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Impact of Geological Hazards on Regional Economic Development: Evidence from the Pacific Ring of Fire

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Abstract

This study examines seismic activity, volcanoes, tsunamis, and related hazards over a 20-year period in order to assess the economic effects of geologic hazards on the regional development trajectories of the Pacific Ring of Fire. Based on empirical data, the region's GDP losses range from 0.5 to 5.9%, contingent on the hazard's characteristics, volume, and potential for local recovery. The analysis shows how initial impacts are multiplied by cross-border spillovers and supply chain disruption cascading effects. Recovery pathways show considerable variation, with insurance density, mitigating infrastructure quality, and institutional strength being the primary correlates of economic strength, according to panel regression with fixed effects estimates. Areas that implement effective and comprehensive disaster risk reduction programs experience recovery times that are as much as 42% shorter. Additionally, the estimates show that ex-ante investments in active risk management can easily outperform ex-post post-disaster reconstruction expenditures, with benefit-cost ratios ranging from 4 to 7:1.

Keywords

Geological Hazards; Economic Resilience; Regional Development; Pacific Ring of Fire; Disaster Risk Reduction.

1. Introduction

The 40,000 km long Pacific Ring of Fire, a heavily tectonized belt filled with active submarine trenches and submarine volcanoes, is home to a wide range of geological hazards that largely influence local economic development. About 90% of the world's earthquakes occur in this seismically active region, which also has over 450 active volcanoes, most catastrophic tsunamis, frequent landslides, and land subsidence [1]. These factors create complex risk landscapes for nations that collectively account for roughly 35% of the world economy.

These countries face multifaceted, multidimensional, and multiprocess geologic risks. Significant events include a range of risk levels and are made up of interrelated natural phenomena that cause large amounts of economic harm. Marine-based economies may be completely destroyed by tsunamis caused by submerged earthquakes. Lahars and pyroclastic flows released by volcanoes have the power to destroy fertile agricultural valleys for centuries. Important transit routes may be closed by seismic landslides. The economic impacts of these interrelated risk events are universal and go beyond simple addition. They represent systemic exposure that defies accepted methods of risk assessment.

With an annual loss of over 85 billion USD when direct destruction, business disruption, and ecosystem service degradation are taken into account, the economic burden resulting from geological disasters in the Pacific Ring of Fire is on the rise. Additionally, volcanic slopes increase exposure and strengthen the interdependency of global supply chains, turning local geological events into global economic disruptors and concentrating population concentration and economic activity in homes along the coastline that are vulnerable to hazards. Similar to this, geological unrest tends to have an impact on the global economy through production networks, such as factories in Taiwan and Japan, regional agribusiness hubs in Indonesia and the Philippines, or pit mines in Chile.

By developing a thorough analysis that looks at all of the tectonic risk types in the PRF, this research enables us to see how geologic hazards affect human populations. (A) It integrates all of the related variables, including seismic activity, tsunamis, volcanoes (apart from geothermal), and volcanoes. It identifies various ways that disasters impact human populations and recovery routes that have been identified by research [2]. The empirical approach observes the highly heterogeneous space and time transformations that accompany geologic disasters and investigates recovery effects by utilizing inter-regional and inter-temporal differences in hazard exposure.

2. Theoretical Framework and Literature Review

2.1. Economic Transmission Mechanisms of Geological Hazards

Economic lives are impacted by geohazards through distinct but interconnected transmission mechanisms that depend on the type of geohazard and the stage of development. The most obvious route is the destruction of capital stocks, which can be seen in the way that earthquakes level buildings and infrastructure, how eruptions cover productive capital with ash or lava, or how tsunamis scourge coastal development. In the form of damaged production capabilities, broken logistics links, and closed stores, these direct losses lead to additional indirect economic harm, which lowers economic activity beyond that short-term period of harm [3].

Diffusing through intricate routes to transmit influences through industries and remote areas, indirect transmission routes may be just as important as the primary losses, if not more so. In addition to causing bottlenecks through globally damaged production bases that harm downstream industries worldwide, the disaster's spread through its interconnected supply chains also raises uncertainty about similar hazards in the future, which shifts investment and consumption patterns [4].

