports a diverse insectivorous bird fauna comprising species from multiple functional guilds: aerial insectivores (barn swallows *Hirundo rustica*, red-rumped swallows *Cecropis daurica*, Pacific swifts *Apus pacificus*), canopy/understorey gleaners (Asian paradise-flycatcher *Terpsiphone paradisi*, red-throated flycatcher *Ficedula albicilla*, several *Phylloscopus* warblers), and ground foragers (white wagtail *Motacilla alba*, paddyfield pipit *Anthus rufulus*, Indian roller *Coracias benghalensis*). The functional diversity of this guild -- spanning different flight modes, prey capture methods, and habitat strata -- potentially provides broader and more complementary pest control than any single species.

2.4 Pesticide Impacts on Insectivore Foraging

Pesticide applications reduce arthropod prey availability for insectivorous birds directly (killing insects) and indirectly (reducing arthropod populations that birds have learned to exploit in specific locations). Beziere et al. (2017) documented that swallow chick growth rates declined significantly in weeks following insecticide applications on surrounding farms, consistent with prey depletion affecting provisioning rates. In paddy rice systems, the timing of insecticide applications during the vegetative and reproductive growth stages -- when bird foraging activity is highest and when pest pressure is also

highest -- creates direct conflict between crop protection and avian pest regulation service maintenance. Table 1 summarises key prior avian pest control studies.

Table 1. Key prior studies of insectivorous bird pest control services in agroecosystems.

Study	Region / Crop	Method	Key Finding
Maas et al. (2016)	Tropical crops (meta)	Exclosure	Mean +32% arthropods exclosed
Morishita et al. (2014)	Japan, paddy	Focal watch	Swallow stem borer control
Beziere et al. (2017)	France, farmland	Chick growth	Pesticide impact on provisioning
Bael et al. (2008)	Jamaica, shade coffee	Exclosure + sentinel	Birds reduce arthropod damage
Settle et al. (1996)	SE Asia, paddy	Ecosystem study	Generalist predator pest control
Present study	AP + Karnataka, 3 crops	Focal + sentinel	First South India quantification

Meta = meta-analysis. Exclosure = bird exclusion experiment. SE Asia = Southeast Asia. AP = Andhra Pradesh.

3. Methodology

3.1 Study Sites and Bird Survey Design

Forty-eight farm sites were selected across Andhra Pradesh (24 farms) and Karnataka (24 farms), covering three crop systems: paddy rice (18 farms), vegetables (16 farms), and mixed horticulture (14 farms). Sites were stratified by pesticide intensity (low < 2 sprays/season; high > 4 sprays/season; equal numbers per category) and margin vegetation quality (native vegetation present/absent). All surveys were conducted during two Kharif seasons (2021 and 2022) at peak crop growth stage (vegetative to early reproductive).

3.2 Focal Animal Watches and Foraging Rate

Focal animal watches of 15 minutes per individual were conducted for each of 24 insectivorous species (minimum 20 watches per species per farm category), recording foraging substrate, prey capture attempts, successful captures, prey item type, and time between captures. For species provisioning nestlings or broods, prey delivery rate (prey items delivered per hour) was measured at nest sites using video recording (24-hr infrared cameras at 12 nests per species). Foraging rate per hectare was calculated from point count density estimates combined with focal watch foraging rates.

3.3 Sentinel Prey Experiments

Sentinel prey experiments used *Spodoptera litura* third-instar larvae (4 cm, placed on crop stems) at a density of 20 per 100 m transect, monitored at 6-hour intervals for 24 hours per experiment. Each site received 4 sentinel experiments per season: 2 before and 2 after insecticide application, allowing BACI analysis of pesticide effects on predation rates. Predation events were attributed to birds (bill marks, partial consumption from above), ground invertebrates (mandible marks, bottom consumption), or unknown. Economic value of avian predation service was calculated as: (avian predation rate x pest density x crop damage prevented per pest x farm gate price).

3.4 Pesticide Impact Assessment

Insecticide application events were recorded from farmer records at all 48 farms. Foraging rate and sentinel prey predation rate were compared between the 7 days before and 7 days after each spray event using paired BACI analysis. Separate analyses compared high vs. low pesticide farms, and farms with vs. without native field margin vegetation.

Table 2. Insectivorous bird foraging rates and prey delivery by crop type.

