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Key Points:

- Increasing mineral production depletes groundwater storage (GS) but promotes vegetation growth in drylands
- Mining-induced dewatering reversed normal positive relationships between vegetation growth conditions and GS
- Unsustainable irrigation bonuses mask the potential risk of long-term vegetation degradation in drylands

Supporting Information:

Supporting Information may be found in the online version of this article.

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Mining Can Exacerbate Global Degradation of Dryland

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Abstract Groundwater storage (GS) is the major water resource for vegetation in drylands. Thus, positive relationships between vegetative growth condition (VGC) and GS are expected in drylands. Since mining-induced dewatering tends to deplete GS surrounding mine sites, VGC should become less favorable due to a shortage of accessible water. However, quantitative analysis repealed the opposite. We found that global annual mineral production in drylands increased by 24%, while GS decreased by 22% but the VGC improved by 37% (2002–2010). And negative relationships between VGC and GS were detected in 84.7% of global dryland mine sites. We concluded that irrigation supported by mining-induced dewatering promoted the vegetation growth surrounding mine sites. However, since the GS is limited, irrigation-supported vegetation growth is unsustainable. This study elucidates the reason behind these abnormal negative relationships and highlights the potential risk of vegetation degradation induced by unsustainable groundwater depletion in global dryland mine sites.

Plain Language Summary The impacts of mining activities on the relationships between dryland vegetation growth condition (VGC) and groundwater storage (GS) have been quantitatively evaluated based on the remote sensing observations. Our results indicate that increasing mineral production depletes GS but improves VGC in drylands. And the abnormal negative relationships between GS and VGC occurs in 84.7% of global dryland mine sites. We conclude that irrigation water sourced from mining-induced dewatering drives an increase in vegetation growth. However, since the GS is limited, irrigation-supported vegetation growth is unsustainable. These results elucidate the unsustainable impacts of mining activities on the transformation of the relationships between GS and VGC in global dryland mine sites.

1. Introduction

Increasing global demands for mineral resources have triggered massive mineral exploitation in recent decades (Alamgir et al., 2017; Lambin & Meyfroidt, 2011), which has caused serious environmental problems, such as groundwater pollution and depletion, air pollution, and deforestation (Butchart et al., 2010; Gibson et al., 2011; Hoffmann et al., 2010; Laurance et al., 2012; Pouzols et al., 2014). However, the global annual mineral production (AMP) in arid and semiarid regions increased by ~120 × 10^8 t from 1990 to 2018 (Figure 1c). The AMP decreased in ≥8% of drylands due to unstable socioeconomic conditions but tended to steadily increase from 700 × 10^4 to 5,300 × 10^4 t in 62% of the global drylands, such as those in North America, South Africa, Asia, and Oceania (Figure 1b). However, the degradation of drylands by mining activities has been greatly neglected, particularly in developing countries, which have largely focused on the benefits of mineral production for socioeconomic development (Lambin & Meyfroidt, 2011). Drylands are home to >38% of the global population (Huang et al., 2017), and 90% of drylands are in developing countries (Armah

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et al., 2011). In addition, the low fertility of soils, insufficient precipitation, and socioeconomic development in drylands render them extremely vulnerable to degradation due to the warming climate and human activities (Huang et al., 2017; Li et al., 2016).

Existing studies have mostly focused on the direct physical damage induced by mining activities, such as damage to vegetation ecosystems surrounding mine sites due to infrastructure construction, excavation, and road construction (Alvarez-Berrios & Mitchell Aide, 2015; Sonter et al., 2014, 2017). For rainforests, physical damage leads to the degradation of vegetation, which can be detected immediately after damage via satellite observation (Sonter et al., 2017). However, unlike rainforests, two-thirds of the global coverage of herbaceous and shrub vegetation predominant in moisture-limited dry to mesic conditions lack sufficient precipitation to recover after physical damage from mining activities and mainly rely on support from the soil moisture content (SMC; 0–200 cm) and shallow groundwater (below 200 cm; Koirala et al., 2017; Madani et al., 2020; Morgan et al., 2011; Tian et al., 2019). Drylands cover ∼41% of the terrestrial land surface, accounting for ∼40% of the global net primary productivity on land (Grace et al., 2006; Huang et al., 2017; Wang et al., 2012; White & Nackoney, 2003). Thus, in addition to physical damage from mining activities, mining-induced damage to vertical water storage leads to latent and long-term impacts on water supplies for dryland vegetation. Groundwater depletion might not cause instant degradation of vegetation (Yang et al., 2018) but will sharply decrease the capabilities of local dryland vegetation to resist future drought events. However, most studies on the impacts of mining activities on vegetation have only focused on variations in the vegetation index (Li et al., 2019; Liu et al., 2019) and ignored the contributions of mining to groundwater depletion and related ecological effects. Specifically, relationships between vegetation greenness and terrestrial water storage have been identified without consideration of human-induced disturbance in recent decades (Xie et al., 2019). Only a few studies have addressed the negative impacts of large-scale open-pit coal mining on groundwater in drylands, such as lake loss (Tao et al., 2015; Zhao et al., 2017). It is thus crucial to quantify relationships between vegetation growth conditions and groundwater storage (GS) under the impact of mining activities at dryland mine sites.

