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# ASSESSING GLOBAL INTERNET INFRASTRUCTURE RESILIENCE THROUGH SUBMARINE CABLE NETWORK TOPOLOGY AND SIMULATED FAILURES

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**Abstract:**

This analysis examines whether national submarine cable provision distinguishes retained international connectivity under infrastructure disruption. Using a 2021 topology snapshot covering 173 countries and territories, 294 international cable systems and 1,262 landing records, it combines bipartite network modelling with exhaustive single cable removal and descriptive comparisons. Mean retention was 99.5917% among units with one cable and 99.9286% among those with two, while all units with at least three shared the same score. Landing diversity provided no consistent additional ordering within comparable redundancy categories. Only 21 of 294 removals fragmented connectivity, and five scenarios accounted for 48.17% of cumulative country pair losses. Shared connecting routes explain how multiple national connections can coexist with dependence on distant infrastructure. Geographical groups differed more in infrastructure provision than in retention. The contribution is a linked assessment of national protection and concentrated network consequences, refining interpretations that equate infrastructure quantity with functional independence. The evidence supports evaluating alternative connections against shared dependencies and reporting critical failure scenarios alongside average resilience scores.

**Key Words:** Cable Redundancy; Connectivity Retention; Infrastructure Resilience; Network Simulation; Submarine Cables.

## 1. Introduction:

A country can appear well connected while remaining dependent on a cable whose failure isolates it from the wider network. This distinction matters because international connectivity depends on the arrangement of national connections and the routes available beyond them. Infrastructure assessments that emphasize cable numbers can overlook shared dependencies, while averages across failure scenarios can conceal severe losses under particular removals. The substantive problem is therefore how to distinguish infrastructure provision from the connectivity that survives disruption.

Research on network robustness establishes that additional connections do not provide equivalent protection in every configuration. Schneider et al., 2011, demonstrate that changing connection arrangements can improve robustness while preserving node degrees. Gao et al., 2016, connect resilience to network structure and the dynamics governing system function. These contributions motivate examining cable redundancy alongside the destinations that remain reachable after disruption. Their implications require attention to measurement: structural connectivity, maintained service and recovery describe different aspects of resilience. Liu et al., 2022, explain these distinctions across networked systems. This analysis focuses on retained structural connectivity under a defined cable removal experiment.

The closest submarine infrastructure research already establishes that vulnerability differs across countries and territories. Franken et al., 2022, construct a global submarine cable network from public records and examine remaining bandwidth capacity under three failure scenarios. Their findings identify uneven redundancy and geographically concentrated vulnerability. Rueda et al., 2017, compare structural and centrality measures across 15 telecommunications networks under multiple failure scenarios, demonstrating the importance of matching robustness assessment to network configuration and disruption type. Together, these contributions establish the relevance of infrastructure distribution and scenario design. They leave a more specific measurement question: how much do national infrastructure counts distinguish retained access when every included international cable is removed separately, and how does that national comparison relate to the concentration of losses across cable systems?

Three observed characteristics organize this inquiry. International cable redundancy counts the distinct cable systems serving a country or territory. Additional systems can provide alternative connections, although their protection depends on where those connections lead. Landing point diversity counts distinct national landing locations and describes a different aspect of infrastructure provision. Several locations may belong to one cable system, while several systems may share one location. Mean absolute landing point latitude describes

geographical position. Barthélemy, 2011, establishes that spatial constraints shape network structure, supporting attention to geography without treating latitude itself as a failure probability. These characteristics therefore require separate interpretation rather than aggregation into a single infrastructure index.

This study aims to assess how submarine cable redundancy, landing point diversity and geographical position relate to simulated international connectivity retention. The central research question asks how national infrastructure configurations distinguish retained access under a common cable removal protocol. Specifically, the analysis compares retention across cable redundancy levels, examines landing diversity among units with comparable cable counts, and describes the geographical distribution of infrastructure and retention. It also identifies which cable removals contribute most to global connectivity losses. These objectives connect national infrastructure characteristics to the consequences of disruption within the shared network.

The empirical setting comprises 173 countries and territories, 294 international cable systems and 1,262 cable landing records from an archived 2021 topology. The infrastructure records originate from TeleGeography's Submarine Cable Map, preserved in the NetSAIL UCI repository. Selection retains international systems with an identifiable ready for service year through 2020. Countries and cable systems form a bipartite graph, with membership connections derived from recorded landings. Each cable system is removed separately, and connectivity retention measures the average proportion of baseline international destinations that remain reachable. The analysis provides a cross-sectional comparison within one archived network. Equal scenario weights establish a common structural evaluation rather than an estimate of real failure probabilities. NetSAIL UCI, 2021, supplies the archived source records.

