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An investigation into the impact of coal mining on mammalian diversity, habitat fragmentation and water depletion in Singrauli District, Madhya Pradesh

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Abstract
The Singrauli district of north-eastern Madhya Pradesh represents one of the most heavily exploited coal mining regions of India, in which opencast mining and thermal power plants co-exist with patches of tropical dry deciduous forest and riparian habitat. To determine the effects of coal mining on mammalian diversity, habitat fragmentation, and water resources, we sampled the landscape using three strata: high impact, intermediate, and low impact reference areas. Camera trapping, line transects, and occupancy modelling were used to survey mammals, and multi-temporal satellite data were used to estimate forest cover and fragmentation metrics. Water resources (groundwater and surface-water) were characterised along the disturbance gradient, and direct and indirect effects of mining on mammal occupancy were evaluated using generalized linear mixed models and structural equation modelling. In our sample period, we generated 9,684 camera trap days, walked 1,126 km on transects, and recorded 31 species in 15 families and seven orders. Mammal species richness decreased from 24 in reference areas to 20 in intermediate areas to 15 in high-impact areas; Shannon–Wiener diversity declined from 2.76 to 1.82. Forest-dependent species occupancy decreased from 0.70 in reference areas to 0.27 in high-impact areas. Forest cover decreased from 67.4% to 31.8%, while patch and edge densities increased and mean patch size, core area, and cohesion declined. Mean groundwater depth increased from 9.8 ± 1.5 m in reference areas to 18.7 ± 2.4 m in high-impact areas. Mining-affected water resources exhibited poorer water quality compared to reference water resources. The structural equation model revealed a direct negative impact of mining on mammal occupancy, as well as indirect impacts mediated by habitat fragmentation and water stress. The total standardized effect of mining on mammal occupancy was −0.58. These results highlight the broad impacts of mining on mammalian diversity through effects on habitat fragmentation, habitat connectivity and water resources. Our results underscore the importance of preserving large continuous forest patches, maintaining functional corridors, protecting natural water sources for wildlife, and restoring disturbed mining areas in an ecologically sustainable manner.

Keywords: Coal mining, Mammalian diversity, Habitat fragmentation, biodiversity, remote sensing, Singrauli

Introduction

Coal remains a principal energy source in India, and Singrauli district in north-eastern Madhya Pradesh hosts one of the country's largest concentrations of opencast collieries and thermal power stations. Extensive surface mining and associated infrastructure have transformed the terrain through removal of native vegetation, stripping of topsoil, accumulation of overburden and expansion of industrial and settlement land (Areendran *et al*., 2013; Kumari *et al*., 2023) [1, 15]. The district's physical transformation is well documented. Multi-date land-cover analysis records conversion of forest and agricultural land to mining, overburden and built-up classes (Areendran *et al*., 2013) [1]; change detection across 2005-2015 reports an approximate 6.9% decline in forest cover and a 23% increase in barren surface associated with thermal power development (Kumari *et al*., 2023) [15]; spectral-index analysis records declining ecological condition over the same period (Kumari *et al*., 2022) [14]; and land-surface temperature analysis documents localised warming around mining and power-plant areas, indicating that habitat quality may decline within patches that remain classified as forest (Kumari & Sarma, 2017) [13].

These land-cover changes subdivide previously continuous habitat, reduce patch size and increase edge exposure. Fragmentation is ecologically distinct from habitat loss alone, because it alters connectivity and isolation independently of the total area removed, and thereby affects movement, gene flow and population persistence (Fahrig, 2003) [7]. The design implication is that habitat amount and habitat configuration must enter analysis as distinct predictors rather than being collapsed into a single disturbance index. Mining landscapes intensify configuration effects structurally. Unlike agricultural mosaics, which typically form a semi-permeable matrix traversable at some cost, mining landscapes generate hard and semi-permanent barriers: active pits, unvegetated overburden, haul-road networks and industrial installations. Movement simulation confirms that these features restructure connectivity even where the mined area is proportionally small, so that the ecological footprint of a mine systematically exceeds its cadastral footprint (Cowan *et al*., 2025) [4, 5]. Reclamation does not straightforwardly reverse this, since revegetated patches may not re-establish ecological connectivity, and evidence from fragmented Indian forest shows that occupancy of a canopy-dependent primate is predicted by patch- and landscape-level attributes including food-tree availability, so that a patch may be present in a land-cover raster while remaining functionally unsuitable (Gogoi *et al*., 2025) [10].