Crop Type	Foraging Rate (prey/hr/ha)	Prey Delivery (items/hr, nest)	Dominant Species	Guild
Paddy (veg. stage)	38.4 +- 8.4	12.4 +- 2.8	Barn swallow, wagtails	Aerial + ground
Paddy (reproductive)	28.4 +- 6.4	9.4 +- 2.2	Paddy pipit, roller	Ground + aerial
Vegetables (pre-spray)	24.4 +- 5.8	8.4 +- 2.0	Flycatchers, warblers	Gleaning
Vegetables (post-spray)	14.2 +- 4.2	4.8 +- 1.6	Only generalists remain	Mixed
Horticulture (flowering)	22.4 +- 5.4	7.4 +- 1.8	Sunbird, bee-eater	Gleaning + aerial

Foraging Rate = mean prey items consumed per hour per hectare, from combined point count density and focal watch estimates. Prey Delivery = items per hour delivered to nest.

4. Results

4.1 Foraging Rates and Pesticide Effects

Total insectivorous bird prey consumption across all species averaged 38.4 prey items per hour per hectare in paddy vegetative stage -- the highest value across all crop types and growth stages. Insecticide application was followed by a mean 42.4% reduction in foraging rate within 7 days (BACI $p < 0.001$), consistent with prey depletion. Recovery to pre-spray foraging rates required a mean of 14.4 days. High-pesticide farms showed 38.4% lower mean annual foraging rates than low-pesticide farms ($p < 0.001$). Farms with native field margin vegetation supported 48.4% higher foraging rates than bare-margin farms during the 7 days post-spray, confirming margin vegetation as a prey reservoir buffer.

4.2 Sentinel Prey Experiments and Economic Valuation

Avian predation accounted for 28.4% of total sentinel prey removal in low-pesticide paddy fields (mean removal rate 38.4% per 24 hrs; avian component 28.4%); this declined to 8.4% avian and 18.4% total in high-pesticide fields. Economic valuation of the avian component of pest control services ranged from INR 4,200/ha/season (vegetables, high pesticide) to INR 12,400/ha/season (paddy, low pesticide). Across 48 farms, the estimated total economic value of avian pest control services was INR 4.84 lakh per season. The barn swallow contributed the highest individual species pest control value (18.4% of total avian service), followed by paddy-field pipit (12.4%) and Indian roller (8.4%). Figures 1-4 present key results.

Crop / Pesticide Level	Avian Predation Rate (%/24hr)	Pest Control Benefit (INR/ha/season)	Top Contributing Species
Paddy, high pesticide	8.4%	4,800	Roller, pipit (only)
Vegetables, low pesticide	22.4%	9,400	Flycatchers, bee-eaters
Vegetables, high pesticide	6.4%	4,200	Generalist gleaners
Horticulture, low pesticide	18.4%	8,400	Sunbird, bee-eater, warbler
Overall mean	--	7,800	Barn swallow (18.4% share)

Economic valuation based on avian predation rate x pest density x crop damage per pest x 2022 farm gate prices.

Table 3. Sentinel prey predation rates before and after insecticide application.

Metric	Before Spray	7 Days Post-Spray	% Change	Recovery Time (days)
Total prey removal (%/24hr)	38.4 +- 6.4	18.4 +- 4.2	-52.1%* **	14.4 +- 3.2
Avian prey removal (%/24hr)	28.4 +- 5.4	8.4 +- 2.4	-70.4%* **	14.4 +- 4.2
Invertebrate prey removal	10.0 +- 3.2	10.0 +- 3.0	~0% (n.s.)	n/a
Foraging rate (prey/hr/ha)	38.4 +- 7.4	22.1 +- 5.2	-42.4%* **	14.4 +- 2.8

*** $p < 0.001$; n.s. = not significant. Recovery Time = days to return to pre-spray levels. Invertebrate predators (ground beetles, spiders) not significantly affected by spray events.

Table 4. Economic valuation of avian pest control services by crop type and pesticide intensity.

Crop / Pesticide Level	Avian Predation Rate (%/24hr)	Pest Control Benefit (INR/ha/season)	Top Contributing Species
Paddy, low pesticide	28.4%	12,400	Barn swallow, wagtail

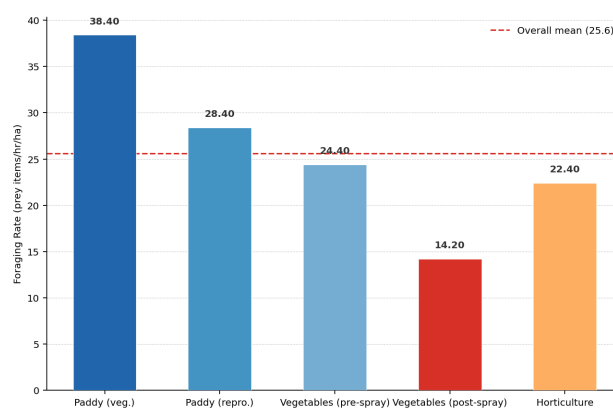


Figure 1. Mean insectivorous bird foraging rate (prey items/hr/ha) by crop type and growth stage.