Dewatering is a prerequisite for mining activity (for both open-pit and underground mines), and it strongly affects groundwater depletion (Wang et al., 2019; Xie et al., 2019). The impact of mining-induced groundwater depletion on dryland vegetation ecosystems is, however, poorly understood. Therefore, we asked the following questions: (a) How much did vegetation growth conditions and GS change at dryland mine sites over recent decades? (b) How did mining activities conducted via dewatering in recent decades impact vegetation growth conditions? Based on the positive relationship between vegetation growth conditions and GS in drylands (Koirala et al., 2017; Madani et al., 2020; Tian et al., 2019), we assumed that dewatering-induced depletion of groundwater in dryland mine sites would lead to intense degradation of vegetation in the long term. Furthermore, since mineral resources and GS are not limitless, we asked a third question: (c) How would vegetation respond to a temporary or permanent cessation of mining activities? To answer the above questions, we studied the relationships between vegetation growth conditions and GS to map mining-induced changes in GS relative to variations in vegetation growth conditions in global drylands. In addition, a regional comparison study between mining impact and nonimpact areas was also performed to study the impacts induced by mining activities on the relationships between vegetation growth and GS.

2. Methods

The whole study schematic consisted of data, indices, and analysis portions (see Figure S1 in Supporting Information S1). A detailed description of the methods and materials used in this study can be found in Supporting Information S1.

3. Data

All data used in this study were acquired from public datasets. A detailed introduction to the data can be found in Supporting Information S1.