The completed analysis contributes by showing how concentrated vulnerability can coexist with compressed national retention scores. Differences are strongest among units with one or two cable systems, while all units with at least three systems receive the same outcome under the implemented protocol. Landing counts provide no consistent additional ordering within comparable redundancy categories. At the network level, the five largest cable removal scenarios account for 48.17% of cumulative pair losses. The contribution is the linked interpretation of national retention and cable specific fragmentation: the first identifies where protection differs, while the second identifies shared infrastructure dependencies that averages can obscure. These findings qualify the use of cable counts as resilience indicators without establishing a universal redundancy threshold. They provide an international basis for reviewing whether alternative connections preserve access beyond existing shared routes, with conclusions bounded by the archived topology and simulated disruption design.

**2. Theory, Conceptual Framework and Research Questions:**

Internet infrastructure resilience depends on whether alternative connections preserve access when a component fails. Network theory links this capacity to the arrangement of connections and the distribution of structural dependencies. Liu et al., 2022, distinguish network robustness from recovery and adaptation, showing why resilience measures must reflect the function and disruption being evaluated. This analysis examines structural robustness through simulated international connectivity retention, defined as the average proportion of initially reachable foreign destinations that remain reachable after removing each included cable system separately.

The framework uses a bipartite graph connecting countries and territories to submarine cable systems through recorded cable landings. Removing a cable system deletes its connections and changes which destinations remain reachable. The dataset contains 173 countries and territories, 294 international cable systems and 1,262 cable landing records. These records describe a 2021 topology snapshot. Each country receives a connectivity retention value calculated across the same 294 cable removal scenarios. The resulting comparisons describe responses within this constructed network.

International cable redundancy represents the number of distinct included cable systems serving a country or territory. Its proposed protective mechanism is substitution: another cable can preserve access when one system becomes unavailable. However, additional cables do not necessarily provide independent routes to every destination. Several connections may depend on the same distant bridge, leaving countries exposed to failures outside their own infrastructure. Schneider et al., 2011, demonstrated that network robustness can improve through changes in connection arrangements while preserving node degrees. Their findings support distinguishing the number of connections from the protection provided by their arrangement.

Evidence from submarine infrastructure supports examining this distinction at the country level. Franken et al., 2022, identified uneven cable redundancy and differences in vulnerability across states and territories using public infrastructure data and simulated cable failures. This evidence motivates comparing connectivity retention across cable counts. It does not establish a universal increase in protection from every additional cable. The present descriptive comparison therefore evaluates the distribution of retention values within and across observed redundancy levels.

RQ1: How does simulated international connectivity retention vary across levels of international cable redundancy?

Landing point diversity measures the number of distinct recorded landing locations serving each country or territory. It distinguishes the geographical presence of infrastructure from the number of cable

systems. Multiple cables may enter through one location, while a cable system may serve several locations within the same country. These measures therefore capture different infrastructure characteristics.

The interpretation depends on the graph representation. Countries form aggregate nodes, so separate landing locations identify infrastructure diversity without becoming separate failure units. Landing diversity can consequently describe differences in national infrastructure configurations, but its independent protective effect is not established by the cable removal experiment. Gao et al., 2012, explain that connectivity in interconnected systems depends on the arrangement and strength of dependencies, rather than connection counts alone. This theoretical insight supports examining whether countries with similar cable redundancy display different retention values alongside different landing point counts.

RQ2: Among countries and territories with comparable international cable redundancy, how does simulated connectivity retention vary with landing point diversity?

Landing point latitude describes the geographical position of infrastructure. This analysis measures it as the mean absolute latitude of distinct landing locations within each country or territory. Barthélemy, 2011, shows that spatial constraints shape network construction and topology, making geography relevant to understanding infrastructure configurations. Nevertheless, mean absolute latitude measures position rather than the distance between landings or their route independence. Its role in this framework is therefore descriptive: it identifies how cable redundancy, landing diversity and connectivity retention are distributed geographically.

RQ3: How are international cable redundancy, landing point diversity and simulated connectivity retention distributed across countries and territories with different mean absolute landing point latitudes?

The conceptual framework treats cable redundancy, landing point diversity and mean absolute latitude as separate observed characteristics. Connectivity retention is a calculated outcome of the cable removal experiment. The relationships represent exploratory descriptive comparisons, rather than estimated causal effects or indicators of a latent construct. These questions can be resolved through distributions, grouped comparisons and examination of countries with similar infrastructure counts but different retention values. This approach preserves the distinction between recorded infrastructure attributes and connectivity outcomes generated by the network model.

## 3. Data:

This analysis documents the archived infrastructure records, sample selection and construction of the connectivity measures. It separates recorded cable attributes from simulated outcomes and establishes the basis for descriptive comparisons across countries and territories.