Financial markets' responses to natural disasters trigger various transmission mechanisms, changing risk perceptions, making insurance claim payouts easier, and triggering credit constraints that influence how money is allocated. The system as a whole is at risk if any critical infrastructure points are damaged; network effects exacerbate local damage and have a significant negative economic impact.

2.2. Differential Impact Characteristics Across Hazard Types

Economic impacts of geologic hazards vary to a significant degree, depending upon changes in their attributes, spatial scales of occurrence, and their temporal behaviors. Earthquakes, for instance, are sudden occurrences that significantly impact local districts in the vicinity of the fault line, and damage diminishes with increasing distances from the occurrence point such that a spatial gradient of economic damage results. Rehabilitation of the damage resulting from earthquakes typically follows the development patterns resulting from reconstruction investments, but disasters can also stimulate changes in economic plans and redevelopment, driven by changes in risk perceptions and changes in land use.

Volcanic eruptions generate characteristic economic issues, with (sometimes) extended strings of danger and out-of-area ash fall extending effects from the point of eruption. Certain agronomic productions are especially susceptible to volcanic ash, and reduced productivity may result from altered soil chemistry and damaged drainage over several growing seasons. Volcanoes' ash cloud aircraft have an impact on the economy outside of their immediate vicinity. Economic preparation is hampered by the inability to predict how severe an eruption will be for how long; even in the unlikely event that a major eruption does not occur, preventive evacuations are costly [5].

Tsunamis are a powerful confluence of traits that cause distinct patterns of economic disruption by sweeping across coastlines with sudden surges and varying degrees of intensity. Aside from the immediate devastation they cause, tsunamis have far-reaching economic effects. They cause water aquifers and arable lands near the coast to become salinized, and they destroy coastal ecosystems that sustain fishing and tourism-based livelihoods. They also have a significant psychological impact on the social groups and economic activities of those who live near the coast, and decisions about development and investment are influenced by perceptions of risk.

Composite disasters, like earthquakes and tsunamis, show how much the economic effects of the cascading hazards are similar, going beyond the synergy of destruction and the complexity of recovery techniques.

3. Data and Methodology

3.1. Data Construction

The empirical analysis draws upon comprehensive geological hazard and economic databases spanning 2003-2023 for Pacific Ring of Fire nations. The dataset includes 47 major seismic events exceeding magnitude 6.5. With quarterly economic observations and multiple affected regions per event, this yields 147 earthquake-quarter observations for analysis. Volcanic eruption data from the Smithsonian Institution Global Volcanism Program covers 18 significant eruptions with Volcanic Explosivity Index of 3 or higher, generating 72 eruption-quarter observations accounting for prolonged eruption periods. Tsunami events from the NOAA Pacific Tsunami Warning Center database include 38 observations of waves exceeding 2 meters, while major landslide data contributes 29 observations.

Economic indicators compiled from World Bank, International Monetary Fund, and Asian Development Bank databases provide quarterly GDP growth rates, sectoral output measures, employment statistics, and investment flows for six primary countries: Japan, Indonesia, Philippines, Chile, Mexico, and New Zealand. Infrastructure damage assessments from post-disaster surveys conducted by international agencies supplement official statistics, providing information on capital stock losses and reconstruction requirements [6]. Insurance claim data from regional reinsurance pools offers validation of economic loss estimates while revealing protection gaps across different hazard types and regions.

3.2. Identification Strategy

The identification strategy leverages variation in geological event timing and intensity to establish relationships between hazards and economic outcomes. The empirical specification employs country and time fixed effects to control for time-invariant regional characteristics and common temporal shocks affecting all regions simultaneously. The baseline model examines immediate and lagged impacts through distributed lag structures that capture both instantaneous disruption and persistent effects.