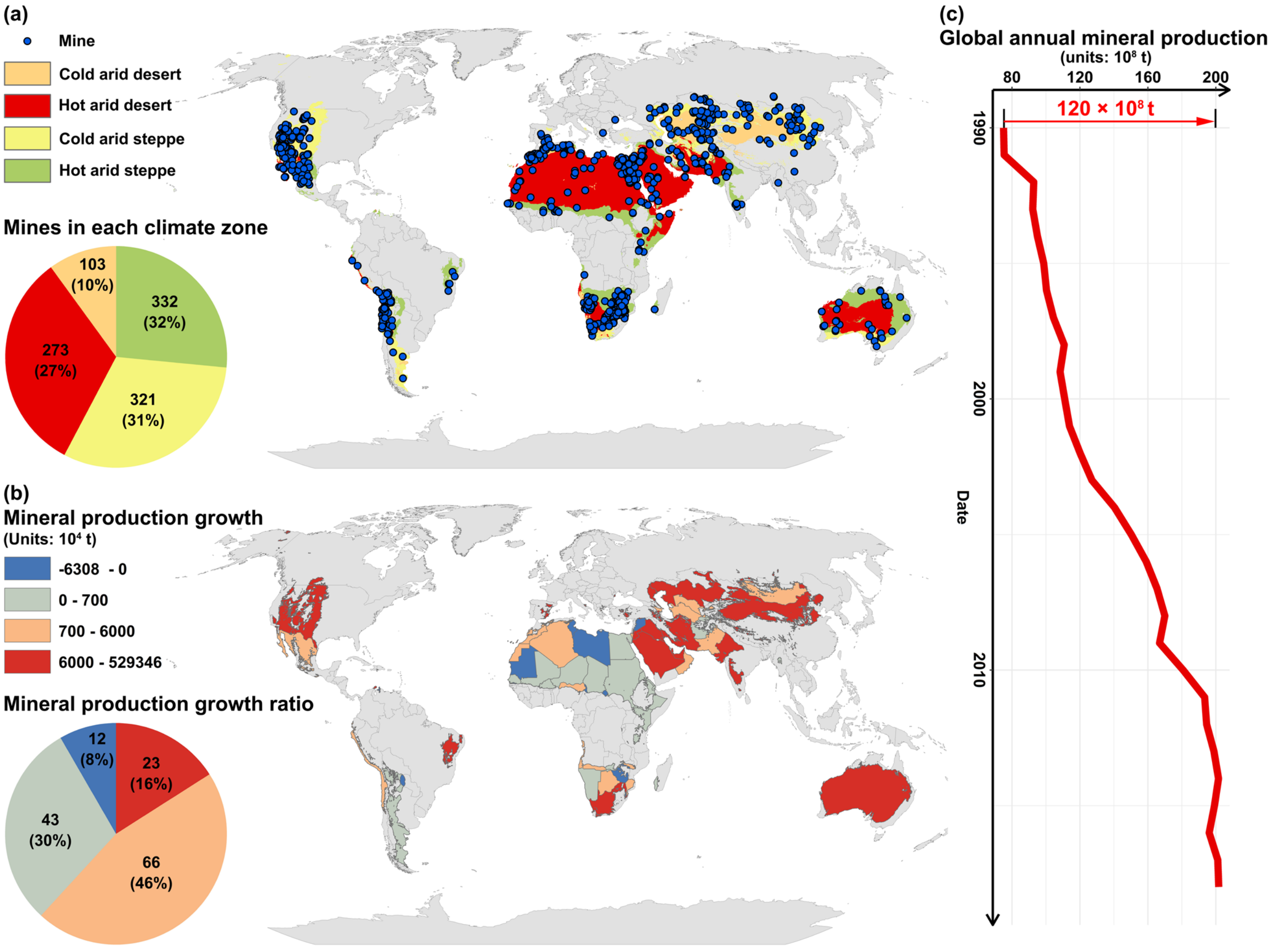

Figure 1. (a) Global spatial distribution of mines in arid and semiarid climate zones based on the Köppen-Geiger climate classification. Information about the locations of the mines was acquired from the United States Geological Survey (USGS, https://mrdata.usgs.gov/). (b) Spatial pattern of annual growth in mineral production in arid and semiarid countries worldwide from 1990 to 2018. (c) Temporal variation in the gross annual mineral production in arid and semiarid countries. Data on mineral production were acquired from the British Geological Survey (BGS, https://www2.bgs.ac.uk).

4. Increasing Mineral Production Depletes GS but Enhances Vegetation in Drylands

The growth of vegetation in arid areas depends on the supply of water from the 0 to 200 cm soil layer and from groundwater stored below 200 cm when precipitation is insufficient. Positive relationships between vegetation and its growth indicated by the NIEI and GS indicated by the NGGRACE at the monthly scale have been reported for global drylands undisturbed by human activities (Huang et al., 2017; Xie et al., 2019). Unlike water stored in the 0–200 cm soil layer, which is influenced by evaporation in drylands, groundwater stored below 200 cm may be the main source of water for the survival of most dryland vegetation during droughts. However, because of production safety, both open-pit and underground mines share the same demand for the drainage of groundwater during production. For open-pit mines, mining-induced excavation directly damages the shallow groundwater and further leads to a decrease in GS. For underground mines, the extraction of confined groundwater leads to a cone of groundwater depression, which further leads to decreases in both shallow and deep GS. Hence, we initially assumed that mining-induced decreased GS would lead to the degradation of vegetation conditions in drylands.

However, in contrast, further findings disagree with our initial assumption. The global AMP in arid and semiarid regions increased by ~120 × 10^8 t from 1990 to 2018 (Figure 1c). Increasing AMP (by 24%) over global drylands intensified the groundwater depletion indicated by the NGGRACE (decreased by 22%) and

