Nickel mining reduced forest cover in Indonesia, but had mixed outcomes for well-being

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Summary

Soaring demand for nickel to support the low-carbon transition is driving extensive mining in mineral-rich countries, but the environmental and social impacts of nickel mining remain underexplored. Here, we use a counterfactual approach to examine nickel mining outcomes on forests and well-being of nearby communities in Sulawesi, Indonesia – a region renowned for its biodiverse tropical forests, and now a global centre of nickel production. By examining changes across 7,721 villages between 2011 and 2018 we show that deforestation doubled in nickel mining villages. During the early stages of mining, environmental well-being, living-standards, and education outcomes declined, but improvements were observed in health, infrastructure, and social relations. Environmental well-being continued to substantially deteriorate in the later stages of mining production, especially in villages with already high poverty. These findings highlight the environmental and social consequences of nickel mining, underscoring the need for greater accountability of local outcomes if the sector is to support a just and sustainable low-carbon transition.

Introduction

The development and adoption of low-carbon technologies is crucial for reducing the effects of climate change and meeting the Paris Climate Agreement targets[1]. As it stands, less than a fifth of energy production comes from renewables[2], so dramatic expansion of the sector is expected in coming decades[3]. Yet renewable energy production is highly mineral intensive, and an additional 3 billion metric tons of metal is expected to be required to realise the Paris Agreement goals[1]. The global transition to low-carbon energy will not be possible without nickel extraction[1]. Nickel is a critical component in rechargeable batteries and is widely used in stainless steel production. Between 2011 and 2018, demand for nickel increased by 43% globally[4], and it is increasingly recognised as a critical mineral for energy (Table S1). Over a third of all nickel is mined in Indonesia, making it the largest producer in the world[5], employing 1.3 million people[6]. In 2021, >1 million metric tons was produced in the country, with most of this coming from Sulawesi (Figure 1); a near four-fold increase of nickel produced in a decade[4]. The role of extractive industries in alleviating poverty and creating job opportunities has been used to justify policies that ease business and foreign direct investment into the nickel mining industry[7]. However, this justification has also been criticised for overlooking the detrimental environmental and social impacts on communities directly affected by mining operations. Environmental damage and communal violence associated with nickel mining have already been reported in the region[8].

It is widely acknowledged that mining is one of the major drivers of land cover change, having significant implications on biodiversity and ecosystem functioning[9]. Similarly, the expansion of mining has the potential to radically transform local societies and economies[10]. Yet, few studies address the observed impacts of nickel mining specifically. Previous studies evaluating mining impacts have typically aggregated multiple mineral commodities together[11,12], rather than examining variation among them[11]. This is in stark comparison to individual agricultural commodities[13,14], where environmental and social effects of producing specific crops are thoroughly evaluated (e.g. Santika *et al.* [14]). Indeed, the impacts of mining for different mineral commodities will vary depending on, for example, the amount of land required, the extraction technique, water used, and pollution generated. In Sulawesi, nickel is mostly derived from nickel laterite ores, close to the earth's surface[15]. The extraction process typically involves digging shallow open cut mines to access the nickel ore, which can lead to large areas of land being cleared[16]. Moreover, nickel mining relies heavily on machinery, requiring a workforce with specialised skills and higher levels of education compared to more labour-intensive forms of mineral extraction[17,18]. Nickel mining may have limited local employment opportunities if communities do not match the required human capital[17]. It is crucial to account for these variations to robustly assess land-use change patterns and understand how the benefits and costs of producing different mineral commodities impact local communities[11].

While there is some evidence evaluating the impact of nickel mining, the highly localised context of these studies makes it challenging to derive general insights. Some case-studies have found that nickel mining has contributed to increasing local income[19], while in others, waste from nickel mining extraction damaged local fishing and farming production, resulting in greater economic losses overall[8]. Such case-studies offer valuable insights into the effects of nickel mining on local communities and ecosystems, but few are widely generalisable due to methodological inconsistences[20]. In contrast, aggregated measures, such as the percentage of national GDP attributed to the nickel mining sector, risk overlooking the spatial characteristics that can reveal patterns resulting from nickel mining activities[21]. A robust impact evaluation of nickel mining that accounts for spatial variation over broad areas could yield crucial insights for improving policy design and implementation, ultimately supporting better environmental and social outcomes[22].

Evaluating the causal effects of mining interventions is complex due to confounding factors influencing both the outcomes of interest and the underlying pattern of where production occurs (e.g. biophysical characteristics; land governance). Impact evaluation methodologies can help address this problem by comparing outcomes to a counterfactual condition where no intervention has occurred[22]. Such evaluations can be enhanced by tracking outcomes over time, both before and after the mining intervention, further strengthening estimates of causal effects.

To date, large-scale mining impact studies have highlighted the potential environmental and social risks involved [23,24], especially those that overlap protected areas or indigenous lands[25]. Yet, impact evaluation studies addressing ongoing mining impacts tend to focus exclusively on either environmental outcomes[9,11,26,27], or well-being[28,29], but rarely both. Furthermore, well-being is often limited to a single economic or institutional indicator to signal societal development. Indeed, the impacts of land-use change may be experienced differently across various types of communities and the type of livelihood activities they engage in[30]. Using a combination of indicators can simultaneously capture the benefits and costs on both the environment and local communities[31], and help to identify the contexts in which synergies or trade-offs between environmental and well-being outcomes exist[32].

Here, we use rigorous impact evaluation methods to examine and quantify the environmental and social impacts of nickel mining extraction, focusing on forest cover change and the well-being of villages across Sulawesi, Indonesia. By collating data at the village level, we capture local effects over a large spatial scale and reveal general patterns. We specifically investigate the effects of nickel extraction compared to other types of mining to understand the relative implications on forests and well-being. We found that deforestation was higher in villages with nickel mining compared to those with no mining. For villages overlapping nickel mining areas, we found slower improvements to overall well-being and mixed outcomes across different well-being dimensions. We also identify the biophysical and socio-economic factors moderating the intensity of these impacts. Our findings highlight the extent to which nickel mining affects forest ecosystems and community livelihoods. These insights can inform policymakers and mining companies aiming to implement sustainable practices, ensuring that nickel mining production aligns with environmental and development objectives.

Results

Methods summary

Nickel mining data were derived from Indonesia's mining concession map released by the Ministry of Energy and Mineral Resources. Mining concessions were overlaid with high-resolution estimates of forest cover as well as socio-economic data from Indonesia's *'Potensi Desa'* (or 'village potential', *PODES*) census to estimate the environmental and social changes attributed to nickel mining production and how this compared with other mineral commodities. To establish a causal estimate of nickel mining impacts on environmental and social outcomes, we apply statistical matching within a Before-After-Control-Impact (BACI) analytical design to measure counterfactual outcomes in the absence of mining[33]. Such an approach avoids misleading findings by a) accounting for the contextual dynamics through which forest cover and well-being might have occurred, while b) isolating impacts of nickel mining extraction from other biophysical, political, and social factors that influence environmental and social outcomes.

To measure the impact of nickel mining (and other mineral commodities) on deforestation, we quantify the change in forest cover across individual villages in Sulawesi throughout the eight-year evaluation period. If the expansion of nickel mining caused deforestation, we would expect to observe a greater reduction in forest cover within nickel mining villages compared to that experienced in non-mining (control) villages. Forest cover was estimated in the year 2011, 2014, and 2018 to match the timepoints of the PODES census. Well-being outcomes were tracked using 18 indicators derived from PODES, which we evenly grouped into six dimensions[34] (Table 1): education (access to education facilities and support), environment (the occurrence of natural disasters and pollution), health (accessibility of health facilities, and cases of diseases), infrastructure (access to markets and financial support), living standards (basic living conditions), and social relations (cooperation and incidence of conflict). The overall well-being score is the total combination of all six dimensions, each given equal weighting. If nickel mining improved the well-being of local communities, we would expect a positive change in well-being relative to non-mining villages. Again, well-being was measured in the year 2011, 2014, and 2018 to follow the years the PODES census was implemented. All references to the datasets cited can be found in Table S2 in the Supplemental Information.

Background changes in forest cover and well-being

After excluding villages with no forest within their boundaries, the average village in Sulawesi had around 36% forest cover in 2011 (n=4,458, Figure 2A), which dropped to 34% by 2018 (a decline of 2 percentage points, equating to 15 ha for a median village area of 763 ha). Over the same period village well-being increased across Sulawesi by 4 percentage points (Figure 2B). Living standards improved by nearly 40 percentage points in both mining and non-mining areas compared to the 2011 baseline (Figure 2C). Health also improved by 5 percentage points, while education, social, and environmental well-being declined by 3, 4, and 6 percentage points, respectively.

The impact of nickel mining and other mineral types

We estimated the relative impact of nickel mining on forest cover compared to non-mining (control) villages. The analysis indicates that nickel mining exacerbated deforestation over the eight-year period. Deforestation was 2 percentage points greater in nickel mining villages relative to non-mining villages (n=132; 95% confidence interval [CI]: -3.1 to -0.9, Figure 3A). Villages associated with other mineral types (n=115) also experienced greater deforestation compared to controls; however, this difference was marginal (-0.4 percentage points, 95% CI: -1.5 to 0.7). Since the 2011 baseline year, forest cover declined by 4.4 percentage points in nickel mining villages, while the decline was 2.4 percentage points where there was no mining (Figure 3B) – representing a near two-fold increase in deforestation associated with nickel mining compared to controls (see Table S3). Villages overlapping nickel mining also experienced slower improvements in overall well-being, which is reflected in the negative coefficient in Figure 3C (-2.1 percentage points, 95% CI: -4.5 to 0.2, see Table S4).

We further partitioned our analyses to examine mining outcomes at an early (1-3 years) and later (4-7 years) stage of production to reflect the accumulation of impacts over time. The negative coefficient in Figure 4A shows that nickel mining villages lost 1.2 percentage points more forest than control areas in the first three years of production (95% CI: -2.3 to -0.1), and a further 0.4 percentage points (-1.6 percentage points; 95% CI: -2.5 to -0.7) thereafter. For villages associated with other mines, the impacts took longer to accrue (-1.8 percentage points at 4-7 years, 95% CI: -4.3 to 0.7; Figure 4A). Nickel mining villages experienced a five-fold decrease in their overall well-being between the early (-0.5 percentage points, 95% CI: -3.6 to 2.6) and later (-2.5 percentage points, 95% CI: -6.6 to 1.7) stages of production (Figure 4B). This was mostly driven by large reductions in environmental well-being (-11.3 percentage points, 95% CI: -21.8 to -0.8; Figure 4C). Education, health, and social well-being also declined overtime, while infrastructure and living standards improved. However, the effect sizes were highly variable, as reflected by wide confidence intervals. For villages near other mines, overall well-being marginally improved compared to controls (0.2 percentage points 4-7 years after production; 95% CI: -3.7 to 4.2; Figure 4B). Across the six dimensions, there were marginal differences in well-being outcomes between mining of other commodities and non-mining villages.

Factors influencing the impacts of nickel mining

To further explore the heterogeneity of nickel mining impacts, we selected potential characteristics that could be expected to moderate the effect size. Results in Supplemental Information (Table S5, Figure S1-S2) imply that the effects of nickel mining on deforestation and well-being are indeed highly heterogenous. Nickel mining was associated with greater deforestation in villages that were more accessible, as shown by the positive values for the interaction terms (Figure S1, Table S5). Accessibility was evaluated using a travel-cost surface model that accounts for the topography, landcover, and road density (Table 2). Nickel mining was also associated with greater deforestation at higher elevations and steeper slopes.