Terrestrial mammals are especially exposed to these changes, since many require large contiguous areas or functional movement corridors, and global assessment identifies extractive industry as a rapidly growing driver of biodiversity loss whose overlap with areas of conservation importance is projected to widen (Sonter *et al*., 2020, 2022; Martins-Oliveira *et al*., 2021) [17, 28]. Empirical work supports the pattern. Cristescu *et al*. (2016) [6], tracking large omnivores across surface mines and reclaimed land, documented altered movement and distribution persisting for years, with reclamation failing to restore pre-disturbance use within the study period. Owusu *et al*. (2018) [19] surveyed medium-to-large mammals before mining commenced and again ten years after mine closure, recording declines within adjoining forest reserves that were not themselves mined and attributing these to mining-induced hunting and logging rather than to the mined footprint alone. Indian evidence is more limited but consistent in direction: camera-trap survey in a tropical forest adjacent to a coal-mining landscape documented a mammal community of conservation significance persisting under mining pressure (Palei *et al*., 2023) [20], and work on mine discharge in Singhbhum recorded altered riverine habitat use by elephants and other mammals downstream of operations (Singh & Chowdhury, 1999; Sonter *et al*. 2018 and Giljum *et al*. 2022) [9, 25, 27].

Hydrological pressures act in parallel. Groundwater abstraction for mining, dust suppression and power generation, combined with altered surface drainage, has been associated with measurable groundwater-level decline in the Singrauli coalfield (Sonkar *et al*., 2023) [26], while isotopic and hydrogeochemical work in mining landscapes has established that mining-induced land-use change propagates into both groundwater and surface-water systems (Kausher *et al*., 2023) [11]. Physico-chemical analysis around the Singrauli coalfield has documented impairment of surface and groundwater relative to potable and ecological standards (Khan *et al*., 2013) [12]. These pressures are unlikely to act independently of habitat change. Loss of cover and loss of water may compound one another by simultaneously reducing refuge availability and access to drinking water, and by drawing mammals toward anthropogenic water sources at the settlement interface.

For Singrauli, patch density, edge density, mean patch size and connectivity indices have not been computed, no effort-standardised mammal survey has been published, and no analysis relates mammalian occurrence to either habitat configuration or water availability. Individual mine blocks hold baseline biodiversity surveys and wildlife conservation plans prepared for environmental clearance, but these are lease-specific by design and do not address landscape-scale connectivity. To our knowledge, integrated studies combining mammal survey, connectivity assessment and hydrological measurement remain uncommon in India, most work addressing biodiversity or water resources but not both.

The present study was undertaken to close that gap. We assessed the combined effects of coal mining on mammalian diversity, habitat fragmentation and water availability in Singrauli district, with five specific aims: to estimate mammalian species richness, relative abundance and occupancy along a mining-forest-agriculture gradient with explicit modelling of detection probability; to quantify landscape fragmentation and delineate habitat patches and potential corridors using multi-temporal remote sensing and connectivity modelling; to evaluate groundwater-level trends and surface-water quality across that gradient; to examine interactions among mammal occurrence, habitat connectivity and water availability in order to identify the dominant drivers of mammal distribution; and to derive evidence-based rehabilitation and management recommendations covering corridor restoration, water-resource management and revegetation strategy.

Four hypotheses were specified before data collection, each with the evidence that would support it and the evidence that would falsify it (Table 1). Fixing falsification conditions in advance protects the analysis against post hoc reinterpretation, and the conditions stated there are the ones against which the results below are assessed.

Table 1: Pre-specified hypotheses with supporting and falsifying evidence

Hypothesis	Supporting evidence	Falsifying evidence
H1. Mammalian richness and occupancy are lower near active mines and thermal-power installations than in continuous forest, with the strongest effect on large-bodied, forest-dependent species.	Negative association between occupancy and mining proximity persisting after detection probability and habitat covariates are modelled.	No association, or association eliminated once detection probability is modelled.
H2. Fragmentation metrics are negatively related to richness and occupancy, with fragmented sites supporting more generalists and fewer specialists.	Configuration metrics retain explanatory power for specialist taxa in models already containing habitat amount.	Configuration terms non-significant once habitat amount is included.
H3. Groundwater levels and surface-water quality are lower in the mining stratum than at reference sites, and reduced water availability corresponds to reduced mammal activity at water points.	Stratum differences in water-table depth and quality indices, with concordant differences in water-point detection rates.	No stratum difference, or water variables non-significant once vegetation structure is controlled.
H4. Reclaimed spoil dominated by invasive plantation species supports lower native-mammal use than naturally regenerating patches or native-species restoration plots.	Lower richness and occupancy on invasive-dominated reclaimed sites after controlling for patch area and isolation.	Parity between reclaimed and control sites once area and isolation are controlled.

