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Multi-temporal satellite mapping of coal mine expansion and forest loss in the Hasdeo Arand Forest, India

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Abstract
Open-cast coal mining in forested regions presents a persistent sustainability challenge, as cumulative physical disturbance often unfolds incrementally and remains poorly captured by administrative clearance records. This case study presents a mine-scale, time-resolved reconstruction of surface expansion at the Parsa East and Kente Basan (PEKB) open-cast coal mine, located within the ecologically sensitive Hasdeo Arand forest of central India. The objective is to reconstruct the year-by-year growth of a single open-cast mine and quantify associated forest conversion over time. Using multi-temporal satellite imagery (Landsat 8 and PlanetScope) and consistent visual-interpretation, we delineated annual changes in the mine's surface footprint and estimated forest-to-mine conversion between 2013 and 2025. Results show that the mine footprint expanded from 218 hectares in 2013 to 1,389 hectares by mid-2025. Over the same period, approximately 1,013 hectares of closed-canopy forest were converted, such that 73% of the final footprint overlapped land that was forested at the outset. Expansion occurred in distinct phases, including a period of rapid lateral growth, a temporary slowdown, and renewed acceleration after 2023. By documenting how a legally approved mine physically expands through forested terrain over time, this study demonstrates the value of mine-level, time-resolved satellite reconstruction for revealing cumulative environmental transformation that is obscured in aggregated land-use statistics. Such approaches provide an independent spatial basis for post-clearance monitoring, cumulative impact assessment, and environmental accountability in mining-affected forest landscapes.

Keywords Land use change, Open-cast coal mining, Remote sensing, Habitat fragmentation, Forest conservation

1 Introduction

Open-cast coal mining is one of the most extensive forms of human-induced land transformation in forested regions, particularly across parts of the Global South where near-surface coal deposits overlap biodiverse landscapes. Unlike underground extraction, open-cast mining requires large-scale removal of vegetation, soil, and overburden, resulting in direct forest loss, habitat fragmentation, and long-term alteration of land surface structure [1–4]. In India, where coal remains the primary source of energy production, accounting for approximately 74% of national electricity generation [5], surface mining has expanded rapidly across central and eastern forest belts dominated by Gondwana formations [6]. Numerous studies have documented the environmental consequences of this expansion, including deforestation, biomass loss, carbon emissions, and increased human-wildlife conflict, particularly in elephant-bearing landscapes of central India [4, 6–9]. These documented impacts highlight the need for spatially explicit approaches capable of tracking how extractive infrastructure physically transforms forested terrain over time.

Most existing research on coal mining-related forest loss in India has operated at aggregated spatial scales, using district- or regional-level assessments to quantify land-use change, forest diversion, and associated biomass or carbon losses [6, 9–13]. For example, studies in the Korba-Hasdeo region have reported substantial expansion of mining areas alongside large-scale forest loss and carbon emissions between 2001 and 2020 [9]. While such analyses provide critical regional context, they typically treat mining as a static land-use category rather than as a dynamic physical process that unfolds progressively within individual leases. As a result, the year-by-year trajectory through which a specific open-cast mine initiates clearing, expands laterally, and replaces standing forests remains poorly documented in the peer-reviewed literature. This gap is particularly relevant in legally approved mining landscapes, where forest diversion is authorized in discrete administrative stages, but cumulative biophysical outcomes emerge incrementally on the ground [10]. Mine-level time-resolved reconstructions are therefore needed to bridge the disconnect between clearance records and observable patterns of forest-to-mine conversion.

Documenting mine expansion at the level of individual leases is scientifically important because many of the ecological and social consequences of surface mining arise from the cumulative geometry and timing of physical disturbance, rather than from aggregate land-use totals alone [10, 14]. Mine-level reconstructions make it possible to observe how forest clearance progresses through space and time, how pits expand laterally, how overburden areas encroach into intact canopy, and how previously contiguous forest blocks become incrementally fragmented [15, 16]. Such information is rarely visible in administrative statistics or regional land-use inventories, yet it is central to understanding cumulative environmental transformation in extractive landscapes [3]. Earth Observation data provide an independent means of reconstructing these long-arc physical trajectories, allowing the translation of formal forest diversion approvals into spatially explicit records of on-ground change [4, 17]. In this sense, mine-scale time-resolved analysis complements landscape-scale assessments by revealing the physical processes through which authorized extraction reshapes forested terrain over time.

The Hasdeo Arand forest of northern Chhattisgarh provides a particularly relevant setting in which to examine these processes. The region represents one of central India's largest remaining contiguous tracts of tropical deciduous forest and is widely recognized for its ecological significance, including the role within the Central Indian elephant landscape [7, 8, 18, 19]. At the same time, Hasdeo Arand overlaps an actively developed coalfield, where multiple open-cast blocks have been allocated and brought into production over the past two decades [20–22]. State and national assessments document substantial diversion of forest land in this region for non-forestry purposes, with mining accounting for a major share of recent clearances [18, 23, 24]. This juxtaposition of high ecological value and intensive surface mining makes Hasdeo Arand an important landscape for examining how legally approved extractive activities physically transform forested environments, and for understanding the cumulative spatial consequences of mine expansion within a biodiversity-rich setting.