We further explored if other factors, such as poverty baseline conditions (low versus high well-being scores in 2011), livelihood type, and accessibility in villages, moderated the impacts of nickel mining on well-being. Smaller well-being improvements in nickel mining villages were found where poverty conditions were already high (Figure S2A). Well-being impacts were worse in villages where capture fisheries were the dominant livelihood (Figure S2B). Accessibility had no observable influence on the effect size (Figure S2C). We further examined the specific pathways in which nickel mining impacts could be moderated by poverty baseline conditions by running an additional matching and regression analyses by low versus high poverty villages. Within the first three years of production, deforestation was greatest in nickel mining villages where poverty conditions were initially low (-1.4 percentage points, 95%

CI: -2.4 to -0.4), rather than high (-1.1 percentage points, 95% CI: -2.1 to -0.1; Figure 5A). In the later stages of production, deforestation was similar between the two poverty groups. In villages where poverty levels were initially high, well-being declined by 1.8 percentage points (95% CI: -7 to 3.5) (Figure 5B). This decline was mostly driven by a 13.7 percentage point decrease in environmental well-being (95% CI: -26.7 to -0.7) and a 13 percentage point reduction in health outcomes (95% CI: -24.7 to -1.2) but was countered by improvements to living standards and infrastructure (Figure 5C).

In contrast, villages with initial low levels of poverty experienced short-term improvements to health (6.1 percentage points, 95% CI: 0.1 to 12.1; Figure 5C). At the same time, living standards improved substantially 4-7 years post-production (10.6 percentage points, 95% CI: -3.9 to 25.2).

Discussion

The demand for low carbon energy is a key driver of nickel production[35]. Examining empirical evidence on the ways in which landscapes and people are being transformed by nickel mining is crucial to address sustainability challenges. Our analysis identified the multiple impacts of nickel mining in one of the largest producing regions of the world. Combining rich spatial data across 7,721 villages, we highlight the differential impacts of mining nickel versus other mineral commodities, variations of outcomes over time, and the factors that minimised, or exacerbated environmental and social outcomes.

Nickel mining impacts deforestation and well-being

Nickel mining contributed to a significant increase in deforestation since the expansion of the sector in Indonesia around 2011. Studies using similar methods elsewhere have found limited evidence of deforestation attributed to mining, as other drivers of forest cover change would be present even in the absence of mining[26]. Conversely, others reported mining to be a key contributor to deforestation across Sulawesi[36,37]. We find that the extent of deforestation associated with nickel mines was substantial – a near double that observed in matched control areas. The environmental sustainability narrative frequently used to justify the increasing supply of nickel therefore risks overlooking other environmental consequences resulting from nickel mining. This is particularly relevant in Sulawesi, which is globally recognised for its unique ecosystems and biodiversity[38]. Concerted resources to mitigate against deforestation are therefore needed.

The marginal decline in overall well-being associated with nickel mining was largely driven by a decrease in environmental indicators. Waste materials and pollution resulting from nickel extraction and processing is a longstanding issue[15]. Our analysis supports the notion that safeguards against pollution and mining-related disasters should be strengthened to minimise negative environmental impacts that affect people's well-being. Incorporating environmental and social standards into existing international and national governance mechanisms, such as the Extractive Industries Transparency Initiative (EITI), could be a positive step towards such endeavours. However, such standards are currently lacking due to alleged inconsistences between governing bodies of extractive industries at the local level, and the EITI at the Indonesian national level[39]. Greater coordination and alignment between local, regional and national government in Indonesia is crucial to ensure consistency in implementing environmental and social safeguards[40]. Other actors, including local and international non-governmental organisations, along with industry groups, play crucial roles in holding mining companies accountable to adhering with international standards, such as the OECD's Due Diligence Guidance[41]. Due diligence protocols can help companies to better integrate human rights into environmental and social assessments, and further avoid negative social and environmental impacts of nickel mining.

Reductions in social well-being were also typical of areas overlapping nickel mines. Conflict driven by environmental damage and land acquisition from nickel mining activities has been reported in Indonesia[8]. However, we also found social well-being was highly variable between individual villages, making it difficult to draw conclusions. It is important to also acknowledge the positive contribution nickel mining has on local living conditions and infrastructural development. These improvements are likely to be attributed to the construction of transportation and water-based infrastructure[17]. Revenue from nickel mining may have facilitated local government investment within communities[17]. Greater variability across villages was also evident for these indicators, implying that both positive and negative outcomes are experienced collectively across Sulawesi, and more information is needed to understand what is driving this variation. Migration may have also been influenced by nickel mining and resulted in changes in well-being. The in-migration effect from large-scale nickel mining has been related to both improvements in social cooperation[19] as well as worsening living conditions[42]. As future research progresses with new data and advancements in impact evaluation methods, further work will play a key role in identifying these other factors that influence the impact of nickel mining extraction.

Certain effects of nickel extraction, such as the decline in environmental well-being, were only detected 4-7 years after the issuance of mining lease. One explanation is that some indicators, such as environmental pollution and flooding, take time to accrue, making them detectable only after several years[43]. Indeed, given the relatively short- to mid-term trends we uncover, the longer-term effects of nickel mining should also be assessed, including after mine closure. Evidence from historical tin mining in Indonesia demonstrated negative effects on local employment once the mines were closed[44]. When data become available in the nickel sector such studies will be important to address the lasting effects of mining, as well as opportunities for restoring and rehabilitating post-mining landscapes.

Comparisons between nickel and other mines

By disaggregating mining concessions by mineral commodity, we determined the impacts of nickel mining compared with other types of mines. Our results reveal that the onset of deforestation in nickel mining villages occurs faster than it does in villages where other types of mines are present. This implies that the land-cover changes associated with mining depend on the mineral commodity extracted. We also found differences in well-being between mining nickel versus other minerals, in terms of effect size and directionality. All mining was associated with worsening environmental well-being, but this was stronger in nickel mining areas. Conversely, impacts on social well-being were divergent – nickel mining worsened social well-being, while slight improvements were associated with other mines. Incorporating mineral commodity level data into impact evaluation assessments therefore helps inform specific mineral commodity chains[11,32]. Nonetheless, we also found large variations across individual villages, which could be due to other factors that have not been included in the analyses. The source dataset on mine locations classified concessions by mineral commodity but missed information on other mining characteristics that may have also influenced the type of deforestation and well-being patterns detected. For example, commercially sensitive information on the amount of production, extraction methods, and the type of legal ownership (such as being domestic or foreign owned), is not accessible. More detailed information on such mining characteristics will better capture how these specific attributes can shape well-being and deforestation[45], but this requires these data to be made available[32].

Other factors moderating nickel mining impacts

Identifying the underlying conditions that improve or hinder efforts towards reducing deforestation and improving the livelihoods of local communities is important to inform the management of mining activities and land-use planning. As expected, more accessible villages lost more forest compared to less accessible areas, implying that accessibility of transport, facilities, and infrastructure to clear forest incentivises companies to clear more land. That said, we also found nickel mining had led to greater deforestation at higher elevations. While we may assume that upland sites would be more difficult to establish mining operations and disincentivise forest clearance, such outcomes could be due to the relatively low rates of deforestation experienced in these areas more broadly. These results imply that nickel mining may be one of the key drivers of deforestation in upland regions, especially compared to others, such as logging and agriculture, which tend to be greater in the lowlands[37]. Our analysis points to specific biophysical regions that require greater attention should policies focus on targets to avoid deforestation.

We also found that the well-being impacts of nickel mining differed according to livelihood type and poverty baseline conditions. Villages where the primary source of income was from capture fisheries experienced greater reductions in well-being compared to those where other livelihoods (e.g. commercial fisheries and market orientated) were dominant. This is consistent with our findings of declines in environmental well-being attributed to nickel mining, and observations in the broader literature. For example, water and environmental pollution from the largest nickel mine in Indonesia has led to reduced fish stocks in water bodies that are close to extraction sites[46].

We focus our analyses on land-based concessions and thus provide conservative estimates of the damage to water-based livelihoods, such as fisheries, from nickel mining production. Nickel mining also extends to offshore locations, employing large trawls being carried across the ocean floor to extract nickel from the seabed[47]. Under Indonesia's Omnibus Law (*Undang-Undang Cipta Kerja*, Law 11/2023), offshore mineral mining is no longer limited within the 12 km coastline and can now take place in all maritime (including deep water) areas within the country's jurisdiction. While we were only able to account for mines that overlapped with onshore villages, the disturbance from offshore mining activities and the waste produced may have even greater adverse effects on marine ecosystems and the livelihoods of fishers in the future[48].

Poorer villages were more likely to experience the negative effects of nickel mining on environmental well-being and health. Villages with high levels of deprivation may have limited resources and capacity to cope against environmental pollution associated with mining activities, leading to adverse health effects[49]. While initial poverty baseline conditions influenced the impacts from nickel mining, we are not suggesting this should be the sole consideration when establishing concessions. On the contrary, engaging local communities in decision-making, development, and implementation processes can strengthen mining governance and planning[50] and further empower marginalised social groups[10,51]. Indonesia has made significant developments in engaging communities in Environmental Impact Assessment regulations by making public participation mandatory[52]. To be effective, engagement efforts should be paired with greater resources and action to strengthen the capacity of local communities, thereby reducing their vulnerability to potential negative impacts of land use activities[53].

Informing the low-carbon transition

There are multiple potential pathways to a low-carbon transition, including policy action that lowers nickel demand by improving the recyclability of renewable technologies, and reducing overall consumption of energy[54,55]. Yet, despite such actions, there remain questions about whether this will be enough to curb projected mineral demand trends in coming decades[35]. With more countries looking to electrify transport to achieve 2050 net-zero emission targets, heightened demand for nickel is anticipated, with some projections predicting a more than doubling of current levels[1,35,56]. Around 75% of this supply is expected to come from

Indonesia[35], which is seeking to attract more foreign investment and increase the ease of business, as evidenced in the Omnibus Law in 2023[57]. Nickel is expected to be a key resource at the centre of Indonesia's business and investment ventures[58].

There are rising concerns about potential weakening of environmental and social regulations under the new Omnibus law[57]. Yet since its initial announcement in 2020, the law has faced several implementation challenges, with few regulations fully realised[57]. Our study is therefore well timed to inform the design of implementing regulations under the new Law, ensuring that the nickel mining sector operates sustainably by balancing the economic gains with environmental and social responsibility. One potential approach is to harmonise policies between land-use sectors, including forestry and mining, which often remain largely separated. In the case of Indonesia, these divisions exist in licensing, development planning, and environmental impact assessments, and have led to challenges in overlapping resource concessions and unclear tenure rights[59]. While permission may be granted to undertake mining operations within concessions, this does not necessarily cover indirect impacts in surrounding areas[11]. Mining extraction rarely occurs in isolation, with disturbances also occurring off-site via road development, energy infrastructure, and settlements. While distinguishing the direct and indirect impacts of mining was outside the scope of our work, previous studies have identified the need to include the cumulative impacts of deforestation outside of concessions[9,11]. Governance mechanisms such as the One Map Policy (*Kebijakan Satu Peta – KSP*) in Indonesia, can potentially overcome these challenges. The initiative aims to harmonise spatial data from government departments and incorporate them into a single database. Promoting initiatives that actively encourage the coordination and integration across sectors can lead towards a more cohesive multi-sectoral approach to natural resource regulation in an attempt to reduce both deforestation and poverty[60].

As the mining of critical minerals continues to expand in Indonesia and other countries, it will be important to deepen our understanding of environmental and social impacts so that improvements to sustainability can be targeted. Our work provides the first synthesis of the environmental and social outcomes from nickel mining, providing the broad overview across the sector in Sulawesi. However, nickel mining on other Indonesian islands also warrants examination as relevant datasets become available. A caveat to our evaluation is that the outcomes are aggregated to the village administrative unit, reflecting the spatial scale of the census data. This village-level analysis can mask important variations between households or individuals within communities, where some may benefit more or less than the average village outcome. In-depth case-studies on how different individuals and groups are impacted by mining will remain valuable for identifying and supporting those most vulnerable to negative impacts, while also highlighting the conditions that foster greater benefits. The spatial nature of our analysis enables targeted case-studies in areas where mining outcomes have been particularly positive or negative. Furthermore, studying mining outcomes in relation to subjective well-being, which considers how people evaluate their own well-being related to the aspects of life they consider as important[61], could deepen our understanding of the diverse ways mining interventions impact local communities. Integrating qualitative methods into impact evaluations can offer a richer spectrum of possible outcomes, ensuring the voices and perspectives of affected communities are included[62].