Materials and methods

1. Study area

The study was conducted in the Singrauli coalfield in north-east Madhya Pradesh, including portions of adjacent areas in Uttar Pradesh. The district has been called India's energy capital for its many collieries and thermal-power stations. Landscapes consist of gently undulating plateau surfaces (elevation ca. 300–500 m amsl) with intervening forested ridges and river valleys, and areas affected by mining and industrial development (Areendran *et al*., 2013) [1]. The focal area falls mostly within the Singrauli Forest Division and extends into parts of Sidhi district, where ecological connectivity and hydrologic linkages warrant inclusion. Boundary limits were defined using GIS maps to include: Active and abandoned opencast coal mines (Nigahi, Jayant, Amlohri, and Dudhichua blocks); Thermal-power complexes and nearby industry, which transform the landscape and create water stress; Varying-aged overburden and spoil dumps, some still bare; Interspersed agriculture and human settlements;Isolated patches of tropical dry deciduous forest, mostly of sal (*Shorea robusta*), tendu (*Diospyros melanoxylon*) and mixed bamboo.

Riparian zones and water bodies, including the Rihand reservoir, Son river, tributaries, and seasonal water holes used by wildlife. The resulting landscape mosaic includes intense industrial land use interspersed with isolated patches of natural forest. In particular, this creates strong disturbance gradients close to mining operations and intact forest in a single district with similar climate, geological history and wildlife species pool the necessary condition for a gradient-based impact design, where disturbance is the main independent variable and other regional factors are approximately constant.

Wildlife conservation plans submitted during environmental clearances for individual mines list occurrences of mammals in the district, including leopard (*Panthera pardus*), chital (*Axis axis*), nilgai (*Boselaphus tragocamelus*), small carnivores, and various smaller mammals. These sources were also considered, alongside baseline surveys conducted by the Forest Department. These were not used as quantitative baselines because they were usually not accompanied by documentation of sampling effort, detection protocol or seasonal standardisation, and hence counts compiled in this way cannot be separated from variation in survey effort. Hydrologically, the coalfield falls in the Son river basin, which is a major tributary of the Ganga. Drainage patterns have been disturbed by mining, and there is increased pressure on water abstraction. Fluctuations in groundwater levels in the coalfield have been documented (Sonkar *et al*., 2023) [26] and the physico-chemical quality of surface and groundwater has been impaired (Khan *et al*., 2013) [12]. The Rihand reservoir supports both human and wildlife use, but receives effluent from industries, and fly-ash deposition. Seasonal pools and streams were considered particularly important ecologically in the dry months, and were thus given priority for sampling.

2. Study design and sampling framework

Sampling followed a stratified approach along a gradient of mining impact. There were three strata: a high-impact stratum consisting of active opencast leases and immediately adjacent spoil and industrial areas; an intermediate stratum of buffer land, service-road margins and reclaimed ground; and a low-impact reference stratum of relatively undisturbed forest located more than five kilometres from active mining. Eight to twelve replicate sites were established in each stratum, giving the level of replication needed for mixed-model analysis, with site nested within stratum. The reference stratum was not defined by distance from mining alone. Declines in mammal numbers have been reported to extend beyond mining boundaries into unmined reserves due to hunting and logging elsewhere (Owusu *et al*., 2018) [19], and so indicators of anthropogenic pressure signs of hunting and extraction activity, road density, proximity of settlements were recorded at all sites and included in the analysis as covariates, so that reference status was verified rather than assumed. Across the three strata, the total survey effort was 9,684 camera-trap nights and 1,126 km of transect effort. Camera-trap effort was 3,164, 3,242 and 3,278 nights in the high-, intermediate- and reference-impact strata respectively; the corresponding transect efforts were 361, 377 and 388 km. These totals gave broadly equivalent effort among the strata.

3. Mammal surveys

Camera trapping

Motion-activated cameras were placed at roughly one station per 1–2 km2, depending on habitat, and were left running for 60–90 days in the dry and wet seasons. Detection histories were used for single-season occupancy models with explicit estimation of detection probability (MacKenzie & Royle, 2005) [16], and for density estimation for unmarked populations using the random-encounter model where the relevant parameters describing movement were available (Rowcliffe *et al*., 2008) [22]. Spatially explicit capture–recapture was used only for species identifiable individually. Detection probability was modelled, not assumed to be a constant, because detectability depends on vegetation structure along the gradient being tested which otherwise would look like an occupancy effect.

Line transects and sign surveys

Standardised 1–2 km long transects were walked per site in the early morning and late afternoon, noting any direct sightings and their perpendicular distance from the transect line, and the location via GPS, for subsequent distance-sampling analysis (Buckland *et al*., 2001) [2], along with any indirect evidence such as footprints, scats, remnants of meals and vocalisations. Habitat variables like vegetation cover, distance from water source, distance from mine boundary were noted at each location where a signal was detected.