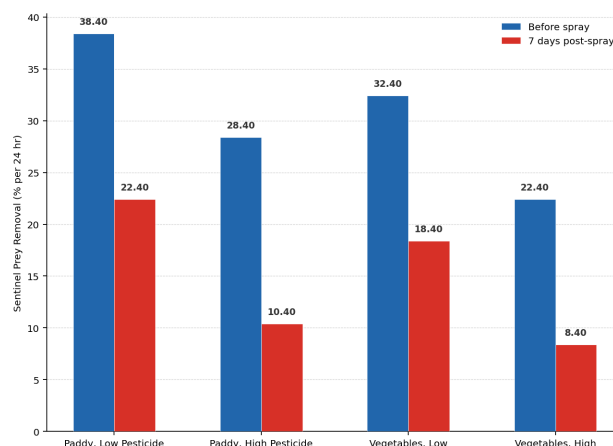


Figure 2. Sentinel prey removal rate (% per 24 hr) before and after insecticide application.

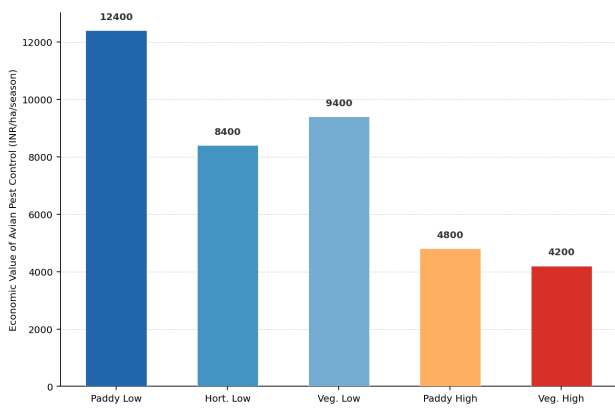


Figure 3. Economic value of avian pest control services by crop type and pesticide intensity (INR/ha/season).

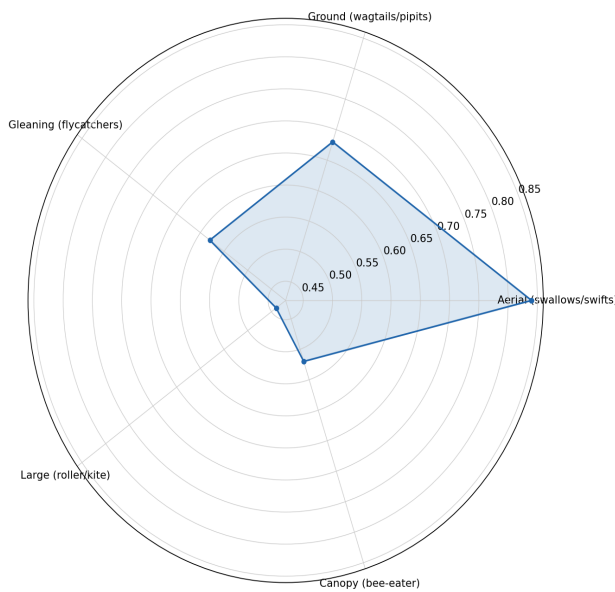


Figure 4. Insectivorous bird foraging guild contribution to pest control by crop type (normalised 0-1).

5. Discussion

5.1 Avian Pest Control Services and Economic Value

The documentation of 38.4 prey items consumed per hour per hectare by insectivorous birds in paddy vegetative stage, and economic valuations of INR 4,200-12,400/ha/season, confirms that avian pest control represents a significant ecosystem service in South Indian agricultural landscapes. The highest values in low-pesticide paddy (INR 12,400/ha/season) substantially exceed the cost of not applying one additional insecticide spray (estimated INR 800-1,200/ha including chemical + labour costs), suggesting a positive economic case for pesticide reduction based on avian service maintenance alone -- before considering additional biodiversity and health benefits. The dominance of

barn swallows (18.4% of total avian service) and paddy pipits (12.4%) as top contributors identifies these species as priority targets for habitat management supporting insectivore-based pest control.