Nickel extraction is expected to boom in coming years through a global low-carbon transition. We show how this can conflict with other environmental and development objectives. Pinpointing where these environmental and social divergences occur is a crucial step towards addressing these challenges, minimising trade-offs, and further promoting mining extraction that contributes towards a sustainable future, for both people and planet.

Resource Availability

Lead Contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Michaela G.Y. Lo (M.Lo@kent.ac.uk)

Materials Availability

This study did not generate any new unique materials.

Data and Code Availability

Mining concession data was derived from the Ministry of Energy and Mineral Resources. Visualisations of the mining concessions maps are available at Nusantara Atlas of Deforestation and Industrial Plantations in Indonesia (nusantara-atlas.org), and the ESDM One Map - Exploring Energy and Mineral Resources of Indonesia (geoportal.esdm.go.id). Data used to measure forest cover change derived from the 30m resolution Global Forest Change database (https://glad.earthengine.app/view/global-forest-change). Well-being and other socio-demographic data were sourced from the PODES census village survey led by the Indonesian Bureau of Statistics. These data can be visualised using the WebGIS PODES portal (https://sig.bps.go.id/webmap/podes/). The code for replication of the statistical analysis can found at the following link: https://doi.org/10.5281/zenodo.13884414.

Experimental Procedures

The Study area

Approximately 20 million people live in Sulawesi across its six provinces[63]. The complex geological history of central Indonesia has also resulted in highly unique ecosystems, making Sulawesi a globally important region for biodiversity and endemism[38]. Compared to western Indonesian islands, small-scale agriculture and other subsistence-based livelihoods are more dominant in Sulawesi, and commodities such as coffee, cacao, and coconut are more commonly grown than industrial-scale products such as oil palm[38]. Consequently, deforestation rates have been much lower in Sulawesi compared to neighbouring Borneo and Sumatra, where deforestation is primarily driven by the expansion of large-scale oil palm and paper-pulp plantations[36,64]. However, a recent deforestation surge in Sulawesi has been linked, in part, to mining, a sector that experienced rapid growth during the last decade[37].

The 2009 mining law in Indonesia decentralised the power of issuing mining permits, granting greater authority to local and regional officials[65]. This shift, implemented in 2010[38], resulted in a sharp increase in the issuance of mining licenses throughout the country, with most of the permits for establishing nickel mining operations granted in Sulawesi (Figure 1). By 2020 over 65% (424,270 ha) of Indonesia's active nickel-mining concessions were on Sulawesi, with a further 672,100 ha under exploration. The rapid proliferation of mining permits reportedly led to several licensing issues, including overlapping boundaries of land-use activities and difficulties in monitoring and ensuring that mining companies adhered to national procedures[66].

Forest cover data

To track annual forest cover change between 2011 and 2018 we used data from the Global Forest Change (GFC) repository v1.6 (Table S2). The GFC dataset provides consistent and accurate estimates of forest loss when applying national definitions of forest cover, and was therefore appropriate to use to measure forest cover change. Here, forest cover is defined as at least five hectares of >70% tree canopy cover of natural composition and structure in a 30 m resolution Landsat pixel[14,36], including mangrove forests (Table S2). This definition corresponds with those used for primary and secondary forest by Indonesia's Ministry of Environment and Forestry[67]. Using conservative measures of forest minimised the inclusion of deforestation that may have been temporary rather than permanent, and we excluded tree cover changes in other land cover types (plantations, agroforests, mixed gardens regrowth and scrublands)[36]. All forest maps were converted to the Asia South Albers Equal Area Conic projection to reduce distortions in area and distance. Spatial data were then aggregated to 180 x 180m pixel size to ease computational processing. Using the conservative definition of forest cover, we restricted tree cover pixels from the GFC dataset to form a baseline forest cover map for 2000. We then applied the forest loss data to the forest cover map and calculated the proportion of village areas forested for the years 2011, 2014, and 2018 to match the years for which well-being data were available.

Well-being data

Data on well-being were extracted from Indonesia's village-level census, PODES, which provides a rich and extensive source of socio-economic, and demographic information across Indonesia. PODES data are collected from village authorities around three times per decade, with the results aggregated at the village (*desa*) administration level (thus inference should not be linked to the individual or household level). As with all census surveys, the accuracy of responses may vary depending on the capacities and resources available within each village. Rigorous protocols have been developed by the Indonesian Bureau of Statistics (BPS) to ensure that the collected data is consistent and accurate across villages[68]. Previous studies have used PODES to assess environmental and social effects of land-use policies and other types of interventions, including oil palm certification [14,69], and protected areas[34,70]. PODES therefore remains the richest and most extensive source of well-being data covering the whole of the Indonesian archipelago. Well-being was characterised across three consecutive censuses in 2011, 2014, and 2018 (Table S2), and due to changes in village boundaries, observations were harmonised to those in 2014. We chose 2011 as the baseline following the announcement of the new mining regulatory regime in 2009, which was officially implemented in 2010[65].

We define well-being as a multidimensional concept that recognises the multiple assets, abilities, and attributes that are needed to support and achieve a better life[71]. To capture these multiple facets, our overall well-being index comprises six dimensions: living standards, environment, infrastructure, health, social, and education (Table 1[34]). Each dimension was assigned three equally weighted indicators derived from the PODES questionnaire. To calculate overall well-being, each indicator was given an equal weighting within a dimension (1/3). Each individual indicator is given the binary score of 0 or 1, where 0 denotes a village falling below the acceptable threshold specific to that indicator. The overall well-being index was calculated as the average score across the six dimensions. The indicator dimensions, thresholds, and directionality of measures were informed by established well-being and poverty frameworks, including the global multidimensional poverty index[31], and Indonesia's Village Development Index[72]. The possible mechanisms and directionality of well-being outcomes for each indicator are presented in the Supplemental Information (Figure S3 and Table S6).

Mining data

We used national mining concession data from Indonesia's Ministry of Energy and Mineral Resources, containing detailed information on the type of commodity and stage of mining activity (Table S2). Compared to other mining databases available, such as the S&P Global Market Intelligence database[73] and the mining data from Maus et al. [74], the national concession database provides greater coverage on mining areas in Indonesia[75], with more specific information on production status and mining characteristics.

Exploration and production require separate mining permits. We focus our analysis on the local impacts of mining concessions at the stage of production only. While the specific type of activity is not detailed in the mining concession data, construction, extraction, processing, refining, and transportation are all grouped into the stage of production[76]. The unit of analysis was the village boundary level, matching the same scale as the PODES data. After narrowing our sample to Sulawesi, a totally of 417 mining polygons were included in our analysis, covering around ~540,000 hectares (Table S7).

Villages exposed to mining were identified as those with concessions covering at least 15% of the village area (the median value across the Sulawesi dataset). Mining villages were then divided into two groups: nickel mining villages, where nickel was the primary mineral commodity extracted; and other mining villages for all other minerals produced. Non-mining villages were considered as those where no mining activity occurred during the same period for any of the commodities. We excluded villages where mining production operations occurred 10 years before the baseline year, as well as villages where mining concessions covered more than 0% but less than 15% of the village area. The mining database provides a comprehensive list of concessions that have formally received a permit but does not include unlicensed operations. Therefore, to avoid the possible inclusion of informal mining activities, we excluded villages containing concession areas where any exploration activities had taken place prior to and during the study period (2000 to 2018). This assumes that expected informal mining may occur where exploration or scoping studies have been conducted, which also provide estimates of where nickel resources are located. Mining concessions were merged by mineral commodity groups (nickel or other mineral) and year of production to avoid issues of overlapping boundaries. Villages with overlapping mining concessions producing a mixture of nickel and other mineral commodities were excluded from our sample.

Mining villages also include mining concessions that were issued mining production licenses in 2011 because a) the 2011 PODES survey was carried out in April 2011 so information is likely to reflect the status of villages in the previous year[68], and b) the steps from the decision to the construction and startup of mines take time and would therefore expect a delay in observing impacts[77]. After applying our inclusion/exclusion criteria and removing villages with missing data, 461 villages were excluded, resulting in a sample of 7,721 villages across Sulawesi. Of this total, 7,474 villages experienced no mining activities between 2000 and 2018, 132 villages contained nickel mining concessions that were in 1-7 years of production, and 115 villages overlapped with other mineral commodities excluding nickel (Table S8). Figure S4 maps mining polygons by nickel and other mineral commodity from 2011 to 2018.

Analytical framework and methodology

For the matching analysis, we carried out two assessments: the first comprised nickel mining villages matched to non-mining villages; and the second matched other mining villages (excluding nickel) with non-mining villages. For the regression analysis we estimated and compared the difference in forest cover and well-being between the mining and non-mining villages, within each set. To increase the robustness of our estimates, we included covariates at both stages which served to reduce any leftover bias resulting from the matching process[78].

Covariates of forest cover change and well-being

There are multiple factors other than mining that could affect how interventions are spatially distributed, and further interact with the outcome of interest. Therefore, to reliably measure the impact of mining, other factors that might influence the assignment of mining concessions (e.g. proximity to roads) or forest cover and well-being outcomes (e.g. poverty baseline conditions) should be controlled for[33]. We identified 16 covariates that may influence the selection process of mining and non-mining villages, and influence forest cover and well-being outcomes (Table 2). These reflected a) biophysical conditions, b) land governance, and c) and socio-demographic features of villages. This selection identifies factors that were known to affect the allocation of mining sites, as well as other factors that influence forest cover and well-being outcomes. We log-transformed covariates prior to the matching process that were highly skewed.

Statistical matching

For each set of mining interventions (nickel mining villages, and other mining villages), we performed a 1:1 paired matching analysis to balance observed covariates between the mining villages and non-mining villages and make them comparable. We also matched across two periods to account for possible time lags in the impacts from mining[43]. Throughout, we used genetic matching with replacement, a method that specifically uses a matching algorithm to iteratively search for the best balance[79]. Analyses were undertaken using the Matching and MatchIt packages in R[80,81]. As villages were either assigned a binary value of being exposed to a mining intervention or not, using a logistic regression to estimate the propensity scores of villages from the covariates listed in Table 2 was the most appropriate statistical model. For both sets of interventions, all mining villages were matched to a non-mining villages (Table S8). After comparing the covariate balance before and after matching, we observed a significant improvement in the overall distribution between mining and non-mining groups in both sets. The normalised differences for all covariates were below 0.2 (Table S9-S10), implying a strong balance was found across our mining and non-mining villages.

Regression analysis

With the matched datasets, we implemented a Before-After-Control-Impact (BACI) approach to infer the effects of mining. This approach first uses longitudinal data to compare changes in forest cover and well-being before and after a mining intervention takes place. This change is then compared with cross-sectional differences in forest cover and well-being between mining and non-mining villages[22] (see visual diagram of the analysis in the Supplemental Information, Figure S5). Changes in forest cover and well-being were measured over 1 to 7 years (i.e. up to two census intervals available in the data) after a mining intervention had been introduced, with another set of analyses to further observe changes 1 to 3 years, and 4 to 7 years after the mining intervention (the intervals matching the census years). In the analysis, standard errors were clustered a) by subclass, which represents pairs between the paired mining and non-mining village, b) by village, which accounts for non-mining villages that were included more than once in our matched sample, and c) at the regency (*kabupaten*) level, as most permits within our sample were issued at this level, therefore accounting for other unobserved political factors within regencies[82].

Interaction terms were used to examine the factors that might influence the intensity of nickel mining impacts on deforestation and village well-being. We hypothesise that villages with greater accessibility may increase the intensity of deforestation caused by nickel mining. As nickel mining is highly capital intensive, the additional costs of transporting resources and labour with limited infrastructure, as well as low access to markets for outputs, may result be a greater disincentive to clearing larger areas of forest lands[60]. Similarly, establishing nickel mining concessions on steep slopes at high elevations may be more restricting in the expansion of mining operations, resulting in the greater retention of forest cover.

