CLIMATE CHANGE RISKS FOR COPPER MINE CLOSURE IN THE AMERICAS: REGIONAL ANALYSIS USING GEOSPATIAL AND QUANTITATIVE METHODS

by

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GLOSSARY or NOMENCLATURE

Acid Rock Drainage (ARD)
The outflow of acidic water from mine waste, caused by the oxidation of sulfide minerals, often leading to metal leaching and environmental contamination.

Aridity Index (AI)
A measure of long-term moisture availability, calculated as the ratio of precipitation to potential evapotranspiration. Lower values indicate drier conditions.

Climate Model Intercomparison Project Phase 6 (CMIP6)
A coordinated global climate modeling effort that provides standardized climate projections under various greenhouse gas emissions scenarios.

Coupled Model Intercomparison Project (CMIP6) Scenarios
Shared Socioeconomic Pathways (SSPs) used in climate modeling which include:

- **SSP126 (Low Emissions Scenario):** A sustainability-focused scenario with rapid decarbonization and limited global warming.
- **SSP245 (Intermediate Emissions Scenario):** A middle-of-the-road scenario with moderate climate policies and technological advancements.
- **SSP585 (High Emissions Scenario):** A fossil-fuel-intensive scenario leading to high greenhouse gas concentrations and severe climate impacts.

Drought Probability Distribution (DPD)
A statistical measure estimating the likelihood of drought occurrence over a historical period based on precipitation trends.

Drought Frequency Index (DRFE)
A measure identifying the frequency of extreme drought events based on historical and projected climate data.

Köppen-Geiger Climate Classification
A widely used system that categorizes global climate zones based on temperature and precipitation patterns. Used to assess climate shifts in mining regions.

Mine Closure Planning
The process of designing and implementing strategies for environmental stabilization, water management, and land reclamation after mining operations cease.

Pit Lake Hydrology
The study of water balance, quality, and stability in open-pit mines that have been filled with water post-closure.

Rainfall Erosivity Factor (R-Factor)
A measure of the erosive power of rainfall, calculated based on precipitation intensity and duration, which influences soil erosion risk.

Revegetation
The process of re-establishing vegetation on disturbed mine lands to enhance soil stability, prevent erosion, and restore ecological function.

Standardized Precipitation-Evapotranspiration Index (SPEI)
A multi-scalar drought index that quantifies drought severity by considering both precipitation and potential evapotranspiration.

Shared Socioeconomic Pathways (SSPs)
Are scenarios used in climate modeling that describe different ways global society, demographics, and economics might change over the 21st century. They are paired with greenhouse gas concentration trajectories to evaluate how future social and economic developments could influence climate change impacts and mitigation or adaptation challenges.

Tailings Storage Facility (TSF)
An engineered structure designed to store fine-grained mining waste materials (tailings) that remain after ore processing.

Transitional Climate Shifts
Climate variability that causes fluctuations between wet and arid conditions rather than a consistent trend toward aridification or wetting.

Water Balance
The assessment of water inputs and outputs in a system, considering precipitation, evaporation, runoff, and groundwater exchange, essential for hydrological stability in mine closure planning.

ABSTRACT

Climate change is creating new challenges for mine closure, especially in copper-producing regions where shifting precipitation, prolonged droughts, and extreme weather events threaten long-term stability. These risks are particularly acute in arid and semi-arid regions like the Southwestern United States and Western South America, where copper mining is concentrated and water scarcity already complicates post-mining reclamation. This study evaluated climate-driven closure risks across seven major copper regions using CMIP6 climate projections and Köppen-Geiger classifications. Scenarios under low (SSP126), intermediate (SSP245), and high (SSP585) emissions pathways were analyzed for two future periods: 2041–2070 and 2071–2099, compared against a historical baseline (1991–2020). Six climate indices were calculated to quantify risk: the Standardized Precipitation-Evapotranspiration Index (SPEI), Aridity Index (AI), Drought Frequency (DRFE), Drying Period Duration (DPD), Annual Maximum 1-day Precipitation (RX1day), and Rainfall Erosivity (R-Factor). Geospatial analysis identified regions with shifts in climate classification, highlighting areas vulnerable to drying trends, precipitation extremes, and transitional instability. Results show widespread aridification in the Arizona Copper Belt, Great Basin Copper Region, and Northern Chilean Copper Belt, particularly under SSP585. Declining AI and increased drought frequency signal heightened water stress, posing risks to pit lake hydrology, revegetation, and acid rock drainage. In contrast, the Southern Chilean and Central Peruvian Copper Belts exhibit increasing precipitation intensity, raising concerns over flooding, tailings stability, and erosion. The Northwestern Argentina Copper Belt shows high climate variability, complicating closure planning due to unstable wet-dry patterns. These findings underscore the need for climate-adaptive closure strategies. Future mine closure planning should incorporate hydrological modeling, slope stability assessments, and regulatory frameworks that account for long-term climate risks. As global copper demand rises, proactive adaptation in mining practices, water management, and reclamation will be essential to ensure environmentally responsible and resilient closures.

CHAPTER ONE

INTRODUCTION

Problem Statement

The mining industry, particularly copper mining, faces growing challenges in balancing operational demands with environmental responsibilities. Climate change is increasingly recognized as a critical factor in long-term mine closure planning, complicating efforts to mitigate environmental risks. Changes in temperature, precipitation patterns, and extreme weather events directly impact key closure risks, including acid rock drainage (ARD), revegetation success, and contamination of groundwater and soils.

One of the most significant risks is acid rock drainage (ARD), as climate-driven shifts in precipitation and drought cycles can accelerate acid formation or mobilize acidic, metal-laden water from mine waste, causing long-term environmental damage. Similarly, revegetation efforts, essential for stabilizing disturbed mine lands, depend on consistent climatic conditions. Prolonged droughts or unseasonal rainfall can hinder vegetation establishment, increasing the risk of erosion and land degradation. Groundwater and soil contamination, often linked to tailings seepage and waste mismanagement, is further influenced by climatic variability, requiring adaptive closure strategies that integrate climate resilience. Copper mining regions in the Americas, including the Atacama Desert, the Central Andes, and the arid Western United States, are particularly vulnerable to climate change due to water scarcity and ecological sensitivity. However, region-specific mine closure strategies remain underexplored, creating a significant gap in understanding and preparedness. Therefore, my study addresses that gap by

evaluating climate-driven risks to mine closure in high-risk copper-producing regions and exploring adaptive strategies informed by CMIP6 climate models and Shared Socioeconomic Pathway (SSP)-based projections.

Knowledge Gap

Recent research by Bulovic et al. (2024) evaluated climate-related mine closure risks in Australia, with a focus on Queensland. In contrast, the research presents an independent analysis that applies a similar risk framework to copper mining regions across the Americas, where comparable assessments have been lacking. Chile, Peru, and the Southwestern United States represent a major share of global copper production, collectively accounting for approximately 39% of the world's total output in 2024 (U.S. Geological Survey [USGS], 2024; Investing News Network, 2024). Chile alone contributed 5.3 million metric tons (23%), Peru 2.6 million metric tons (11%), and the United States 1.1 million metric tons (5%) (USGS, 2024). Yet, these regions' arid and semi-arid climates, water scarcity challenges, and regulatory frameworks introduce unique closure risks that require a region-specific approach. Although research has explored the environmental impacts of copper mining and the effects of climate change on mine closure, fewer studies have specifically examined how increasing copper demand, driven by global renewable energy goals, intersects with climate-related closure risks. As copper remains essential for electric vehicles, solar panels, and grid infrastructure, the expansion of mining operations may exacerbate environmental risks, particularly related to ARD, groundwater contamination, landform stability, and revegetation success.

Research Questions

Using CMIP6 climate projections, Shared Socioeconomic Pathways (SSPs), and geospatial analysis, the research evaluates how climate change may influence closure challenges across copper-producing regions in the Americas. The key research questions include:

- How will climate change impact critical mine closure risks, including ARD, pit lake hydrology, landform stability, flood risk, and revegetation success in major copper-producing regions?
- How will increasing copper demand, driven by renewable energy expansion and global electrification, influence the scale and severity of closure-related environmental risks?
- What adaptive strategies, informed by climate modeling and geospatial analysis, can be implemented to mitigate long-term climate-induced risks in copper mine closures across the Southwestern United States and the Andes?

Significance

Copper is indispensable to the global energy transition and will underpin the development of renewable energy infrastructure. Demand for copper is projected to nearly double by 2050, driven by use in technologies such as solar panels, wind turbines, and electric vehicles. As production intensifies to meet this demand, mining operations, and their eventual mine closures, will pose increasingly complex environmental risks. The Americas, home to some of the world's largest copper mining regions, will be at the forefront of this transition. The Atacama Desert and Central Andes in South America, and the arid regions of the western United States, collectively account for a major share of global copper production, with the Central Andes alone responsible for approximately 39% of global output (Garzione & Eiler, 2018; USGS, 2024). Chile, home to

the Atacama Desert, remains the world's largest copper producer, while Arizona dominates U.S. production (EPA, 2008). In investigating climate-induced risks specific to these regions, I aim to provide insights that can inform mining companies, policymakers, and environmental advocates. Developing adaptive mine closure strategies informed by climate projections can minimize long-term environmental and social impacts, aligning copper mining practices with global sustainability goals. The analysis contributes to a growing body of knowledge by emphasizing the need for forward-looking, region-specific solutions as climate change and resource demand accelerate. The CMIP6 climate models, using SSPs, provide scenario-based projections to assess the long-term effects of temperature, precipitation, and extreme weather patterns on mine sites. SPEI (Standardized Precipitation-Evapotranspiration Index) and AI (Aridity Index) help predict water availability for pit lakes and revegetation, while RX1day (Extreme Daily Precipitation) informs risk assessments for tailings storage facilities (TSF) and erosion-prone landscapes.

CHAPTER TWO

LITERATURE REVIEW

Climate Change and Mining

Climate change poses significant challenges to mine operations and closure, affecting infrastructure stability, water management, and long-term environmental recovery. Increasing occurrence of extreme weather events such as heavy rainfall, storms, and prolonged droughts amplify risks to tailings storage facilities (TSFs), pit lakes, landform stability, and revegetation efforts (IISD, 2022). Failures in TSFs, as seen in Canada's Mount Polley (2014) and Brazil's Brumadinho (2019) disasters, highlight the catastrophic consequences of climate-driven infrastructure instability, including water contamination, ecosystem destruction, and human casualties (Macklin et al., 2016; Hatamura, 2020).

Mine hydrology is also affected by climate change. Increased precipitation intensifies ARD, while drought conditions limit water availability for operations and reclamation (Karam & Holmes, 2018). In arid regions such as Chile's Atacama Desert, copper mines rely on desalination and wastewater recycling to mitigate water shortages (Orellana et al., 2024). Conversely, flooding in high-rainfall regions like Papua New Guinea and Canada accelerates ARD formation, increasing the risk of heavy metal contamination in groundwater (Northey et al., 2017). Meanwhile, in desert mining regions like Australia's Pilbara, heat stress accelerates soil degradation, complicating revegetation and post-closure land rehabilitation (Valdivia et al., 2019). Understanding future climate risks is essential for effective mine closure strategies.

Regional Focus

The Andes and the Atacama Desert in South America and the Southwestern United States are among the world's most critical copper-producing regions, essential for global supply chains and the low-carbon transition. Chile and Peru account for over 40% of global copper production, supplying metals for renewable energy, electric vehicles, and power grids (Orellana et al., 2024). Similarly, Arizona and New Mexico remain key domestic producers in the United States, supporting North America's clean energy growth (Hodgkinson & Smith, 2021) (Table 1).

Table 1. Major copper mines: Locations, status, and estimated annual production.

Mine Name	Country	State/Region	Latitude	Longitude	Status	Details	Ownership	Estimated* Annual Production (tons)
Taca Taca	Argentina	Salta	-25.65	-66.5	In Process	Planned 2025	First Quantum Minerals	244,000
Los Azules	Argentina	San Juan	-30.17	-69.48	In Process	Planned 2027	McEwen Mining	180,000
Chuquicamata	Chile	Atacama	-22.33	-68.92	Active	Until 2057	Codelco	330,000
Escondida	Chile	Atacama	-24.261	-69.076	Active	Until 2078	BHP	1,000,000
Collahuasi Mine	Chile	Antofagasta	-20.786	-68.637	Active	Until 2088	Glencore Plc	630,000
El Teniente Mine	Chile	Cachapoal	-34.081	-70.374	Active	Until 2072	Codelco	463,000
Los Bronces Mine	Chile	Santiago	-33.242	-70.282	Active	Until 2057	Anglo American	328,000
Sierra Gorda	Chile	Antofagasta	-23.56	-69.25	Active	Until 2038	South32 & KGHM	N/A
Gabriela Mistral	Chile	Atacama	-22.33	-69.78	Active	Until 2035	Codelco	N/A
El Abra	Chile	Antofagasta	-21.97	-68.91	Active	Until 2045	Freeport-McMoRan & Codelco	N/A
Cerro Verde	Peru	Central_Andes	-16.538	-71.632	Active	Until 2051	Freeport-McMoRan	450,000
Antamina Mine	Peru	Ancash	-9.48	-77.347	Active	Until 2028	Glencore Plc	426,700

Las Bambas Project	Peru	Apurimac	-14.089	-72.065	Active	Until 2038	China Minmetals	383,600
Toquepala Mine	Peru	Tacna	-17.256	-70.408	Active	Until 2049	Grupo Mexico	231,200
Antapaccay Mine	Peru	Cusco	-14.766	-71.636	Active	Until 2031	Glencore Plc	197,000
Quellaveco	Peru	Moquegua	-17.25	-70.8	In Process	Started 2022	Anglo American	300,000
Constancia	Peru	Cusco	-14.06	-71.36	Active	Until 2045	Hudbay Minerals	N/A
Pampacancha	Peru	Cusco	-14.05	-71.38	Active	Until 2040	Hudbay Minerals	N/A
Morenci Mine	USA	Arizona	33.0481	-109.335	Active	Until 2044	Freeport-McMoRan	450,000
Bingham Canyon	USA	Utah	40.523	-112.151	Active	Until 2032	Rio Tinto	250,000
Safford Mine	USA	Arizona	32.9472	-109.6509	Active	Until 2053	Freeport-McMoRan	100,000
Sierrita Mine	USA	Arizona	31.8739	-111.1339	Active	Until 2080	Freeport-McMoRan	95,000
Bagdad Mine	USA	Arizona	34.5847	-113.2119	Active	Until 2101	Freeport-McMoRan	100,000

*Note: Estimated annual production values are based on publicly available reports, industry databases, and government repositories, which include the U.S. Geological Survey (USGS) Mineral Commodity Summaries, the Chilean Copper Commission (COCHILCO), the Peruvian Ministry of Energy and Mines (MINEM), and the Argentine Geological and Mining Survey (SEGEMAR), S&P Global Market Intelligence and the International Copper Study Group (ICSG). Mines with N/A indicate that no verifiable production estimates were found at the time of compilation. Status designations reflect either active operations, planned future production, or closure timelines as reported by ownership entities. Production estimates are rounded to the nearest 1,000 metric tons.

