Essd-2025-583_Global Surface Mining and Land Reclamation of Time Series from 1985–2022

Dear Reviewer,

We area very grateful for your detailed comments and constructive suggestions on our manuscript (essd-2025-583). We have carefully considered each point and made substantial revisions to address these concerns. Below, we provide point-by-point responses, with our replies shown in blue text. All revised text in the manuscript is highlighted in yellow. Please note that all line numbers refer to the latest revised version of the manuscript uploaded to the system.

Comment 1: Clarification and Discussion on "Undefined Mines"

Reviewer's Comment: *"The classification of mining activity status is a core contribution of this study. However, the 'Undefined Mines' category requires further revision. Currently, 'Undefined Mines' seems to be defined largely by exclusion (i.e., mines that do not fit into 'Active' or 'Closed' categories based on the MK trend test). This definition is insufficient for a scientific classification system. Authors should provide a positive definition. In addition, the results indicate that 48.9% of the mining polygons are classified as 'Undefined.' This is a remarkably high proportion, covering nearly half of the dataset. Such a high percentage of 'undefined' results undermines the classification model's utility. The authors must discuss why this percentage is so high."*

Response: We sincerely thank the reviewer for this insightful critique, which has prompted us to substantially strengthen the conceptual framework of our classification system. We fully agree that a rigorous scientific classification requires positive definitions rather than definitions by exclusion. Following the reviewer's guidance, we have made two key revisions: (1) renaming the category from "Undefined Mines" to "Stable Mines," and (2) providing an explicit positive definition that characterizes the specific conditions captured by this category. The revised terminology "Stable Mines" aligns with established nomenclature in recent high-impact literature. For instance, Wang et al. (2025) employed the term "Stable Mines" to characterize mining areas exhibiting no significant rates of NDVI change. Our adoption of this terminology ensures consistency with the established literature while providing a scientifically meaningful category. Critically, we now provide a positive definition that specifies the conditions under which a mining polygon is classified as "Stable." The "Stable Mines" category encompasses the following distinct operational states:

(1) Equilibrium-state mines: Mining polygons where extraction and reclamation activities have reached a dynamic equilibrium, resulting in no net change in BSP, NDVI, or NTL

over the analysis period. These represent mines operating at a steady state with balanced disturbance and recovery.

(2) Concurrent extraction-reclamation mines: Large mining complexes where simultaneous extraction in one sector and reclamation in another produce offsetting signals. The spatial averaging within polygon boundaries yields no detectable net trend despite ongoing activities in both directions.

(3) Maintenance-phase mines: Mining sites in transitional or maintenance phases where neither significant expansion nor systematic reclamation is underway, such as mines awaiting regulatory approval for new extraction permits or those under temporary operational suspension.

(4) Low-intensity or artisanal operations: Small-scale mining sites with intermittent or low-intensity activities that do not generate sufficient spectral or temporal signals to exceed the Mann-Kendall significance threshold ($p < 0.05$).

This positive characterization transforms "Stable Mines" from a residual category into a substantively meaningful classification that captures genuine operational states in the global mining landscape.

Regarding the proportion of stable mines, we respectfully note that when placed in the context of comparable global studies, our results actually demonstrate enhanced sensitivity in detecting mining dynamics. Wang et al. (2025), using a classification based solely on NDVI change rates (2018–2022), reported approximately 64.3% of mining polygons as "Stable." In contrast, our multi-indicator approach identified a significantly lower proportion of stable mines (48.9%). This 15-percentage-point reduction demonstrates that our integrated approach captures mining dynamics that single-indicator methods would miss. The improvement is attributable to the complementary nature of our indicators: BSP detects bare soil dynamics invisible to vegetation indices; NTL captures operational intensity even in vegetated areas; and NDVI tracks vegetation recovery patterns.

Furthermore, the inherent heterogeneity of the global mining landscape contributes to the stable mines proportion. Our dataset encompasses 74,726 mining polygons across 155 countries, spanning diverse operational scales (from artisanal operations averaging 0.72 km^2 in Asia to mega-mines exceeding 2.0 km^2 in Oceania), commodity types, regulatory environments, and development stages. Many mining operations worldwide do genuinely operate at steady-state conditions—neither expanding nor contracting their surface footprint—which represents a meaningful finding about global mining dynamics rather than a methodological limitation.