Within the Hasdeo Arand coalfield (HAC), the Parsa East and Kente Basan (PEKB) block provides a particularly suitable case for mine-level reconstruction. The HAC covers approximately 1,880 square kilometres and comprises twenty three coal blocks, including Tara, Parsa, PEKB, and the Kente Extension. Among these, PEKB and the adjacent Chotia block were identified as the only actively producing open-cast mines as of March 2023, while several other allocated blocks had not yet entered production [21]. The PEKB lease has received central approval for large-scale surface mining under Sect. 2(ii) of the Forest (Conservation) Act, 1980, including in-principle (Stage I) clearance for 1, 898.238 hectares of forest land granted by the Ministry of Environment, Forest and Climate Change (MoEFCC) [20, 21]. The mine operates completely within a sal-dominated forest landscape recognized as active elephant habitat [7, 8, 20]. Its operational history spans more than a decade, during which progressive pit expansion and associated forest clearance are clearly observable in satellite imagery. These characteristics make PEKB well suited for documenting how an individual, legally approved open-cast mine physically expands through forested terrain over time, providing a focused lens on cumulative landscape transformation at the scale of a single lease.

Against this background, this study presents a mine-scale, time-resolved reconstruction of surface coal mining expansion within the PEKB block of the Hasdeo Arand forest. Specifically, the case study aims to (i) reconstruct the year-by-year expansion of the PEKB open-cast mine between 2013 and 2025 using multi-temporal satellite imagery; (ii) quantify the cumulative conversion of dense forest associated with this expansion; and (iii) identify and describe distinct phases of physical mine growth over the study period.

2 Data and methods

2.1 Study area

The study area lies within the Hasdeo Arand forest of northern Chhattisgarh, central India (Fig. 1). Hasdeo Arand occupies the northern part of the state across the Surguja and Surajpur districts, extending southward into parts of Korba and Raigarh. The region is characterized by undulating low hills and lateritic plateaus, with elevations ranging approximately between 410 and 420 m above mean sea level [18]. The climate is tropical to semi-tropical, with distinct monsoon (June-September), winter (October-February), and summer (March-May) seasons.

Vegetation is dominated by tropical dry and moist deciduous forest, with sal (*Shorea robusta*) forming the principal canopy species, alongside *Diospyros melanoxylon*, *Madhuca longifolia*, *Buchanania lanzan*, *Lagerstroemia parviflora*, and *Terminalla elliptica* [18, 19]. Biodiversity assessments conducted by the Wildlife Institute of India report the presence of at least 25 mammal species (including nine Schedule I species), over 80 bird species (six Schedule I species), multiple endangered herpetofauna species, and more than 160 plant species, including several classified as threatened [18]. The State Forest Department has recorded the presence of approximately 40–50 elephants in this

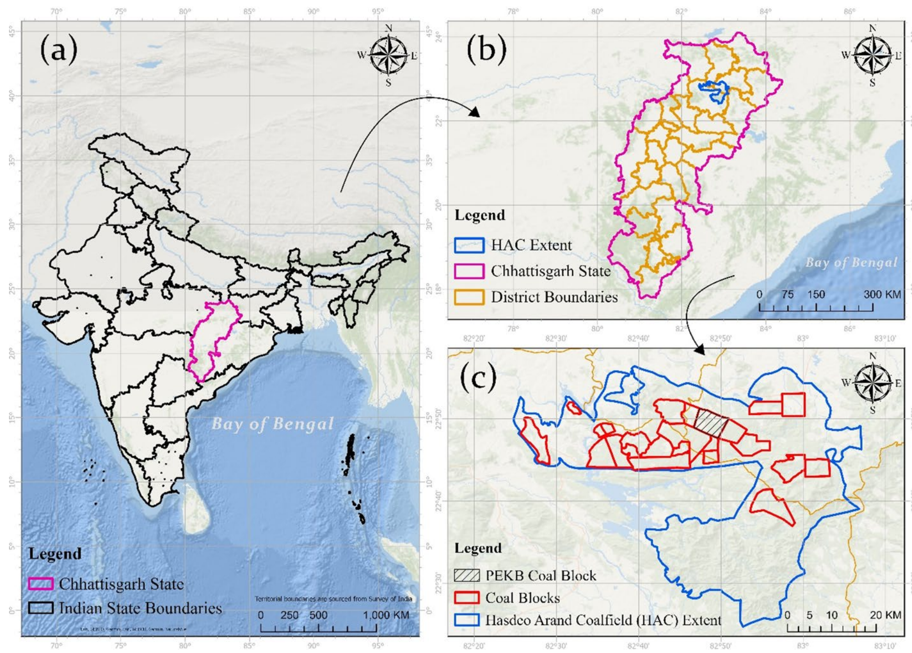

Fig. 1 Study area map. **a** Chhattisgarh state within India, **b** HAC extent within northern Chhattisgarh (marked in blue), overlaid on state and district boundaries, **c** HAC extent and individual coal blocks, with the PEKB block highlighted

landscape, identifying the region as an important movement corridor, with reported dispersal of tigers from adjacent protected areas [7, 18].

Drainage in the region is controlled by the Hasdeo River and its tributaries, which flow through forested catchments before entering agricultural and settlement landscapes downstream [18, 19]. Forest-dependent villages and cultivated clearings are embedded within this forest-river mosaic, where rural populations, predominantly indigenous communities have historically lived in close proximity to active forest use and recognized elephant movement routes [8, 18, 25]. Non-timer forest products (NTFPs) contribute substantially to local livelihoods, accounting for an estimated 46% of average monthly household income in forest-adjacent communities within the broader Hasdeo Arand landscape [18].