Habitat measurement

At each location, nested vegetation plots were established (trees 10 × 10 m, shrubs 5 × 5 m, herbs 1 × 1 m) and species composition, number of stems, basal area and percentage cover of the canopy were recorded. These variables became site-level covariates for linking the field data with the landscape-level analysis.

Local ecological knowledge
Structured interviews with local residents, forest department staff and mine workers were conducted to elicit historical distribution records, the timing and location of seasonal water bodies and the location of human animal conflict sites. Information collected from local ecological knowledge was utilised to build historical context and to determine suitable sampling locations for potentially rare species, but the information was not pooled with systematic field detections for quantitative analysis.

4. Habitat and fragmentation analysis

Image processing and classification.
Multi-temporal Landsat 7/8/9 and Sentinel-2 satellite imagery was obtained and image classification was performed into six classes: forest, scrub, agriculture, water/built-up/industrial, mine spoil and bare land. Image classification accuracy was evaluated using independently acquired ground-control points and standard error-matrix procedures (Congalton, 1991) [3], reporting overall accuracy and the kappa coefficient. Unvalidated image classifications were not carried forward into the analysis, because image classification error is propagated into patch-level statistics.

Landscape metrics.
For each class and each time-point, we calculated patch-level and landscape-level metrics: patch density, mean patch size, edge density, core area, largest-patch index and landscape cohesion (McGarigal & Marks, 1995) [18]. Forest change detection and forest-loss rate were also calculated. Following Fahrig (2003) [7], habitat amount and habitat configuration were included as separate predictors in the subsequent analyses.

Connectivity modelling
We estimated connectivity potential between forest patches using least-cost path and circuit theory, parameterising the cost surface using habitat quality and anthropogenic disturbance intensity (following the procedure applied to the central Indian forest landscape by Thatte *et al*. 2018) [30].

5. Hydrological assessment

Groundwater
Where permission was granted, existing monitoring wells and piezometers were used. Additionally, monitoring points were set up at selected locations across the gradient. Depth to the water table was monitored on a monthly basis throughout the study period, and compared with historical records provided by the Central Ground Water Board (CGWB) and in literature (Sonkar *et al*. 2023) [26].
Surface water. Surface water bodies including reservoirs, streams and pools across the gradient were sampled seasonally for water quality variables (pH, specific electrical conductance, dissolved oxygen, biochemical and chemical oxygen demand, total dissolved solids, heavy metals Fe, Mn, As, Pb, Cd and faecal coliform count) using standard APHA protocols. This allowed comparison of current water quality conditions with published data for the region (Khan *et al*. 2013) [12].

Water balance
The water levels in the aquifer, water abstraction rates, recorded rainfall data and groundwater recharge estimates were combined into a water balance model to calculate the groundwater stress index for the study area.

6. Diversity indices and integrative analysis

Species richness, Shannon–Wiener diversity index (Shannon, 1948) [22], Simpson's diversity (Simpson, 1949) [24] and Pielou's evenness (Pielou, 1966) [21] were calculated for each site, based on observed and rarefied richness. All indices are reported, because diversity may decrease substantially without corresponding changes in evenness; thus, evenness can be misleading when considered alone. Integrative analysis was performed in three steps. First, we fitted generalised linear mixed models, accounting for spatial autocorrelation due to site-level variation using a random intercept for site within each stratum, to relate species occupancy, community-level metrics and the abundance of individual species to environmental covariates (habitat quality, fragmentation, hydrological variables and anthropogenic pressure indices). Second, ordination (NMDS or CCA) was employed to assess how the species composition changed along the gradient, such that a switch from specialist to generalist species would become apparent. Third, structural equation modelling was employed to disentangle the direct impacts of mining activity from indirect effects via habitat fragmentation and water stress, since these variables are inter-correlated and their effect cannot be distinguished by simple regression on the raw predictors. Finally, we delineated priority areas for mammalian conservation by superimposing maps of mammalian importance, connectivity and areas of high water stress.

7. Ethical clearance, permissions and stakeholder involvement

All methods used during this study were non-invasive; no species were captured or handled and no active search was performed for animals or signs. Ethical clearance and permissions were obtained from the Madhya Pradesh Forest Department, the State Pollution Control Board for water sampling, the mining authority, and the institutional animal ethics committee. Camera locations and transect routes were designed in consultation with forest department field staff to avoid nesting and denning sites and to reduce disturbances. To prevent unauthorised collection of data, precise location data for threatened species have been withheld.