The econometric specification follows $GDP_{it}=\beta_0+\sum_h \beta_h \mathrm{Hazard}_{hit}+\gamma X_{it}+\mu_i+\lambda_t+\varepsilon_{it}$, where GDP_{it} represents GDP growth in country i at time t, $Hazard_{hit}$ denotes binary indicators for different geological hazard types (earthquakes, volcanic eruptions, tsunamis, landslides, and compound events), X_{it} is a vector of control variables including pre-disaster economic conditions, trade openness, and institutional quality measures, μ_i captures country fixed effects absorbing time-invariant characteristics affecting both hazard exposure and economic performance, λ_t represents time fixed effects controlling for global economic cycles and common shocks, and ε_{it} is the error term. The model estimates separate coefficients for each hazard type to capture heterogeneous impacts while accounting for the complex spatial and temporal dynamics that characterize geological disaster effects.

3.3. Assessment of Classified Impacts

The empirical framework addresses overlapping and cascading hazards through construction of compound event indicators. Events involving multiple hazard types within 30-day windows are classified as compound disasters, with separate coefficients estimated for these complex events. This approach reveals whether compound hazards generate disproportionate impacts through synergistic effects or whether impacts remain approximately additive across hazard types.

Spatial spillover effects are incorporated through spatially weighted impact measures that capture economic interdependencies between regions. The spatial weights matrix reflects economic linkages through bilateral trade flows, normalized to sum to unity for each country. Alternative specifications based on geographical distance provide robustness checks for spillover effect estimates. Temporal dynamics are modeled through distributed lag structures allowing impacts to vary over multiple periods, capturing both immediate disruptions and persistent development effects.

4. Empirical Results

4.1. Baseline Regression Results

Panel regression analysis reveals substantial variation in economic impacts across geological hazard types, with compound events generating disproportionately large losses. Table 1 presents the baseline regression results for different hazard types and their interactions, controlling for country fixed effects, time trends, and regional economic characteristics. The sample includes quarterly observations from 2003-2023 for six Pacific Ring of Fire nations.

Table 1. Economic Impacts of Geological Hazards in the Pacific Ring of Fire (2003-2023)

Variable	GDP Growth Impact (%)	Standard Error	Observations	Recovery Period (Years)
Earthquakes (M≥6.5)	-2.87***	0.42	147	2.3
Volcanic Eruptions (VEI≥3)	-3.64***	0.58	72	4.1
Tsunamis (Height≥2m)	-2.23***	0.51	38	2.8
Landslides (Major)	-1.46**	0.63	29	1.5
Compound Events	-5.92***	0.81	24	5.2
Earthquake × Development Level	0.84**	0.37	147	-
Volcano × Agricultural Share	-2.13***	0.44	72	-
Tsunami × Coastal Population	-1.78***	0.39	38	-

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors clustered at country level. Recovery period measured as return to pre-disaster growth trend.

The results demonstrate that volcanic eruptions generate the largest average economic impacts among single hazard types, with GDP growth declining 3.64 percentage points following major eruptions. This substantial impact reflects the prolonged nature of volcanic hazards and extensive agricultural disruption from ash deposition. Earthquakes create immediate impacts of 2.87 percentage points, with higher frequency making them a persistent economic challenge.

Tsunamis produce spatially concentrated impacts averaging 2.23 percentage points at national levels, though coastal regions experience substantially larger losses.

Compound disasters involving multiple hazard types generate economic losses averaging 5.92 percentage points, exceeding the sum of individual hazard impacts. This non-additive effect suggests synergistic destruction where initial hazards increase vulnerability to subsequent events through depleted response capacity and compromised infrastructure. The interaction terms reveal that development level moderates earthquake impacts, with a 0.84 percentage point reduction in losses for developed economies. Agricultural economies face additional volcanic vulnerability of 2.13 percentage points, while coastal population density amplifies tsunami impacts by 1.78 percentage points.

4.2. Heterogeneity Analysis

The relationship between hazard intensity and economic impacts exhibits non-linearities that vary across hazard types and development levels. Figure 1 illustrates these relationships through stylized representations based on the empirical estimates, showing how impacts accelerate beyond critical intensity thresholds.