Another group of interactions with nickel mining was carried out to assess whether livelihood type, poverty baseline conditions, and accessibility moderated the outcomes of interest. Based on other literature, livelihoods are known to influence well-being outcomes[30]. Therefore, we hypothesised that livelihoods with a greater dependency on natural resources are more likely to be affected by the negative environmental externalities derived from mining operations. Furthermore, we may also expect poverty baseline conditions to moderate mining outcomes. According to the 'natural resource curse' theory, natural resource extraction exacerbates poverty[17]; therefore, we would expect poorer areas to experience a worsening in well-being. In contrast, following the 'natural resource blessing' theory, we would expect to see the opposite trend[17]. The poverty baseline conditions of villages were determined as the inverse of the well-being index (the negative directionality of each well-being indicator). Before matching, we grouped each village into two classes of equal intervals – low and high poverty – based on their poverty status in 2011. We also assessed whether the accessibility of villages moderated the impact of nickel mining production on the well-being of local communities. We might also expect nickel mining extraction in more accessible areas might be more profitable due to fewer additional costs in transport related facilities, as well as easier access to resources and markets. These profits may lead to greater investment into the local economy, and results will show a greater improvement in well-being overtime.

To further assess the pathways in which baseline factors moderated the outcomes of deforestation and across various dimensions of well-being, we ran another matching analysis (Table S11) by the initial poverty status of villages. We reran the same statistical matching analysis across all poverty groups between nickel mining and non-mining villages to assess deforestation trends, and well-being outcomes across each dimension overtime.

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Author Contributions

Conceptualization, M.G.Y.L., M.J.S.; Data Curation, M.G.Y.L., C.L.M, T.S.; Methodology, M.G.Y.L., C.L.M., T.S., M.V., M.J.S.; Resources, T.S., S.M.; Formal Analysis, M.G.Y.L., T.S., M.V.; Investigation, M.G.Y.L.; Writing – Original Draft, M.G.Y.L., M.J.S., Z.G.D.; Writing – Reviewing & Editing, all authors; Visualization, M.G.Y.L., M.J.S.; Supervision, M.J.S., Z.G.D.; Projection Administration, M.J.S., Z.G.D.; Funding Acquisition, M.J.S., Z.G.D.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Inclusion and diversity

We support inclusive, diverse, and equitable conduct of research.

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Figures

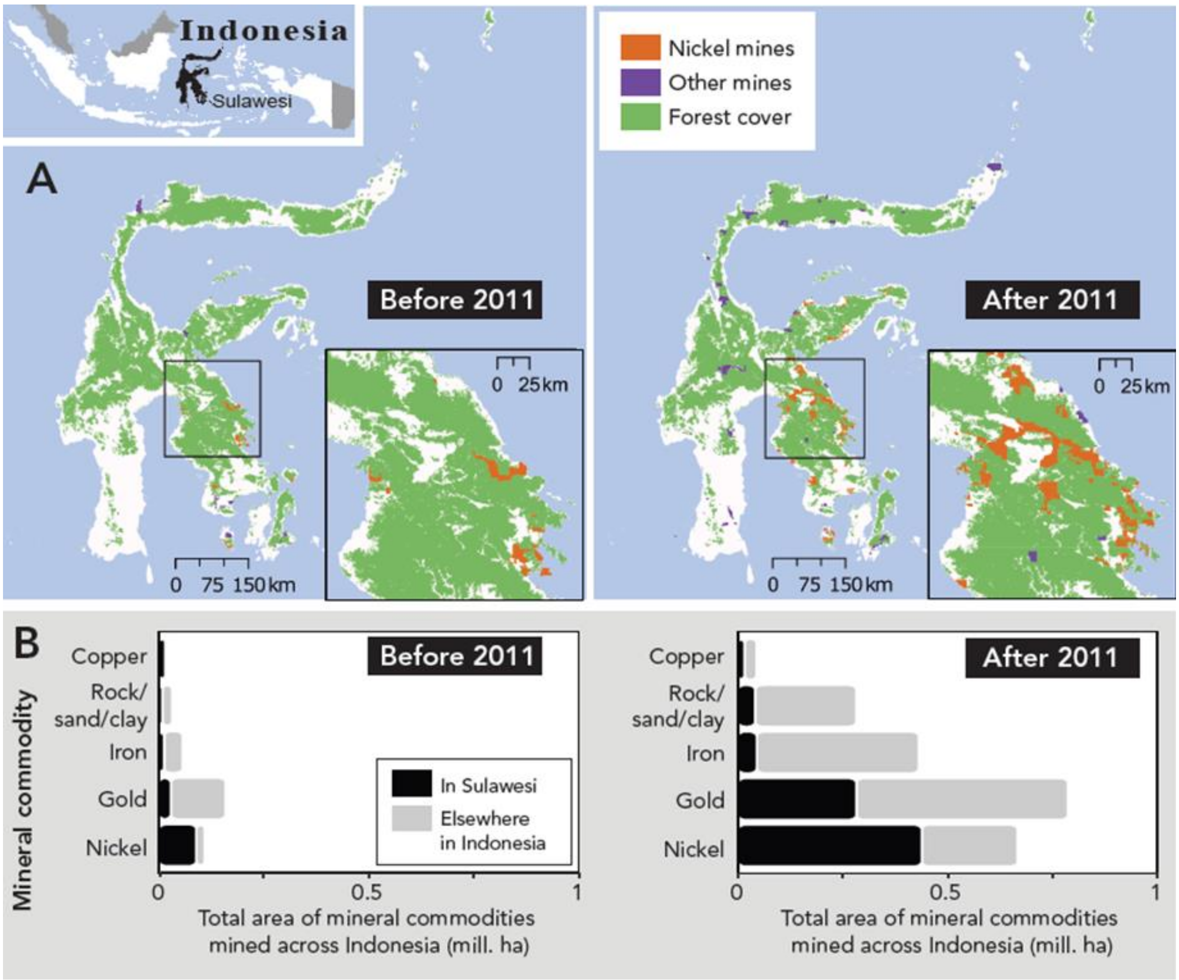


Figure 1. Mining concessions across Sulawesi and Indonesia. (A) Nickel mining (orange) concessions and other mining (purple) concessions in production phase in Sulawesi before (2000-2010) and (B) after (2011-2020) mining policy changes were introduced. Forest cover in 2011 is shown in green. (C) Total area of mining concessions for the top five mineral commodities produced in Sulawesi (black), before and after the mining policy changes, in relation to the rest of Indonesia (grey), according to the Indonesian Ministry of Energy and Mineral Resources.

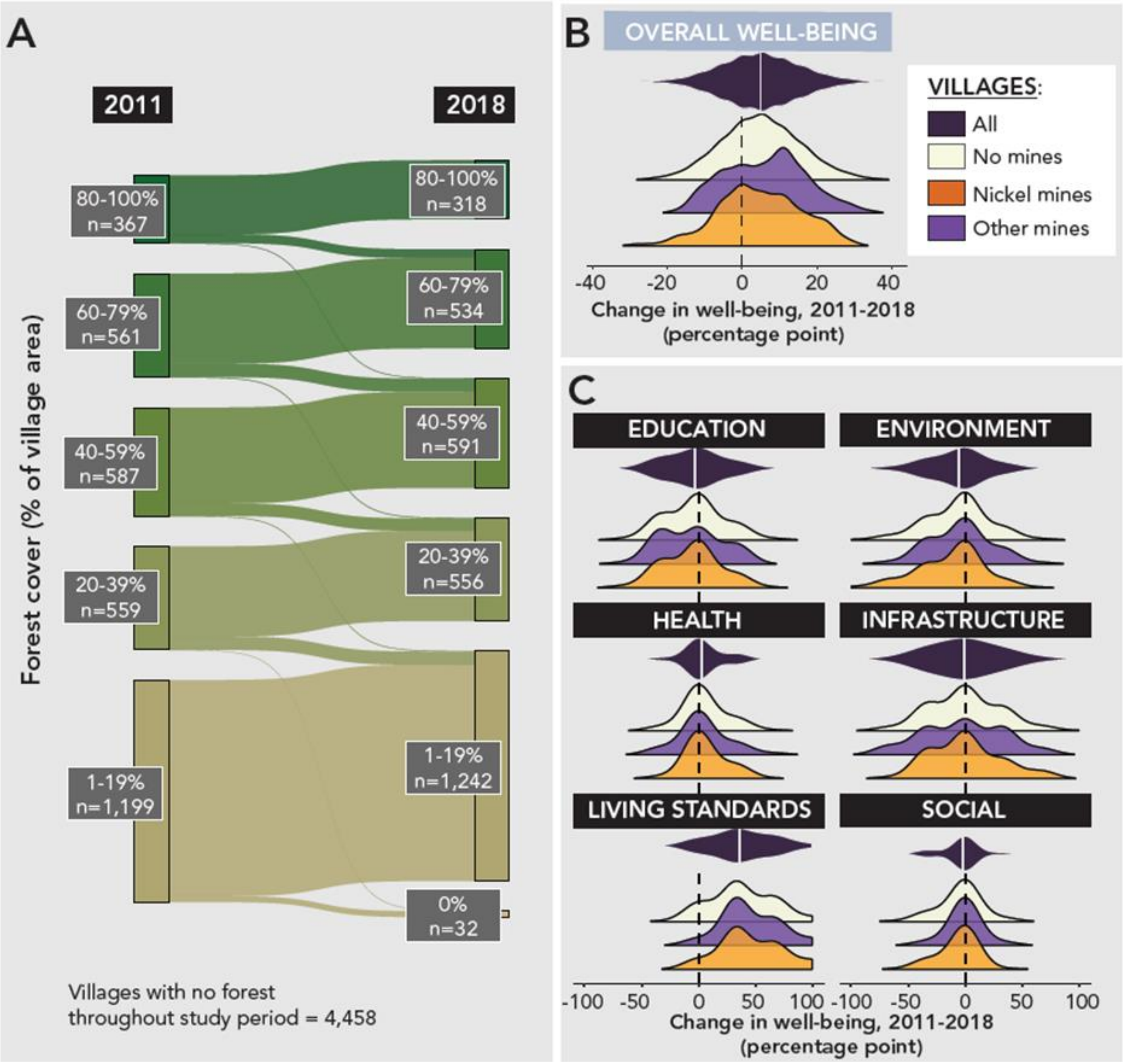


Figure 2. Background (i.e., unmatched) changes in forest cover and well-being between 2011 and 2018.

(A) Changes in forest cover between 2011 and 2018, with n indicating the number of villages in each forest cover category. (B) Change in overall well-being and (C) across the six well-being dimensions (the indicators used within each dimension can be found in Table 1), by subgroups. Well-being changes in nickel mining villages are shown in orange, other mining villages (all other mineral commodities excluding nickel) are shown in purple, and non-mining villages (no mines present from 2000 to 2018) are shown in white.