### 3.1 Data Sources, Population, and Sample Construction:

The infrastructure records originate from Tele Geography's Submarine Cable Map, preserved in the Internet Resilience repository maintained by NetSAIL at the University of California, Irvine. The extraction uses commit 992c0b9bb775489ad62e55b6f1985a12f7a79df5, dated 8 June 2021. Cable identifiers, service dates and nested landing records come from the archived cable JSON files. The workbook retains an individual source URL for every included cable. The archive date defines the version used; the retrieval date is recorded separately in the workbook metadata. The map documentation specifies the Creative Commons Attribution Non Commercial Share Alike 3.0 Unportedlicence. NetSAIL UCI, 2021, provides the repository and access route.

The target population comprises countries and territories connected through international submarine cable infrastructure represented by the archived network. The accessible frame contains 470 cable records with landing lists and 179 geographical labels. This frame is an archived inventory rather than a verified census of every operating cable. Selection retains systems with an identifiable ready for service year through 2020 and landings in at least two geographical labels. Earlier commissioned cables remain part of the infrastructure stock. Their commissioning dates do not create earlier observations.

The analytical unit is a country or territory. The retained data form a cross section of 173 units associated with one archived topology snapshot. The infrastructure sample contains 294 international cable systems and 1,262 cable landing records. These records support comparisons of structural connectivity under a common disruption protocol. They do not constitute annual observations throughout 2010 to 2022. Franken et al., 2022, demonstrate the relevance of comparing national vulnerability within a global submarine network, while Carter et al., 2014, establish that recorded cable disruptions provide evidence about infrastructure exposure.

Table 1: Sample construction

| Stage | Units | Observations | Reason or Rule |
|---|---|---|---|
| Accessible cable frame | 470 cable systems | 470 cable records | Archived cable objects containing landing lists |
| Exclusion for unavailable service year | 3 cable systems removed | 467 records remaining | No identifiable ready for service year |
| Exclusion for later service year | 34 cable systems removed | 433 records remaining | Ready for service year after 2020 |

| Stage | Units | Observations | Reason or Rule |
|---|---|---|---|
| Exclusion of domestic systems | 139 cable systems removed | 294 records remaining | Fewer than two geographical labels |
| Retained infrastructure sample | 294 cable systems | 1,262 landing records | Nested landing records extracted from eligible systems |
| Constructed network | 173 countries and territories | 970 distinct cable and country memberships | Multiple landings on the same national cable connection consolidated |
| Final descriptive sample | 173 countries and territories | 173 analytical records | Complete values for all four analytical measures |
| Disruption evaluation | 294 cable removals | 294 network scenarios | Each included cable system removed separately |

The exclusions are sequential and mutually exclusive. Infrastructure filtering reduces geographical coverage from 179 to 173 labels. Eligibility rules appear in the construction code before connectivity calculations. They are implemented selection decisions, without a preregistered protocol. Spatial representation and dependency structure determine how these records translate into network relationships, consistent with Barthélemy, 2011, and Gao et al., 2012.

**3.2 Data Integration, Cleaning, and Quality Assurance:**

Integration preserves the archive's hierarchical structure. Each cable identifier links one cable record to its landing records. Each landing identifier identifies a location that may appear on several cables. The extraction assigns geographical labels from the final country or territory component of each landing name. The network then consolidates repeated national memberships within the same cable system. The analytical tables retain one observation per country or territory and one variable per column, following the organizational principles described by Wickham, 2014, and Broman and Woo, 2018.

The audit identifies no duplicate cable identifiers, duplicate analytical units or duplicate combinations of cable and landing identifiers. All 1,262 retained landing records match an included cable. Repeated locations across different cables represent infrastructure relationships and remain in the source table. Consolidation produces 970 distinct cable and country memberships and 722 distinct landing identifiers. The increase from cable records to landing records results from extracting nested relationships.

Eighteen landing identifiers contain coordinate variants across cable records. Their names and geographical assignments agree. The implemented aggregation uses the last coordinate encountered when cable identifiers are processed alphabetically. A sensitivity audit substitutes the minimum and maximum available absolute latitude for each repeated identifier. The largest resulting range in a national mean latitude is 0.000391 degrees. These coordinate choices leave cable counts, landing counts and connectivity retention unchanged. Deterministic processing and explicit checks make this convention reproducible, consistent with Sandve et al., 2013, and Wilson et al., 2014.

All retained coordinates satisfy geographical bounds. Cable counts, landing counts and connectivity denominators are positive. The audit verifies that retained and lost connected pairs sum to the baseline total in every scenario. It also verifies that cumulative losses across countries equal twice the cumulative loss of unordered country pairs. All 173 analytical records contain complete predictor and outcome values. No imputation, interpolation or outlier trimming is applied.

The analysis uses a fixed archive rather than retrospectively combining different map versions. Systems with service years after 2020 are excluded consistently. The archived inventory can omit retired or undocumented systems, so its coverage should not be interpreted as a historical operating census. The exact commit and construction sequence preserve the source version and selection decisions, reflecting the version control principles discussed by Bryan, 2018.