Within this landscape, a contiguous cluster of allocated coal blocks overlaps the northern forest belt, forming the Hasdeo Arand Coalfield (HAC). The HAC extent and individual coal-block boundaries were digitized from a publicly available coalfield map [26] and overlaid on Survey of India administrative boundaries to situate mining activity within the regional context (Fig. 1). Among these blocks, the PEKB lease is an active open-cast coal mine and forms the focus of this study. In the analysis that follows, 'PEKB' refers specifically to the actively excavated open pit and contiguous disturbed ground, including overburden dumps and visibly cleared staging areas, as identified through satellite-image interpretation.

2.2 Data

The analysis draws on three sources of satellite imagery: Landsat 8 surface reflectance scenes, PlanetScope high-resolution optical imagery, and historical high-resolution satellite imagery (primarily Maxar) accessed via Google Earth Pro (Table 1). PlanetScope

Table 1 Satellite imagery used for visual interpretation and analysis

Date acquired (YYYY-MM-DD)	Product	Cloud cover (%)	Spatial resolution	Notes on use
2009-10-XX	Google Earth Pro	–	–	Pre-construction baseline
2013-12-27	Landsat 8	0	30 m	Phase I (initial expansion)
2014-12-30	Landsat 8	0	30 m	
2015-12-01	Landsat 8	0	30 m	
2016-10-21	PlanetScope Scene	0	3 m	
2017-10-17	PlanetScope Scene	0	3 m	Phase II (rapid expansion)
2018-10-16	PlanetScope Scene	0	3 m	
2019-10-15	PlanetScope Scene	0	3 m	
2020-10-13	PlanetScope Scene	0	3 m	Phase III (slowdown)
2021-10-24	PlanetScope Scene	0	3 m	
2022-10-20	PlanetScope Scene	0	3 m	
2023-10-27	PlanetScope Scene	0	3 m	Phase IV (renewed surge)
2024-10-21	PlanetScope Scene	0.02	3 m	
2025-06-08	PlanetScope Scene	0	3 m	

(Dates marked 'XX' indicate month known but exact day not available; cloud cover values are based on respective datasets metadata and not applicable to Google Earth Pro imagery)

imagery was accessed through Planet Labs under an Education and Research Basic license associated with the DEPRIMAP project. These datasets were selected to enable consistent visual reconstruction of mine expansion and associated forest conversion over the 2013–2025 period, with priority given to spatial resolution, temporal continuity, and cloud-free coverage.

For the early phase of mine development (2013–2015), Landsat 8 imagery (30 m resolution) was used as PlanetScope data were not available prior to 2015. From 2016 onward, PlanetScope scenes (3 m resolution) [27] were used to delineate the evolving mine footprint, as this resolution allows clear discrimination of open pits, overburden dumps, and newly cleared staging areas from intact forest canopy. The transition from Landsat 8 to PlanetScope reflects data availability rather than a methodological shift, and the analysis focuses on cumulative landscape-scale change rather than pixel-level land-cover classification. PlanetScope imagery has been widely applied for manual, semi-manual and automated delineation of mining activity and landscape modification in comparable studies [11–13, 28, 29].

Image acquisition dates were selected to maintain seasonal consistency and minimise cloud cover. Where possible, scenes from the post-monsoon (October-December) were chosen, when vegetation-soil contrast is strongest in central India. The final PlanetScope scene (June 2025) represents the most recent cloud-free image available at the time of analysis. Additional cloud-free scenes within the same years were reviewed where necessary to verify boundary interpretation but were not used for primary digitization to maintain temporal consistency.

For both Landsat 8 and PlanetScope imagery, false-colour composites were generated by assigning the near-infrared (NIR), red, and green bands to the red, green, and blue display channels, respectively. This composite enhances the reflectance of healthy vegetation appearing in vivid red hues, facilitating visual separation of dense sal-dominated forest from exposed soil, bare ground and cleared staging areas [30–32]. Historical high-resolution imagery accessed via Google Earth Pro was used exclusively for contextual purposes, including identification of pre-2013 settlement clusters and visual cross-checking of selected delineations. No quantitative measurements were derived from Google Earth Pro imagery.

2.3 Methods

The overall analytical workflow, from satellite imagery acquisition through baseline mapping, annual footprint delineation, forest conversion attribution, and phase identification, is summarised in Fig. 2.

2.3.1 Pre-construction baseline

A pre-construction baseline was established using high-resolution satellite imagery acquired in October 2009 and accessed via Google Earth Pro (primarily Maxar). This imagery predates visible surface mining activity at PEKB site and was used to digitize settlement clusters and areas of dense forest cover within the PEKB coal block boundary (Fig. 3). Settlement clusters were identified as compact built-up patterns embedded within agricultural clearings and were mapped for contextual reference, to indicate pre-existing habitation patterns within the PEKB block (Fig. 3a). In contrast, the dense forest layer, identified as contiguous closed-canopy vegetation with minimal internal clearing (Fig. 3b), formed the analytical baseline against which subsequent forest conversion associated with mine expansion was assessed.