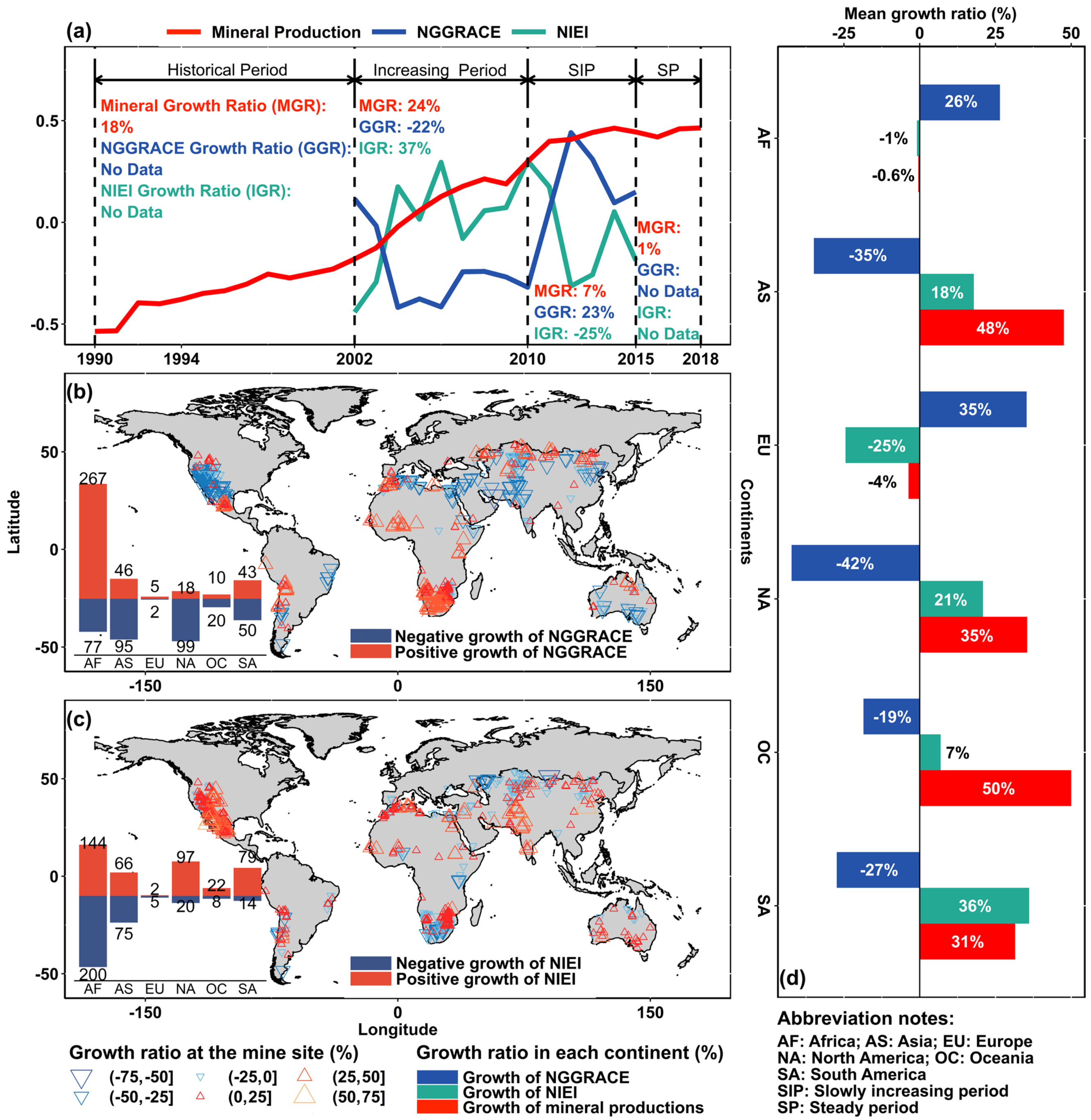

Figure 2. Spatiotemporal variations in the GS (NGGRACE), vegetation living and growth conditions (NIEI), and annual mineral production (AMP) in global dryland mining sites on both global and continental scales. (a) Annual variation in the average NGGRACE, NIEI, and AMP among global dryland mining sites. Spatial patterns of growth ratios for the (b) NGGRACE and (c) NIEI at global dryland mining sites. (d) Growth ratios of the average NGGRACE, NIEI, and AMP among dryland mining sites on a continental scale.

modified the vegetation and growth indicated by the NIEI (increased by 37%) from 2002 to 2010 (Figure 2a). On the continental scale, given that AMP increased by 48%, 35%, 50%, and 31% in drylands of Asia, North America, Oceania, and South America, the mean GS decreased by 35%, 42%, 19%, and 27% in these regions, respectively, during the period from 2002 to 2015 (Figure 2d and see Figures S2a–S2f in Supporting Information S1). In contrast, the mean vegetation biomass in these regions increased by 18%, 21%, 7%, and 36%, respectively (Figure 2d and see Figures S2a–S2f in Supporting Information S1).