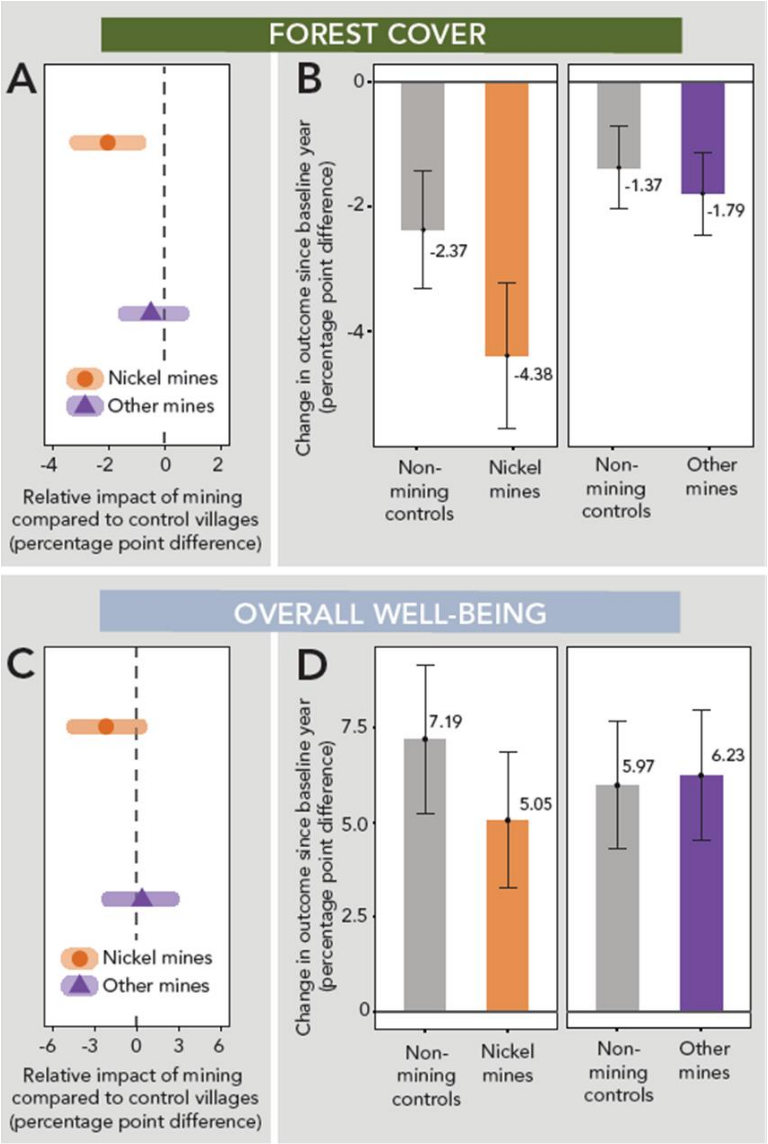


Figure 3. The relative impact of mining nickel and other commodities on changes to forest cover and well-being in Sulawesi.

Coefficient plot (A) compares forest cover change in villages with nickel mines (n=132, orange dots) or other mines (n=115, purple triangles) relative to their respective non-mining control villages. The error bars represent 95% confidence intervals - if these cross the zero line there is no significant difference between mining interventions and non-mining control villages. Bar plots (B) depict the change in forest cover since the 2011 baseline year in nickel mining villages and matched controls, and other mining villages versus their matched controls. Here, the confidence intervals show whether forest cover in 2018 differed from the baseline year (i.e., by not crossing the zero line). Plots C and D should be interpreted in the same way but for overall village well-being. Further details on the interpretation of the figure can be found in Tables S3 and S4. Table 1 provides an overview of the well-being dimensions and indicators, which together comprise the overall well-being score.

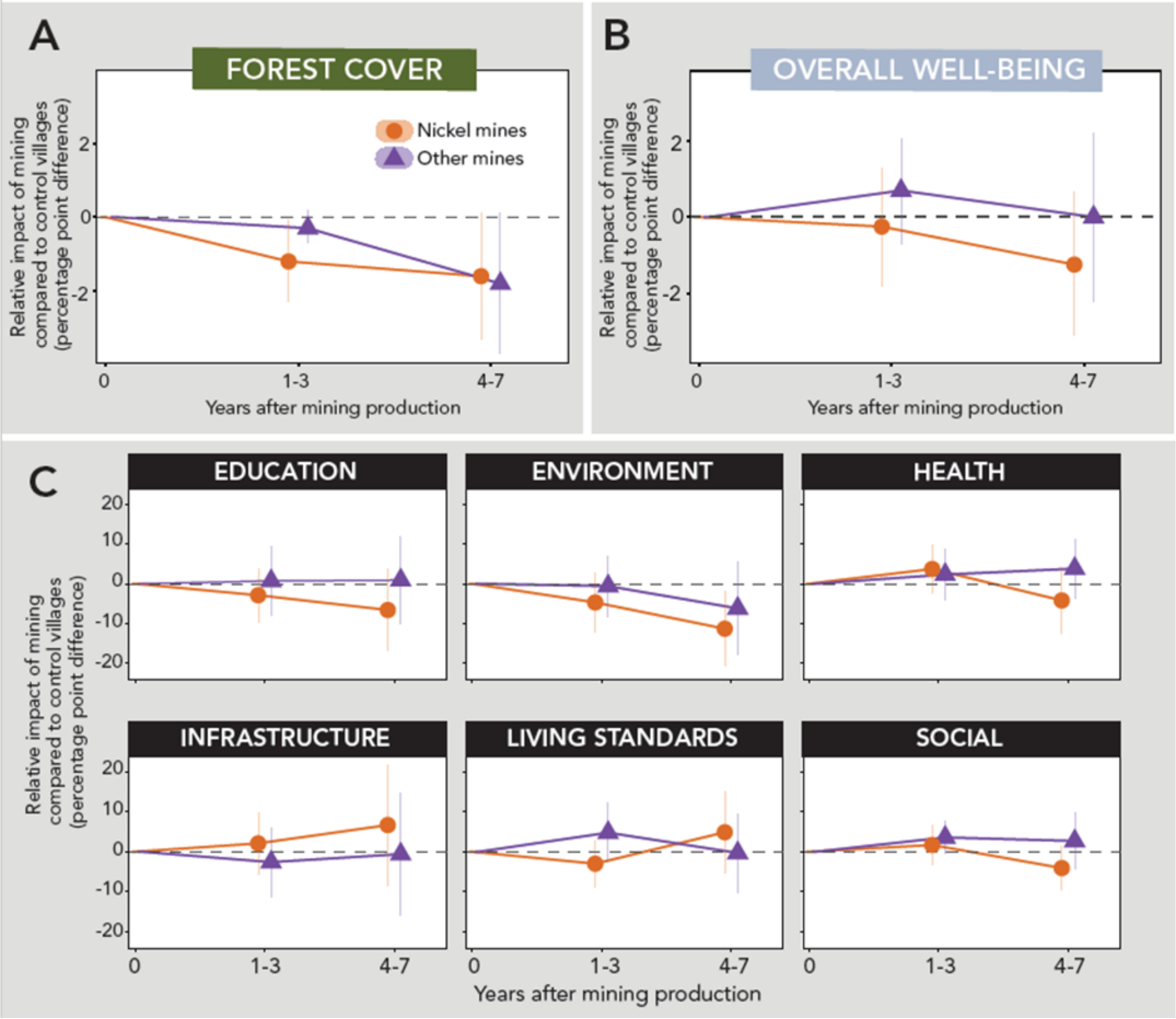


Figure 4. Relative mining impacts across villages in Sulawesi over time. Impact of nickel mining (orange dots) or other mining (purple triangles) relative to changes occurring in non-mining control villages 1-3 years (n=132 for nickel; n=115 for other mines) and 4-7 years (n=44; n=47) following production. The 1-3 and 4-7 year intervals post-mining are determined by the availability of census data. Panels (A) and (B) show the impacts for forest cover and overall well-being, respectively. Panel (C) shows the well-being outcomes by dimension. Error bars represent 95% confidence intervals between mineral commodities and control villages (the zero line). Table 1 provides an overview of the six dimensions and 18 indicators, which together comprise the overall well-being score.

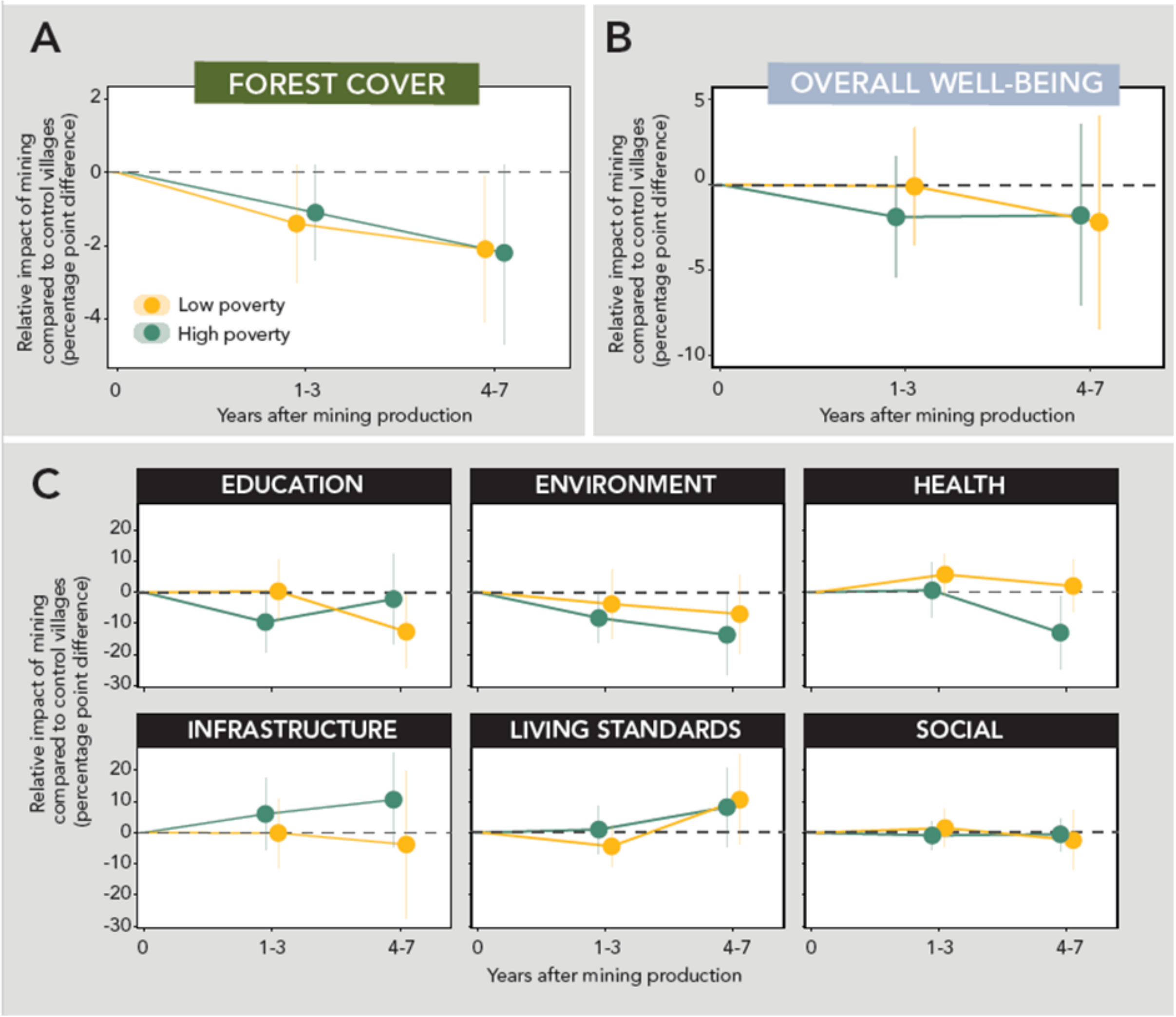


Figure 5. The role of poverty baseline conditions in determining forest cover change and well-being outcomes in nickel mining villages.

Impact of nickel mining where 2011 poverty baseline conditions were low (n=61 [1-3 years], n=19 [4-7 years], yellow dots), or high (n=70 [1-3 years], n=34 [4-7 years], green dots), compared to non-mining (control) villages with the similar poverty baseline conditions. Panels (A) and (B) show the impacts for forest cover and overall well-being, respectively. Panel (C) shows the well-being outcomes by dimension. The 1-3 and 4-7 year intervals post-mining are determined by the availability of census data. Error bars represent 95% confidence intervals between nickel mining and control villages (the zero line). Table 1 provides an overview of the six dimensions and 18 indicators, which together comprise the overall well-being score.

Tables

Table 1. The construction of a well-being index for Indonesia.