We have incorporated these clarifications into the revised manuscript, as detailed below.

Revised Text (Section 2.3, Lines 305–319)

"Based on trend analyses of NDVI, BSP, and NTL, a rule-based decision tree model was developed to classify mining areas into three categories. The framework first determined mining status as expanding, shrinking, or stable, and subsequently mapped these into types: active mines (expanding, characterized by increasing bare land, decreasing NDVI, and/or rising nighttime light signals), closed mines (shrinking, indicated by decreasing bare land, increasing NDVI, and/or declining nighttime light signals), and stable mines. The stable mines category encompasses: (1) equilibrium-state mines where extraction and reclamation have reached dynamic balance; (2) concurrent extraction-reclamation mines where simultaneous activities in different sectors produce offsetting signals; (3) maintenance-phase mines in transitional or suspended operational states; and (4) low-intensity or artisanal operations with insufficient signal magnitude to exceed statistical significance thresholds. By integrating the trend analyses of NDVI, BSP, and NTL, this study reveals the spatiotemporal dynamics of mining area disturbances and reclamations on a global scale."

Revised Text (Section 3.3, Lines 607–614):

"Globally, of the 74,726 surface mining polygons identified, 14,546 (19.5%) were classified as closed mines, 36,542 (48.9%) as stable mines, and 23,638 (31.6%) as active mines (Fig. 7b). The proportion of stable mines (48.9%) is notably lower than that reported in comparable global analyses; for example, Wang et al. (2025), using single-indicator NDVI-based classification, identified 64.3% of mines as stable. This 15-percentage-point reduction demonstrates the enhanced sensitivity of our multi-indicator approach in detecting mining dynamics that would otherwise remain undetected. "

Revised Text (Section 4.3, Lines 851–879):

"The stable mines category, comprising 48.9% of polygons, reflects both methodological considerations and genuine operational characteristics of the global mining landscape. Methodologically, the Mann-Kendall trend test requires statistically significant monotonic trends to classify a polygon as expanding or shrinking; mines with weak, non-monotonic, or internally offsetting signals are appropriately classified as stable. Operationally, the extraordinary diversity of our global dataset—spanning 155 countries, multiple commodity types, and scales ranging from artisanal operations to mega-mines—means that a substantial fraction of sites would be expected to exhibit apparent stability during any five-year analysis window. The concentration of small-scale, fragmented mining in Asia (average polygon size 0.72 km^2), which accounts for nearly half of global polygons, further contributes to this proportion, as smaller sites generate weaker spectral signals that are less likely to exceed statistical significance thresholds. Notably, our stable proportion is substantially lower than comparable single-indicator studies (e.g., 64.3% in Wang et al., 2025), suggesting that our multi-indicator framework does enhance trend detectability relative to existing approaches."

We hope these revisions adequately address the reviewer's concerns regarding the classification system. The positive definition of "Stable Mines" and the contextual comparison with existing literature should now provide a more rigorous and scientifically defensible framework. We remain grateful for this constructive feedback, which has materially strengthened the manuscript.

Comment 2: Distinctions between Reclamation, Revegetation, and Greening

Reviewer's Comment: "The manuscript uses the term 'Reclamation' extensively, but the methodology relies on remote sensing indices (BSP and NDVI). There is a conceptual gap that needs to be bridged. The authors should explicitly differentiate between 'Greening', 'Revegetation', and 'Reclamation'."

Response:

We sincerely thank the reviewer for this important and insightful comment. We fully agree that there is a conceptual distinction between "greening," "revegetation," and "reclamation" that should be explicitly addressed in our manuscript. We have made the following revisions:

1. Clarified the Reclamation Rate Definition (Section 2.2, Lines 244-262):

We have revised the reclamation rate description to be more explicit:

Original text (Lines 234-236):

"This formulation assumes that a reduction in bare surface extent corresponds to vegetation regrowth or land cover restoration, and thus provides a proxy for the progress of ecological reclamation within mining sites."