This baseline allowed forest loss attributable to mining to be distinguished from land uses that existed prior to large-scale excavation, such as agriculture or settlements. Baseline mapping was intended to support change attribution and forest-loss estimation rather than to function as a formal land-cover classification product.

2.3.2 Visual delineation of mine footprint and forest conversion

The PEKB mine footprint was manually delineated for sequential time points between 2013 and 2025 through visual interpretation of satellite imagery in ArcGIS Pro, following an approach commonly applied in mine-scale and landscape-scale disturbance mapping using high-resolution optical data [29]. Manual delineation was selected for mine-scale footprint reconstruction because high-resolution visual interpretation enables consistent discrimination between active excavation, overburden dumps, transitional surfaces, and intact forest. For each year, the mine footprint was defined as the combined area of (i) the active open pit, (ii) overburden dumps, and (iii) visibly cleared staging areas

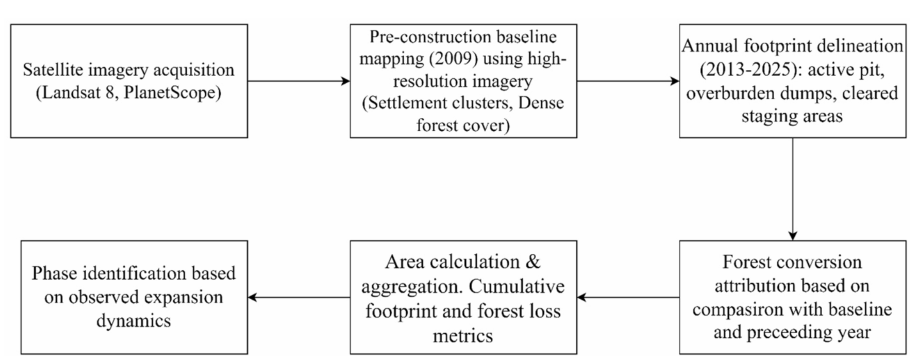

Fig. 2 Workflow for reconstructing mine expansion and forest conversion at the PEKB coal block using multi-temporal satellite imagery

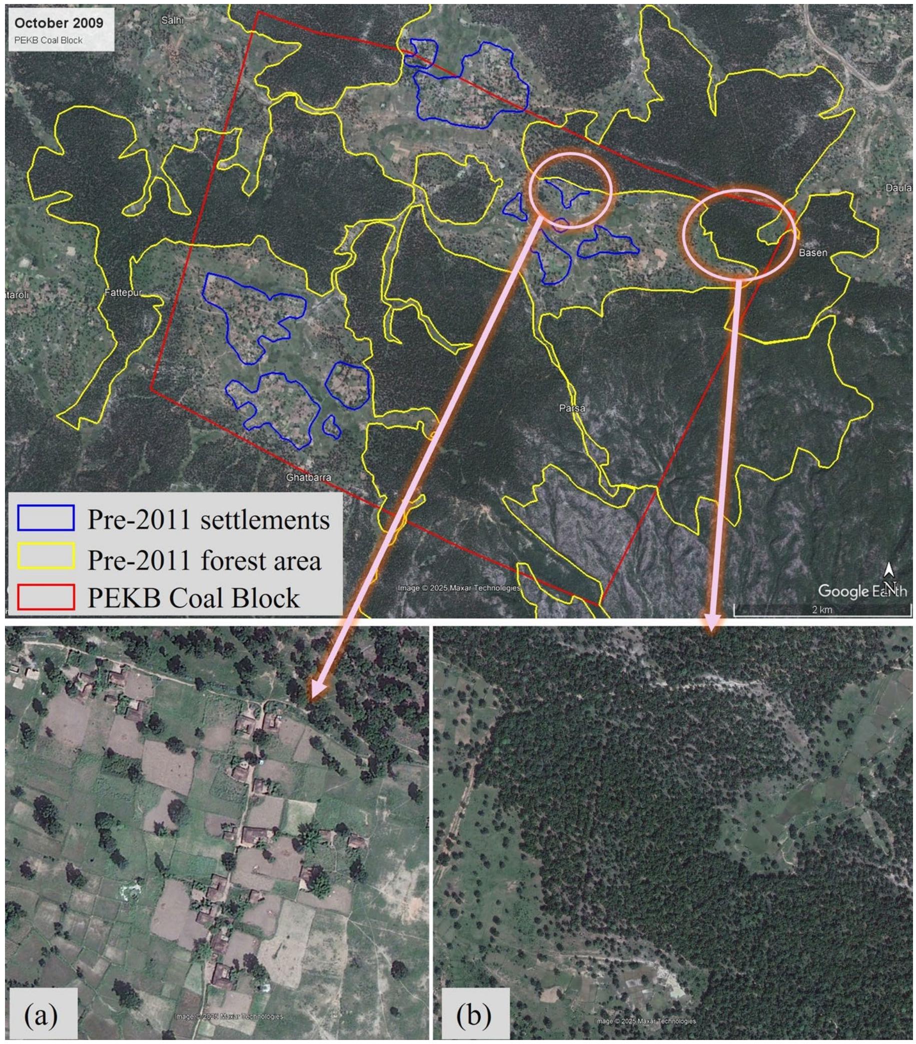

Fig. 3 Pre-construction baseline within the PEKB coal block (October 2009), showing mapped settlement clusters and dense forest cover; **a** representative 2009 settlement cluster; **b** representative dense closed-canopy forest

directly associated with excavation. Haul roads, external access routes, and other linear infrastructure were deliberately excluded to maintain a conservative definition of surface disturbance.