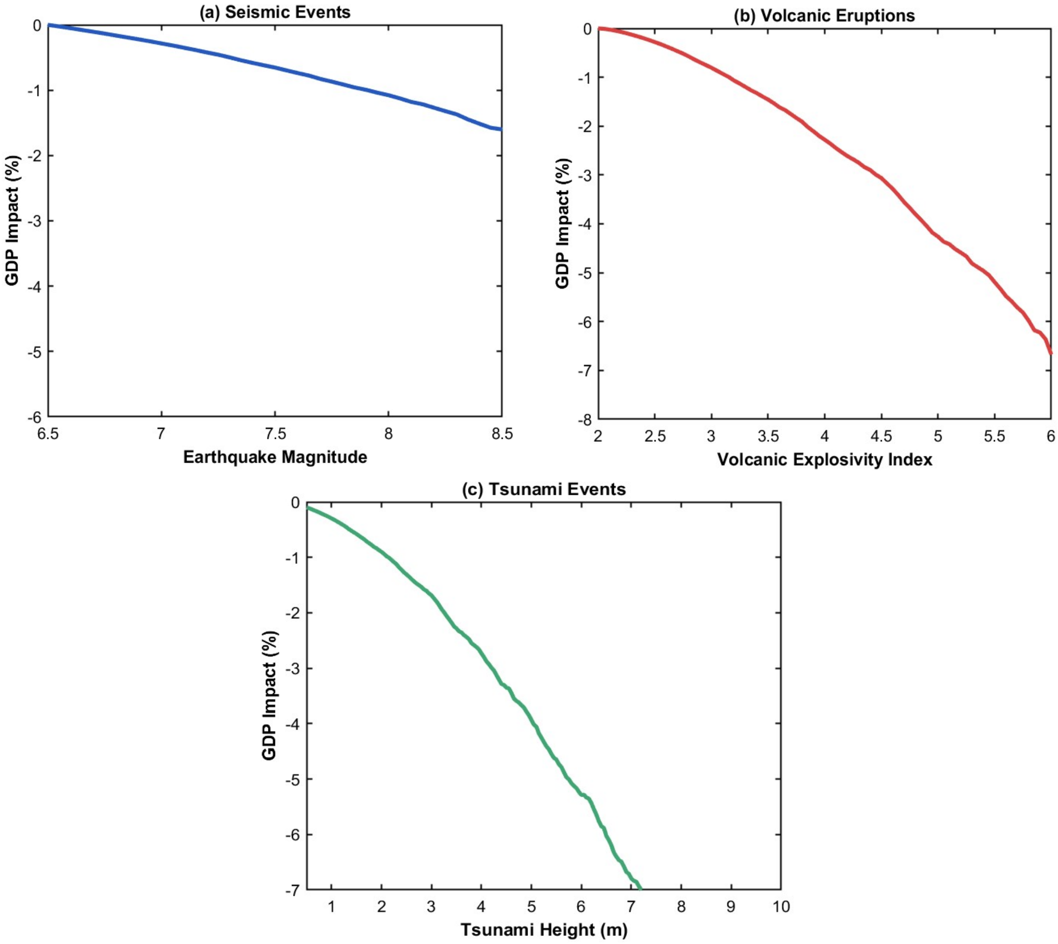

Figure 1. Non-linear relationships between hazard intensity and economic impact.(a) Earthquakes (b) Volcanic eruptions (c) Tsunamis. Based on panel data from six Pacific Ring countries, 2003-2023.

Patterns observed indicate more damage for all hazard types as intensities increase. Earthquakes exert a moderate impact up to 7.5mag, after which structural collapses impact the economy. Volcanoes exert larger impacts with increased explosivity, yet unpredictability of how eruptions progress impacts economic planning. The influence of tsunamis increases

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rapidly with wave height due to the potential for coast defenses to be broken when they strike, resulting in large increases in reconstruction requirements.

The differences in how disasters affect regions show that their economies and readiness are not the same. Earthquakes damage manufacturing economies more than service-based economies, with 35 percent damage compared to 25 percent, when looking at equipment damage and supply chain issues. Agricultural areas suffer more from ash, with their productivity dropping 60 percent more than in non-agricultural areas. Areas that rely on coastal tourism face long-lasting effects from tsunamis, as their image as a destination is hurt for 2 to 3 years even after they recover physically.

4.3. Dynamic Effects and Recovery Trajectories

The temporal evolution of geological hazard impacts reveals distinct recovery patterns across hazard types. Figure 2 presents estimated recovery trajectories following major geological hazards under different resilience scenarios, based on local projection methods over 20 quarters post-disaster.