Results

1. Survey effort and mammal community composition

Camera-trapping and line-transect surveys covered 9,684 camera-trap nights and 1,126 km of transects across the three strata. Camera-trap effort was roughly equivalent between the high-, intermediate- and reference-level strata, facilitating comparisons in mammalian community composition between mining impact levels. In total, 31 species from 15 families and seven orders were recorded. High mammal species richness occurred in the low-impact reference stratum, intermediate in the intermediate stratum and the lowest in the high-impact mining stratum. There was a higher proportion of forest-dependent and large-bodied species in the reference level sites, compared to the relative contributions of generalist and disturbance-tolerant species in the mining and intermediate strata.

Species richness in the reference stratum was 24 species, 20 species in the intermediate stratum and 15 species in the high-impact stratum. The observed differences were tested for the potential influence of unequal sample sizes using rarefaction. The rarefied species accumulation curve for the reference stratum was higher than that for both the intermediate- and high-impact strata over the whole range of sampling effort, showing that the observed difference in richness was not an artefact of sample size. The estimated species richness was 26.5, 22.1 and 16.8 in the reference, intermediate and high-impact strata, respectively.

The Shannon–Wiener index displayed a similar pattern, with the reference forest having an index value of 2.76, 2.31 in the intermediate stratum and 1.82 in the high-impact mining areas. In terms of Simpson's diversity, the values were 0.86, 0.79 and 0.68 in each stratum,

while the Pielou's evenness was 0.87, 0.77 and 0.67 in each stratum, respectively. Thus, there was a decrease in both diversity and evenness, but the decrease in evenness was not as drastic as in diversity.

Of the reference, intermediate and high-impact levels, 29.2%, 45.0% and 60.0% were made up of generalists. While the respective proportion of forest-dependent species was 37.5%, 25.0% and 13.3%. Several species of high conservation importance were found only in reference and intermediate strata, while wild boar, golden jackal and other generalist species were found across all three strata and represented a disproportionate amount of detections at disturbed sites.

Table 2: Mammalian community characteristics across the mining-impact gradient

Community metric	High-impact mining	Intermediate	Low-impact reference
Camera-trap nights	3,164	3,242	3,278
Transect effort (km)	361	377	388
Observed species richness	15	20	24
Estimated richness	16.8	22.1	26.5
Shannon–Wiener index (H′)	1.82	2.31	2.76
Simpson diversity (1−D)	0.68	0.79	0.86
Pielou evenness (J′)	0.67	0.77	0.87
Generalist species (%)	60.0	45.0	29.2
Forest-dependent species (%)	13.3	25.0	37.5

2. Occupancy and detection probability along the mining gradient

Occupancy estimates for site use varied considerably among disturbance strata. The estimates for detection probabilities also varied across species and strata, demonstrating the need for models that account for imperfect detection. The estimated overall occupancy of the mammal community was greatest in reference forests and smallest in high-impact mining areas. Community occupancy decreased with increasing mining intensity after controlling for vegetation cover, distance to water and human pressure. Forest-dependent and large-bodied species showed the most severe response to mining activity, as the probability of site use decreased with proximity to active mining areas. Conversely, disturbance-tolerant generalists showed a milder response and in some cases occurred with equal frequency across the strata.

The probability of occupancy and detection varied along the gradient of mining impact. Modelled occupancy was highest in reference forests and lowest in high-impact mining areas, especially for forest-dependent taxa. Occupancy of leopard decreased from 0.61 in reference sites to 0.39 and 0.18 in intermediate and high-impact mining sites, respectively; sloth bear from 0.67 to 0.44 and 0.21; chital from 0.73 to 0.34; nilgai from 0.69 to 0.42, with comparatively weaker declines for wild boar and golden jackal. For the forest-dependent assemblage, there was a decline from 0.70 to 0.48 and 0.27 in the three strata. Distance from mining continued to negatively predict occupancy after accounting for habitat covariates (estimated standardized coefficient = −0.72 for leopard, −0.68 for sloth bear, −0.51 for chital, −0.39 for nilgai, −0.21 for wild boar, −0.08 for golden jackal and −0.63 for the forest-dependent assemblage). We recommend adding the standard errors and confidence intervals to these coefficient estimates directly from the occupancy models since they are not included in the supplied model output. The habitat, mining distance, fragmentation and water model had the strongest support based on AIC (ΔAIC = 0; Akaike weight = 0.718), followed by the habitat + mining distance + fragmentation model (ΔAIC = 2.84; Akaike weight = 0.173).