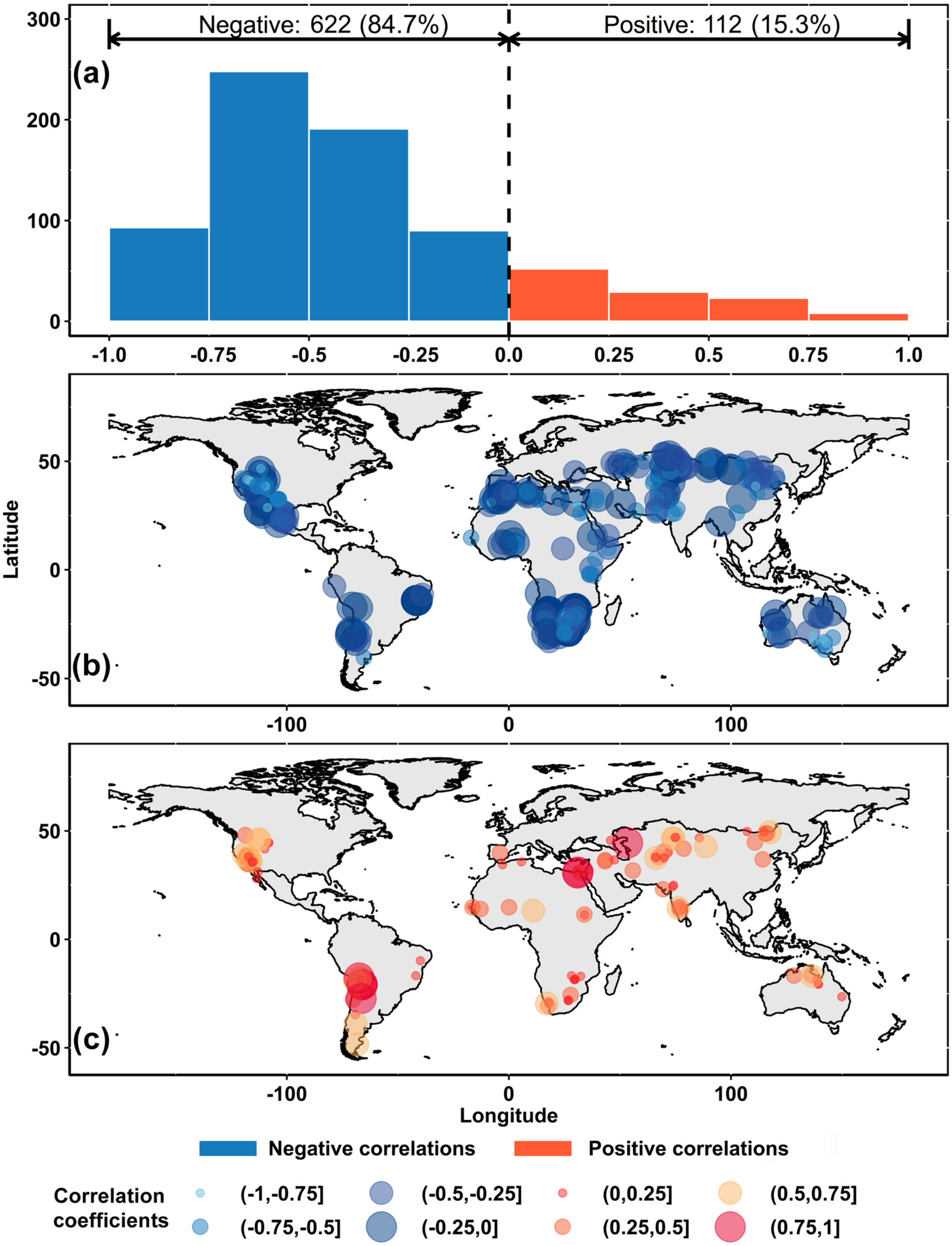

Figure 3. Spatial pattern of relationship between vegetation growth and groundwater storage (GS) for global mines under semiarid and arid climatic conditions. (a) Distribution of relationships between vegetation living and growth conditions (NIEI) and GS (NGGRACE), where blue implies a negative relation and red implies a positive relation. Spatial distributions of global mine sites with (b) negative relations and (c) positive relations.

5. Negative Relationship Between Vegetation Growth Conditions and Mining-Induced Changes in GS

The NIEI and NGGRACE were negatively correlated at 84.7% of mining sites (622 out of 734) across global arid and semiarid regions from April 2002 to December 2015 due to disturbances induced by intense mining activities and were positively correlated at only 15.3% of the sites (Figures 1 and 3). For the 84.7% of mines with negative relationships, 93% of the *p*-values were <0.05. For the 15.3% of mines with positive relationships, 65% of the p-values were <0.05 (Figure S3 in Supporting Information S1). The regional comparison study between the mining impact and nonimpact areas verified the reversed effect on the relationship between the NIEI and NGGRCE induced mainly by mining activities (Figure S4 in Supporting Information S1).