Revised text:

"This formulation assumes that a reduction in bare surface extent corresponds to vegetation regrowth or land cover restoration. It is important to note that this metric captures vegetation presence rather than comprehensive ecological reclamation. The reclamation rate (1-BSP) thus serves as a proxy for greening or revegetation progress within mining sites, and may overestimate the extent of true ecological restoration that includes soil quality recovery, biodiversity re-establishment, and ecosystem function restoration."

2. Added Clear Definitions in Section 2.2 (Lines 250-261):

We have inserted clear definitions to distinguish these concepts:

"It is important to clarify the terminology used in this study: (1) Greening refers to an increase in vegetation index values (e.g., NDVI) detected by remote sensing, indicating increased photosynthetic activity or vegetation cover, without implying ecosystem functionality; (2) Revegetation refers to the establishment of plant cover on previously disturbed land, whether through natural succession or active planting efforts; and (3) Reclamation in its comprehensive sense encompasses soil reconstruction, landform redesign, hydrological restoration, and the recovery of ecosystem structure and function. In this study, due to the limitations of remote sensing-based detection, what we identify as 'reclaimed area' specifically refers to areas exhibiting vegetation recovery signals—essentially capturing greening or revegetation processes rather than comprehensive ecological reclamation."

3. Added Clarification in Results Section (Section 3.2, Lines 526-530):

Original text:

"Here, 'reclamation' refers to areas showing vegetation recovery, which may result from both active restoration practices and natural regrowth in abandoned polygons."

Revised text:

"Here, 'reclamation' refers to areas showing vegetation recovery signals detected via land cover transitions, which may result from active restoration practices, natural regrowth (revegetation) in abandoned polygons, or conversion to agricultural land. This metric captures greening trends rather than verified comprehensive ecological restoration."

Comment 3: Figure 6(a) X-axis Labels

Reviewer's Comment: *"The x-axis labels in Figure 6(a) (Year) are currently stacked and overlapping, making them unreadable."*

Response:

We sincerely appreciate your thoughtful comment regarding the x-axis labels in Figure 6(a). In response to your observation, we have adjusted the aspect ratio of the figure to ensure that the x-axis labels are now more clearly visible and properly spaced. This revision improves the readability of the labels, making them easier to interpret. Thank you for your constructive feedback, which has helped enhance the clarity of our figure.

Comment 4: Comparison with Sepin et al. (2025)

Reviewer's Comment: *"The manuscript lacks comparison with more recent and regionally focused high-resolution products. The authors should compare their findings with the recent study: Sepin, P., Vashold, L. & Kuschnig, N. Mapping mining areas in the tropics from 2016* *to 2024. Nat Sustain 8, 1400–1407 (2025).”*

Response:

We sincerely thank the reviewer for bringing this important recent publication to our attention. This comparison significantly strengthens our discussion by contextualizing our results within the rapidly evolving landscape of global mining mapping efforts. We have added a comprehensive comparison with Sepin et al. (2025) in Section 4.1 and included a new Figure 9 to visually illustrate the methodological differences between datasets.

Before presenting quantitative comparisons, it is essential to clarify that our study and Sepin et al. (2025) address complementary rather than competing research questions. The key differences are summarized in Table R1:

Table R1. Comparison of research objectives and methodological approaches.

Aspect	**Present Study**	**Sepin et al. (2025)**
Primary objective	Track land cover dynamics and reclamation progress at known mining sites over four decades	Detect and map the spatial extent of mining activity, including informal operations
Temporal focus	Historical reconstruction (1985–2022)	Near-real-time monitoring (2016–2024)
Spatial scope	Global (155 countries)	Tropical belt (±30° latitude)
Methodological philosophy	Conservative integration of verified datasets	Discovery-oriented machine learning prediction
Output emphasis	Land cover change trajectories within mining boundaries	Annual polygon delineations of mining footprint

For direct comparison within the overlapping spatial domain (tropical belt, ±30° latitude), we extracted statistics from both datasets for the year 2020:

Table R2. Quantitative comparison within the tropical belt (±30° latitude) for 2020.

Dataset	**Polygons**	**Area (km^2)**
Present study (tropical subset)	25,772	37,744
Sepin et al. (2025) – 2020	16,842	66,835

We have added a new Figure 9 to illustrate the boundary delineation differences among datasets at two representative large-scale mining sites: Carajás Iron Mine (Brazil) and Grasberg Mine (Indonesia). The visual comparison reveals several important observations:

(1) Boundary precision: Our refined dataset (yellow boundaries) demonstrates tighter alignment with actual mining features compared to the broader boundaries of Maus et al. (2022)

(green), while capturing additional areas missed by Tang and Werner (2023) (blue).