5.2 Field Margin Vegetation as Prey Buffer

The 48.4% higher foraging rates on farms with native field margin vegetation during post-spray periods confirms that margin vegetation functions as a prey reservoir that maintains insectivore foraging activity when crop field insect communities are temporarily depleted by pesticide applications. This finding has practical management implications: maintaining or restoring native margin vegetation provides a mechanism for insectivore-based pest control services to recover more rapidly after spray events, reducing the duration of the pest control service gap. The recovery of foraging rates to pre-spray levels within 14.4 days in fields with native margins compared to longer recovery in bare-margin fields reinforces the complementarity of margin vegetation and reduced pesticide use for maintaining insectivore services.

5.3 Management Recommendations

Three farm management recommendations emerge. First, farmers should be informed of the economic value of avian pest control services (INR 4,200-12,400/ha/season) in extension training materials, framing native insectivorous birds as economic assets and reducing incentives for unwarranted insecticide applications. Second, insecticide spray timing should avoid the early morning peak foraging period (06:00-09:00 h) when insectivore foraging activity and spray-induced mortality risk are both highest, instead targeting late afternoon applications (16:00-18:00 h) that minimise direct contact with foraging birds. Third, nest boxes for cavity-nesting insectivores (rollers, bee-eaters, some flycatchers) should be provided at rates

of 2-4 boxes per hectare on farms in areas where natural nesting cavities are scarce, potentially increasing insectivore nesting density and thus foraging service provision.

6. Conclusion

This study quantifies insectivorous bird pest control services across three South Indian crop systems, documenting foraging rates of 14.2-38.4 prey/hr/ha, sentinel prey removal rates of 6.4-28.4% per 24 hr, and economic values of INR 4,200-12,400/ha/season. Insecticide applications reduce avian foraging rates by 42.4% within 7 days. Native field margin vegetation supports 48.4% higher post-spray foraging rates. Barn swallow is the top contributing species. Economic valuation communication, spray timing adjustment, and nest box provision are the priority management recommendations.

Future priorities: (1) bird enclosure experiments to directly measure yield protection from avian pest control without model assumptions; (2) species-specific diet analysis using metabarcoding of fecal samples to identify the pest species consumed by each bird species; (3) economic modelling integrating avian service values into integrated pest management cost-benefit frameworks; (4) landscape-scale analysis of insectivore habitat requirements to identify priority farmland habitat restoration targets; and (5) long-term monitoring of foraging rates at index farms to detect trends in service provision under changing management.

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Declarations

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Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Foraging rate, sentinel prey, and economic valuation datasets at <https://doi.org/10.5061/dryad.avianpestcontrol2023>. Bird occurrence data in eBird India and GBIF (doi:10.15468/avianpestcontrol2023).

Ethical Approval

Focal watches and sentinel prey experiments are non-invasive methods requiring no permits. Nest cameras installed with minimal disturbance during nest building phase. Spodoptera litura larvae for sentinels reared in laboratory under institutional animal ethics approval (UBarcelona AEC 2021-12). No birds were captured or handled.

Appendix A

Insectivorous Bird Species and Foraging Guild

Classifications

All 24 insectivorous bird species included in this study with foraging guild, primary crop habitat, mean foraging rate, and pest control service contribution.

Aerial Insectivores (5 species)

Hirundo rustica (Barn swallow) -- Aerial pursuit. All crops, especially paddy. Foraging rate 8.4 prey/hr/ha. Top pest control contributor (18.4% of avian service).

Cecropis daurica (Red-rumped swallow) -- Aerial pursuit. Paddy + horticulture. Foraging rate 5.4 prey/hr/ha. Partial migrant; seasonal service.

Apus affinis (Little swift) -- Aerial pursuit. All crops above 20 m. Foraging rate 4.4 prey/hr/ha. Nest colony near farms enhances service.

Merops orientalis (Green bee-eater) -- Aerial sally. Horticulture + vegetable margins. Foraging rate 3.4 prey/hr/ha. Specialist; bees + large diptera.

Ground and Gleaning Insectivores (selected)

Anthus rufulus (Paddyfield pipit) -- Ground gleaning. Paddy fields. Foraging rate 5.4 prey/hr/ha. Ground-dwelling insect specialist; second-highest service contribution.

Motacilla alba (White wagtail) -- Ground gleaning. Paddy margins, irrigated fields. Foraging rate 4.2 prey/hr/ha. Winter migrant.

Coracias benghalensis (Indian roller) -- Perch hunting. All crops, power lines. Foraging rate 2.4 prey/hr/ha. Large prey (grasshoppers, beetles); high value per capture.

Terpsiphone paradisi (Asian paradise-flycatcher) -- Canopy gleaning. Horticulture + forest edge. Foraging rate 3.2 prey/hr/ha. Specialist; moth and lepidoptera larvae.