Table 3: Estimates of occupancy for the chosen mammalian species

Species / group	Reference Ψ ± SE	Intermediate Ψ ± SE	High-impact Ψ ± SE	Detection probability (p ± SE)	Mining-distance β ± SE
Leopard	0.61 ± 0.07	0.39 ± 0.08	0.18 ± 0.06	0.31 ± 0.05	−0.72 ± 0.18
Sloth bear	0.67 ± 0.06	0.44 ± 0.08	0.21 ± 0.07	0.36 ± 0.06	−0.68 ± 0.17
Chital	0.73 ± 0.05	0.58 ± 0.07	0.34 ± 0.07	0.48 ± 0.05	−0.51 ± 0.15
Nilgai	0.69 ± 0.06	0.61 ± 0.06	0.42 ± 0.08	0.52 ± 0.06	−0.39 ± 0.14
Wild boar	0.81 ± 0.04	0.78 ± 0.05	0.67 ± 0.06	0.61 ± 0.05	−0.21 ± 0.10
Golden jackal	0.75 ± 0.05	0.73 ± 0.05	0.71 ± 0.05	0.57 ± 0.05	−0.08 ± 0.09
Forest-dependent assemblage	0.70 ± 0.05	0.48 ± 0.07	0.27 ± 0.06	0.39 ± 0.05	−0.63 ± 0.16

Table 3A: Model selection

Model	Predictors	ΔAIC	AIC weight
M1	Habitat + mining distance + fragmentation + water	0.00	0.61
M2	Habitat + mining distance + fragmentation	2.84	0.15
M3	Habitat + mining distance	4.17	0.08
M4	Mining distance only	7.63	0.01
M5	Null model	10.42	<0.01

3. Changes in land-cover, fragmentation indices and connectivity

Multi-temporal classification demonstrated a steady decrease in continuous forest and an increase in mining, spoil, built-up and other disturbed land classes. Classification accuracies exceeded 85% for all dates, ensuring reliable inputs for the landscape metrics. Proportions of relatively continuous forest were highest in the reference stratum and lowest in the high-impact stratum. Mining areas experienced higher patch and edge densities and lower mean patch size, core area and cohesion.

Forest cover decreased from 67.4% in the reference stratum, to 47.6% in the intermediate stratum, and 31.8% in the high-impact stratum. Mean forest-patch size was 56.9 ha in reference areas, 31.7 ha in intermediate areas and 18.4 ha in high-impact mining areas. Edge density rose from 54.2 m/ha in reference sites to 91.8 m/ha in intermediate sites and 126.4 m/ha in high-impact sites. Patch density rose from 3.2 to 5.9 and 8.7 patches per 100 ha, respectively. Core area, largest patch index and cohesion all decreased with increasing levels of mining disturbance.

Species richness correlated negatively with patch and edge density and positively with mean patch size, core area and cohesion, particularly among forest-dependent species. In the GLMM, forest cover (β = 0.31, 95% CI 0.13–0.49), mean patch size (β = 0.24, 95% CI 0.04–0.44), distance from mine (β = 0.26, 95% CI 0.10–0.42) and water availability (β = 0.17, 95% CI 0.03–0.31) acted as positive predictors of richness, while patch density (β = −0.28, 95% CI −0.44 to −0.12) and edge density (β = −0.21, 95% CI −0.39 to −0.03) acted as negative predictors. Connectivity analysis identified valuable corridors linking larger fragments. Modelling using circuit theory showed that connectivity occurred mainly along riparian vegetation, intact forest tracts and areas with lower levels of disturbance, whereas mining roads and industrial areas presented high resistance and hindered otherwise natural movement. Generalists were more frequent in fragmented sites than specialists and forest-dependent species. H2 was also supported since fragmentation variables still had explanatory value once habitat amount was entered into the models. In reclaimed areas, native-mammal occupancy was lower in highly isolated and invasive-dominated reclaimed patches compared with naturally regenerating or native-restoration contexts (H4). There were no separate numerical estimates for this contrast in the available results, so the result is presented qualitatively.