Dimension[a]	**PODES Indicator**	**Description**	**Score of 0 (low well-being) or 1 (high well-being). A score of 1 is given if:**
Living Standards	WATER	Main source of drinking water	Water is obtained from bottled water, refill water, plumbing with meter, or plumbing without meter
	TOILET	Type of toilet facility	Majority of households have a private facility
	FUEL	Type of cooking fuel	Fuel source is LPG or gas
Health	FACILITIES	Availability of healthcare facilities	There are health care facilities, and the nearest polyclinic is <19 km away
	MALNUTRITION	Cases of malnutrition	Where less than two cases of malnutrition are reported per 1000 of the village population in the last year
	DISEASE	Mortality due to malaria or vomiting	No mortality has occurred due to malaria nor diarrhoea reported in the last year
Education	PRIMARY	Presence of primary school	At least one primary school is present
	JUNIOR	Presence of junior high school	Junior high school is less than 3 km away
	LITERACY	At least one literacy support program	At least one literacy support programme is available
Environment	WATER	Occurrence of water pollution	No water pollution has occurred in the last 3 years
	AIR	Occurrence of air pollution	No air pollution has occurred in the last 3 years
	DISASTERS	Occurrence of natural disaster	No natural disaster has occurred in the last 3 years
Infrastructure	SKTM	Number of households with poverty (SKTM) letters	The number of families with SKTM letters is no more than 10% of village household population
	MARKET	Presence of permanent or semi-permanent market in village	Where nearest permanent or semi-permanent market is <10 km away
	CREDIT	Availability of food credit, small business credit, people business credit, and housing credit	Village with any sort of access to credit support
Social	COOPERATION	Mutual-cooperation activities	Mutual cooperation activities are present
	CRIME	Any serious crimes occur in the last 3 years	Village reporting three crimes or less in the past year
	CONFLICT	A report of mass conflict in the past year	No report of mass conflict in the last year

[a] Eighteen PODES[63] indicators were grouped to represent six dimensions of well-being (living standards, environment, infrastructure, health, social and education)[34]. To calculate overall well-being, each indicator was given an equal weighting within a dimension (1/3). Each individual

indicator was given the binary score of 0 or 1, where 0 denotes a village falling below the acceptable threshold specific to that indicator. References and visualisation of the pathways between nickel mining and village well-being outcomes are shown in Figure S3 in the Supplemental Information. Table S6 provides details on the directionality of expected well-being outcomes, and the possible causal pathway mechanisms.

Table 2. Covariates that influence the assignment of mining villages and trends in forest cover and well-being.

Covariate type[a]	**Covariate details**[b]	**Rationale**[b]	**Dataset**[b]
Biophysical	Average elevation (m.a.s.l) *Log(Continuous)*	Correlated with deforestation and livelihood decisions[83]	SRTM 90 m Digital Elevation Database v4.1
	Average slope (degrees) *Log(Continuous)*	Correlated with deforestation and livelihood decisions[83]	SRTM 90 m Digital Elevation Database v4.1
	Average rainfall in dry season *(Continuous)*	Affects livelihood decisions[83]	WorldClim
	Average rainfall in wet season *(Continuous)*	Affects livelihood decisions[83]	WorldClim
	Area of Limestone rock (%) *(Continuous)*	Geological characteristics shape mineral selection[84] (only included in ‘other mineral commodity’ impact evaluation)	RePPProT
	Area of volcanic rock (%) *(Continuous)*	Geological characteristics shape mineral selection[85] (only included in ‘other mineral commodity’ impact evaluation)	RePPProT
	Area of forest cover in 2011 (%)	Previous area of forest cover is correlated with deforestation activities already existing	Forest cover and forest cover change layer
Land governance	Area of village under production forest (*Hutan Produksi*) *(Continuous)*	Mining concessions allowed in production forest sites[6]	Forest Zone Map

Covariate type[a]	Covariate details[b]	Rationale[b]	Dataset[b]
	Area of village under protected forest (*Hutan Lindung*) *(Continuous)*	Underground mining activities can take place in protected forests. Open pit mining is not permitted[6]	Forest Zone Map
	Area of village that is Non Forest estate (*Areal Pengunaan Lain*, *APL*) *(Continuous)*	Mining concessions are allowed on Non Forest estate [86]	Forest Zone Map
	Administrative provincial boundary where villages are located *(Categorical)*	Government decision-making at the province level influences distribution of resources[87]	*Potensi desa* (PODES)
	Area of village (km2) *Log(Continuous)*	Village area linked to size of mining area	*Potensi desa* (PODES)
Socio-demographic	Population density (capita/km2) *Log(Continuous)*	Higher resource extraction is associated with high population levels[88]	*Potensi desa* (PODES)
	Slope, road and landcover to measure level of accessibility to settlements (travel time, hours) *Log(Continuous)*	Greater access to markets and infrastructure can influence livelihood decisions and forest cover[88]	Accessibility layer
	Village poverty score in 2011 *Categorical (Low, High)*	Poverty baseline level may moderate well-being outcomes	*Potensi desa* (PODES)
	Primary village livelihood at baseline year (2011) *Categorical (Capture Fisheries; Commercial fisheries; Market-orientated; Subsistence; Other)*	Livelihood type shapes well-being outcomes[30]	*Potensi desa* (PODES)

[a]Covariates are grouped into three types: i) biophysical, ii) land governance, and iii) socio-demographic. [b]Details, rationale, and source of each covariate included in the analysis. The source of each dataset cited in the table is listed in Table S2 in the Supplemental Information.

Supplemental information

Supplemental figures

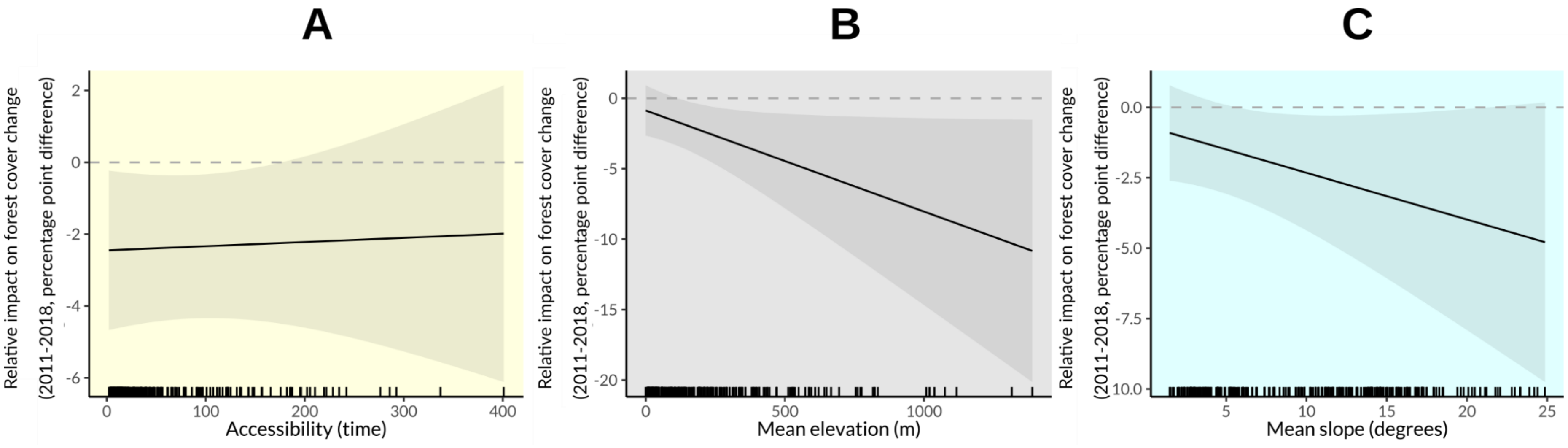


Figure S1. Heterogenous impacts of nickel mining on forest cover change (2011-2018) moderated by accessibility of village (A – yellow panel), average elevation (B – grey panel), and average slope (C –blue background). The grey horizontal line intercepting zero on the y-axis represents no impact from mining production. Shaded areas represent 95% confidence intervals between nickel mining and control villages (the zero line).

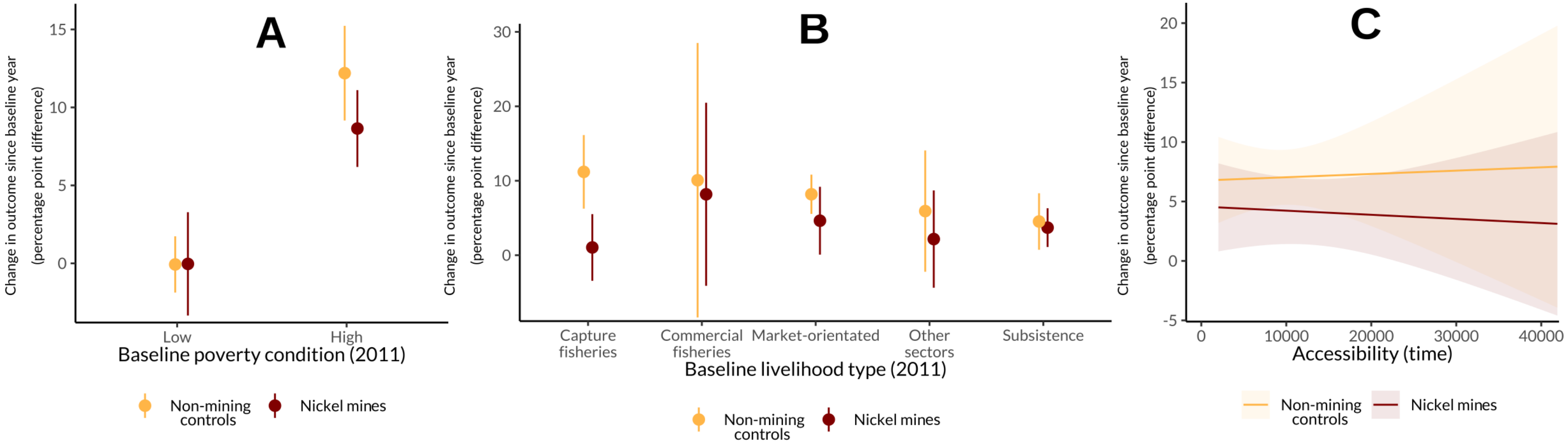
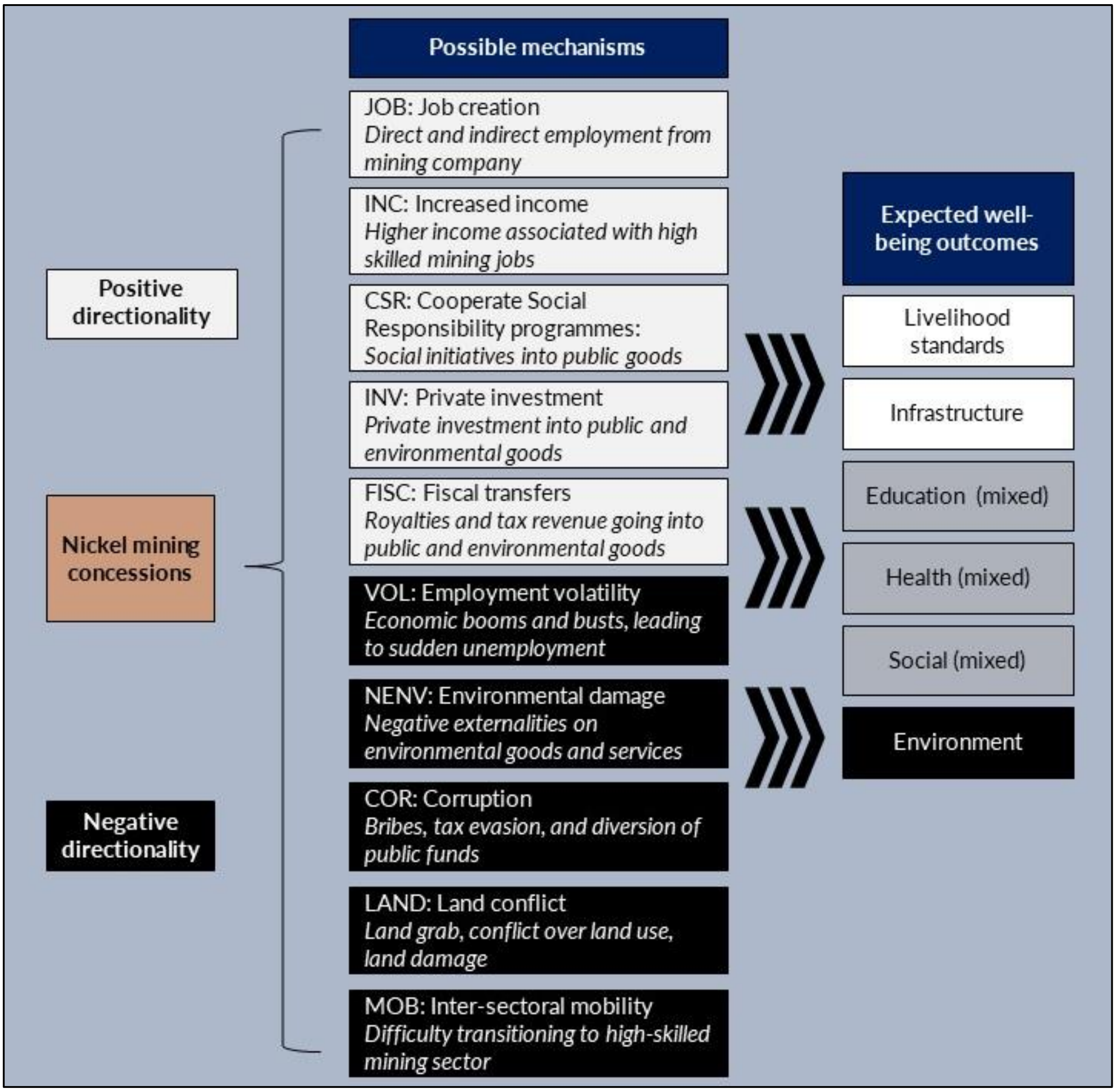