The Andes and Atacama Desert

The Atacama Desert is one of the driest regions on Earth and faces declining precipitation due to climate change and worsening water scarcity (Valdivia et al., 2019). In the Peruvian Andes, glacial retreat is reducing freshwater runoff, increasing competition for water resources between mining, agriculture, and local communities (Orellana et al., 2024). Extreme weather events pose additional risks. Landslides and flash floods have triggered TSF failures, contaminating local water sources with heavy metals and acidic runoff (Hodgkinson & Smith, 2021). In high-altitude regions, freeze-thaw cycles weaken TSF structures, increasing failure risks (Baisley et al., 2016). Mining companies are integrating geospatial monitoring and climate risk assessments to enhance TSF stability and long-term resilience (Bulovic et al., 2024).

The Southwestern United States

The Southwestern United States faces distinct climate-related mining challenges, particularly in Arizona, New Mexico, and Nevada. Although the region benefits from strong regulatory frameworks, issues such as water scarcity, aging infrastructure, and groundwater contamination pose growing concerns (Schmaus, 2023).

Arizona, which produces more than 60% of U.S. copper, has been affected by prolonged droughts, straining mining operations, agriculture, and Indigenous water rights (Brown & Peterson, 2021). To address these challenges, companies like Freeport-McMoRan have invested in aquifer recharge and water recycling systems to reduce reliance on freshwater from the Colorado River (Northey et al., 2017). Despite these efforts, the ongoing megadrought, the worst in 1,200 years, continues to threaten long-term water availability for large-scale mining

(Schmaus, 2023). Groundwater contamination is another persistent issue, particularly near legacy mining sites where ARD remain problematic (Odell et al., 2018). For instance, elevated levels of arsenic and sulfates have necessitated costly remediation efforts at New Mexico's Copper Flat Mine, (Macklin et al., 2016). To mitigate these effects, regulatory agencies now require synthetic liners and enhanced tailings encapsulation to minimize seepage and protect aquifers (Ruiz et al., 2022).

Aging TSFs in Nevada's historic mining districts pose additional risks, as older structures were not designed for the increasing frequency of extreme weather events (Brown & Peterson, 2021). Companies are implementing revegetation and bioengineering techniques to stabilize tailings dams and prevent erosion-related failures. Additionally, researchers are exploring phytoremediation strategies, using plants to absorb and neutralize toxic heavy metals in mine-impacted soils (Anderson et al., 2020). Utah, home to the Bingham Canyon Mine (Kennecott Copper Mine), ranks as the second-largest copper-producing state in the U.S. Unlike Arizona, Utah's mining operations are less vulnerable to extreme drought but face risks from wildfires, tailings dam stability, and air pollution (Macklin et al., 2016). Rio Tinto, which operates Bingham Canyon, has invested in renewable energy, automated water recycling, and climate monitoring technologies to enhance resiliency (Hodgkinson & Smith, 2021). Utah's regulatory framework also ensures strict reclamation and sustainability standards, providing a structured approach to environmental oversight (Brown & Peterson, 2021).

Both regions illustrate how climate factors shape mining adaptation strategies. Andean operations focus on alternative waste supply, glacial runoff management, and extreme weather

mitigation, the Southwestern U.S. emphasizes groundwater protection, tailings management, and adaptive infrastructure management.

Identification of Key Mine Closure Risk Elements

Mine closure planning requires a comprehensive understanding of environmental factors that influence the long-term stability and sustainability of post-mining landscapes. Climate variability and projected changes under different emissions scenarios directly impact several critical mine closure risk elements. Building on existing literature and industry standards, I focus on four key risk categories: hydrology, revegetation, landform stability, and dust and contaminant dispersion. These categories represent the primary environmental processes affecting effective mine site rehabilitation, sustainable water balance, and long-term environmental stewardship.

There are five key elements of climate-sensitive mine closure risks (Figure 1, Panel A), highlighting how climate change influences hydrological stability, ARD, revegetation success, flood risk, and landform integrity. The conceptual framework (**Figure 1**, Panel A) includes the IPCC Representative Concentration Pathways (RCPs) (Panel B) which is the context for future climate projections and copper demand trends (Panel C) highlights the challenge of managing closure risks in an era of increasing resource demand. The specific climate-driven closure risks/elements and its associated biophysical indicator(s) (**Table 2**). These risks, including pit lake hydrology shifts, extended droughts affecting revegetation, increased ARD formation, and heightened erosion and flood risks, are quantified using climate indices such as the Aridity Index (AI), Drought Frequency Index (DRFE), and Rainfall Erosivity Factor (R-factor). Each of these

indices is derived from CMIP6 projections variables precipitation (P) and potential evapotranspiration (PET) (Table 2).

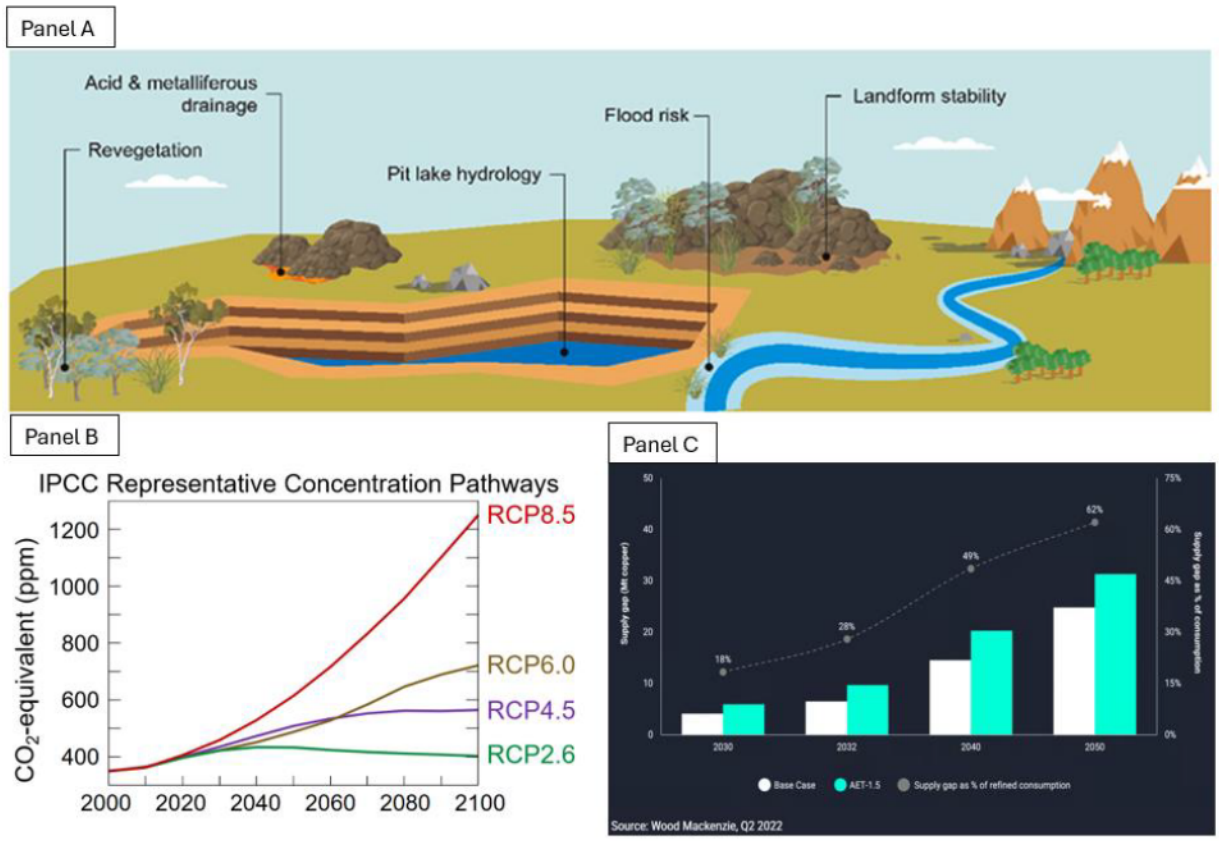


Figure 1: Climate-Sensitive Mine Closure Considerations, IPCC Emissions Pathways, and Copper Demand Projections.

Notes: Panel A presents a conceptual diagram adapted from Climate Change Risks to Mine Closure (Bulovic et al., 2024), illustrating five primary mine closure risk elements influenced by climate change, including revegetation, acid rock drainage/metal leaching, pit lake hydrology, flood risk, and landform stability. Panel B depicts the IPCC Representative Concentration Pathways (RCPs), sourced from the Intergovernmental Panel on Climate Change (IPCC, 2013; accessed April 30, 2025), which show atmospheric CO_2-equivalent concentration (parts per million, ppm) across different future emissions scenarios. Panel C illustrates projected copper supply-demand trends based on industry analysis from Wood Mackenzie, 2022, highlighting a widening supply gap driven by increasing global electrification and renewable energy adoption.

Table 2: Climate-driven mine closure risks and biophysical indicators.

Closure Risk Element	Time Frame	Principal Biophysical Attribute	Index	Climate Variables	Potential Climate Shift Repercussions
Pit Lake Hydrology	Multi-decadal	Water Balance	Aridity Index (AI)	P, PET	Lower AI indicates drier conditions, which could reduce pit lake recharge and increasing salinity risks.
Revegetation	Seasonal	Extended Droughts	Frequency of Extreme Droughts (DRFE)	P, PET	Increased DRFE leads to longer dry periods, which could reduce revegetation success and soil stability.
Acid Rock Drainage (ARD)	Multi-decadal	Drying Period Duration	Drying Period Duration (DPD)	P, PET	Higher DPD extends acid drainage risks, increasing metal leaching and contamination potential.
Landform Stability	Seasonal	Storm Erosive Power	Rainfall Erosivity (R-factor)	P	Higher R-factor increases erosion risks, which stresses tailings and waste rock stability.
Flood Risk	Episodically-Extreme Rainfall Events	Annual Maximum 1-day Precipitation	Annual Maximum 1-day Precipitation (RX1day)	P	Increased RX1day raises flood risks, stressing infrastructure.

Note: Adapted from Bulovic et al. (2024) and additional sources, including Beck et al. (2023), O'Neill et al. (2017), Renard et al. (1997), and Vicente-Serrano et al. (2010). Climate indices and biophysical attributes are derived from CMIP6 projections, with precipitation (P) and potential evapotranspiration (PET) are the primary climate variables utilized.

Acid Mine Drainage

The risk of ARD varies by climate and minerology of the site-specifics of the mine. Wet regions, such as Southeast Asia and Canada, experience accelerated sulfide oxidation due to heavy rainfall, increasing acidic runoff and metal mobility (Northey et al., 2017). In contrast, arid regions like Chile's Atacama Desert see slower ARD formation, but intense rainfall events can rapidly mobilize stored contaminants, causing sudden spikes in pollution (Valdivia et al., 2019).

Pit Lakes & Hydrology

Hydrological stability is a fundamental consideration in mine closure, particularly for open-pit mines that may develop pit lakes post-closure. The balance between precipitation, evaporation, and groundwater exchange dictates the long-term water levels and potential water quality issues such as acidification and salinity accumulation. Changes in aridity, precipitation regimes, and evapotranspiration under different climate scenarios influence the hydrologic equilibrium of pit lakes, as well as broader groundwater recharge dynamics. Climate indices such as the SPEI and AI are used to quantify hydrological stress and potential shifts in water availability over time (Bulovic et al., 2024).

Revegetation

Successful mine closure often requires ecosystem rehabilitation, including the re-establishment of vegetation to stabilize landforms and restore ecosystem function. Water availability and soil properties are critical determinants of revegetation success, particularly in arid and semi-arid mining regions. Extended droughts or shifts in Köppen-Geiger climate zones may limit native

plant species' viability, necessitating adaptive closure strategies such as modified seed mixes or artificial irrigation measures (Bulovic et al., 2024).

Landform Stability

Mine closure designs often involve engineered waste rock dumps, tailings storage facilities, and reshaped landforms to prevent erosion and geotechnical failure. Climate-driven changes in precipitation intensity, freeze-thaw cycles, and extreme wind events influence the long-term stability of these landforms. Heavy precipitation can trigger gullying and slope failures, while prolonged droughts and increased temperatures can lead to soil desiccation and cracking (Bulovic et al., 2024).

Flood Risk

Extreme rainfall can result in flooding of infrastructure such as roads and tailings storage facilities, potentially limiting access or leading to structural or geotechnical failures. For example, a primary cause of tailings dam failures has been unusually high rainfall (Azam and Li, 2010). The RX1day index was selected for use in this study. RX1day index estimates the mean annual maximum 1-day precipitation intensity (in mm) (Bulovic et al., 2024).

Copper Demand Projections

The transition to a low-carbon economy has intensified demand for copper, which is a key material in renewable energy, electric vehicles (EVs), and power infrastructure (IEA, 2021). Global copper demand is projected to nearly double by 2050, driven by electrification, renewable energy expansion, and EV production (World Bank, 2020). An EV requires nearly four times more copper than a conventional vehicle, while offshore wind farms use significantly more

copper per megawatt than coal-fired plants (Hodgkinson & Smith, 2021). As the industry responds to address this significant supply gap, greater environmental and social impacts may result. In general, ore extraction and processing generate large volumes of waste, with tailings disposal contributing to habitat disruption, deforestation, and land degradation (Chavez et al., 2022; Mavrommatis et al., 2019). Refining processes which if not managed correctly can release sulfur dioxide, leading to air and water pollution, acid rain, and biodiversity loss (Odell et al., 2018). Additionally, copper reserves are concentrated in a few key regions, with Chile, Peru, China, and the Democratic Republic of the Congo accounting for over 60% of global production (Orellana et al., 2024). The Andes has become a critical mining hotspot but faces water scarcity, social conflicts, and regulatory uncertainty (Valdivia et al., 2019). In Chile's Atacama Desert, declining freshwater supplies have forced mining companies to invest in desalination plants, increasing operational costs and energy consumption (Lyon et al., 2019). Copper mining in the Southwestern U.S. faces growing concerns over aging tailings storage facilities, groundwater contamination, and stricter water regulations due to prolonged droughts in Arizona and New Mexico (Schmaus, 2023; Baisley et al., 2016).