Delineation was performed at image-appropriate on-screen scales appropriate to the spatial resolution of each dataset, with boundaries placed conservatively along visually stable contrasts between ground and intact vegetation. Mixed or transitional pixels at footprint edges were resolved through comparison with adjacent years to ensure consistent boundary placement over time. No fixed minimum mapping unit was imposed.

Forest conversion was estimated by comparing each newly added portion of the mine footprint to its land cover in the immediately preceding image and, where relevant, to the 2009 pre-construction baseline. Areas were classified as forest only where they exhibited continuous closed-canopy vegetation consistent with dense sal-dominated forest, rather than cropland, shrubland, or pre-existing settlement. Interpretation was carried out by a single analyst using a consistent protocol across all years to minimize intra-temporal variability.

Table 2 Annual and cumulative expansion of the PEKB mine footprint and associated forest loss (2013–2025)

Date	Cumulative mine footprint (ha)	Annual expansion (ha)	Annual growth (%)	Forest loss (ha)	Cumulative forest loss (ha)	Forest share of footprint (%)
Dec-13	218.2	–	–	–	–	–
Dec-14	315.8	97.6	44.7	0	90.3	28.6
Dec-15	405.1	89.3	28.3	67.9	158.2	39.1
Oct-16	503	97.9	24.2	54.8	212.9	42.3
Oct-17	638.8	135.8	27.0	134.4	347.3	54.4
Oct-18	830.1	191.3	29.9	83.8	431.1	51.9
Oct-19	955.2	125.1	15.1	104	535.1	56.0
Oct-20	1038.4	83.2	8.7	7.9	543	52.3
Oct-21	1130.9	92.5	8.9	95	638	56.4
Oct-22	1131.7	0.8	0.1	48.8	686.8	60.7
Oct-23	1177.7	46	4.1	0	686.8	58.3
Oct-24	1261.7	84	7.1	171.5	858.3	68.0
Jun-25	1389.4	127.7	10.1	154.5	1012.8	72.9

Annual expansion and annual growth are not shown for Dec-13 because this is the first mapped year in the time series. Cumulative forest loss from Dec-14 onwards includes forest conversion already present within the Dec-13 footprint relative to the 2009 pre-construction baseline

2.3.3 Area calculation, temporal aggregation, and phase identification

Digitized mine-footprint polygons for each year were converted to area in square meters and subsequently expressed in hectares to generate a time series of cumulative mine extent and cumulative forest conversion. Annual increments were calculated as the difference between successive footprint extents.

To characterize the temporal dynamics of expansion, the 2013–2025 trajectory was grouped into four broad phases of physical growth based on observable changes in the rate and spatial pattern of footprint expansion. These phases represent periods of steady growth, rapid lateral expansion, relative slowdown, and renewed growth, as evident from year-to-year changes in cumulative area. Phase boundaries were defined descriptively rather than through formal statistical segmentation, consistent with the case-study objective of documenting long-term physical transformation rather than modelling predictive trends.

All spatial interpretation, measurement, and aggregation were performed in ArcGIS Pro. Reported areas are intended as indicative estimates of landscape-scale change rather than exact cadastral measurements.

3 Results

3.1 Cumulative mine expansion and forest conversion (2013–2025)

Satellite-based measurements indicate substantial expansion of the PEKB open-cast over the twelve-year observation period. The mine footprint increased from 218 hectares in December 2013 to 1,389 hectares by June 2025, representing nearly a six-fold growth in surface extent. Over the same period, approximately 1,013 hectares of forest were cleared as the pit and associated overburden areas expanded.

By mid-2025, approximately 73% of the cumulative mine footprint overlapped land that was forested at the beginning of the study period, indicating that most of the observed spatial expansion occurred through direct conversion of forest cover. Annual and cumulative values for mine footprint area, yearly expansion, forest loss, and the proportion of forest-derived footprint for each mapped year are summarized in Table-2 and visualized in the cumulative time-series and composition plots in Fig. 4. Years with measurable footprint expansion but no recorded forest loss (e.g., 2014 and 2023) likely reflect phases of development within areas that were already cleared or otherwise non-forested within the lease.

3.2 Temporal phases of expansion

Annual expansion rates varied substantially over the study period, allowing the identification of four distinct phases of physical growth between 2013 and 2025 (Fig. 4). Representative satellite images illustrating each phase are shown in Fig. 5.

Phase I (2013–2016): Initial growth

During the initial phase of activity, the mine footprint expanded from 218 hectares in 2013 to 503 hectares by late 2016. Cumulative forest loss reached approximately 213 hectares by the end of this period. Annual additions were relatively consistent, averaging around 90–100 hectares per year.

Phase II (2016–2019): Rapid expansion

Between 2016 and 2019, the mine experienced the highest annual expansion rates observed in the record. The footprint increased from 503 hectares to 955 hectares over three years. Year-on-year additions included 136 hectares in 2017, 191 hectares in 2018, and 125 hectares in 2019. By the end of 2019, cumulative forest loss exceeded 535 hectares.