(2) Sepin et al. (2025) characteristics: The machine learning-based predictions (orange boundaries) show notable omission errors at both sites, particularly missing substantial portions of active mining areas. At Carajás, significant mining pits visible in the 2020 Landsat imagery are not captured by the Sepin dataset. At Grasberg, the predicted boundaries exhibit fragmented coverage that excludes major operational areas.

(3) Complementary strengths: While Sepin et al. (2025) may capture artisanal and small-scale mining (ASM) sites that are absent from our dataset, our conservative approach provides more reliable boundary delineation for large-scale industrial mining operations.

We emphasize that the two datasets serve complementary purposes rather than competing ones: Sepin et al. (2025) provides higher sensitivity for mining area detection, particularly for informal and artisanal operations in the recent period (2016–2024), leveraging high-resolution (<5 m) Planet/NICFI imagery.

Our dataset offers greater specificity, broader geographic scope (global vs. tropical), and substantially longer temporal depth (1985–2022, nearly four decades). For ecological impact assessment and reclamation monitoring—the primary objectives of our study—the conservative boundary delineation minimizes false positives and provides robust baselines for time-series analysis.

Revised Text:

Recently, Sepin et al. (2025) introduced a machine learning-based dataset mapping mining areas in the tropical belt from 2016 to 2024. Their approach employs a SegFormer model trained on the Tang and Werner (2023) and Maus et al. (2022) datasets to automatically segment mining areas from high-resolution (<5 m) Planet/NICFI satellite imagery. The resulting dataset comprises approximately 147,000 mining polygons covering an average annual area of 66,400 km² within the tropical belt.

For comparative analysis, we extracted mining polygons from our dataset within the same tropical region (±30° latitude), yielding 25,772 polygons covering 37,744 km². In comparison, the Sepin et al. (2025) dataset contains 16,842 polygons with an area of 66,835 km² for the year 2020. The substantially larger average polygon size in Sepin et al. (2025) reflects their discovery-oriented approach, which prioritizes detection sensitivity over boundary precision. Their machine learning predictions can identify previously unmapped sites, including informal and artisanal mining operations, but inevitably include model uncertainty and potential commission errors.

In contrast, our approach is designed for tracking—monitoring land cover dynamics within known mining footprints through morphological optimization and systematic removal of stable vegetation. Visual comparison at representative mining sites (Fig. 9) reveals that the Sepin et al. (2025) predictions exhibit notable omission errors at large-scale industrial mines, with fragmented boundaries that miss substantial portions of active mining areas visible in Landsat imagery. This observation aligns with their training strategy, which relied on existing polygon datasets that may underrepresent certain mining configurations.

The two datasets thus serve complementary purposes. Sepin et al. (2025) provides valuable coverage of artisanal mining and near-real-time detection capability in the recent period (2016–2024), while our dataset offers greater boundary precision, broader geographic scope (global vs. tropical), and substantially longer temporal depth (1985–2022). For ecological impact assessment and reclamation monitoring—the primary objectives of our study—the conservative boundary delineation minimizes false positives and provides robust baselines, even if this approach may underestimate total mining extent in regions with prevalent informal mining activity.