CHAPTER THREE

METHODS

Data Source Determination & Acquisition

In this section, I outline my methodological approach, explaining the analytical steps and data sources I used to assess how climate change may impact mine closure, as summarized in Figure 2.

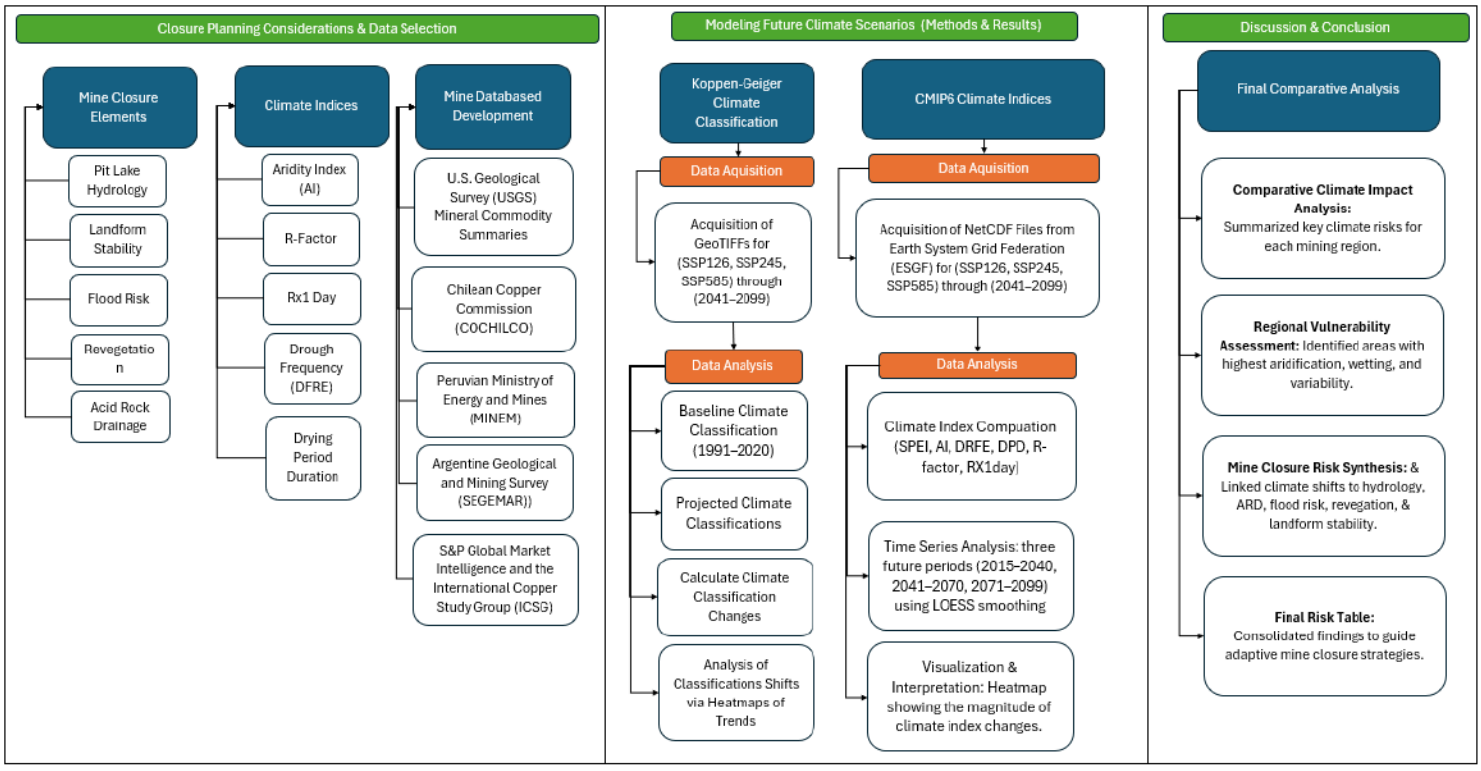


Figure 2. Study workflow and methodological framework for climate and mine closure analysis.

Coupled Climate Projections: CMIP6 Models and SSP Scenarios

To evaluate climate futures, I used three SSP scenarios from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (O'Neill et al., 2017), representing different socio-economic and emissions trajectories:

- **SSP1-2.6 (Low Emissions):** Sustainability-focused with rapid decarbonization and international cooperation. Emissions peak by 2050 and then decline which limits warming to 1.5–2 °C by 2100.
- **SSP2-4.5 (Intermediate Emissions):** A moderate scenario where socio-economic trends follow historical patterns. Emissions rise until mid-century and then then stabilize, leading to 2.5–3 °C warming.
- **SSP5-8.5 (High Emissions):** A fossil-fuel-intensive scenario with weak climate policies where CO_2 concentrations exceed 1000 ppm by 2100 and result in >4 °C warming.

Climate Classification Type Data Selection

Historical (1991–2020) and future (2041–2070, 2071–2099) Köppen-Geiger climate classification datasets were sourced from Beck et al. (2023) who developed high-resolution (1 km) climate maps using constrained CMIP6 projections. These datasets provide a standardized classification of climate zones based on temperature and precipitation patterns. The Köppen-Geiger climate classification maps were acquired in GeoTIFF format (example koppen_geiger_0p1.tif) for the selected time periods (1991–2020, 2041–2070, and 2071–2099).

These files were obtained from publicly available repositories linked to Beck et al. (2023), which ensured that they have consistency with CMIP6 SSP projections.

Climate Index Data Selection & Acquisition

Climate indices were derived from precipitation and potential evapotranspiration data from CNRM-CM6-1 outputs (Table 3). CMIP6 data were accessed via the Earth System Grid Federation (ESGF) portal through the ESGF data repository (https://esgf-node.ipsl.upmc.fr/). Monthly Pr and PET datasets with time periods spanning 2015 to 2100 were downloaded in NetCDF format (.nc) at 250 km resolution per grid cell. Data retrieval was conducted using ESGF's Wget script, which extracted NetCDF files from URLs. Once downloaded, datasets were verified for completeness, checking source institution (CNRM-CERFACS), model identifier (CNRM-CM6-1), experiment identifiers (ssp126, ssp245, ssp585), and units (kg m^{-2} s^{-1} for precipitation, W m^{-2} for evapotranspiration).

Table 3: Derived climate indices and calculation methods for mine closure risk assessment.

Climate Index	Calculation	Required Variables
SPEI (Standardized Precipitation-Evapotranspiration Index)	$SPEI = (P - PET)/\sigma$ (where σ is the standard deviation of the water balance deficit over time)	P, PET
AI (Aridity Index)	$AI = P/PET$	P, PET
DRFE (Drought Frequency Index)	Derived from SPEI using frequency analysis over a given period	SPEI-derived
DPD (Drought Probability Distribution)	Probability function of P over a historical period to estimate drought occurrence likelihood	P
R-factor (Rainfall Erosivity Factor)	$R=\sum E \cdot I_{30}$ (where E is rainfall energy and I_{30} is the maximum 30-minute intensity of precipitation)	P

RX1day (Maximum 1-day Precipitation)	RX1day=max(P) over a given time window	P (Max 1-day event)

Note: Climate indices and calculation methods adapted from Vicente-Serrano et al. (2010), Renard et al. (1997), UNEP (1997), and related sources. Indices quantify hydrological variability, drought severity, and precipitation extremes relevant to mine closure risk assessment.

Data Processing & Analysis

Climate Classification Change Analysis

Köppen-Geiger maps in GeoTIFF format were processed in R (v4.1.2) using spatial analysis libraries (terra, sf, ggplot2, tidyverse). Raster datasets were cropped, resampled, and converted to categorical data for standardized visualization (Beck et al., 2023). Climate classification changes were analyzed by comparing historical (1991–2020) and future (2041–2070, 2071–2099) classifications under three SSP scenarios (SSP126, SSP245, SSP585) across the seven mining regions. The seven mining regions were derived using best judgement of areas that are proximate to each other and have similar climates for accuracy of the regional analysis:

- Arizona Copper Belt (ACB)
- Great Basin Copper Region (GBC)
- New Mexico Copper Region (NMC)
- Northern Chilean Copper Belt (NCC)
- Southern Chilean Copper Belt (SCC)
- Central Peruvian Copper Belt (CPC)
- Northwestern Argentina Copper Belt (NAC)

Each grid cell was classified as stable or changed, with classification shifts quantified as:

$$\%Change = \left(\frac{N\ change}{N\ total}\right) * 100$$

where:

N_{Change} is the number of grid cells that change to a different climate classification.
N_{Total} is the total number of grid cells in the mining sub-region.

Aggregation and Categorization of Climate Transitions

Climate classifications were grouped into four broad categories to assess dominant climate trends in mining regions, following the Köppen-Geiger framework (**Figure 3**). Arid climates include desert (BWh, BWk) and steppe (BSh, BSk) classifications, which are characterized by low precipitation and high evaporation rates. Wet climates encompass equatorial (Af, Am, Aw), temperate (Cfa, Cfb), and boreal (Dfa, Dfb) zones, which have higher precipitation and stable moisture availability. Transitional climates, such as Mediterranean (Csa, Csb) and subarctic (Dfc, Dfd), fluctuate between wet and arid conditions. Polar climates (ET, EF) were included for completeness but are not a primary focus due to their limited relevance to mining regions.

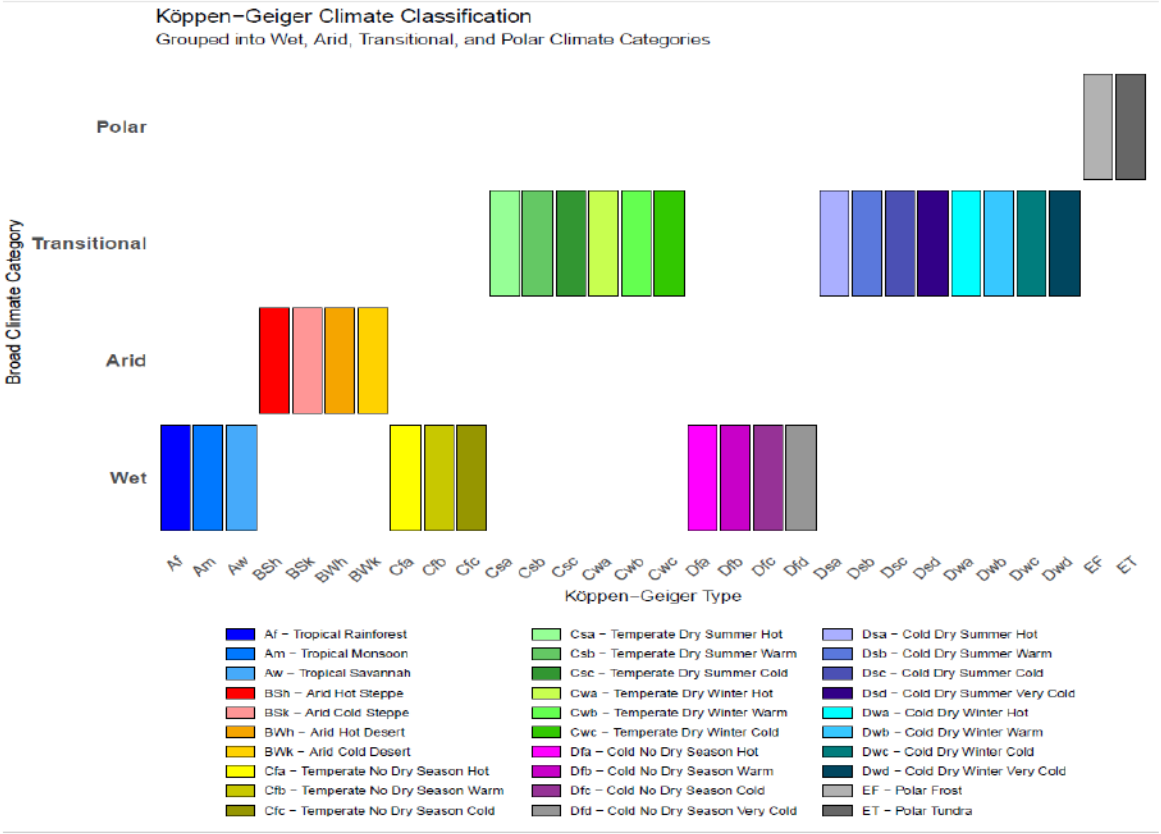


Figure 3: Köppen-Geiger Climate Classification for the Study Regions.

For each mining region, the fraction of grid cells transitioning between these categories under each SSP scenario was calculated. This regional transition data allowed climate classification shifts to be categorized into three distinct trends:

- Aridification Trends: Occurs when grid cells transition from wet or transitional climates to arid classifications, indicating increased drought susceptibility.
- Wetting Trends: Occurs when grid cells shift from arid classifications to wetter categories, suggesting an increase in precipitation and moisture availability.
- Transitional Climate Shifts: Represents instances where grid cells oscillate between wet and arid classifications over time, reflecting increased climatic variability.

The transition rate measures the proportion of grid cells undergoing a specific type of transition (e.g., aridification, wetting, or transitional shifts). To quantify the extent of each transition type, the proportion of affected grid cells was computed using the following formula:

$$\%Transition = \left(\frac{N\ transition}{N\ Change}\right) * 100$$

where:

$N_{Transition}$ *is the number of grid cells experiencing a specific transition type (aridification, wetting, or transitional shifts).*
N_{Total} *is the total number of grid cells in the mining region.*

Visualization of Climate Classification Changes

To effectively interpret classification shifts across mining regions, heatmaps were developed to summarize the magnitude and nature of climate transitions. These heatmaps represent percentage-based measures of climate change impacts, displaying both % Change (overall classification shifts) and % Transition (specific climate trends: aridification, wetting, or transitional shifts of the total % change). Heatmaps were generated for each of the seven mining regions and stratified by SSP scenario (SSP126, SSP245, SSP585) and future time period (2041–2070, 2071–2099). By comparing each future period to the baseline climate (1991–2020), these visualizations provided a quantitative representation of the extent and nature of climate classification changes. To visualize spatial patterns of climate shifts, heatmaps were generated in R using ggplot2 to display the percentage of each mining region experiencing classification changes. These heatmaps captured overall climate change impact (total grid cells undergoing any classification shift), aridification trends (transitions to drier climates), wetting trends (transitions to wetter climates), and transitional shifts (fluctuations between wet and arid conditions).