Why do negative relationships between vegetation conditions and GS dominate at these mining sites (Huang et al., 2017; Xie et al., 2019)? Dewatering is a prerequisite for mining activity (for both open-pit and underground mining) to maintain dry and stable operational surfaces (Wang et al., 2019), and dewatering depletes groundwater, as indicated by a decreased NGGRACE, and increases surface biomass, as indicated by an increased NIEI (Figure 2). We also evaluated this phenomenon in our regional study on the relation between vegetation conditions and GS under massive mining activities based on field surveys (Shen et al., 2020). Continual and widespread dewatering associated with mining further exacerbates the depletion of GS because agricultural irrigation and climate change have decreased GS and even depleted groundwater reserves (Aeschbach-Hertig & Gleeson, 2012; Condon et al., 2020; Dalin et al., 2017; Rodell et al., 2009; Scanlon et al., 2012), limiting the water supply in primary countries and regions of food production, such as central and western Asia (e.g., Iran, Pakistan, and Saudi Arabia), India, China, and North America (e.g., high plains and Central Valley in California).

It is reasonable to say that mining-induced dewatering leads to the depletion of GS. Irrigation using extracted groundwater tends to improve the vegetation conditions surrounding mine sites, as reflected by increases in the NIEI (Figures 2a and Figures S5–S8 in Supporting Information S1), which is defined as the irrigation bonus. That is, dewatering due to mining decreased GS but increased the SMC at mining sites and their surroundings, thereby decreasing GS but increasing surface biomass by increasing the SMC. Our regional study comparing mining nonimpact and impact areas also verified the irrigation bonus (Figure S4 in Supporting Information S1). However, previous studies have demonstrated that chemical components within drainage groundwater tend to threaten vegetation in different ways and on different timescales and further lead to sharp decreases in vegetation (Simate & Ndlovu, 2014). In contrast, based on our regional survey, we found that due to local environmental policies, drainage groundwater was required to be used and discharged after purification at some mines (Shen et al., 2020). In addition, based on covariations between the NGGRACE and NIEI (Figure 2a and Figures S5–S8 in Supporting Information S1), drainage groundwater increased the growth of vegetation instead of resulting in a sharp decrease in vegetation. In general, mining-induced dewatering is the main cause of the negative relationship between the NIEI and the NGGRACE in areas surrounding mine sites.

However, agricultural irrigation might be another cause resulting in the negative relationships between vegetation growth and GS. To study the impacts of agricultural production, we further analyzed the ratios of majorly irrigated cropland (with surface and groundwater as water sources) of surrounding areas in squares, each with a mine as the center and 4° distance as the side length. Based on global 1 km cropland data from the USGS (https://e4ftl01.cr.usgs.gov/), 94.41% of mine site surrounding areas contained only 0%–5% majorly irrigated cropland (see Figure S9 in Supporting Information S1), which demonstrated that groundwater irrigation for agriculture was not the major driver of groundwater depletion over 94.41% (693 out of 734) of global dryland mine sites and surrounding areas.

To determine the main water source of SMC at mine sites in drylands, we performed an attribution analysis of SMC using a linear regression model of the SMC, precipitation, and GS (see Supporting Information S1, Methods 3). GS is the main water source instead of precipitation (defined as a groundwater-dominated SMC) in >77.6% of mines under arid and semiarid climatic conditions (see Figure S10 in Supporting Information S1). Based on a conjoint analysis of water sources for the SMC and relationships patterns between vegetation growth and GS (see Methods 5 and Table S1 in Supporting Information S1), we found that a UG status occurred in 90.3% of mines with a groundwater-dominated SMC and even in 65.2% of mines with a precipitation-dominated SMC (Figure 4a). Dewatering during mining activities in arid and semiarid regions therefore interferes with the balance between vegetation conditions and GS not only in areas with a groundwater-dominated SMC but also in areas with a precipitation-dominated SMC.

The variable impact of mining activities on GS led to spatial heterogeneity in the relationships between the NIEI and NGGRACE in global arid and semiarid mining areas (Figure 3). The NIEI and NGGRACE were