Phase III (2020–2022): Slowdown

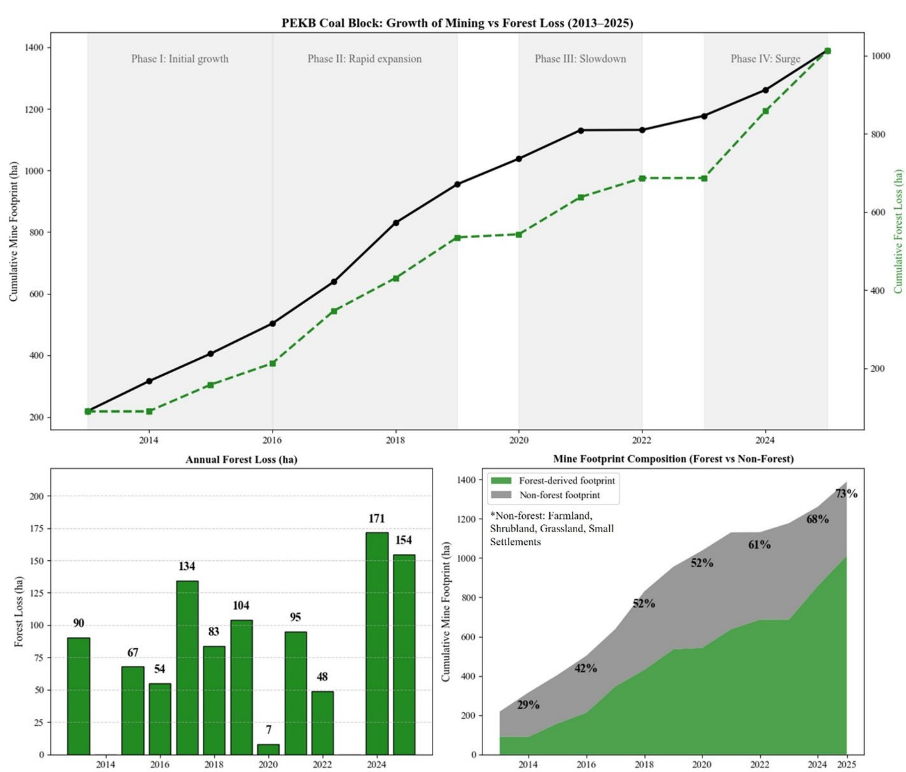

Fig. 4 Mine expansion and forest conversion in the PEKB coal block, 2013–2025. Top panel: cumulative mine footprint (black) and cumulative forest loss (green), with shaded phases. Bottom left: annual forest loss. Bottom right: composition of the cumulative mine footprint, showing the proportion derived from forest versus non-forest land