**3.3 Variable Measurement, Construction, and Validation:**

Submarine cable network topology is represented by three observed characteristics: international cable redundancy, landing point diversity and mean absolute landing point latitude. These measures remain separate. Simulated international connectivity retention is calculated from the constructed network. The distinction between infrastructure characteristics and evaluated network function follows the measurement concerns discussed by Oehlers and Fabian, 2021, and Liu et al., 2022. International cable redundancy counts distinct included cable systems serving each country or territory. Equation 1 defines the measure.

$$X_{1i} = |C_i|$$

Here, $X_{1i}$ denotes international cable redundancy for country or territory i, and $C_i$is its set of included international cable identifiers. Higher values indicate more cable memberships. They do not establish that every connection provides an independent route. Schneider et al., 2011, show that connection arrangements can change robustness even when node degrees remain unchanged. Landing point diversity counts distinct landing identifiers within each geographical unit. Equation 2 defines the measure.

$$X_{2i} = |P_i|$$

Here, $X_{1i}$ denotes landing point diversity, and $P_i$is the set of distinct included landing identifiers in country or territory i. Multiple cable records referring to the same landing identifier contribute one location. Countries remain aggregate graph nodes, so landing counts describe infrastructure configuration rather than independently simulated landing failures. This distinction preserves the relationship between the observed records and the chosen network representation, as emphasized by Boccaletti et al., 2014. Mean absolute latitude describes the geographical position of national landing infrastructure. Equation 3 defines its construction.

$$X_{3i} = \frac{\sum_{p \in P_i} |\phi_p|}{m_i}$$

Here, $X_{3i}$ denotes mean absolute landing point latitude, $\phi_p$is the latitude of landing point p, and $m_i$ is the number of distinct landing points in country or territory i. Absolute values combine northern and southern positions on a common scale. Higher values indicate locations farther from the equator. Each distinct location receives equal weight. The network contains country nodes and cable system nodes. A membership edge connects a country to a cable serving it. Each scenario removes one entire cable system and its membership edges while retaining every country node. Equation 4 defines the outcome.

$$Y_i = \frac{\sum_{k=1}^{K} R_{ik}}{KB_i}$$

Here, $Y_i$ denotes simulated international connectivity retention, Kis the number of cable removal scenarios, $R_{ik}$is the number of other geographical units reachable from unit iafter removal k, and $B_i$ is its baseline number of reachable destinations. In the constructed network, $K = 294$ and $B_i = 172$for every unit. Each scenario receives equal weight. The outcome is a fraction between zero and one, with higher values indicating greater retention. Equal weighting defines a structural experiment rather than an estimated distribution of failure probabilities. Gross and Barth, 2022, explain why robustness interpretations depend on the removal process and connectivity measure.

Table 2: Variable dictionary

| Variable or Indicator | Analytical Role | Definition and Construction | Source and Identifier | Unit and Frequency | Transformation and Direction | Missing Value Rule | Coverage and Limitation |
|---|---|---|---|---|---|---|---|
| International cable redundancy | Infrastructure characteristic | Count of distinct included cable identifiers serving each unit | Archived cable id and landing records | Cable systems; single snapshot | Untransformed count; higher means more memberships | Complete; no imputation | 173 units; excludes domestic systems |
| Landing point diversity | Infrastructure characteristic | Count of distinct landing identifiers within each unit | Archived landing_points.id | Locations; single snapshot | Untransformed count; higher means more locations | Complete; no imputation | 173 units; locations are not separate failure nodes |
| Mean absolute latitude | Geographical characteristic | Equal weighted mean of absolute latitude across distinct landings | Archived landing_points.latlon | Degrees; single snapshot | Absolute latitude; higher means farther from the equator | Complete; documented coordinate convention | 173 units; describes position |
| Connectivity retention | Calculated outcome | Mean fraction of baseline destinations remaining reachable across cable removals | Constructed graph and archived cable identifiers | Fraction; scenario average | Equal scenario weights; higher means greater retention | Complete; positive denominator verified | 173 units; structural reachability under single cable removal |

Table 3: Descriptive statistics

| Variable | Valid Count | Mean | Standard Deviation | Median | Minimum | Maximum |
|---|---|---|---|---|---|---|
| International cable redundancy | 173 | 5.607 | 7.403 | 3 | 1 | 63 |
| Landing point diversity | 173 | 4.173 | 6.082 | 2 | 1 | 49 |
| Mean absolute latitude, degrees | 173 | 23.510 | 16.118 | 18.240 | 0.394 | 64.016 |
| Connectivity retention, fraction | 173 | 0.998786 | 0.001340 | 0.999387 | 0.992663 | 0.999387 |

Standard deviations use the sample denominator. Connectivity retention has six distinct values, with 143 units sharing the maximum. This concentration limits differentiation through the aggregate outcome and makes the scenario records useful for interpreting individual cable contributions.