Heatmaps were stratified by future periods (2041–2070, 2071–2099) and climate scenarios (SSP126, SSP245, SSP585).

Climate Index Trend Analysis:

The analysis of climate indices was conducted in R using the terra, ncdf4, and SPEI packages for data extraction, spatial processing, and index calculation. NetCDF files containing climate model outputs were loaded, preprocessed, and standardized to ensure consistency in format and spatial coverage. To analyze climate trends within seven mining regions across the Southwestern United States and Western South America, raster datasets were clipped to predefined bounding boxes for each region. A custom function (fix_longitude) was applied to adjust longitude values to the -180° to 180° range. Climate data were extracted for the key variables, precipitation and potential evapotranspiration. Each dataset was subgrouped for the baseline period (1991–2020) and two future projection periods (2041–2070, 2071–2099) under three SSP emission scenarios. After spatial processing, climate indices were calculated in R using the SPEI, terra, and dplyr packages. SPEI was computed using the spei() function, which standardizes the climate water balance (precipitation minus PET) over a 12-month rolling window. AI was derived by taking the ratio of precipitation to PET, using simple arithmetic operations. DRFE measured the percentage of months with SPEI < -1 over a 36-month window, while DPD identified the longest consecutive drought period by applying a run-length encoding (rle()) approach.

For precipitation extremes, R-factor was estimated by multiplying monthly precipitation by an empirical erosivity coefficient, and RX1day was computed as 0.12 times the monthly precipitation total, approximating the maximum daily precipitation event.

Time Series Analysis and Visualization

Time series plots were generated for each mining region, illustrating projected trends for six climate indices under SSP126, SSP245, and SSP585. Each figure contained six plots, capturing all 18 scenario-based projections across both future periods (2041–2070, 2071–2099). To improve clarity, LOESS smoothing (span = 0.6) was applied to each time series this was done to minimize short-term fluctuations and noise in the time series plots to focus on long-term trends. The plots incorporated shaded background regions to delineate time periods (2015–2040, 2041–2070, 2071–2100) and dotted threshold lines for indices like SPEI, AI, and DRFE to aid interpretation of drought and aridity conditions.

CHAPTER FOUR

RESULTS

Climate Classification Changes Across Mining Regions

Overview of Climate Transitions

The analysis of Köppen-Geiger climate classifications across seven major copper mining regions in the Southwestern United States and Western South America reveals substantial shifts in climate zones under all three SSP scenarios (SSP126, SSP245, SSP585). These transitions are driven by projected changes in temperature and precipitation patterns which leads to increasing aridity in some regions, rising precipitation in others, and heightened climate variability in certain areas. The spatial distribution of copper mines and mining regions for the United States (Figure 4) and for South America (Figure 5), highlights the geographic extent of these mining operations. The information used in the figures is from **Table 2** above which provides the mine locations, operational status, and estimated production.

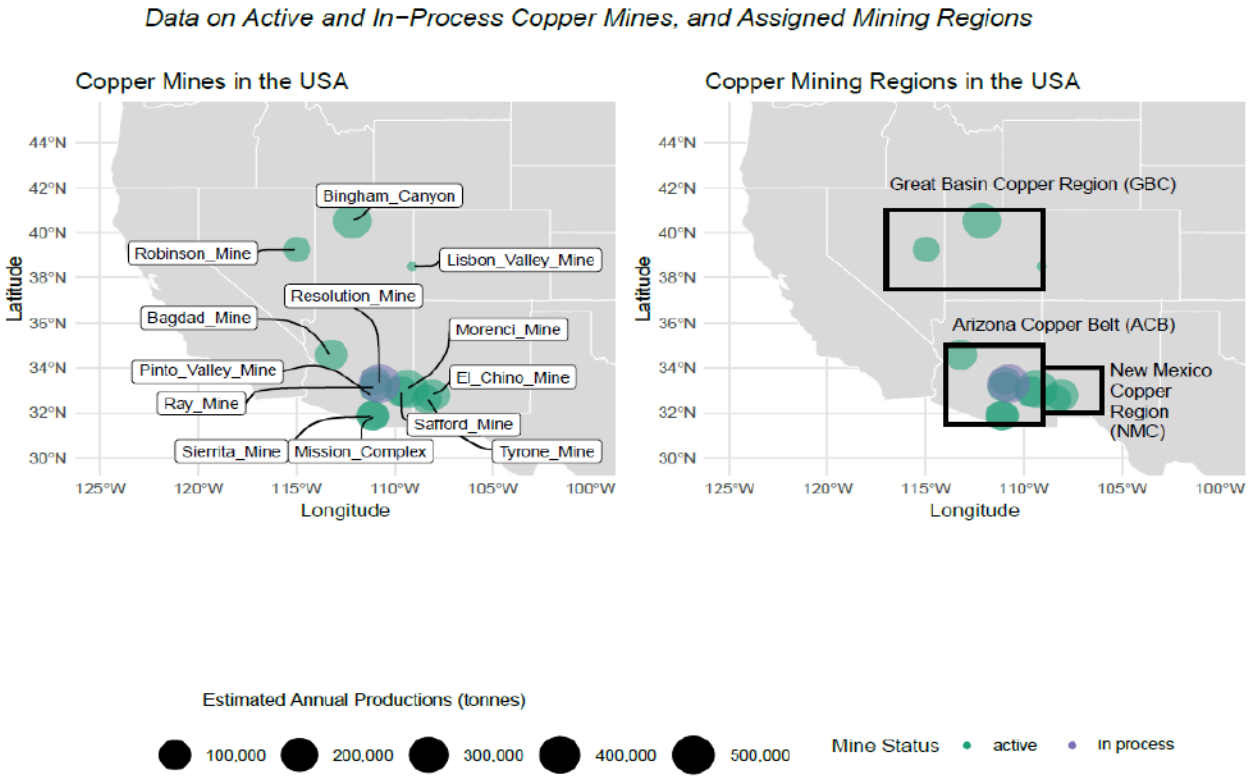


Figure 4. Spatial distribution of copper mines and defined mining regions in the United States. Mine locations are shown with operational status and estimated production volumes, based on compiled data from Table 2.

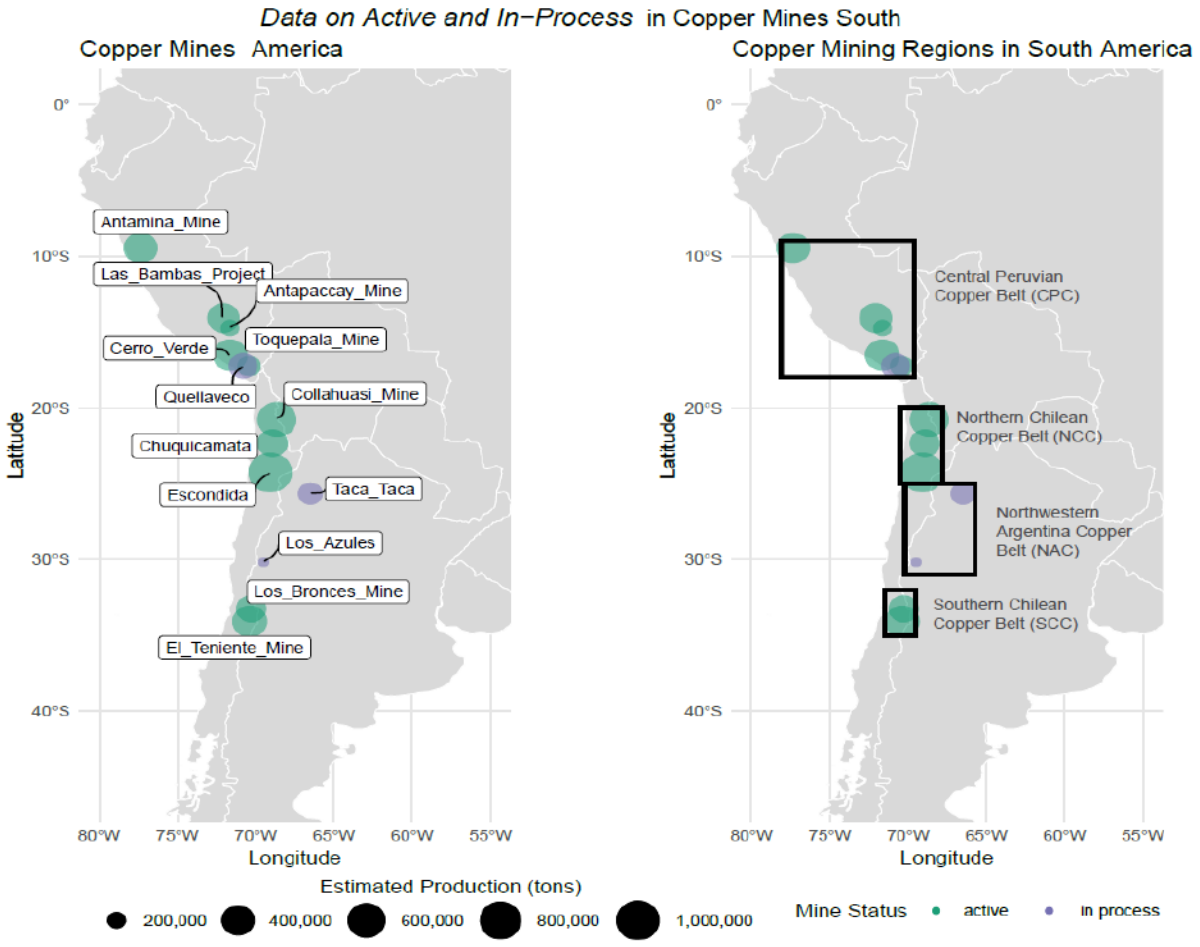


Figure 5: Spatial Distribution of Copper Mines and Mining Regions in South America

Baseline climate classifications (1991–2020) for mining regions in the U.S. and South America indicate that most sites fall within arid to semi-arid climate zones, highlighting their inherent vulnerability to water scarcity and hydrological stress under future climate change scenarios (Figure 6).

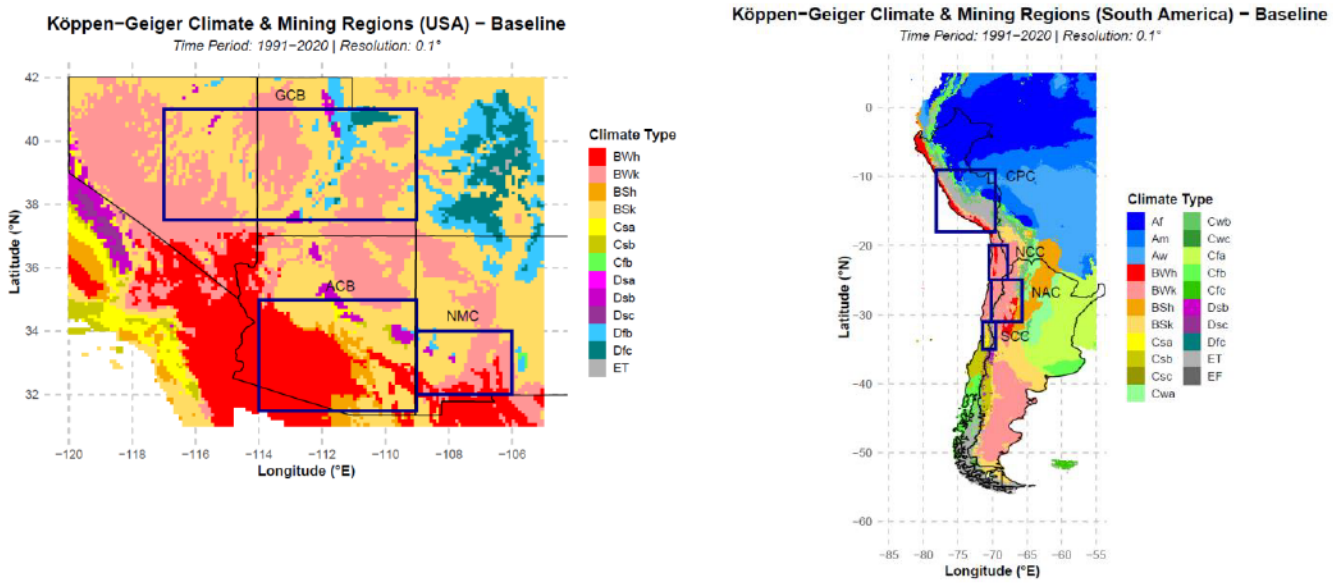


Figure 6: Baseline Köppen-Geiger Climate Classification for Copper Mining Regions in the United States & South America (1991–2020)

Projected climate shifts under SSP126, SSP245, and SSP585 indicate a clear trend toward increasing aridity in the U.S. Southwest and Northern Chile, alongside rising climate variability in parts of the Central Andes (Figures 7 and 8). Areas undergoing significant climate classification changes (shown in red) align closely with key copper mining regions, revealing geographic hotspots of transition and climate stress (Figures 9 and 10).

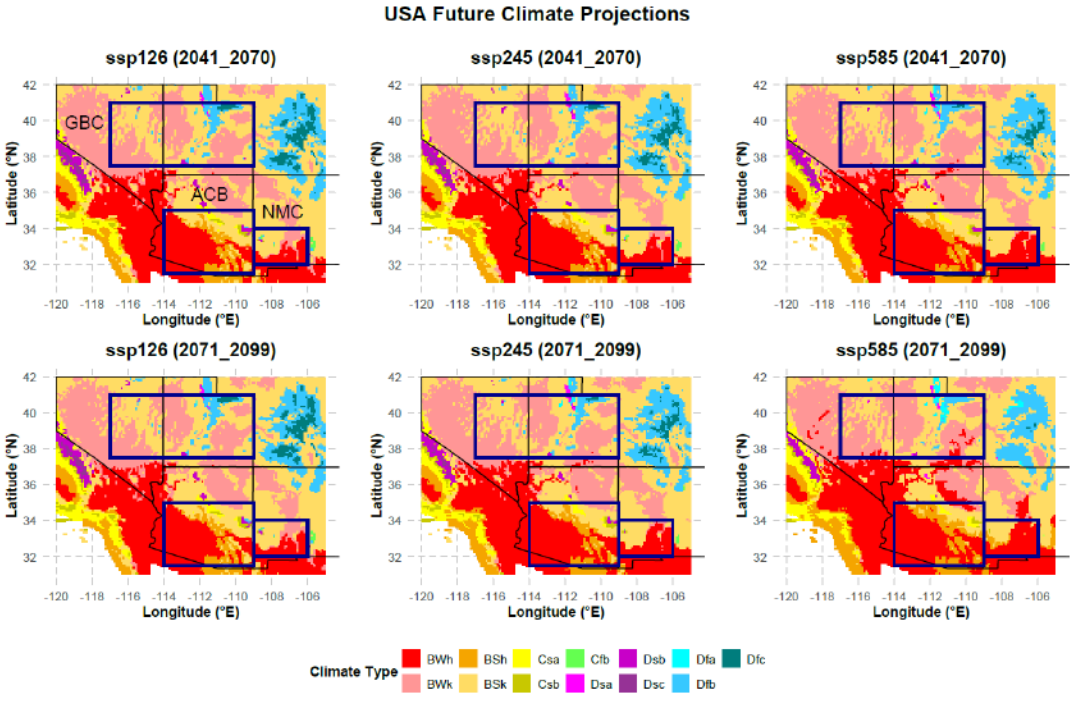


Figure 7: Projected Köppen-Geiger Climate Classification for Copper Mining Regions in the United States under SSP126–SSP585.