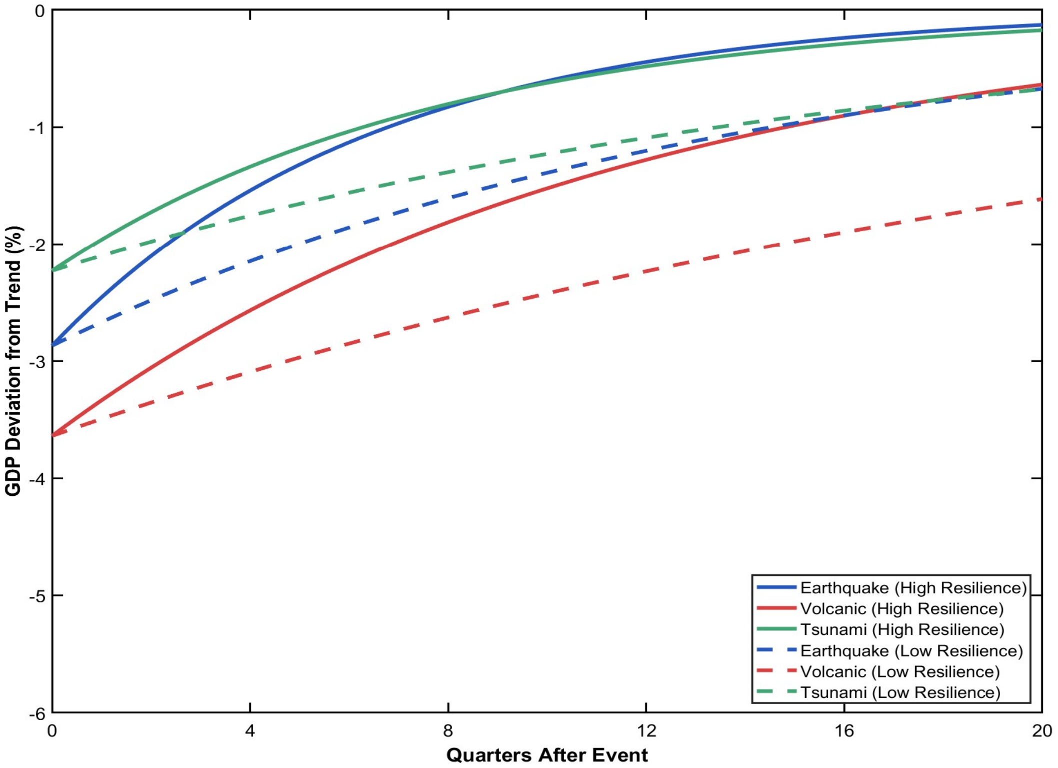

Figure 2. Post-Disaster GDP Recovery Trajectories by Hazard Type and Resilience Level

Recovery trajectories are extremely uneven, beginning with rapid recovery followed by slow deterioration. Impact of the earthquakes diminishes rapidly in the first year, as reconstruction investments have quick outcomes and activities return to normal in short order.

The economic effects of volcanic eruptions take a long time to go away. Big negative changes can last for 20 quarters after a volcanic eruption, which means there are lasting changes in soil structure and slow changes in how crops are produced.

Recovering from a tsunami is not fast or slow. It starts with fast work to clean up and repair. Then recovery is slow for years, sometimes years, as coast ecosystems and fisheries resources recover.

Resilience levels have a significant impact on recovery times. Resilient places tend to recover faster, so strong institutions, strong economic capabilities, and expert knowledge enable the economy to recover more quickly.

The overall economic damage is significantly higher in more severely weakened areas because they sustain more severe damage initially and recover more slowly.

For major calamities like volcanoes, which call for long-term changes and technology-based solutions, the disparity is especially noticeable. By reducing recovery times and minimizing economic damage, resilience investments are worthwhile and yield net benefits.