**3.4 Analytical Framework, Identification, and Reproducibility:**

The analysis is descriptive. It compares connectivity retention across observed cable counts and landing counts and examines their geographical distribution. The quantities of interest are the distributions of infrastructure characteristics and the connectivity retained under a common removal protocol. All measures refer to the same topology, eligibility rules and geographical aggregation.

The 294 scenarios exhaust the included single cable removals. They are evaluations of one network rather than independent empirical observations. Countries also share cable systems and distant connections, creating structural dependence between their outcomes. Interpretation therefore concerns the constructed topology and disruption protocol.

Reproducibility rests on preserving the source commit, selection rules, graph construction and calculation sequence. Peng, 2011, and Donoho, 2010, identify executable computation and accessible inputs as essential for assessing computational results. The supplementary package provides construction and audit scripts, extracted records, grouped summaries and descriptive statistics. The construction script reproduces every analytical record in the supplied workbook.

Validation combines identifier checks, coordinate bounds, denominator checks and reconciliation of country losses with network pair losses. The coordinate sensitivity exercise evaluates the consequences of the recorded variants using a consistent sample. These checks establish internal computational consistency. Mesirov, 2010, distinguishes reproducible computational procedures from broader verification of scientific claims, while Stodden et al., 2016, emphasize disclosure of data, code and workflows.

The descriptive questions and subsequent coordinate audit are exploratory. Their interpretation follows the implemented measures without treating simulated connectivity as observed service performance. This distinction maintains alignment between evidence and claims, consistent with the reporting principles discussed by Munafò et al., 2017.

## 4. Methods:

### 4.1 Research Design and Analytical Scope:

This analysis combines descriptive comparisons with a deterministic network removal experiment. The analytical units are the 173 countries and territories retained under the eligibility rules documented in Table 1. Each unit receives infrastructure measures and a connectivity retention score from the same archived topology. The research questions concern differences across cable redundancy levels, landing configurations and geographical positions.

The experiment evaluates every included international cable system separately. Each removal begins from the unchanged baseline network, allowing differences in computed connectivity to be attributed to the specified deletion within the represented graph. National comparisons describe structural relationships within that graph. They do not estimate causal effects of infrastructure investment or observed outage probabilities.

The disruption protocol removes an entire cable system, including its national membership connections. Countries remain present even when isolated. All scenarios receive equal weight, providing a common comparison across infrastructure configurations. This choice makes the interpretation conditional on the specified removal process, consistent with the distinction between failure scenarios and robustness measures developed by Rueda et al., 2017.

### 4.2 Network Representation and Disruption Specification:

The network is an undirected bipartite graph containing geographical nodes and cable system nodes. A connection links a geographical node to each included cable serving it. Equation 5 defines the baseline representation.

$$\mathcal{G}_0 = \langle N \cup C, E \rangle, \qquad E = \{\{i, c\} : i \in N,\ c \in C_i\}$$

Here, $\mathcal{G}_0$ denotes the baseline graph, N is the set of geographical nodes, C is the set of included cable systems, Econtains their membership connections, and $C_i$is the set of cables serving geographical unit i. Multiple landings belonging to the same national cable membership generate one graph connection. All landings assigned to a geographical unit share one node, allowing connections through that node within the model. Equation 6 specifies each disruption.

$$\mathcal{G}_k = \mathcal{G}_0 \setminus \{c_k\}, \qquad k = 1, \ldots, 294$$

Here, $\mathcal{G}_k$ denotes the graph after removing cable system $c_k$and every connection incident to it. Each scenario removes one cable from the baseline rather than accumulating removals. A depth first traversal identifies connected components. For each geographical unit, the algorithm counts other geographical nodes in its component. Cable nodes facilitate connections but do not count as destinations. Equation 4 converts these scenario counts into national connectivity retention using the baseline number of reachable destinations and equal scenario weights. Global connectivity is evaluated through the proportion of baseline unordered geographical pairs that remain connected. Equation 7 defines this measure.

$$Q_k = \frac{\sum_j n_{jk} \left[ n_{jk} - 1 \right]}{173 \times 172}$$

Here, $Q_k$ denotes global pair retention after removal k, j indexes connected components, and $n_{jk}$is the number of geographical nodes in component j. The baseline graph connects all 173 units, producing 14,878 unordered pairs. National retention and global pair retention therefore evaluate related consequences at different aggregation levels. Their interpretation follows the removal and connectivity definitions rather than assuming that robustness measures are interchangeable, as emphasized by Gross and Barth, 2022.