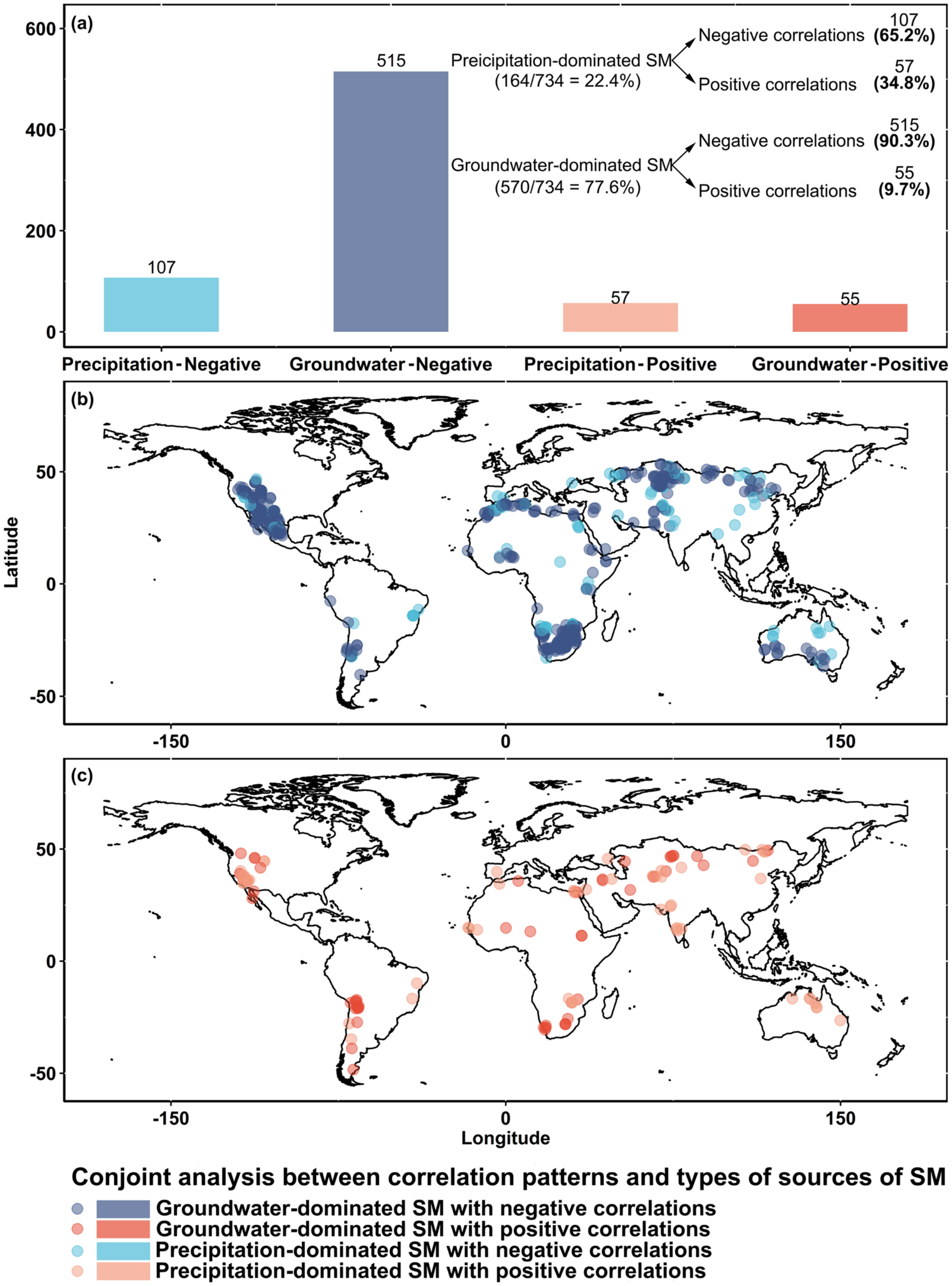

Figure 4. Conjoint analysis between water sources for soil moisture (SM) and relationship patterns between vegetation conditions and groundwater storage over global mines under arid and semiarid climatic conditions. (a) Combinations between sources of SM and the relationship patterns. (b) Spatial patterns of precipitation- and groundwater-dominated SMs with negative relationships. (c) Spatial patterns of precipitation- and groundwater-dominated SMs with positive relationships.

positively correlated at 15.3% of the mining sites, perhaps because the intensity of dewatering at these mine sites did not interfere with the natural balance between vegetation growth and GS (Figure 3a). However, it should be noted that most positive correlation coefficients between vegetation growth and GS were between 0.00 and 0.25 (Figure 3a), implying that mining activities in global drylands substantially alleviated the positive relationships by dewatering. Changes in the NIEI and NGGRACE for the weaker positive relationships tended to be abnormally discordant, based on typical case studies in South Africa and Europe (see Figures S11–S13 in Supporting Information S1). Some of the mine sites considered in this study might, however, be prospective, abandoned, or under construction phases without dewatering actions. At these mine sites, mining activities have a limited capability to interfere with the groundwater balance (Brawner, 1982). Thus, the variances of the NIEI based on case studies in North America, South America, North Africa, Asia, and Oceania were highly consistent with the variances of the NGGRCE (see Figures S11–S13 in Supporting Information S1).