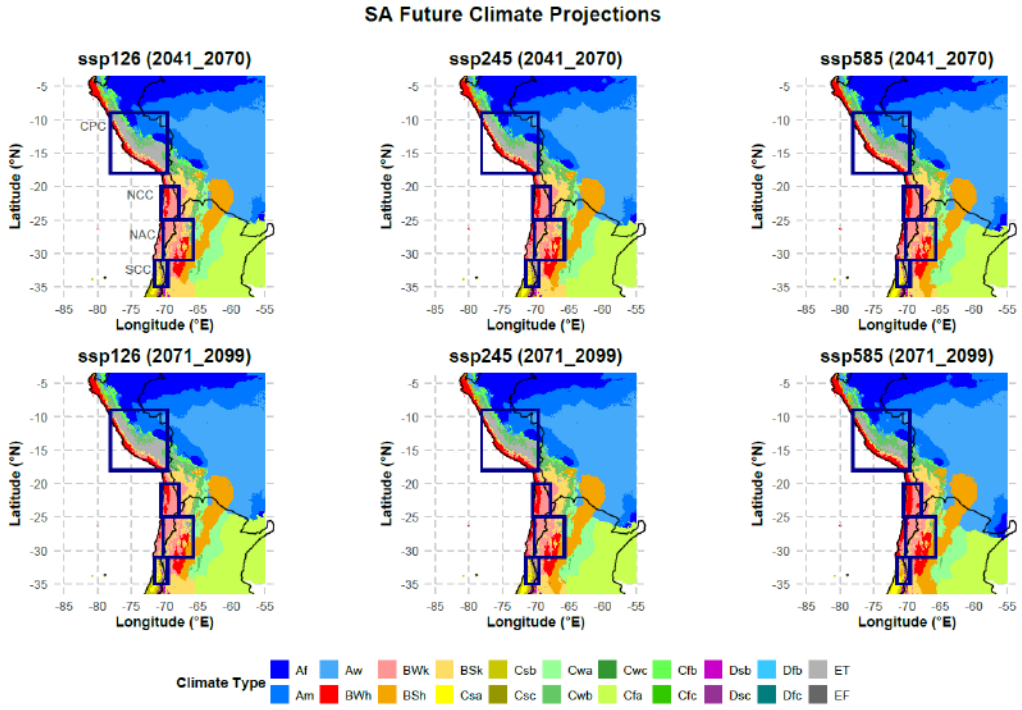


Figure 8: Projected Köppen-Geiger Climate Classification for Copper Mining Regions in South America under SSP126–SSP585.

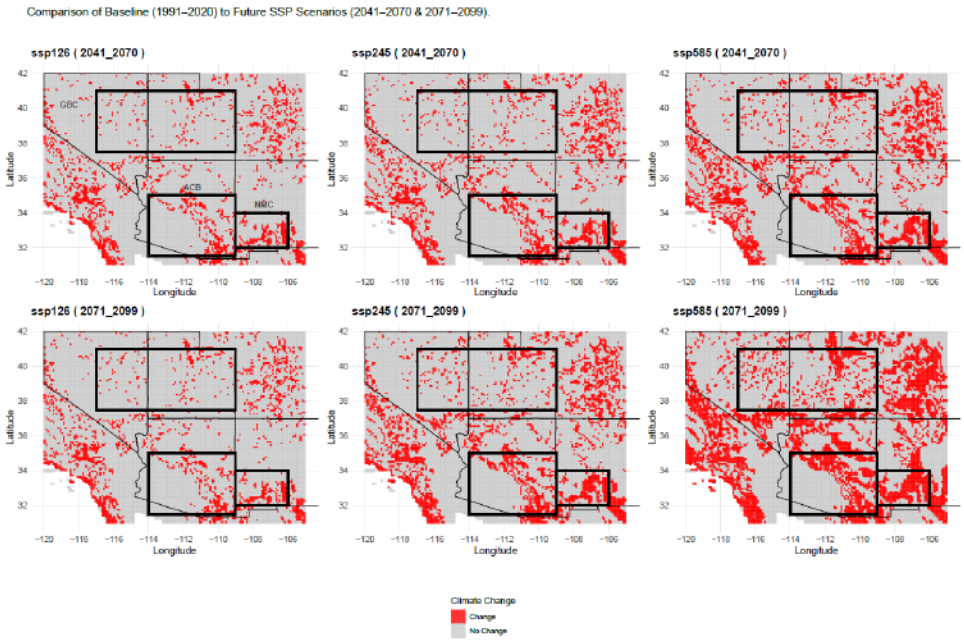


Figure 9: Climate Classification Changes in Copper Mining Regions in the United States (2041–2099)

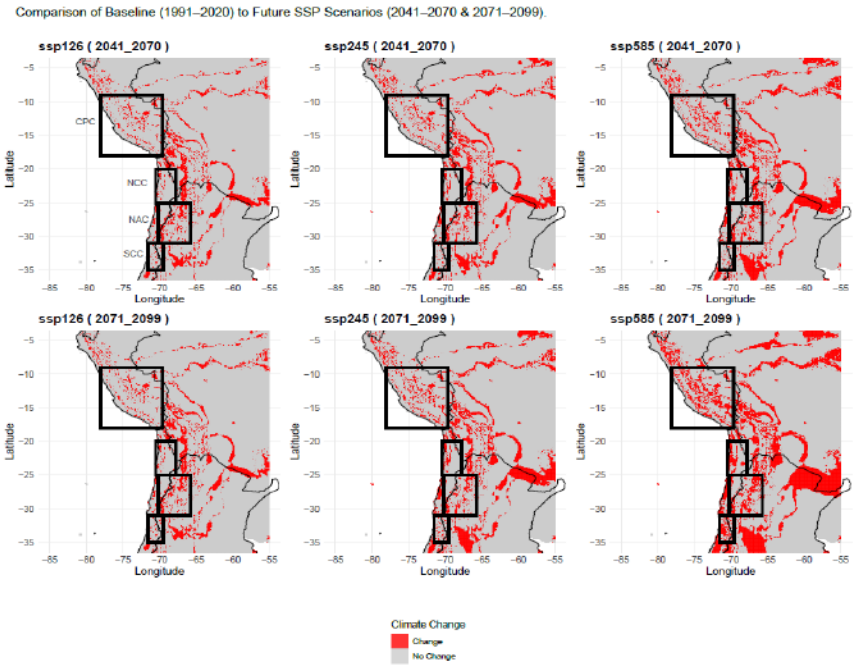


Figure 10: Climate Classification Changes in Copper Mining Regions in South America (2041–2099)

To quantify regional climate transitions, this analysis categorized shifts into aridification, wetting, and transitional classifications. The Arizona Copper Belt and Northern Chilean Copper Belt emerge as regions with the greatest extent of climate change, with large portions shifting toward more arid conditions (Figure 11). Widespread aridification occurs in the U.S. Southwest and Northwestern Argentina under the high-emissions SSP585 scenario (Figure 12). In contrast, localized wetting trends appear in the Southern Chilean and Central Peruvian Copper Belts under SSP126 and SSP245, suggesting modest increases in precipitation (Figure 13). Transitional shifts, where climate fluctuates between wet and arid states, are concentrated in Chile and Peru,

reflecting high interannual variability and climate instability (Figure 14).

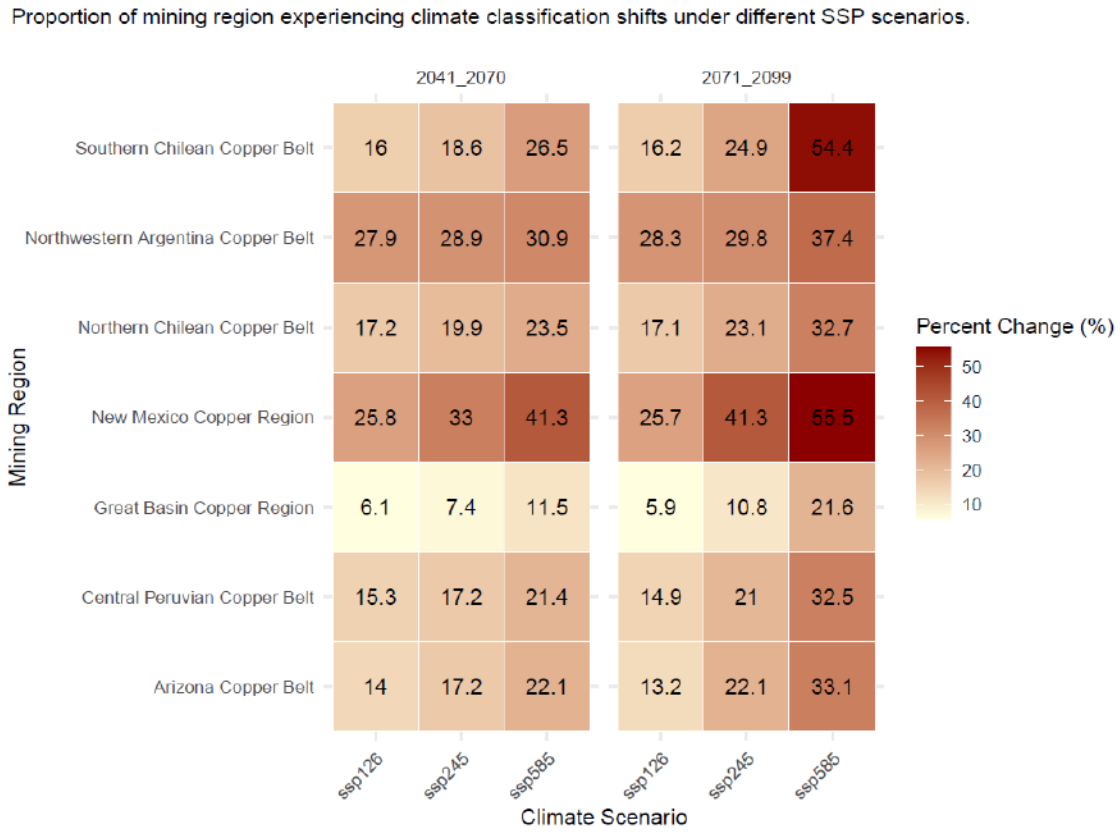


Figure 11: Percentage of Mining Region Area Experiencing a Climate Classification Shift.

Aridification Trends

Aridification emerges as a dominant trend in several copper mining regions, especially under the high-emissions SSP585 scenario, with the Arizona Copper Belt and Northern Chilean Copper Belt exhibiting near-total transitions to drier climate classifications by 2099. The Great Basin and Northwestern Argentina regions also experience significant drying, particularly in the late-century projections (Figure 12).

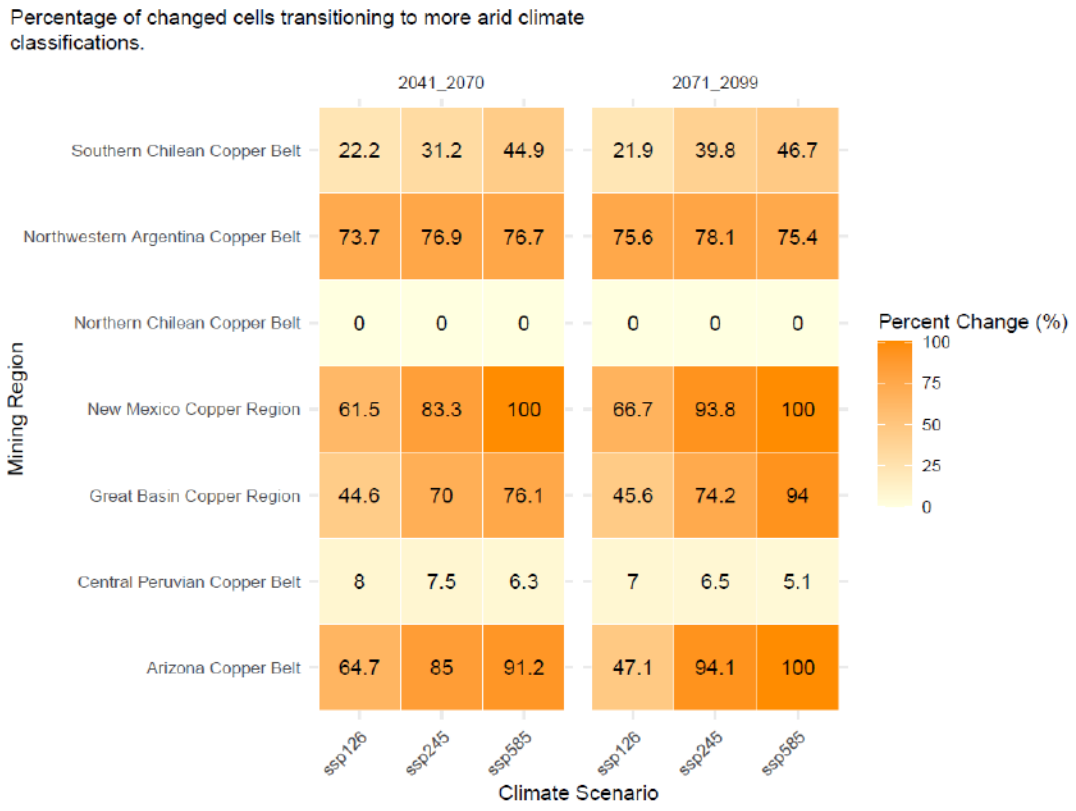


Figure 12: Heatmap of Aridification Trends in Copper Mining Regions: Areas Transitioning to Drier Climate Classifications

In North America, the Arizona Copper Belt and New Mexico Copper Region exhibit the highest rates of transition toward arid conditions, with 100% of affected grid cells shifting to drier classifications by 2099 under SSP585. The Great Basin Copper Region also shows a considerable increase in aridity, with approximately 44–76% of affected cells transitioning toward more arid classifications, depending on the emissions scenario. This trend is particularly evident in later decades (2071–2099), suggesting a progressive intensification of aridity over time. In South America, aridification is most pronounced in the Northwestern Argentina Copper Belt, where over 75% of changed cells exhibit a transition to more arid conditions across all scenarios. This pattern reflects an increasing dominance of semi-arid and arid classifications in

the region. The Southern Chilean Copper Belt and Central Peruvian Copper Belt also demonstrate moderate rates of aridification, with SCC showing a notable increase in aridity under higher emissions scenarios (SSP585). These findings suggest that while certain regions are experiencing progressive drying, others maintain a more balanced distribution of shifting climate classifications.