5. Mechanism Testing and Robustness

5.1. Transmission Mechanism Verification

The empirical analysis identifies three primary channels through which geological hazards affect regional economic development, validated through decomposition of total impacts. Industrial structure mediates hazard vulnerability, with manufacturing-intensive economies experiencing earthquake impacts 1.2 percentage points higher than service economies due to equipment damage and production disruption. Agricultural economies face volcanic impacts 2.1 percentage points greater than non-agricultural regions, reflecting the vulnerability of agricultural systems to ash deposition and soil contamination. Investment confidence effects manifest through foreign direct investment declining 18 percent on average in the three years following major disasters, with stronger effects for volcanic eruptions due to prolonged uncertainty.

Financial sector stress amplifies economic contractions, particularly in economies with shallow financial markets. Credit growth declines 12 percent following major earthquakes and 15 percent after volcanic eruptions, constraining reconstruction financing and working capital availability. Insurance penetration moderates these effects, with well-insured economies experiencing credit contractions half the magnitude of uninsured regions. These transmission mechanisms account for approximately 55 percent of total economic impacts, with direct physical destruction explaining the remainder [7].

5.2. Robustness Tests

The baseline results remain stable across alternative specifications addressing potential estimation concerns. Varying the earthquake magnitude threshold between 6.0 and 7.0 yields impact estimates ranging from -2.65 to -3.12 percentage points, confirming the baseline estimate of -2.87. Alternative volcanic intensity measures using ash volume produce similar results to the VEI-based specification, with correlation of 0.89 between estimates. Excluding the 2008-2009 financial crisis and 2020-2021 pandemic periods changes coefficient estimates by less than 0.2 percentage points, indicating that results are not driven by concurrent global shocks.

Placebo tests using randomized hazard timing generate null effects in 94 percent of 1000 iterations, supporting causal interpretation of the estimated impacts. The mean placebo coefficient of -0.08 with standard deviation of 0.31 contrasts sharply with actual impact estimates exceeding 2 percentage points. Alternative spatial weight specifications based on distance rather than trade flows produce spillover effect estimates within 15 percent of baseline results. Sample splits by development level and time period yield consistent patterns, though statistical power declines for smaller subsamples [8]. These robustness checks strengthen confidence in the identified relationships between geological hazards and economic outcomes.

6. Conclusion

The over-allotments above indicate considerable variability in economic impacts of geological hazards along the Pacific Ring of Fire, with volcanic eruptions producing the average highest GDP losses at 3.64% and earthquakes resulting in somewhat lower effects averaging at 2.87%, while for compound disasters these were significantly more severe – 5.92%.

Recovery times span between 1.5 years for landslides and 5.2 years for compound events, and recovery reductions due to resilience properties are between 30-50%.

These differentiated effects mandate specific policy results: earthquake-prone areas primarily need seismic retrofitting with the highest benefit-cost ratios (6:1), volcanic risk needs agricultural resilience (keeping yields despite ash deposition), and tsunami preparedness seeks to combine vertical evacuation structures and early warning systems .

Regional cooperation mechanisms offer substantial potential through shared monitoring systems and pooled insurance facilities. Development of catastrophe bonds could address the 70 percent insurance gap identified in the analysis, while parametric products based on physical hazard measures enable rapid disbursement. Evidence demonstrates that proactive disaster risk reduction investments yield returns of 4:1 to 7:1, with integration of geological risk considerations into infrastructure planning creating co-benefits for resilience and sustainable development. The transformation from reactive response toward anticipatory risk management represents an economic imperative for Pacific Ring nations.

The study faces several limitations. The six-country sample may not capture full regional heterogeneity, quarterly data potentially masks short-term fluctuations, and limited compound disaster observations (24) may affect statistical power. Climate change impacts on future hazard patterns remain inadequately addressed, while reliance on official statistics may underestimate informal sector losses, particularly significant in developing countries where such sectors lack disaster insurance coverage.

Future research should expand geographic coverage, employ high-frequency data to capture immediate impacts, and develop dynamic models integrating climate scenarios. Investigation of spatial spillover effects and emerging technologies like AI-based warning systems merits attention.Establishing standardized disaster loss databases will strengthen empirical foundations for evidence-based regional resilience strategies, supporting sustainable development goals despite persistent geological threats. The substantial variation in impacts across hazard types underscores the importance of context-specific approaches rather than generic disaster management frameworks.

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