**4.3 Descriptive Comparisons and Scenario Decomposition:**

The measures defined in Table 2 and Equations 1 to 4 remain separate throughout the analysis. Descriptive statistics include valid counts, arithmetic means, medians, minima, maxima and sample standard deviations. Retention fractions are multiplied by 100 for presentation as percentages. Differences between percentage values are expressed in percentage points.

The first research question compares countries and territories by their observed cable counts. The reported summary distinguishes one cable, two cables and at least three cables. The second examines landing counts within matching cable redundancy categories. These comparisons retain all eligible units and identify configurations that share infrastructure counts but differ in connectivity retention.

The geographical comparison uses mean absolute latitude bands of zero to below 15 degrees, 15 to below 30 degrees, 30 to below 45 degrees, and 45 degrees or higher. Boundary values enter the band beginning at that value. These bands organize exploratory comparisons rather than represent estimated hazard thresholds. Equation 8 defines the group mean used in these comparisons.

$$\overline{Y}_g = \frac{\sum_{i \in I_g} Y_i}{n_g}$$

Here, $\overline{Y}_g$ denotes mean national retention in group g, $I_g$ is the set of units assigned to that group, $Y_i$ is national retention defined in Equation 4, and $n_g$ is the number of units in the group. Each geographical unit receives equal weight.

Scenario decomposition ranks cable removals by the number of lost unordered pairs. The contribution of the five largest removals is calculated by dividing their combined losses by losses summed across all 294 scenarios. This proportion describes the concentration of consequences within the experiment. It does not weight scenarios by their likelihood.

The comparisons and scenario rankings are exploratory. Reported quantities are deterministic descriptions of the archived network. Countries share cable systems and connecting routes, so their outcomes are structurally dependent. Interpretation concerns the represented topology rather than sampling uncertainty from independent national observations.

**4.4 Computational Validation, Sensitivity and Replicability:**

Construction and auditing use Python 3 with standard library modules for JSON processing, collections, descriptive statistics and file handling. The traversal exhaustively evaluates all included cable removals. Its outputs depend on the archived inputs and processing rules. Validation checks identifier uniqueness, membership matching, coordinate bounds, positive denominators and retention values within their permitted range. For each scenario, retained and lost pairs must sum to the baseline pair count. Across scenarios, cumulative destination losses summed over countries must equal twice cumulative losses of unordered pairs. This identity checks consistency between national and global calculations.

Coordinate sensitivity addresses the 18 landing identifiers with recorded variants. The implemented construction uses the last coordinate encountered under alphabetical cable processing. The audit additionally calculates national latitude bounds using the minimum and maximum available absolute latitude for each distinct landing identifier. These substitutions preserve cable memberships and therefore leave connectivity outcomes unchanged. No analytical records require imputation, interpolation or outlier removal. Replication materials contain the construction script, audit script, extracted records, coordinate variants and descriptive outputs. The source version is fixed at repository commit 992c0b9bb775489ad62e55b6f1985a12f7a79df5. The construction script reproduces all 173 analytical records in the workbook. These materials preserve the computational sequence and distinguish reconstruction from independent validation of the source inventory, following the reproducibility principles discussed by Sandve et al., 2013, and Peng, 2011. The methodological contribution is the transparent alignment of national comparisons and cable specific connectivity losses within one reproducible experiment.

**5. Findings:**

This analysis evaluates how cable redundancy, landing point diversity and geographical position relate to simulated connectivity retention. It examines 173 countries and territories across 294 separate cable removal scenarios. The findings answer the three exploratory research questions through comparisons of infrastructure characteristics, national outcomes and network fragmentation.

The analytical sample contains 294 international cable systems and 1,262 landing records from the 2021 topology snapshot. Every geographical unit has complete values for the four analytical measures. International cable redundancy ranges from one to 63 systems, while landing point diversity ranges from one to 49 locations. Mean cable redundancy is 5.607, compared with a median of three, indicating an uneven distribution of infrastructure. Mean connectivity retention is 99.8786%, with values ranging from 99.2663% to 99.9387%. However, 143 units, representing 82.66% of the sample, share the maximum value. This concentration makes differences between vulnerable units more informative than the overall average. The

outcome measures structural connectivity under the specified removals, consistent with the distinction between network function and broader resilience developed by Liu et al., 2022.

The first research question concerns variation in retention across cable redundancy levels. All 29 units served by one international cable fall below the observed maximum. Their mean retention is 99.5917%, compared with 99.9286% among the 33 units served by two cables. The difference is 0.3368 percentage points. Every unit with at least three cables records retention of 99.9387%, despite cable counts extending to 63. The observed relationship therefore concentrates at the lower end of the redundancy distribution. Additional cables above three do not differentiate this outcome within the implemented experiment. This pattern is consistent with the uneven distribution of submarine infrastructure vulnerability documented by Franken et al., 2022, while identifying where differentiation occurs in the present network.