6. Unsustainable Irrigation Bonuses Cover the Potential Risk of Vegetation Degradation in Drylands

We considered a follow-up question: Can this irrigation bonus from drainage water for dryland vegetation be sustained, given the steady loss of groundwater and increasing drought risk in the coming decades? The answer is certainly no, as groundwater resources and mineral extraction activities are limited. Unlike agricultural lands, the massive demand for and economic value of mineral resources may attract more attention than natural vegetation conditions, especially considering thriving vegetation under the irrigation bonus. It is most likely that the steady depletion of groundwater in areas covered by thriving vegetation have been overlooked. Since the total AMP of drylands in Africa and Europe decreased by 0.6% and 4%, the lack of intense disturbance from dewatering during mining activities led to the mean GS in Africa and Europe increasing by 26% and 35%, respectively. The loss of sufficient water supplies from GS due to dewatering caused a drop in the mean vegetation conditions in Africa and Europe by 1% and 25%, respectively.

Drylands, as defined by the aridity index, have expanded over the last 60 yr and are projected to continue to expand in the 21st century (Chen & Chen, 2013; White & Nackoney, 2003). Drying is substantial along the semiarid-to-arid to dry-to-humid transition regions, as indicated by the largest decrease in the SMC, with aridity indices in semiarid-to-arid and dry-to-humid regions ranging from 0.5 to 0.6 and from 1.0 to 1.1, respectively (Gu et al., 2019). The degradation of vegetation ecosystems will be intensified by an increase in severe droughts in the future (Yao et al., 2020), particularly in dryland vegetation ecosystems, such as shrublands, grasslands, and savannas (Morgan et al., 2011). Vegetation in drylands relies heavily on SM in the topsoil and on groundwater stored below 200 cm (Nepstad et al., 1994; Oliveira et al., 2005). In this study, these two sources of water were strongly influenced by evapotranspiration and human activities (Shen et al., 2020; Xie et al., 2019), such as mining-induced dewatering. Mining activities decreased GS but increased the extracted water used for irrigating vegetation; thus, the biomass of vegetation ecosystems increased (NIEI, see Figures S6 and S7 in Supporting Information S1). Such an increase in the biomass of vegetation ecosystems, however, is temporary and expected to decrease due to the lack of water supply from mining dewatering after the temporary or permanent closure of mining sites. Droughts will trigger the degradation of drylands in the coming decades based on Coupled Model Intercomparison Project Phase 5 (CMIP5) projections (White & Nackoney, 2003; Yao et al., 2020). Uncertainties and ambiguities, however, will be introduced into our understanding of changes in the SMC and groundwater and associated impacts on vegetation variations by failure to consider the impact of mining activities on GS (Schlaepfer et al., 2017; Tao et al., 2015; Xie et al., 2019).

The impact of mining activities on ecosystems in arid and semiarid regions is less visible than that of deforestation from physical clearing and building infrastructure in regions with tropical rainforests (Alvarez-Berrios & Mitchell Aide, 2015; Sonter et al., 2014, 2017) since the consequences are delayed. Mining-induced dewatering depletes groundwater, altering the local hydrological cycle and causing a UG status. This process takes time. Vegetation near mining sites is expected to become green in the short term because of the irrigation bonus, but this vegetation greening is not sustainable. Vegetation can also degrade due to temporarily or permanently terminated groundwater-related irrigation because of shifts in the production plan or the closure of mining sites (see Figures S6–S8 in Supporting Information S1), and these phenomena are globally prevalent. Groundwater depletion is unavoidable in regions where groundwater irrigation is dominant (Aeschbach-Hertig & Gleeson, 2012; Condon et al., 2020; Dalin et al., 2017; Rodell et al., 2009; Scanlon et al., 2012); therefore, the expansion of arid regions and drying tendency of the SMC within deeper soil layers could accelerate mining-induced groundwater depletion in a warming climate. This accelerated depletion would further exacerbate groundwater shortages and create pronounced degradation risks for vegetation in drylands (Schlaepfer et al., 2017; Shen et al., 2020; Yao et al., 2020). The negative relationships between vegetation growth and GS detected in 84.7% of global mines raise concerns about the likely massive degradation of vegetation in drylands, given the dense distribution of mine sites in drylands (Figures 1 and 3).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

And the data and codes used in this study have been upload to the Github repository for public. And the link of the repository is https://zenodo.org/badge/latestdoi/330483257. And the DOI for the repository is https://doi.org/10.5281/zenodo.4750998.

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