Figure S2. Heterogenous impacts of nickel mining on change in well-being (2011-2018) moderated by baseline poverty condition of village (A), primary livelihood type (B), and accessibility (C). Error bars in column A and B, and shaded areas in column C represent 95% confidence intervals show difference in overall well-being from in 2018 differed from the baseline year.



FigureS3. Possible mechanisms of nickel mining concessions on village well-being. Identified mechanisms and outcomes are based on empirical evidence in Table S4 in the supplemental information. The categorisation of mechanisms is based on relevant literature reviews addressing mining impacts on well-being and poverty alleviation [1-3]. White boxes depict positive mechanisms and outcomes, and black boxes represent negative mechanisms and outcomes on well-being. Grey boxes show that well-being outcomes are expected to be mixed.

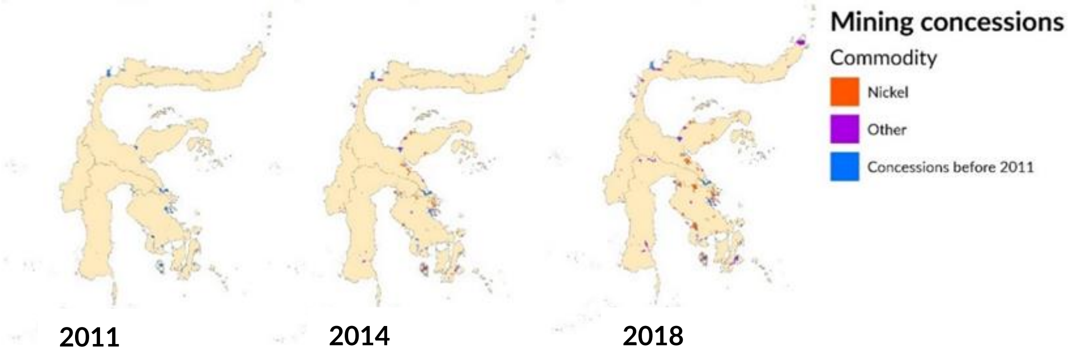
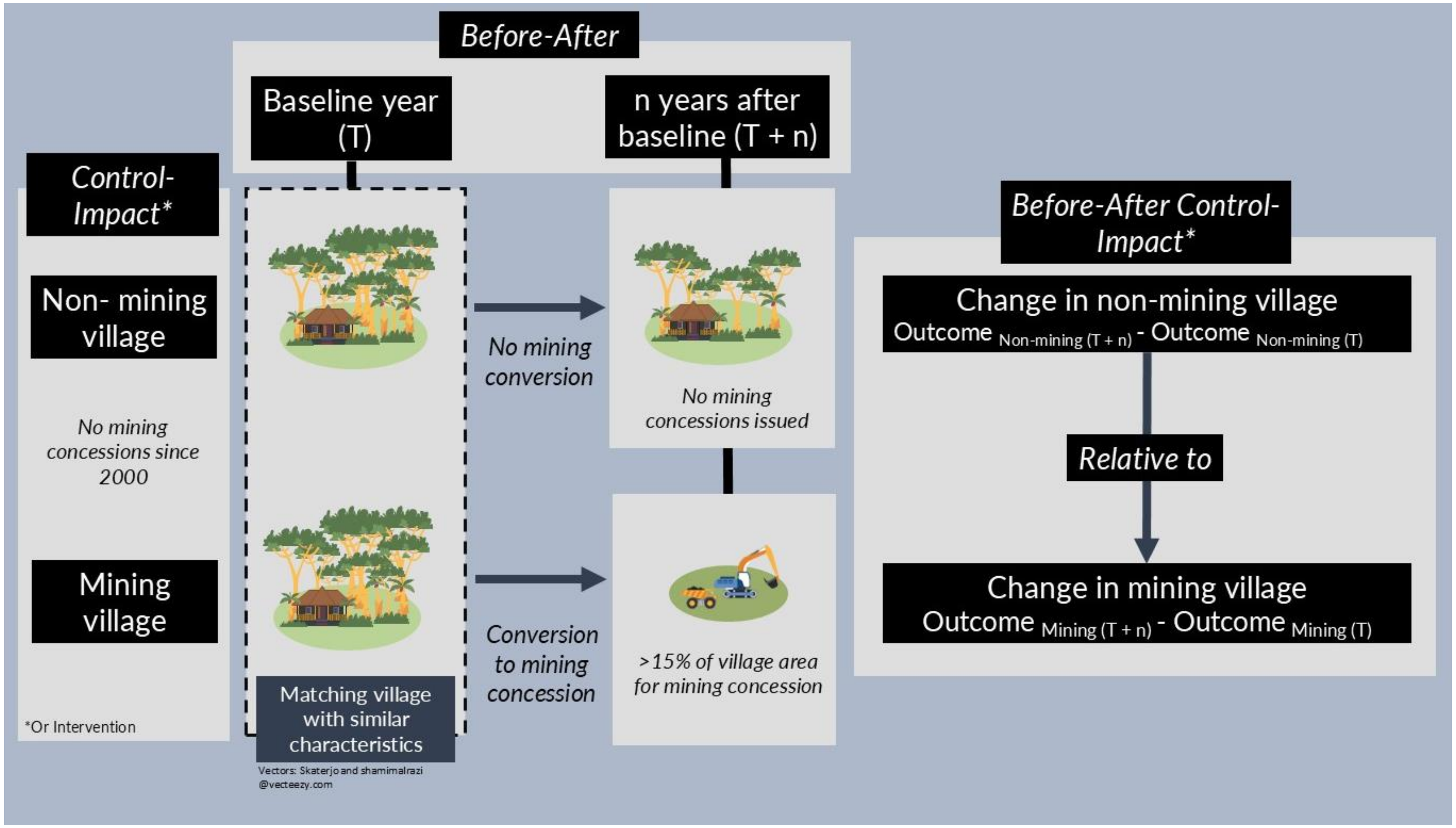


Figure S4. The establishment of mining concessions with a production permit across Sulawesi in 2011, 2014, and 2018. The blue polygons are all mining concessions (nickel and other mineral commodities) that were established before 2011 (earliest recorded mining permit was in the year 2006). Polygons that produce nickel after 2011 are shown in orange, and other mineral commodities are shown in purple.



Vectors: Skaterjo and shamimalrazi @vecteezy.com

Figure S5. Conceptual diagram illustrating the matching assessment and Before-After Control-Intervention approach to quantify the impact of mining (nickel or other) on forest cover and village well-being outcomes. All village units in the matching and regression analysis only includes villages where no mining concessions have occurred since the year 2000 up until the baseline year. Each village unit was classified as a mining village if over 15% of the village area was under mining concession. Non-mining villages were villages units where no mining concessions were allocated during the analysis period. Villages with less than 15% mining concession cover were excluded from the sample. The 15% threshold is the median proportion of village area allocated to mining concessions across Sulawesi. The number of villages in the mining and non-mining village were different depending on the mineral commodity (nickel or other) and the time frame (1-7 years, 1-3 years, 4-7 years). This information can be found in Table S6.

Supplemental tables

Table S1. List of geo-political bodies listing nickel as a critical mineral. Geo-political bodies include countries, international agencies, and geo-political blocs. References are provided in the 'Source' column.

Geo-political bodies	Source
United States Geological Survey (USGS)	USGS, (2022). 2022 final list of critical minerals. US Geological Society. https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/media/files/2022%20Final%20List%20of%20Critical%20Minerals%20Federal%20Register%20Notice_2222022-F.pdf.
Canada	Natural Resources Canada (2022). The Canadian Critical Minerals Strategy from exploration to recycling: Powering the Green and Digital Economy for Canada and the World. https://www.canada.ca/content/dam/nrcan-rncan/site/critical-minerals/Critical-minerals-strategyDec09.pdf
Australia	The Australian Government (2023). Australia's Critical Minerals List and Strategic Materials List. https://www.industry.gov.au/publications/australias-critical-minerals-list-and-strategic-materials-list#footnote-2.
The European Parliament	European Parliament (2024). Regulation (EU) 2024/1252 of the European Parliament and of the council In European Parliament, ed. 2024/1252
The International Energy Agency (IEA)	IEA (2024). Global critical minerals outlook 2024. IEA. https://www.iea.org/reports/global-critical-minerals-outlook-2024.

Table S2. List of datasets used in the impact evaluation analysis. The type of data extracted from each dataset is provided, including the dataset source.

Dataset	Data	Source
Mining concession map (2020)	Mining data: concession locations, mining commodity, and permit details	Ministry of Energy and Mineral Resources (ESDM) https://geoportal.esdm.go.id/
P*otensi desa* (PODES) 2011,2014, 2018	Village data: well-being, population density, poverty baseline condition, livelihood activities, and village boundaries	Morgans et al. [4], Statistics Indonesia (BPS)
Forest and forest cover change layer	Forest cover (including mangrove and primary forests) and forest cover change	Giri et al. [5,]Hansen et al. [6,]Margono et al. [7]
Accessibility layer	Level of accessibility to settlements (travel time, hours) using slope, roads, and land cove measures.	Deere et al. [8]
National land-use maps (2010)	Forest zones: production forest (h*utan produksi*), protected forest (*hutan lindung*), non-forest estate (*areal pengunaan lain*)	Ministry of Environment and Forestry (KLHK) https://gis-gfw.wri.org/arcgis/rest/services/commodities/MapServer/13
RePPProT	Land systems including geophyiscal characteristics	RePPProT [9]
SRTM 90 m Digital Elevation database v4.1	Slope and elevation	Jarvis et al. [10]
WorldClim	Average rainfall	Fick and Hijmans [11]

Table S3. Average effects of mineral commodities (nickel and other mining) on deforestation. Values in column 'Intervention' and 'Control' are the average change in forest cover since the baseline year (Before-After). Column 'Difference (Intervention-Control)' shows difference in forest cover change between the intervention and control group. The last column shows the difference in forest cover change in proportion to change in the control group. The 95% confidence intervals are in brackets. Values correspond to Figure 3A and 3B in the main text. pp.=percentage point.