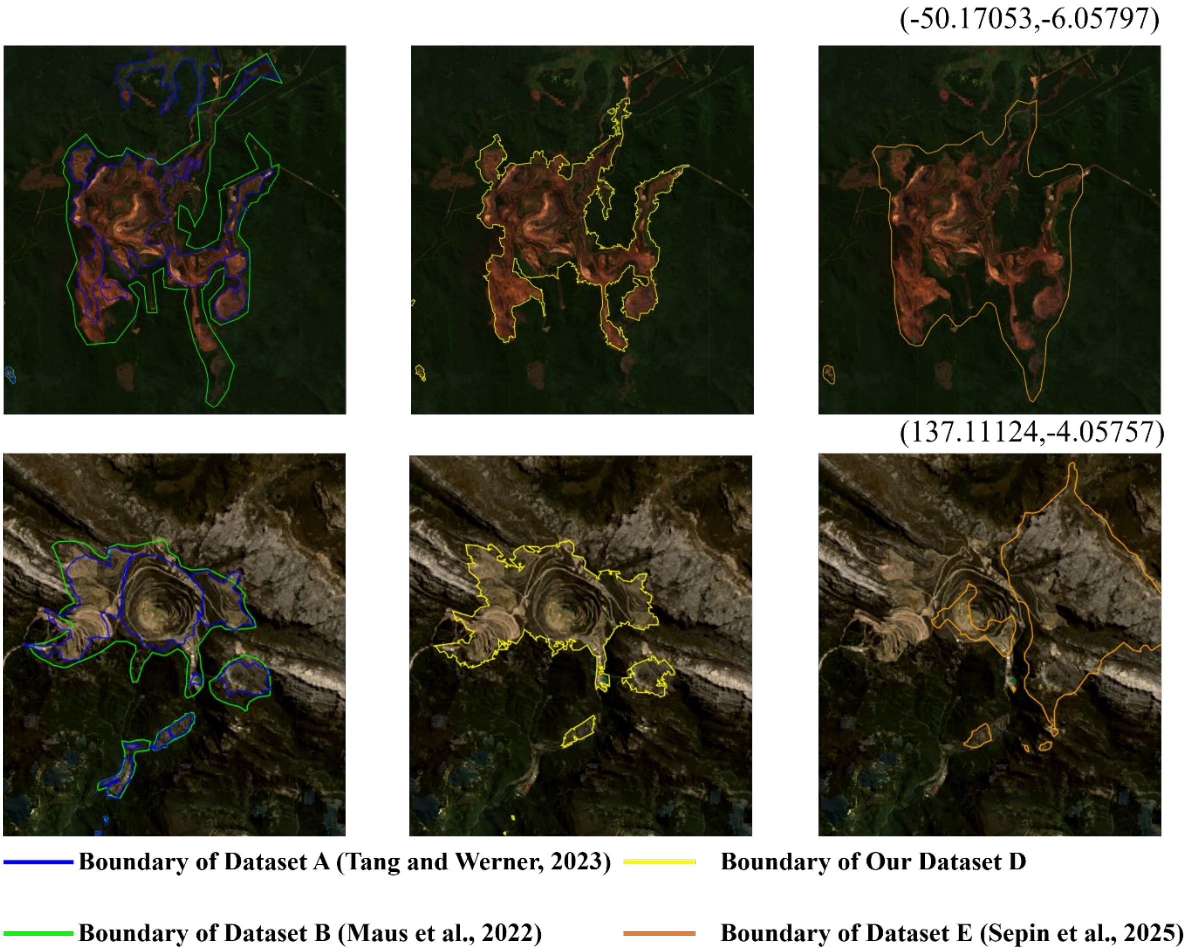

Figure 9. Comparison of mining area boundary delineations among four datasets at two representative tropical mining sites. Top row: Carajás Iron Mine, Brazil (50.171°W, 6.058°S);

Bottom row: Grasberg Mine, Indonesia (137.111°E, 4.058°S). Each row displays three panels showing different dataset combinations: left panel – Dataset A (Tang and Werner, 2023; blue) and Dataset B (Maus et al., 2022; green); middle panel – our refined Dataset D (yellow); right panel – Dataset E (Sepin et al., 2025; orange). Background imagery: Landsat 8 OLI true-color composite (2020). The comparison illustrates that our refined boundaries (yellow) achieve tighter alignment with visible mining features, while the Sepin et al. (2025) predictions (orange) exhibit omission errors at both sites, missing substantial portions of active mining areas.

New Reference Added:

Sepin, P., Vashold, L., and Kuschnig, N.: Mapping mining areas in the tropics from 2016 to 2024, Nat Sustain, 8, 1400–1407, https://doi.org/10.1038/s41893-025-01668-9, 2025.

Wang, K., Zhou, J., Yang, R., Xu, S., Hu, Z., and Xiao, W.: Deploying photovoltaic systems in global open-pit mines for a clean energy transition, Nat. Sustainability, 8, 1037–1047, https://doi.org/10.1038/s41893-025-01594-w, 2025.