Wetting Trends

Wetting trends occur primarily in select regions, with the Great Basin Copper Region, Central Peruvian Copper Belt, and Southern Chilean Copper Belt showing the most notable increases in precipitation, particularly under lower-emissions scenarios (SSP126 and SSP245), suggesting a potential shift toward wetter climate classifications in these areas (**Figure 13**).

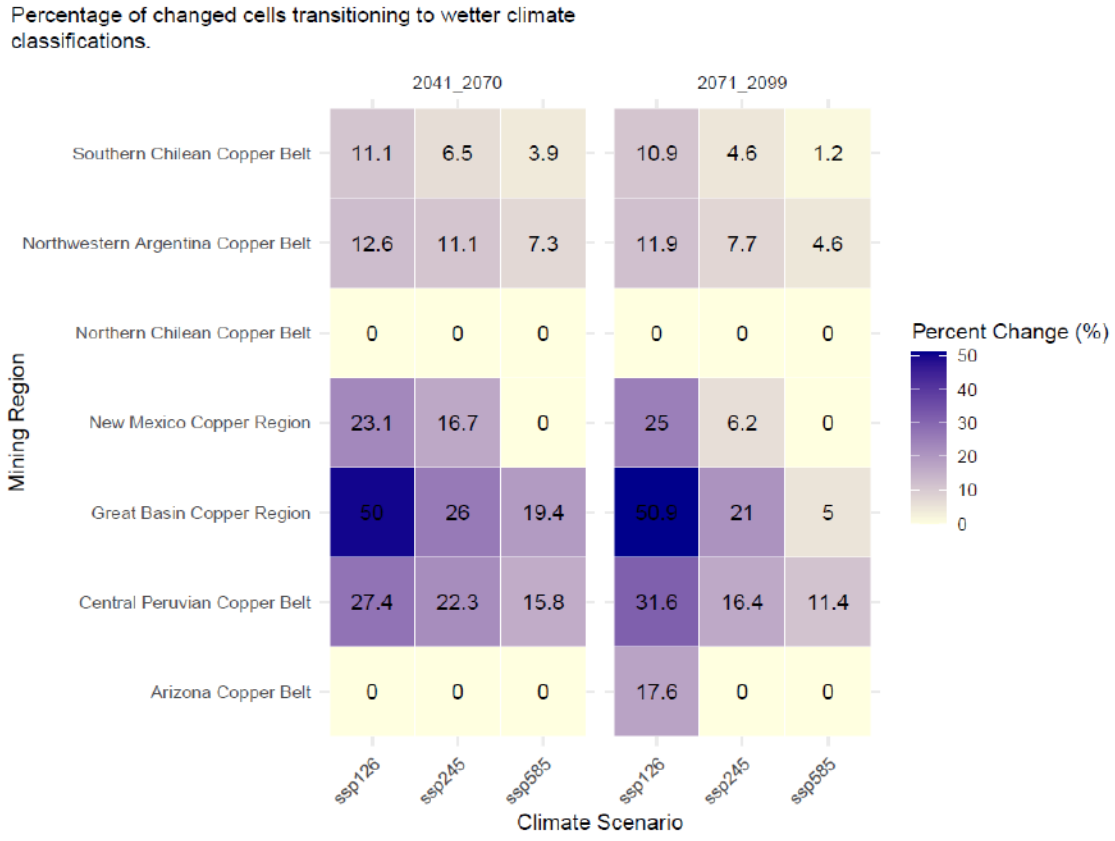


Figure 13: Heatmap of Wet Climate Shifts in Copper Mining Regions: Areas Transitioning to Wetter Climate Classifications

In North America, the Great Basin Copper Region demonstrates the most significant wetting trends, with nearly 50% of affected grid cells shifting toward wetter climate classifications under SSP126 and SSP245. This pattern suggests that while aridification is occurring in some portions of the region, concurrent trends toward increased precipitation and wetter climate classifications are also evident, indicating a spatially heterogeneous climate response that may result in both water scarcity and localized flood risk within the same mining region. In South America, the Southern Chilean Copper Belt and Central Peruvian Copper Belt exhibit increasing wetting trends, particularly under SSP126. In Central Peruvian Copper nearly 30% of all changed cells shift toward wetter classifications, aligning with projected increases in regional precipitation under low- to moderate-emissions scenarios. However, wetting trends appear more limited in SSP585, indicating that increased temperatures and evaporation rates under higher emissions may counteract gains in precipitation. Overall, wetting trends appear more prominent in scenarios with limited global warming (SSP126, SSP245), whereas in higher-emissions scenarios (SSP585), drying trends become dominant.

Transitional Climate Shifts

Regions characterized by transitional climate shifts, fluctuations between wet and arid classifications, indicate increasing climate instability that may complicate long-term planning for water management and landform stability (Figure 14). The Southern Chilean Copper Belt and Central Peruvian Copper Belt show the highest rates of transitional shifts, particularly under SSP245 and SSP585, where up to 77% of affected grid cells exhibit changes between wet and

arid classifications. This pattern suggests that these regions may experience high interannual variability in precipitation patterns, leading to unstable climate classifications over time.

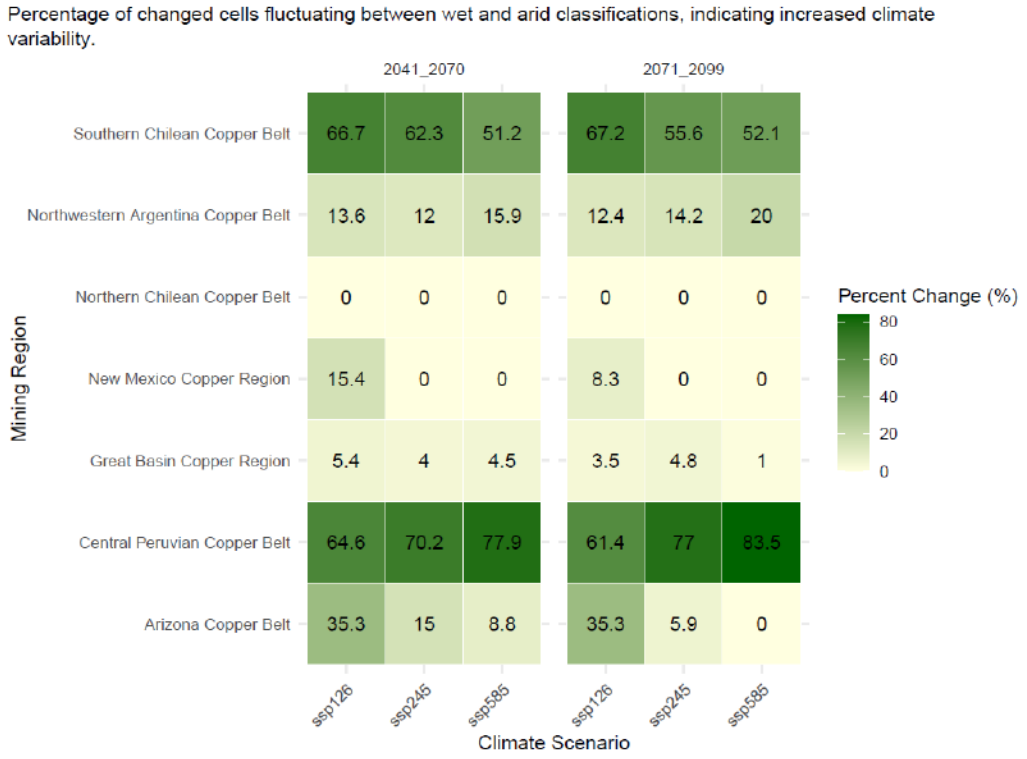


Figure 14: Heatmap of Transitional Climate Shifts in Copper Mining Regions: Areas Fluctuating Between Wet and Arid Conditions.

The Northwestern Argentina Copper Belt also exhibits high variability, with 12–20% of affected grid cells fluctuating between wet and arid classifications under SSP245 and SSP585. This indicates that the region may not experience a steady shift toward a particular climate state, but rather increased climate fluctuations, possibly driven by shifting precipitation regimes and temperature variations. Such transitional patterns highlight the complex and dynamic nature of climate change in certain mining regions, where projected precipitation increases may be offset by rising temperatures and evaporation rates, leading to oscillations between drier and wetter

climate classifications. These shifts suggest that some regions may be subject to greater seasonal and interannual climate variability, which could complicate long-term environmental planning, water resource management, and mining operations.

Climate Index Trends Across Mining Regions

I calculated six climate indices, SPEI, AI, DPD, DRFE, R-factor, and RX1day, to evaluate how climate shifts affect water availability, drought frequency, and extreme precipitation events. Temporal trends in these indices for each mining region under all three SSP scenarios from 2015 to 2100 (Figures 15–21).

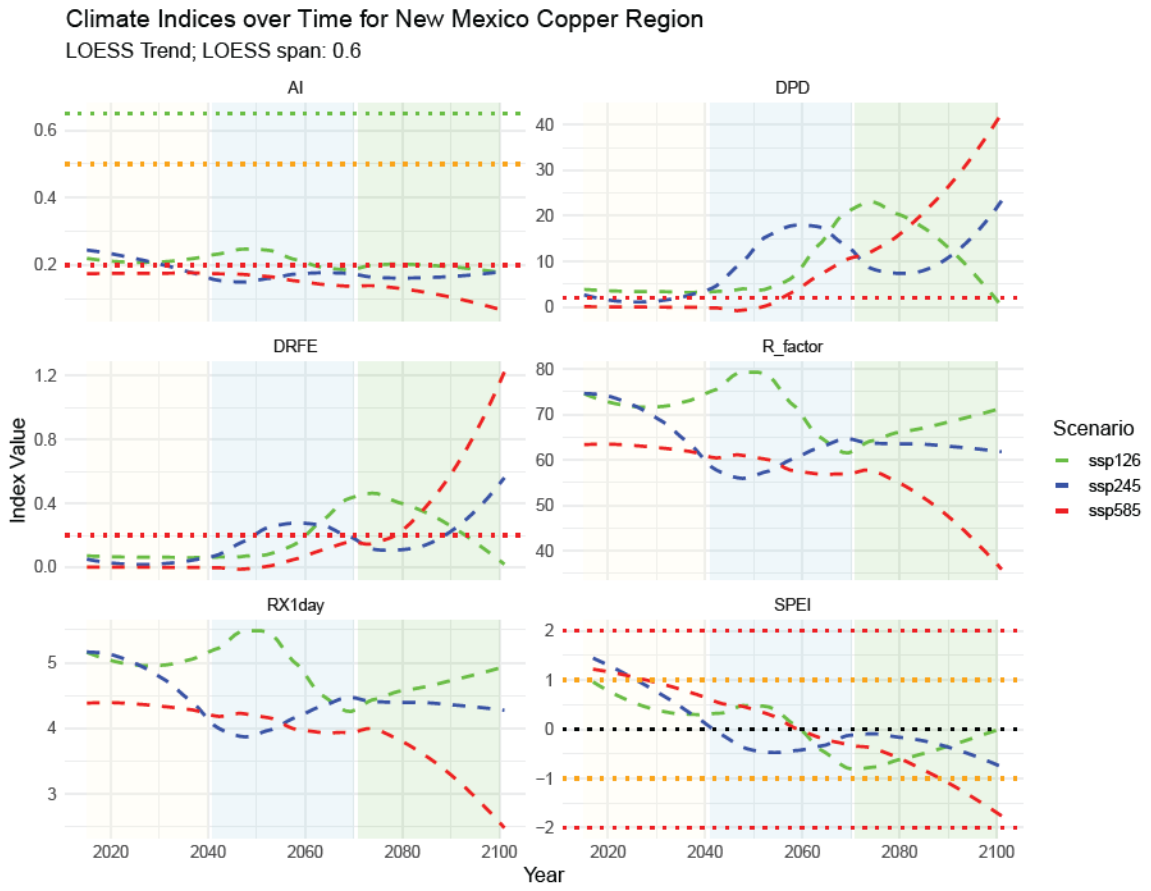


Figure 15: Temporal Trends in Climate Indices for the New Mexico Copper Region

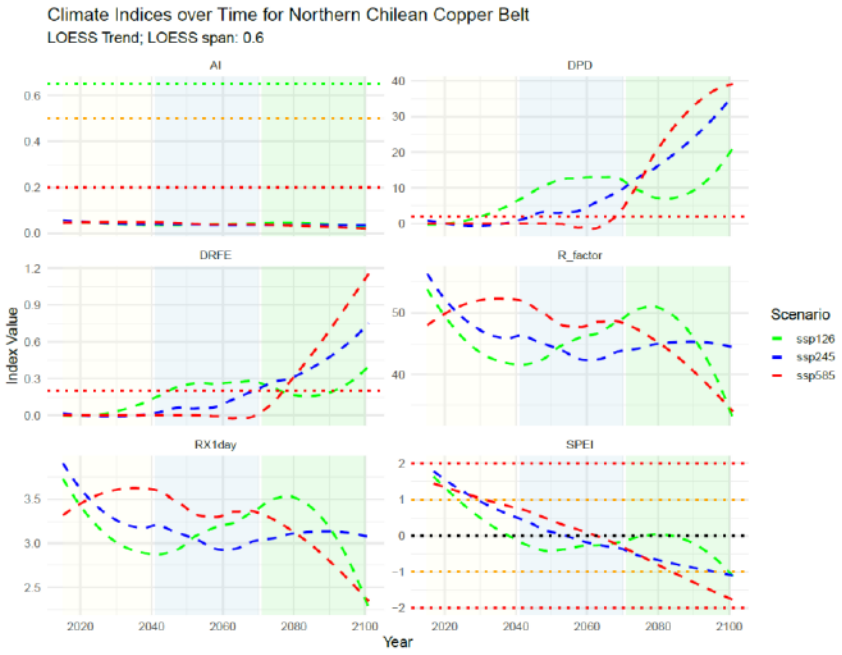


Figure 16: Temporal Trends in Climate Indices for the Northern Chilean Copper Belt