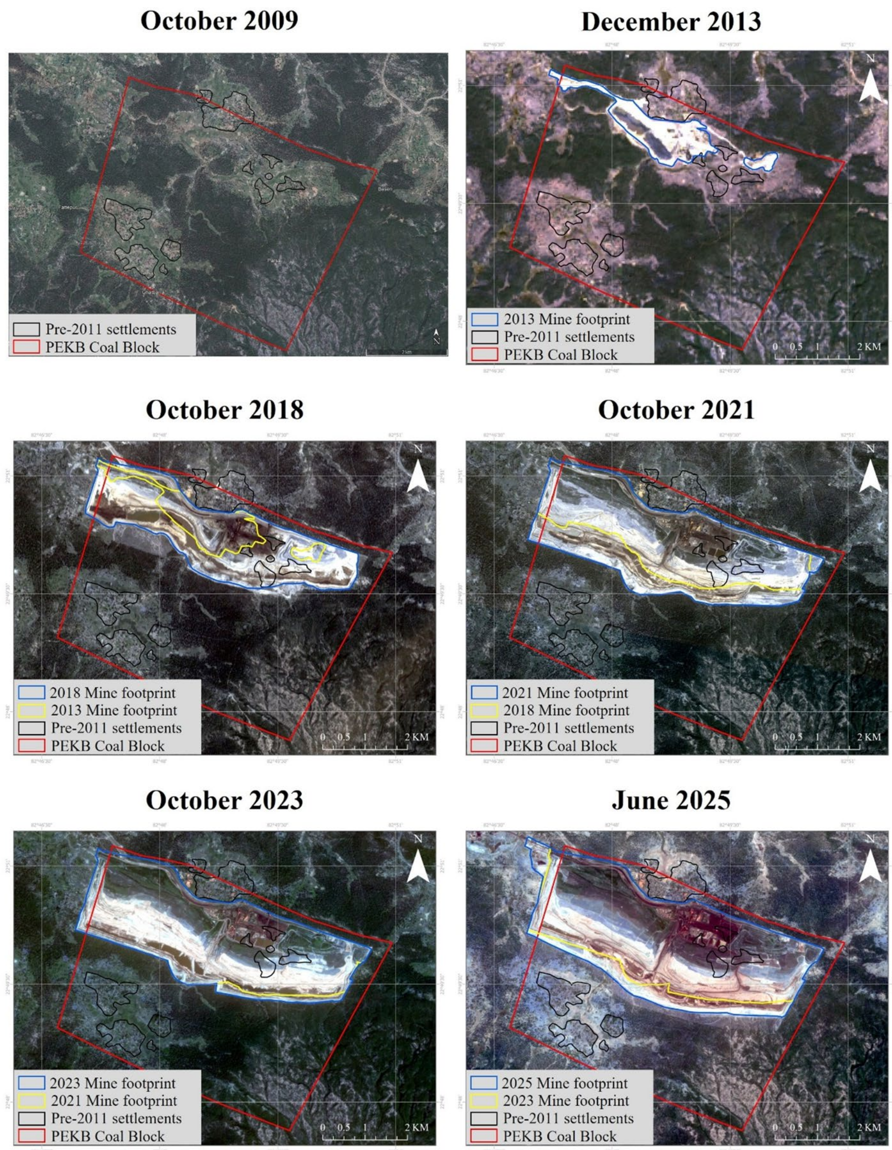

Fig. 5 Multi-temporal satellite views of the PEKB coal block, 2009–2025. Background imagery sourced from Google Earth Pro for October 2009, Landsat 8 for December 2013, and Planet Scope Scenes for October 2018, October 2021, October 2023, and June 2025

From 2020 to 2022, expansion rates declined. The mine footprint increased from 1,038 hectares to 1,132 hectares over this interval. Annual additions fell to 83 hectares in 2020, and 93 hectares in 2021, with negligible net expansion in 2022. By the end of this phase, cumulative forest loss reached approximately 687 hectares.

Phase IV (2023–2025): Renewed surge

Following the slowdown, a renewed phase of outward expansion was observed. The mine footprint increased from 1,178 hectares in 2023 to 1,389 hectares by June 2025. Additions during this phase included 84 hectares in 2024 and 128 hectares during the first half of 2025. Forest clearing also accelerated during this period, with approximately 172 hectares cleared in 2024 and 155 hectares in early 2025, bringing cumulative forest loss above 1,000 hectares. By mid-2025, about 73% of the total mine footprint lay on land that was originally dense forest.

4 Discussion

4.1 Mine expansion dynamics and governance context

The expansion of the PEKB open-cast mine between 2013 and 2025 followed a distinctly episodic trajectory rather than a smooth or incremental pattern. The satellite record reveals four broad phases characterised by alternating periods of steady growth, rapid lateral expansion, relative slowdown, and renewed acceleration. Such stepwise growth is typical of large surface mines, where excavation advances through spatially discrete benches and overburden zones rather than through continuous outward spread [3, 16]. At PEKB, these phases translated into a cumulative footprint that expanded more than six-fold over twelve years, with forest conversion occurring progressively as new sections of the lease were brought into active use.

Importantly, these expansion phases reflect not only mining geometry but also the governance context in which surface mining operates. In India, forest diversion for mining is approved through staged administrative clearances under the Forest (Conservation) Act, accompanied by compliance conditions, land acquisition processes, and operational sequencing [33, 34]. As a result, physical expansion on the ground often occurs in bursts when regulatory permissions, logistical capacity, and operational readiness align, rather than as a uniform annual process. The slowdown observed between 2020 and 2022, followed by renewed expansion after 2023, is consistent with broader patterns documented in other Indian coalfields, where administrative delays, legal challenges, or public contestation temporarily constrain outward growth before expansion resumes [24, 26, 35].

Mine-scale, time-resolved reconstruction makes these governance-mediated dynamics visible on the landscape. While clearance approvals are issued as discrete administrative acts, their ecological consequences unfold incrementally as pits deepen, overburden areas expand, and intact forest is progressively absorbed into the operational footprint. By capturing when and where expansion occurred within a single lease, this analysis provides a physical record of how legally approved mining materialises over time, complementing clearance statistics with spatially explicit evidence of cumulative disturbance [10, 14].

4.2 Ecological and social implications of mine-scale forest conversion

4.2.1 Ecological implications

The ecological significance of the PEKB expansion lies not only in the total area of forest converted, but in the spatial pattern through which conversion occurred. Because most expansion took place through direct replacement of dense sal-dominated forest rather than infill of previously disturbed land, disturbance progressively encroached into interior forest areas that were intact at the beginning of the study period. In landscapes such as Hasdeo Arand, characterised by high canopy continuity and documented use by wide-ranging fauna, large open pits and overburden dumps function as hard structural barriers that interrupt habitat connectivity and alter landscape permeability [7, 8].

Independent assessments identify the Hasdeo–Lemru–Tamor Pingla belt as an active elephant movement zone, where fragmentation and narrowing of forest corridors are associated with increased mortality and human–elephant conflict [7, 8, 18, 25]. Although this study does not quantify movement pathways or corridor widths, the spatial coincidence between PEKB's expanding footprint and previously contiguous forest blocks is consistent with patterns reported from other surface coal mining regions in central and eastern India, where mine-driven forest loss has contributed to long-term habitat degradation beyond the immediate pit boundary [6, 9, 11]. Similar dynamics have been documented internationally, underscoring that the ecological effects of surface mining are shaped as much by disturbance geometry as by total area cleared [3, 12, 17].

4.2.2 Social implications

The satellite record also documents changes relevant to human land use within the PEKB block. Several small settlement clusters visible in the 2009 baseline imagery no longer appear as discrete features in later scenes, having been absorbed into expanding pit and overburden areas by the late 2010s. While satellite imagery cannot reconstruct the legal or social processes underlying these changes, it provides clear spatial evidence that inhabited and cultivated spaces present prior to mining were physically replaced as expansion progressed. These spatial observations align temporally with documented reports of village displacement, contestation over forest rights, and protests against mining in Hasdeo Arand and neighbouring blocks [23, 26, 35, 36].