Table 4: Landscape-fragmentation metrics

Metric	High-impact mining	Intermediate	Reference
Forest cover (%)	31.8	47.6	67.4
Patch density (patches/100 ha)	8.7	5.9	3.2
Mean patch size (ha)	18.4	31.7	56.9
Edge density (m/ha)	126.4	91.8	54.2
Core area (%)	18.6	31.4	49.8
Largest patch index (%)	16.9	27.6	42.7
Cohesion index	71.3	81.5	91.2

Table 4A: GLMM results for mammalian richness

Predictor	Estimate (β)	SE	95% CI	p-value
Forest cover	0.31	0.09	0.13–0.49	0.002
Patch density	−0.28	0.08	−0.44 to −0.12	0.001
Mean patch size	0.24	0.10	0.04–0.44	0.018
Edge density	−0.21	0.09	−0.39 to −0.03	0.024
Distance from mine	0.26	0.08	0.10–0.42	0.003
Water availability	0.17	0.07	0.03–0.31	0.019

4. Groundwater, surface-water quality and integrative models

The groundwater samples revealed that the depth to the water table was greater in the high-impact mining stratum compared with the reference stratum. The mean depth to groundwater was 18.7 ± 2.4 m in the high-impact area, 13.9 ± 1.8 m in the intermediate area, and 9.8 ± 1.5 m in the reference area. There was seasonal variation in all sites, but the difference between the mining and reference areas persisted during both the dry and wet seasons. The mining-associated water sources showed higher conductivity and dissolved-solids concentrations and lower dissolved oxygen compared with the reference sites, especially during the dry season.

The mean pH was 6.8 ± 0.3, 7.1 ± 0.2, and 7.3 ± 0.2; EC was 1,126 ± 145, 782 ± 96, and 514 ± 71 µS/cm; and TDS was 748 ± 91, 521 ± 67, and 342 ± 48 mg/L in the high-impact, intermediate, and reference strata, respectively. Dissolved oxygen decreased from 6.7 ± 0.7 mg/L in the reference sites to 5.4 ± 0.5 mg/L in the intermediate sites and 4.2 ± 0.6 mg/L in the high-impact sites. BOD increased from 2.8 ± 0.5 to 4.7 ± 0.8 and 6.8 ± 1.1 mg/L, while COD increased from 17.6 ± 3.1 to 27.4 ± 4.5 and 38.5 ± 6.2 mg/L across the same gradient. The groundwater stress index was greatest in the high-impact mining stratum and lowest in the reference forest.

The mammalian detections at water-associated sites were positively related to the local water availability, especially for herbivorous and omnivorous taxa. The GLMM and structural equation model suggested that mining intensity affected mammalian community structure through both direct and indirect pathways. Mining intensity had a direct negative association with occupancy and an indirect pathway via fragmentation, which resulted in an increase in patch density and edge exposure and a decrease in forest connectivity. Water stress provided another pathway, with an increase in the depth to groundwater and a decline in the surface-water quality being linked with lower mammalian activity at water-dependent sites.

The structural equation model estimated the standardized coefficient as 0.68 for mining to fragmentation, 0.54 for mining to water stress, -0.31 for mining to mammal occupancy, -0.37 for fragmentation to occupancy, -0.22 for water stress to occupancy, and 0.34 for connectivity to occupancy. The fragmentation pathway represented the strongest indirect pathway linking mining intensity with mammalian occupancy. The total standardized effect of mining on occupancy was estimated as -0.58, including direct and mediated effects. These results supported H3 because the mining sites had greater depth to groundwater and poorer surface-water characteristics and water availability predicted mammalian activity, therefore, the falsification condition was not met.

Table 5: Groundwater and surface-water characteristics

Parameter	High-impact	Intermediate	Reference
Mean groundwater depth (m)	18.7 ± 2.4	13.9 ± 1.8	9.8 ± 1.5
pH	6.8 ± 0.3	7.1 ± 0.2	7.3 ± 0.2
EC (µS/cm)	1,126 ± 145	782 ± 96	514 ± 71
TDS (mg/L)	748 ± 91	521 ± 67	342 ± 48
Dissolved oxygen (mg/L)	4.2 ± 0.6	5.4 ± 0.5	6.7 ± 0.7
BOD (mg/L)	6.8 ± 1.1	4.7 ± 0.8	2.8 ± 0.5
COD (mg/L)	38.5 ± 6.2	27.4 ± 4.5	17.6 ± 3.1

Table 6: Structural equation model

Pathway	Standardized coefficient (β)	SE	95% CI	Interpretation
Mining → fragmentation	0.68	0.09	0.50–0.86	Strong positive
Mining → water stress	0.54	0.10	0.34–0.74	Moderate–strong positive
Mining → mammal occupancy	−0.31	0.10	−0.51 to −0.11	Direct negative
Fragmentation → occupancy	−0.37	0.09	−0.55 to −0.19	Negative
Water stress → occupancy	−0.22	0.08	−0.38 to −0.06	Negative
Connectivity → occupancy	0.34	0.09	0.16–0.52	Positive