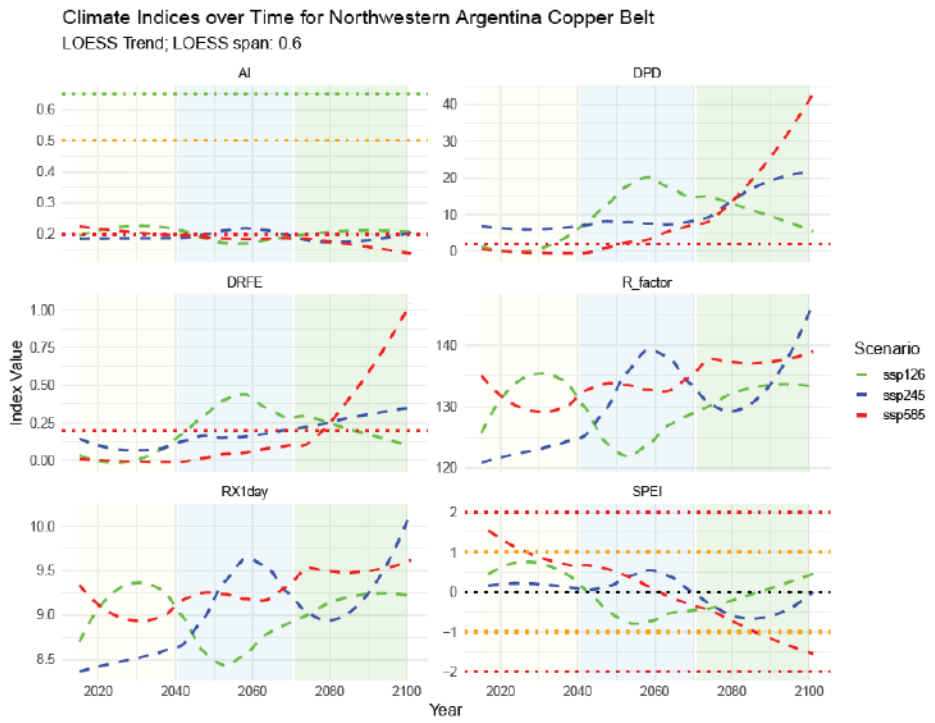


Figure 17: Temporal Trends in Climate Indices for the Northwestern Argentina Copper Belt

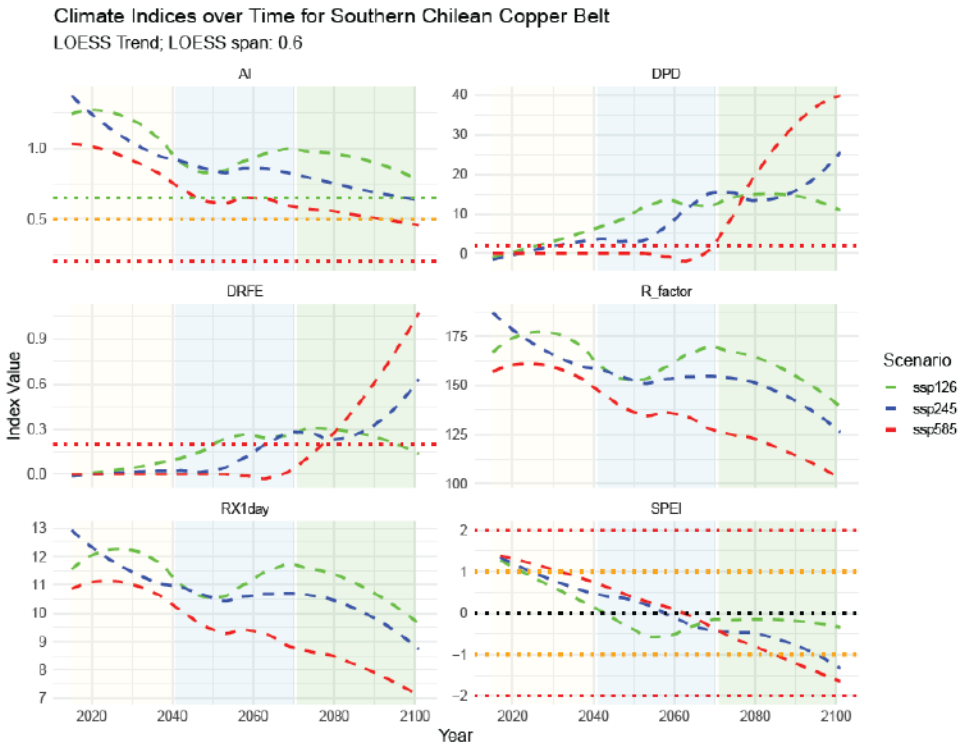


Figure 18: Temporal Trends in Climate Indices for the Southern Chilean Copper Belt

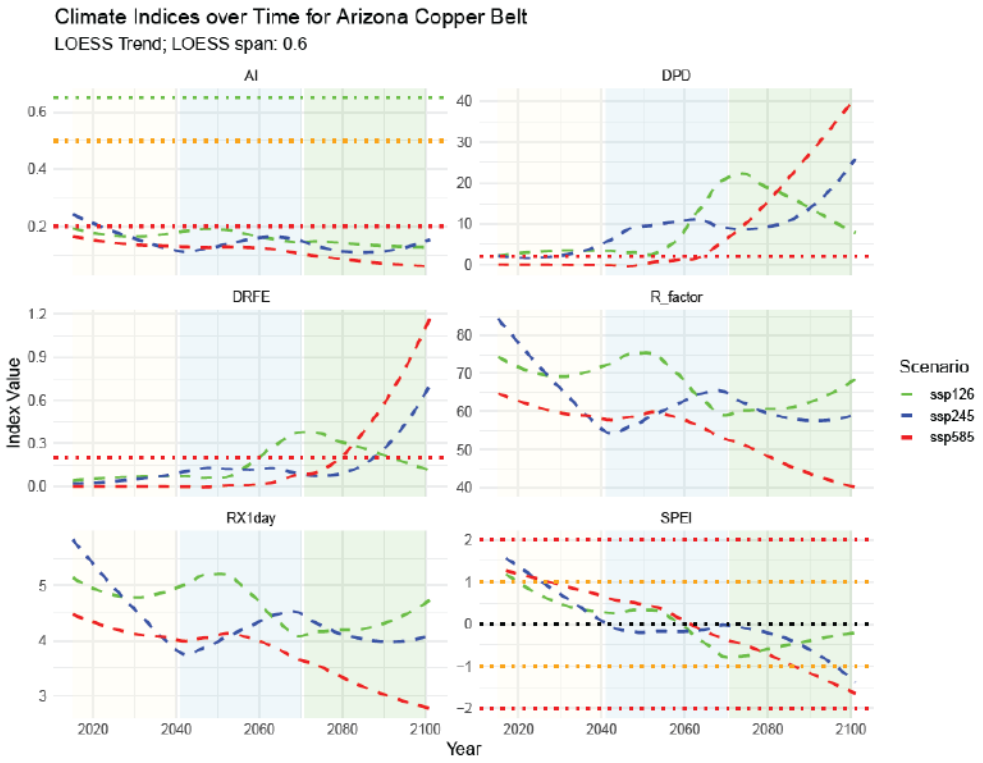


Figure 19: Temporal Trends in Climate Indices for the Arizona Copper Belt

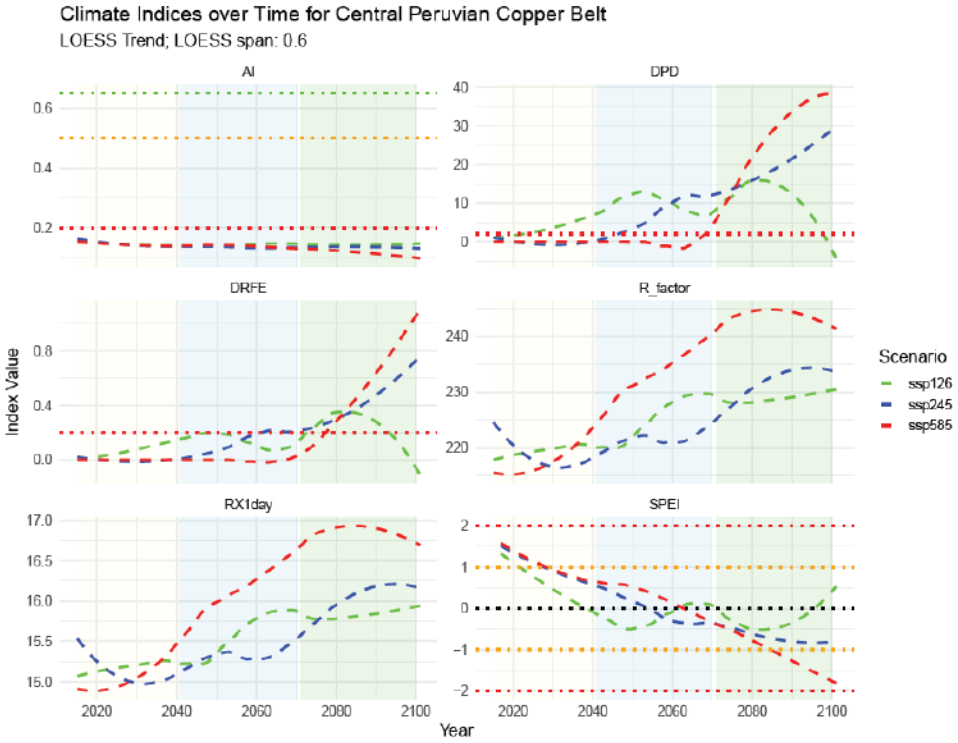


Figure 20: Temporal Trends in Climate Indices for the Central Peruvian Copper Belt

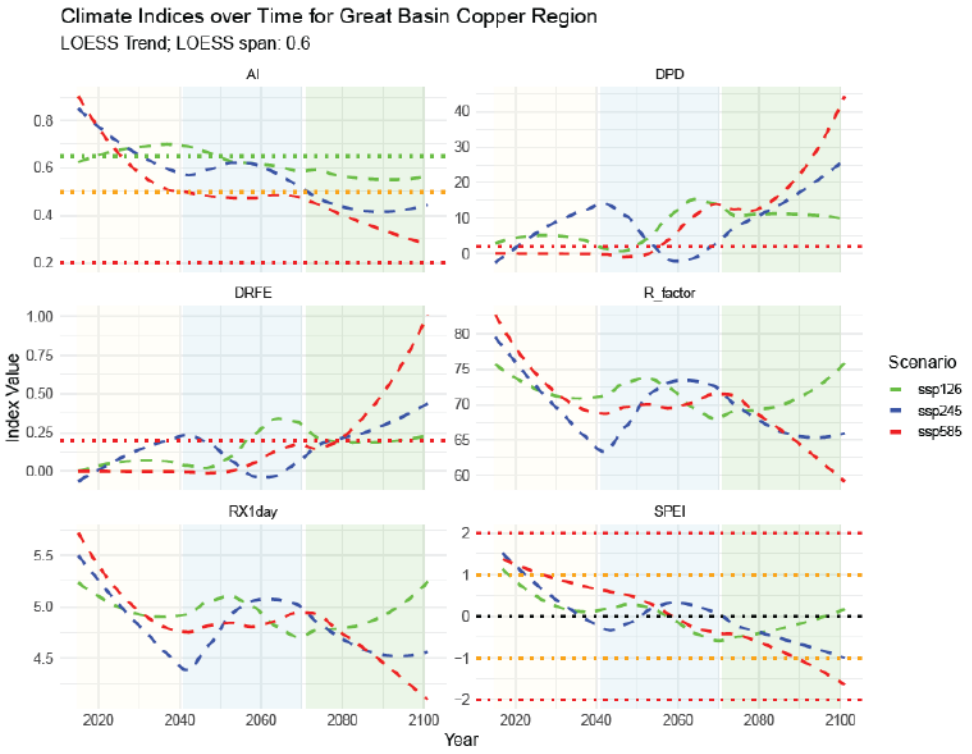


Figure 21: Temporal Trends in Climate Indices for the Great Basin Copper Region

Aridity and Drought Indicators

The Arizona Copper Belt (**Figure 19**) and Great Basin Copper Region (**Figure 21**) exhibit consistent declines in SPEI values under SSP245 and SSP585, indicating prolonged drought conditions. South American regions, particularly the Northern Chilean Copper Belt (**Figure 16**), show a dramatic decline in SPEI post-2050, which aligns with increased aridity trends observed in climate classification analysis.

The Great Basin Copper Region (**Figure 21**) and Northwestern Argentina Copper Belt (**Figure 17**) experience a 30–50% decline in AI by 2099 under SSP585, reinforcing the trend of

increasing aridity. Conversely, regions like the Southern Chilean Copper Belt (**Figure 18**) show a stable or increasing AI under SSP126, which likely reflects wetter conditions in some scenarios.

Drought Frequency and Duration

A higher frequency of drought events in indicated in the New Mexico Copper Region (**Figure 15**) and Northern Chilean Copper Belt (**Figure 16**) under SSP245 and SSP585. In some cases, under SSP585, droughts become nearly continuous, with more than 70% of months exhibiting SPEI < -1. The probability of extended drought periods increases sharply post-2050 in the Arizona Copper Belt and Northern Chilean Copper Belt, with projected multi-year droughts becoming common under SSP585.

Extreme Precipitation and Erosivity

While aridification dominates in some regions, extreme precipitation events are projected to increase in intensity across all SSP scenarios. The Central Peruvian Copper Belt (**Figure 20**) and Southern Chilean Copper Belt (**Figure 18**) show substantial increases in R-Factor and RX1day post-2050, which suggests a greater likelihood of extreme rainfall events, flash floods, and erosion risks.