In forest-dependent regions where indigenous and rural livelihoods rely heavily on non-timber forest products and access to forest land, the progressive conversion of forest to mine infrastructure has implications that extend beyond the loss of tree cover alone [18]. Mine-scale reconstructions such as this provide a spatial framework within which social, legal, and ethnographic analyses can be more precisely situated.

4.3 Broader implications

The PEKB case illustrates the value of mine-level, time-resolved reconstruction as a complement to landscape-scale land-use assessments. Regional studies across India consistently identify surface coal mining as a dominant driver of forest loss, biomass reduction, and carbon emissions [6, 9], but typically treat mining as a static land-use category observed at coarse temporal intervals. Such approaches obscure how individual mines physically grow, pause, and re-accelerate within their lease boundaries.

By reconstructing PEKB's footprint year by year over more than a decade, this study shows that cumulative forest loss emerges through distinct phases rather than through uniform annual change. From a governance perspective, this distinction matters: environmental impacts are often evaluated project by project, while ecological consequences accumulate incrementally through successive expansions within the same lease [10, 14]. Mine-scale reconstruction translates administrative approvals and clearance records into observable outcomes on the ground, offering a form of environmental accountability grounded in spatial evidence.

Importantly, the approach applied here is transferable. Similar reconstructions can be conducted for other open-cast mines using freely or commercially available satellite imagery, enabling comparative analysis across coalfields and regulatory contexts. In regions where surface mining continues to expand within forested terrain, systematic documentation of mine growth trajectories is a necessary step toward more transparent evaluation of cumulative environmental transformation and the effectiveness of existing clearance and monitoring frameworks.

5 Limitations

This study provides indicative, landscape-scale estimates of mine expansion and forest conversion derived from manual visual interpretation of multi-temporal satellite imagery. While manual digitization enables precise identification of mine features at high spatial resolution, it introduces limited interpretation uncertainty at disturbed margins and transitional edges. Such uncertainty is expected to affect boundary placement at fine scales but does not alter the magnitude, direction, or temporal pattern of expansion documented over the twelve-year period. No independent ground-based validation or inter-analyst comparison was conducted, and therefore formal accuracy assessment and inter-rater reliability were not quantified. The use of multiple imagery sources with different spatial resolutions (Landsat 8 at 30 m and PlanetScope at 3 m) reflects data availability rather than methodological inconsistency; early-year boundaries may therefore lack the fine spatial detail visible in later imagery, though the analysis focuses on cumulative change rather than cadastral precision. Forest conversion was identified through visual discrimination of contiguous closed-canopy sal forest and does not represent a formal land-cover classification.

This study did not implement automated land-use/land-cover classification, predictive modelling, or formal landscape-fragmentation metrics, as the objective was geometric reconstruction of a single mine's footprint rather than categorical mapping or scenario forecasting. Future research could extend this approach by integrating classification workflows, spatial metrics, or comparative multi-mine analysis to support broader regional or predictive assessments.

Ecological and social implications discussed in the manuscript are inferred from observed spatial change in conjunction with established literature and documented reports, rather than from field-based ecological surveys or socio-economic data. Finally, this analysis represents a single mine-scale case study within a specific ecological and governance context. While it does not statistically represent all coal mines in India, the approach is designed to be transferable and illustrative of how legally approved surface mining physically transforms forested landscapes over time.

6 Conclusion

Using multi-temporal satellite imagery, this study reconstructs more than a decade of surface coal mining expansion within the PEKB block of the Hasdeo Arand forest. The mine footprint increased from 218 ha in 2013 to 1,389 ha by 2025, with approximately 1,013 ha of dense forest converted as pits and overburden areas expanded outward. Expansion followed a distinctly episodic trajectory, marked by phases of rapid growth, slowdown, and renewed acceleration, rather than a uniform annual pattern. By mid-2025, nearly three-quarters of the mine footprint overlapped areas that were forested at the beginning of the study period, indicating that growth occurred primarily through direct forest replacement rather than reuse of previously disturbed land.

Beyond quantifying change, this study demonstrates the value of mine-scale, time-resolved reconstruction for understanding cumulative environmental transformation. While forest diversion approvals are issued administratively, their ecological consequences unfold incrementally on the ground. Satellite-based reconstruction provides an independent means of translating clearance decisions into observable spatial outcomes, complementing regional land-use assessments and clearance statistics. The approach applied here is readily transferable to other open-cast mines and large infrastructure projects, offering a practical framework for post-clearance monitoring, cumulative impact assessment, and more transparent evaluation of how extractive activities reshape forested landscapes over time.

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Author contributions
S.G. V conceived the idea, curated and collected data, performed the analysis, wrote the manuscript, prepared the figures and edited the manuscript. A. K and S.H. Q helped in data curation and supported in writing and revising the manuscript. All authors reviewed the final version of the manuscript.

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Data availability
Landsat 8 imagery and Google Earth Pro data are publicly available. PlanetScope imagery is subject to licensing restrictions and cannot be shared. The datasets generated during the current study, including shapefiles of the Hasdeo Arand Coalfield extent, coal block boundaries, and mine footprints, are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Clinical trial registration
Not applicable. This study does not involve any clinical trails.

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