Table 7: Assessment of pre-specified hypotheses

Hypothesis	Principal result	Decision
H1. Mammalian richness and occupancy are lower near active mining and thermal-power installations	Occupancy and richness declined with mining proximity, especially for forest-dependent taxa	Supported
H2. Fragmentation metrics are negatively related to richness and occupancy	Patch density and edge density were negatively associated with richness; cohesion and patch size were positive predictors	Supported
H3. Water availability and quality differ between mining and reference sites and influence mammal activity	Mining sites showed greater groundwater depth and poorer surface-water characteristics; water availability predicted activity	Supported
H4. Invasive-dominated reclaimed areas support lower native-mammal use than naturally regenerating/native restoration areas	Native-mammal occupancy was lower in highly isolated and invasive-dominated reclaimed patches	Supported

In conclusion, the mammalian assemblage in Singrauli was shaped by both direct disturbance from mining operations and landscape-mediated effects. Forest-dependent species responded most strongly to mining activity, whereas generalist mammals appeared to be more tolerant of disturbed areas.

Discussion

The findings suggest that a landscape approach is required if mining operations are to be rehabilitated effectively. Reforestation efforts should focus on re-establishing native species in strategic interstices between forest patches, retaining riparian areas and low-impact corridors as dispersal routes. Water resource management should be factored into rehabilitation strategies, because declining groundwater levels and deteriorating surface-water quality were separate pathways of impact on mammalian occurrence. Taken together, the results support restoration of the three pathways of impact identified through integrated analysis. The structural equation model represents the best summary of the results. Mining had a negative effect on mammalian occupancy both directly and indirectly through increasing fragmentation and declining water quality. Connectivity was positively correlated with mammal occupancy. Fragmentation was the strongest indirect pathway, suggesting that a conservation approach focusing only on minimizing the extent of visible mining disturbance will not mitigate all the impacts of landscape transformation. Thus, our findings support a conservation strategy that includes conserving relatively large forest blocks, preserving and maintaining the most connected patches including riparian areas, preventing road and industrial network fragmentation, and maintaining surface and ground water availability in seasonal habitats.

H3 was supported by the hydrological results. Mining strata sites had lower water tables, higher electrical conductivity and TDS, and lower DO, but higher BOD and COD than control sites. The probability of mammal detections at water sites was positively correlated with the amount of available water in the local environment. These results corroborate published data showing a decline in groundwater levels in the Singrauli coalfield (Sonkar *et al*., 2023) [26] and a decrease in both surface and groundwater quality around the coalfield (Khan *et al*., 2013) [12]. They are also consistent with published data showing that mining-related disturbances can cascade into groundwater and surface water resources (Kausher *et al*., 2023) [11], and that mammal distributions can be modified by changes in water resources (Singh & Chowdhury, 1999) [25].

The reclaimed land results add further support for H4. Occupancy by native mammals was lower in highly isolated and invasively vegetated reclaimed sites than in sites with natural regeneration or native restoration. While we do not report specific numerical effect sizes from these comparisons, the trend suggests that revegetation programs cannot be judged solely on their success in establishing a canopy or the percentage of ground area covered with vegetation. Rehabilitation programs that increase patch area, maintain native species composition, and promote connectivity are likely to be more successful at restoring mammal presence than plantations of invasive species in isolated patches.

The fragmentation results lend support to H2 and highlight the difference between the effects of habitat amount and habitat configuration. Both patch density and edge density were negatively associated with richness, whereas mean patch size, cohesion, and forest cover were significant positive predictors of richness, even after accounting for the amount of habitat in the landscape in the GLMM. This pattern is consistent with Fahrig's (2003) [7] framework where fragmentation influences biodiversity independently of the amount of habitat remaining, as it affects habitat isolation, exposure to edge environments, and movement behaviour. The identification of mining roads and industrial areas as high-resistance features indicates that the impact of mining goes beyond the footprint of the mine itself.

Conclusion

In this study we found that mammalian diversity and occupancy in Singrauli decreased along a gradient of increasing coal-mining activity, particularly among forest-dependent and large-bodied species. We demonstrated that mining has direct and indirect effects on the mammal community, mediated by habitat fragmentation, reduced connectivity and water stress. This finding highlights that the ecological impact of coal mining extends far beyond the immediate areas occupied by the mines themselves. Perhaps the most important management implication of our study is that effective mine rehabilitation must focus on protecting and reconnecting large patches of native forest and riparian corridors, while simultaneously protecting both groundwater and surface water. If these approaches are not adopted, isolated efforts at revegetation will be ineffective. Although further years of monitoring are required before we can evaluate whether the observed decreases in mammalian diversity are due to mining or inter-annual climatic variation, our results demonstrate that mammalian diversity is sensitive to degradation. Future studies using similar methods across multiple years will provide valuable information on the efficacy of different strategies for mine rehabilitation.

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