	Intervention (Before-After) [Panel Fig. 3B]	Control (Before-After) [Panel Fig. 3B]	Difference (Intervention-Control) [Panel Fig. 3A]	Difference proportional to Control
Forest cover change	**Nickel mines (pp.)**	**Non-mining (pp.)**	**(pp.)**	**(%)**
	-4.38	-2.37	-2.02	85.23
	[-5.45 to -3.31]	[-3.1 to -1.6]	[-3.16 to -0.87]	
	Other mines (pp.)	**Non-mining (pp.)**	**(pp.)**	**(%)**
	-1.79	-1.37	-0.42	30.66
	[-2.45 to -1.12]	[-2.06 to -0.68]	[-1.42 to 0.59]	

Table S4. Average effects of mineral commodities (nickel and other mining) on improving well-being. Values in column ‘Intervention’ and ‘Control’ show the average changes in well-being since the baseline year (Before-After). Column ‘Difference (Intervention-Control)’ shows the difference in well-being change between intervention and control group. The last column shows the difference in well-being changes in proportion to change in the control. The 95% confidence intervals are shown in brackets. Values correspond to Figure 3C and 3D in the main text. pp.=percentage point.

	Intervention (Before-After) [Panel Fig. 3D]	Control (Before-After) [Panel Fig. 3D]	Difference (Intervention-Control) [Panel Fig. 3C]	Difference proportional to control
Well-being change	**Nickel mines(pp.)**	**Non-mining (pp.)**	**(pp.)**	**(%)**
	5.05	7.19	-2.14	-29.81
	[3.32 to 6.78]	[5.28 to 9.11]	[-4.55 to 0.27]	
	Other mines (pp.)	**Non-mining (pp.)**	**(pp.)**	**(%)**
	6.51	6.24	0.26	4.22
	[4.8 to 8.2]	[4.21 to 8.28]	[-2.02 to 2.55]	

Table S5. Heterogenous impacts of nickel mining on forest cover in matched samples. Negative interaction terms suggest a greater impact intensity in deforestation due to nickel mining production between 2011 and 2018. Standard errors are in parentheses and 95% confidence intervals are in brackets.

	Nickel - Accessibility	**Nickel - Elevation (m)**	**Nickel - Slope (deg)**
Mining impact	-2.451	-0.869	-0.665
	(1.143)	(0.909)	(0.943)
	[-4.690, -0.212]	[-2.652, 0.913]	[-2.514, 1.184]
Covariate	-0.00005	-0.001	-0.119
	(0.00005)	(0.001)	(0.051)
	[-0.00014, 0.00004]	[-0.003, 0.001]	[-0.220, -0.018]
Interaction	0.00001	-0.007	-0.166
	(0.006)	(0.004)	(0.117)
	[-0.0001, 0.00013]	[-0.014, -0.00001]	[-0.395, 0.063]
No. of villages	264	264	264
AIC	1691.352	1677.156	1678.965
BIC	1709.232	1695.036	1696.845

Table S6. Description of indicators in each dimension, possible mechanisms between nickel mining and well-being outcomes and expected directionality. Abbreviations and description for possible mechanisms can be found in Figure S3 in the Supplemental Information. Expected outcome and directionality are based on empirical studies found in in the 'Source' column. Expected directionality for well-being outcomes + = positive, - = negative, +/- = mixed. INC: Income, INV: Private Investment, FISC: Fiscal transfers, NENV: Environmental damage, CSR: Corporate Social Responsibility programmes, JOB: Job creation, LAND: Land conflicts, VOL: Employment volatility, COR: Corruption, MOB: Inter-sectoral mobility.

Dimension	PODES Indicator	Description	Possible mechanisms	Expected outcome:	Expected Directionality	Sources
Living Standards	WATER	Main source of drinking water	INC, INV, FISC	Access to safe drinking water	+	12,13
	TOILET	Type of toilet facility	INC, INV, FISC	Access to improved toilet facilities	+	13
	FUEL	Type of cooking fuel	INC, INV, FISC	Access to LPG or Gas	+	13
Health	FACILITIES	Availability of healthcare facilities	INV, FISC	Access to health facilities improve	+	13
	MALNUTRITION	Cases of malnutrition	INC, NENV	Larger expenditure spent on food. Local production of foods less accessible	+/-	13
	DISEASE	Mortality due to malaria or vomiting	INC, INV, FISC	Improvement in vaccinations and health care treatments.	+	12
Education	PRIMARY	Presence of primary school	CSR, INV, FISC	Investment into schools	+	12,14
	JUNIOR	Presence of junior high school	CSR, INV, FISC	Investment into schools	+	12,14
	LITERACY	At least one literacy support program	CSR, INV, FISC	Access to literacy programmes improve	+	12
Environment	WATER	Occurrence of water pollution	NENV	Greater occurrence of water pollution	-	15-19
	AIR	Occurrence of air pollution	NENV	Greater occurrence of air pollution	-	15-20
	DISASTERS	Occurrence of natural disaster	NENV	Greater occurrence of natural disasters	-	21
Infrastructure	SKTM	Number of households with poverty (SKTM) letters	JOB; INC	Decrease in the number of households receiving SKTM	+	13,22

Dimension	PODES Indicator	Description	Possible mechanisms	Expected outcome:	Expected Directionality	Sources
	MARKET	Presence of permanent or semi-permanent market in village	JOB; INV; FISC	Greater access to markets in village	+	[21]
	CREDIT	Availability of food credit, small business credit, people business credit, and housing credit	INV; FISC	Greater availability of credit support	+	[12]
Social	COOPERATION	Mutual-cooperation activities	CSR, LAND, ENEV	In-migration and shift in labour can fragment mutual cooperation activities Corporate Social Responsibility initiatives encourage greater cooperation activities	+/-	[12,14,23]
	CRIME	Any serious crimes occur in the last 3 years	VOL; COR; LAND	Increase in the number of crimes reported	-	[13]
	CONFLICT	A report of mass conflict in the past year	COR; LAND; NENV; MOB	Greater occurrence of conflict.	-	[13,17]

Table S7. Description of spatial mining layer across Sulawesi before and after 2011 by mineral commodity: nickel and other. The number of permits only include those that were issued for mining production. The area of mining concessions in production are shown in million hectares, both before and after the year 2011.

	Nickel		**Other**	
Description	**2000-2010**	**2011-2018**	**2000-2010**	**2011-2018**
Mining polygons (n)	77	227	150	190
Permits (n)	48	177	44	141
Area (mil. ha)	0.09	0.31	0.08	0.23

Table S8. Number of villages in the *Potensi Desa* (PODES) dataset before and after the matching analysis to assess the change in forest cover and well-being at the village level. 454 villages were excluded as the mining area was more than 0% but less than 15% of the village area, and/or contained mining concessions with exploration permits. A further seven mining villages were excluded due to polygon overlap between nickel mining and other mining concessions. By using various PODES census timepoints (2011, 2014, 2018), we assessed the impact of mining (Other and Nickel) from 1-7 years, 1-3 years (short term), and 4-7 years (mid-term) after the mining concession had been developed.

Non-mining villages[a]		**Mining villages**[b]		**Intervention characteristics**			
Before matching	**After matching**	**Before matching**	**After matching**	**Mineral Commodity**	**Age of mining concession**	**Baseline year**	**PODES census year**
7,474	101	115	115	Other	1-7 years	2011	2018
7,474	45	47	47	Other	1-3 years	2011	2014
7,474	58	68	68	Other	1-3 years	2014	2018
7,474	45	46	46	Other	4-7 years	2011	2018
7,474	116	132	132	Nickel	1-7 years	2011	2018
7,474	51	53	53	Nickel	1-3 years	2011	2014
7,474	70	79	79	Nickel	1-3 years	2014	2018
7,474	42	44	44	Nickel	4-7 years	2011	2018

[a] No mining concessions were present between 2000 and 2018.

[b] Villages where mining concessions in production were established.

Table S9. Covariate balance between nickel mining villages and non-mining villages before and after matching analysis. The SMD is the Standard Mean Difference between the nickel mining and non-mining group for each covariate. SMD values under 0.2 indicate there is sufficient overlap between the two groups after the matching analysis. These results are averaged across three timeframes (PODES census points 2011-2014, 2014-2018, and 2011-2018).

	Before matching		After matching		
Covariate	**Nickel mining**	**Non-mining**	**Nickel mining**	**Non-mining**	**SMD**
Log(elevation)	4.802	4.682	4.802	4.761	0.030
Log(slope)	2.406	2.164	2.406	2.386	0.052
Log(access)	7.875	7.427	7.875	7.929	0.055
Log(area)	2.605	2.231	2.605	2.557	0.048
Log(population density)	4.150	5.158	4.150	4.132	0.015
Av. rainfall - Dry	98.280	100.064	98.280	96.907	0.061
Av. rainfall - Wet	203.183	212.979	203.183	203.010	0.079
Forest cover (%)	0.34	0.16	0.34	0.34	0.025
Other lands (%)	60.828	74.290	60.828	61.256	0.033
Production forest (%)	20.456	10.425	20.456	19.706	0.029
Protect forest (%)	15.300	10.744	15.300	13.850	0.061

Table S10. Covariate balance between other mining villages and non-mining villages before and after matching analysis. The SMD is the Standard Mean Difference between the other mining and non-mining group for each covariate. SMD values under 0.2 indicate there is sufficient overlap between the two groups after the matching analysis. These results are averaged across three timeframes (PODES census points 2011-2014, 2014-2018, and 2011-2018).

	Before matching		**After matching**		
Covariate	**Other mining**	**Non-mining**	**Other mining**	**Non-mining**	**SMD**
Log(elevation)	5.296	4.682	5.296	5.249	0.065
Log(slope)	2.539	2.164	2.539	2.512	0.065
Log(Access)	8.192	7.427	8.192	8.127	0.068
Log(Area)	3.015	2.231	3.015	2.956	0.070
Log(population density)	4.239	5.158	4.239	4.242	0.043
Av. rainfall - Dry	109.875	100.064	109.875	109.768	0.033
Av. rainfall - Wet	201.054	212.979	201.054	198.998	0.061
Forest cover (%)	0.321	0.160	0.321	0.322	0.037
Other lands (%)	53.449	74.290	53.449	55.320	0.062
Production forest (%)	26.516	10.425	26.516	25.734	0.042
Protect forest (%)	17.704	10.744	17.704	17.361	0.026

Table S11. Number of villages in the PODES dataset before and after the matching analysis by poverty status. By using various PODES census timepoints (2011, 2014, 2018), we assessed the impact of nickel mining from 1-7 years, 1-3 years, and 4-7 years after the mining concession had been developed. The baseline poverty condition is the inverse of the well-being index calculated for the year 2011 across Sulawesi. Villages were then categorised as either Low or High as defined by the median poverty score at the regional level.

Non-mining villages[a]		**Mining villages[b]**		**Intervention characteristics**				
Before matching	**After matching**	**Before matching**	**After matching**	**Mineral commodity**	**Age of mining concession**	**Baseline year**	**PODES year**	**Baseline poverty condition[c]**
7,474	18	19	19	Nickel	1-3 years	2011	2014	Low
7,474	40	43	42	Nickel	1-3 years	2014	2018	Low
7,474	15	15	15	Nickel	4-7 years	2011	2018	Low
7,474	33	34	34	Nickel	1-3 years	2011	2014	High
7,474	34	36	36	Nickel	1-3 years	2014	2018	High
7,474	27	29	29	Nickel	4-7 years	2011	2018	High

[a] No mining concessions were present between 2000 and 2018.

[b] Villages where mining concessions in production were established.

[c] The baseline poverty condition is the inverse of the well-being index calculated for the year 2011 across Sulawesi. Villages were then categorised into two quantiles - Low and High. We carry out separate matching processes for each baseline poverty group (Poverty 2011).

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