Table 4: Connectivity retention by international cable redundancy

| International Cable Systems | Countries and Territories | Mean Retention % | Minimum Retention % | Maximum Retention % |
|---|---|---|---|---|
| One | 29 | 99.5917 | 99.2663 | 99.6104 |
| Two | 33 | 99.9286 | 99.6045 | 99.9387 |
| Three or more | 111 | 99.9387 | 99.9387 | 99.9387 |
| Full sample | 173 | 99.8786 | 99.2663 | 99.9387 |

Georgia provides the exception among units served by two cables. Its retention is 99.6045%, whereas the other 32 units in this category reach the observed maximum. Removing the Georgia Russia cable separates Georgia and Bulgaria into a component containing two countries, disconnected from the remaining 171 units. Removing the Caucasus Cable System isolates Bulgaria. Bulgaria consequently records the lowest national retention, at 99.2663%. These results demonstrate that national cable counts do not fully describe dependence on connections elsewhere in the network. The two-cable configuration provides different protection depending on where its connections lead.

The second research question examines landing diversity among units with comparable cable redundancy. Within the one cable category, mean retention is 99.5881% for 21 units with one landing point, 99.6014% for seven units with two landing points, and 99.6005% for the single unit with four landing points. These values do not establish a consistent ordering by landing count. Among units with two cables, the 16 units with one landing point average 99.9178%, while the 17 units with multiple landing points record 99.9387%. This difference is entirely attributable to Georgia. The other 15 units with two cables and one landing point also reach the maximum. All 111 units with at least three cables share that outcome despite variation in landing diversity. The evidence therefore identifies no consistent additional separation through landing counts within the observed redundancy categories. This finding accords with Schneider et al., 2011, who demonstrate that connection arrangements can distinguish robustness even when connection counts remain unchanged.

The third research question concerns geographical distribution. Exploratory comparisons use four absolute latitude bands, with each boundary assigned to the band beginning at that value. Units below 30 degrees average approximately four cable systems, compared with more than eight in both higher latitude bands. Landing diversity follows a similar pattern. Connectivity retention differs less: group means range from 99.8689% to 99.8953%, a spread of 0.0264 percentage points. The highest latitude band does not record the highest retention. Geography therefore distinguishes infrastructure concentration more clearly than this aggregate connectivity measure. This interpretation treats latitude as spatial position, consistent with Barthélemy, 2011, rather than as a directly measured failure mechanism.

Table 5: Infrastructure characteristics and retention by absolute latitude

| Mean Absolute Latitude, Degrees | Countries And Territories | Mean Cable Systems | Mean Landing Points | Mean Retention, % |
|---|---|---|---|---|
| Zero to below 15 | 67 | 4.30 | 3.16 | 99.8689 |
| 15 to below 30 | 52 | 4.06 | 3.29 | 99.8741 |
| 30 to below 45 | 31 | 8.58 | 5.55 | 99.8953 |
| 45 or higher | 23 | 8.91 | 7.26 | 99.8946 |

Scenario results explain why high average retention coexists with concentrated vulnerability. Of the 294 cable removals, 273 preserve all 14,878 baseline unordered country pairs. The remaining 21 scenarios, representing 7.14% of removals, fragment connectivity. Removing Africa Coast to Europe produces the largest loss, eliminating 1,017 connected pairs and reducing global pair retention to 93.1644%. This removal isolates Gambia, Guinea, Guinea Bissau, Liberia, Mauritania and Sierra Leone, leaving the other 167 units connected. Removing ARCOS isolates Belize, Nicaragua and Turks and Caicos Islands, eliminating 513 pairs. The five largest scenarios account for 48.17% of cumulative pair losses.

Table 6: Cable removals producing the largest connectivity losses

| Removed Cable System | Lost Unordered Country Pairs | Global Pair Retention % |
|---|---|---|
| Africa Coast to Europe | 1,017 | 93.1644 |
| ARCOS | 513 | 96.5520 |
| Manatua | 343 | 97.6946 |
| West African Cable System | 343 | 97.6946 |
| Georgia Russia | 342 | 97.7013 |

The high national averages partly reflect averaging severe losses across many removals that preserve connectivity. Every unit with one cable becomes isolated when that cable is removed, even though its average retention exceeds 99%. The common maximum of 99.9387% also remains below complete retention because otherwise connected units lose access to destinations isolated elsewhere. Thus, national vulnerability and network dependence contribute jointly to the outcome. These results illustrate the sensitivity of robustness interpretation to the removal process and aggregation measure emphasized by Gross and Barth, 2022.

The findings resolve the three research questions descriptively. Cable redundancy separates outcomes most clearly among units with one or two systems, while landing diversity provides no consistent additional ordering within comparable redundancy categories. Higher latitude groups contain more infrastructure, but their retention advantage is small and not monotonic. The central result is that concentrated dependence on a limited set of cable systems can coexist with high aggregate connectivity retention.