Regional Comparisons and Implications for Mine Closure

Regional climate impacts, including the rate and magnitude of change in climate indices across mining regions (**Figure 22**). The Great Basin Copper Region, Arizona Copper Belt, and Northern Chilean Copper Belt exhibit the steepest declines in SPEI and AI, reinforcing their susceptibility to long-term aridification. In contrast, the Southern Chilean Copper Belt and Central Peruvian Copper Belt display a more mixed pattern, with some indicators suggesting increased wetting.

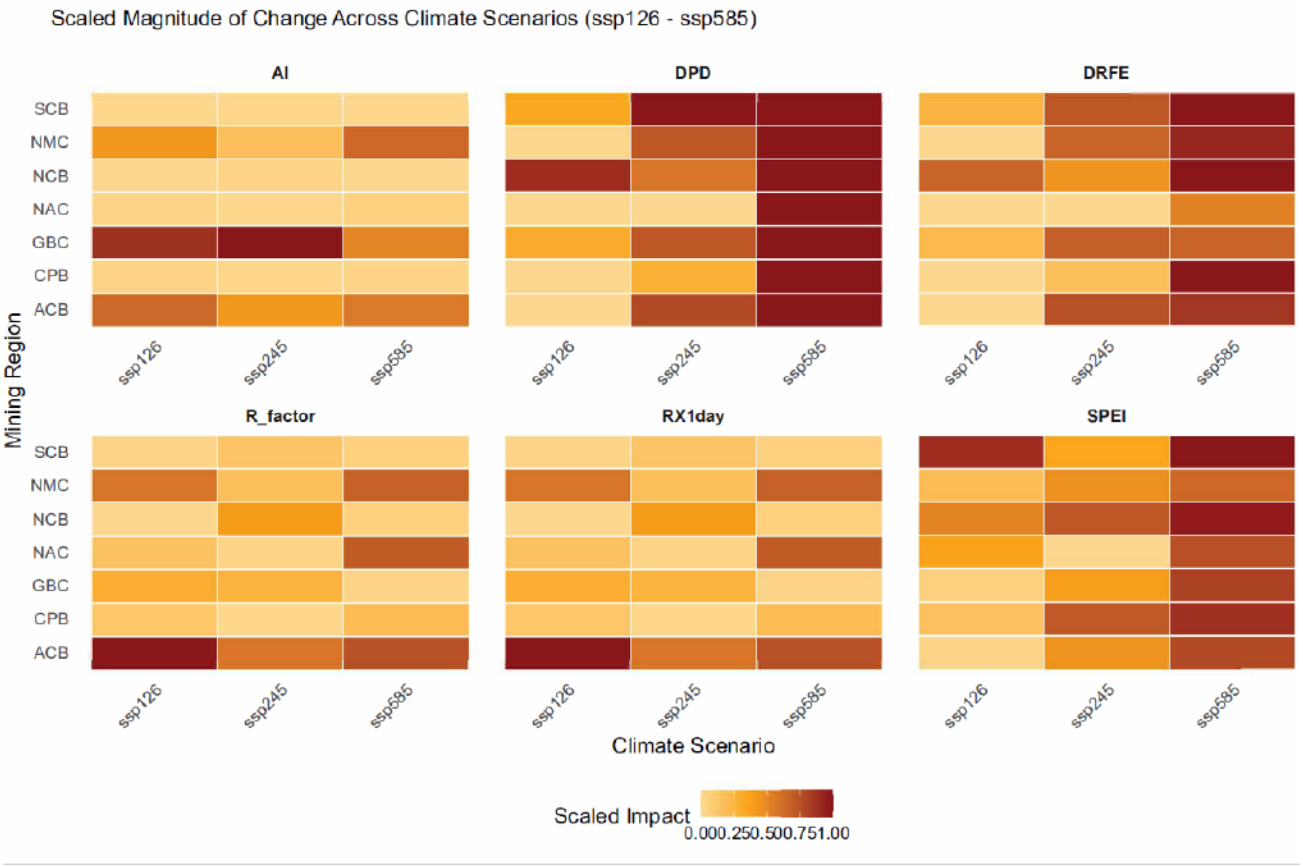


Figure 22: Heatmap of Climate Change Impacts on Copper Mining Regions

CHAPTER FIVE

DISCUSSION

Overview of Climate Shifts

My results indicate substantial climate classification shifts across copper mining regions in the Southwestern United States and Western South America, with trends varying by location and emissions scenario. These shifts, driven by projected temperature and precipitation changes, have direct implications for water availability, drought risk, and extreme precipitation events—critical factors influencing long-term mine closure planning and environmental risk mitigation.

Aridification remains a dominant trend in several mining regions, but not all areas experience a unidirectional shift toward drying. The Arizona Copper Belt and New Mexico Copper Region exhibit the most pronounced aridification, particularly under SSP585, where nearly 100% of affected grid cells transition toward drier classifications by 2099. The Great Basin Copper Region, however, exhibits a dual trajectory: under high-emissions scenarios, 44–76% of affected cells transition toward greater aridity, while under SSP1-2.6 and SSP2-4.5, up to 50% of affected cells shift toward wetter classifications, potentially reflecting the influence of the Wasatch Front within the analysis area and highlighting regional climate complexity.

In South America, aridification is strongest in the Northwestern Argentina Copper Belt, where over 75% of changed cells transition to drier conditions across all scenarios. However, the Southern Chilean Copper Belt and Central Peruvian Copper Belt display high transitional climate shifts (~77%), meaning these regions do not undergo a consistent shift toward aridification or wetting but rather experience high interannual variability in precipitation. Climate indices such

as drought frequency, aridity, and extreme precipitation change across mining regions (**Figure 22**), identifying the Arizona Copper Belt, Great Basin, and Northern Chilean Copper Belt as the most exposed to drying trends. The primary climate risks and closure challenges for each region, including water scarcity, tailings stability, flood risk, and acid rock drainage, are detailed in (**Table 4**).

Implications for Water Availability and Drought Risk

Declining SPEI and AI values in key mining regions underscore the increasing likelihood of long-term water deficits. Many mining operations rely heavily on consistent water availability for mineral extraction, ore processing, and dust suppression, making projected drying trends particularly concerning. The Arizona Copper Belt and New Mexico Copper Region are projected to experience sustained water stress, with multi-year droughts becoming frequent under SSP585. The Great Basin Copper Region, while experiencing some wetting under SSP126 and SSP245, still exhibits declining AI and SPEI under SSP585, suggesting that under high emissions, drying trends may outweigh temporary increases in precipitation. The Northwestern Argentina Copper Belt, despite its strong aridification trend, also exhibits 12–20% transitional shifts, meaning that while it is drying, periodic fluctuations in precipitation may still occur. As water availability decreases in acidifying regions, reliance on groundwater extraction, water recycling technologies, and desalination strategies may become increasingly necessary to maintain operational sustainability. These findings outline the climate risks and associated closure challenges for each mining region (**Table 4**).

Extreme Precipitation and Erosion Risks

While aridification dominates in some mining regions, others experience a concurrent increase in extreme precipitation events, particularly in the Southern Chilean Copper Belt and Central Peruvian Copper Belt. The R-Factor (rainfall erosivity) and RX1day (maximum daily precipitation) indices suggest that these regions will see increased rainfall intensity, raising concerns over soil erosion, landslides, and flooding. Great Basin Copper Region, despite its mixed drying/wetting trends, exhibits heightened risks of erosion and sediment instability, requiring improved drainage infrastructure and sediment management strategies. These precipitation patterns could pose challenges for tailings storage facilities since increased rainfall could lead to stressors resulting in dam failures, sediment mobilization, and water quality degradation. Consequently, mining operations in precipitation change prone regions may benefit from prioritizing infrastructure resilience, improved stormwater management, and robust tailings dam monitoring systems.

Regional Vulnerabilities and Mine Closure Planning

Comparing climate change impacts across mining regions (**Figure 22**) shows distinct regional vulnerabilities and differences. The Arizona Copper Belt, New Mexico Copper Region, and Northern Chilean Copper Belt exhibit the highest susceptibility to aridification, requiring adaptive water management and drought resilience strategies. The Southern Chilean Copper Belt and Central Peruvian Copper Belt experience high transitional climate variability and erosion risks, necessitating enhanced flood control measures and tailings stability improvements. The Great Basin Copper Region demonstrates mixed climate shifts, which could mean mine closure plans would benefit from considering both water stress and extreme precipitation risks. The Northwestern Argentina Copper Belt presents a complex mix of aridification and transitional

instability, requiring flexible adaptation strategies to account for fluctuations between wet and dry conditions.

Table 4: Climate change impacts and mine closure risks by region.

Mining Region	Projected Climate Trend	Key Closure Risk Elements	Relevant Climate Indices	Potential Impacts
Arizona Copper Belt	High aridification (SSP585)	Pit Lake Hydrology, Water Scarcity	AI, SPEI, DPD	Reduced groundwater recharge, higher salinity risks, longer droughts.
Great Basin Copper Region	Mixed shifts of aridification and wetting (SSP245)	Water Management, Tailings Stability	AI, DRFE, RX1day, R-Factor	Increased variability in water availability, erosion risks, and flash flooding.
New Mexico Copper Region	Severe aridification (SSP585)	Revegetation, ARD Risk	AI, DRFE, DPD	Extended droughts reduce vegetation success, increasing dust and ARD formation.
Northern Chilean Copper Belt	Strong aridification across all SSPs	Pit Lake Hydrology, ARD Risk	AI, SPEI, DPD	Declining water availability, acid drainage intensification, water conflict risks.
Southern Chilean Copper Belt	Increased precipitation variability (SSP126)	Flood Risk, Erosion Control	RX1day, R-Factor	Extreme rainfall events threaten tailings stability, requiring enhanced drainage.
Central Peruvian Copper Belt	Transitional shifts: Arid to Wet (SSP245, SSP585)	Landform Stability, Water Scarcity, ARD Risk	AI, R-Factor, RX1day, DRFE	Increasing storm erosivity, mixed wet-dry patterns affecting site reclamation.
Northwestern Argentina Copper Belt	Mixed aridification & extreme precipitation shifts (SSP245, SSP585)	Tailings Stability, Water Scarcity, ARD Risk	AI, RX1day, R-Factor, SPEI	Seasonal climate instability leads to alternating droughts and intense rainfall, increasing risks of tailings dam failures and ARD.

Notes: Climate projections follow the Shared Socioeconomic Pathways (SSP) from the CMIP6 framework, where high-emissions scenarios (SSP585) seems to drive greater aridification, and low-emissions pathways (SSP126) indicate increased precipitation variability. Climate indices used in this study include the Aridity Index (AI) for long-term moisture availability, the Standardized Precipitation-Evapotranspiration Index (SPEI) for drought severity, Drying Period Duration (DPD) for prolonged dry spells, Drought Frequency Index (DRFE) for increasing drought occurrence, Annual Maximum 1-day Precipitation (RX1day) for extreme rainfall events affecting flood risks, and the Rainfall Erosivity Factor (R-Factor) for erosion potential from intense precipitation.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

Summary of Findings

My study analyzed projected climate shifts in seven major copper mining regions using CMIP6 SSP climate projections and Köppen-Geiger classifications. The findings indicate widespread climate classification changes, with increasing aridification in the Arizona Copper Belt, Great Basin Copper Region, and Northern Chilean Copper Belt, particularly under high-emissions scenarios. In contrast, Southern Chilean Copper Belt and Central Peruvian Copper Belt show increased precipitation variability. These changes will impact mine hydrology, revegetation success, landform stability, and contaminant dispersion, requiring climate-adaptive closure strategies. Climate index analysis supports these trends, showing longer droughts (declining SPEI, AI) in acidifying regions and more extreme precipitation (increasing R-Factor, RX1day) in wetter regions. Mine operations in drying regions will face increased water scarcity, while wetter regions must enhance flood control and erosion mitigation.

Climate Change, Electrification, and the Changing Dynamics of Copper Mining

The global push for electrification is driving copper demand, extending mine lifespans and intensifying water and land use. Climate change will exacerbate these challenges, particularly in arid regions (e.g., Northern Chile, Southwestern U.S.), where water scarcity will impact mine closure strategies. In contrast, regions with increasing precipitation (e.g., Central & Southern Chile) will face flooding, soil erosion, and ARD risks.

Regulatory conditions will influence how these risks are managed. Countries with strong environmental policies (e.g., USA and Chile) are more likely to integrate climate adaptation into mining regulations, although regions with weaker oversight may face greater environmental and financial risks at closure. Future copper market dynamics remain uncertain due to potential shifts in battery technology, material substitution, and recycling, necessitating flexible and scenario-based closure planning.

Future Research Directions

Future research should focus on refining site-specific climate risks, particularly in relation to pit lake hydrology and long-term water balance in arid regions, where declining aridity indices demonstrate increasing challenges for water retention and quality. Understanding the impact of extreme precipitation on tailings stability and flood risk remains critical, as heightened rainfall variability could accelerate erosion, compromise containment structures, and lead to increased contaminant dispersion. Further study is needed on climate-resilient reclamation strategies, including the efficacy of drought-resistant revegetation and advanced stormwater control measures in mitigating soil degradation and stabilizing post-mining landscapes. Additionally, the socioeconomic implications of climate-driven changes in mining regions, particularly the increasing potential for water conflicts and rising operational costs, require further examination to ensure long-term economic and environmental sustainability.

Practical Applications and Policy Recommendations

Ensuring the long-term sustainability of mine closure strategies necessitates the integration of climate-adaptive water management, geotechnical stability measures, and nature-based reclamation approaches. In arid regions, implementing water-efficient reclamation techniques,

dry-stack tailings, and improved groundwater conservation strategies will be essential for maintaining water availability and reducing long-term hydrological deficits. Conversely, in regions projected to experience more intense precipitation patterns, strengthening flood control measures, enhancing erosion mitigation strategies, and improving ARD prevention systems will be necessary to maintain site stability and prevent large-scale environmental contamination. Regulatory and mine management practice frameworks should evolve to incorporate climate-adjusted closure risk assessments. Decision-support tools that leverage real-time climate data, machine learning, and predictive modeling could improve risk assessments and enhance the ability of mine operators to proactively respond to emerging environmental threats.

Conclusion

My findings highlight the need for climate-adaptive mine closure planning. Projected climate risks differ significantly across mining regions, which underscores the importance of tailored adaptation strategies rather than a one-size-fits-all approach. As climate change accelerates, mining operations must embed climate risk assessments into long-term closure strategies to ensure sustainable post-mining landscapes. Proactive investment in climate-resilient solutions will help the mining sector reduce environmental risks, strengthen long-term resilience, and support responsible resource development in a changing global climate.

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