**6. Discussion:**

High average connectivity can conceal complete isolation under particular cable failures. Table 4 shows that retention differs most clearly between countries with one and two cable systems, while every country with at least three systems receives the same outcome. Read together, Equation 1 and Equation 4 distinguish infrastructure quantity from the differentiation provided by the retention measure. The observed plateau is specific to this topology and removal protocol; it does not establish three cables as a universal resilience threshold. The contribution is the identification of a concentrated vulnerability pattern beneath an otherwise compressed distribution of national scores. Gao et al., 2016, connect resilience to network structure and system dynamics. This analysis adds a measurement insight: a connectivity score can cease to distinguish infrastructure configurations while substantial differences in cable provision remain.

The Georgia and Bulgaria configurations reveal how dependence on a connecting cable shapenational outcome. Georgia has two cable memberships, yet removing the Georgia Russia system separates both countries from the larger network. The structural explanation is visible through the deletion experiment: multiple national connections can lead into a shared route whose removal prevents access to distant destinations. Table 4 therefore captures differences that the cable count in Equation 1 cannot explain alone. Buldyrev et al., 2010, demonstrate how dependencies can transmit disruption across interconnected systems. The present contribution specifies a related connectivity problem within an international cable topology: national redundancy and access to independent onward connections are distinct properties. This changes the interpretation of redundancy from an inventory count to a question about the destinations and connecting routes that remain accessible.

The scenario decomposition locates vulnerability in a small subset of cable systems. Only 21 removals fragment connectivity, and the five largest scenarios account for 48.17% of cumulative pair losses. Table 6 shows that Africa Coast to Europe contributes the largest loss because several national connections depend on that system. This concentration explains how the high averages generated by Equation 4 coexist with severe consequences in individual scenarios. The contribution is to distinguish the frequency of disruptive scenarios within the experiment from their concentration of consequences. Parshani et al., 2010, establish that dependency structure can alter the fragmentation behaviour of interconnected networks. Here, the relevant theoretical signal is the uneven distribution of shared dependence: equal treatment of cable removals in the average does not imply equal structural importance.

Landing diversity and latitude expose the importance of matching each indicator to the disruption represented. Equation 2 counts physical locations, but the country aggregation does not preserve those locations as separate failure units. The absence of a consistent retention ordering within comparable cable categories therefore describes this representation, rather than establishing that landing diversity lacks protective value. Similarly, Table 5 shows that higher latitude groups contain more infrastructure without a corresponding monotonic ordering of retention. Equation 3 measures position, while Equation 4 evaluates removals without geographical hazard weights. Bashan et al., 2013, demonstrate that spatial embedding can materially shape vulnerability in interdependent networks. The distinction clarifies the contribution here: geographical infrastructure concentration, location diversity and simulated functional independence describe different properties and should not be treated as interchangeable resilience indicators.

The international relevance lies in evaluating national exposure and shared network consequences together. The European configuration involving Georgia and Bulgaria and the West African losses in Table 6 show that vulnerability arises through identifiable connection arrangements across different geographical

settings. Rueda et al., 2017, compare structural and centrality measures across 15 telecommunications networks, illustrating how robustness assessment depends on the metric and failure scenario. This analysis contributes a linked interpretation of country retention and global pair losses within one international topology. For infrastructure assessment, Table 4 should therefore accompany the critical removal results in Table 6: cable counts identify limited redundancy, while scenario analysis identifies shared connections requiring closer examination. Decision makers can use this distinction to review whether proposed alternatives preserve access beyond existing connecting routes. The theoretical implication is that resilience assessment should retain both the distribution of national outcomes and the concentration of consequences across infrastructure components.

**7. Conclusion and Implications:**

Global connectivity can remain vulnerable even where infrastructure appears abundant. This analysis shows that protection depends on how connections preserve access through the wider network, while additional locations and geographical position provide different information about infrastructure provision. Its contribution is the identification of concentrated dependence beneath compressed national resilience scores. The evidence refines structural interpretations of resilience by distinguishing the quantity of infrastructure from the independence of onward connections and the consequences of individual failures. Managers should assess proposed alternatives against shared connecting routes, rather than treating additional infrastructure as sufficient protection. Regulators can complement national inventories with coordinated disruption assessments that identify dependencies crossing jurisdictional boundaries. Operational teams can use critical cable scenarios to prioritize contingency reviews and verify whether alternative connections preserve access to international destinations. These practices can help protect access to services on which businesses and communities depend.

The archived snapshot provides opportunities for longitudinal evaluation using successive infrastructure inventories. Incorporating capacity, traffic demand, routing policies and observed outages would clarify how structural reachability translates into maintained service. Modelling landing locations separately would examine protection obscured by national aggregation. Comparing alternative disruption weights and simultaneous failures would test whether the identified concentration persists under broader operating conditions.

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