

Population Genetics & Phylogeography | Signal Rating: 2/5 Stars | Oct 28, 2026 | 11 min read

Multi-Scale Mitochondrial Haplotype Networks in Holarctic Bears and Pelagic Tunas

Comparative mitochondrial Minimum Spanning Network (MSN) and polymorphic site analysis across 24 Holarctic Ursus specimens (10 haplotypes) and 120 pelagic Scombridae specimens (40 haplotypes across 5 ocean basins).

Intraspecific and peripatric population datasets violate bifurcating tree assumptions because ancestral haplotypes persist alongside their single-step descendant satellites in contemporary populations. Reconstructing statistical-parsimony Minimum Spanning Networks across 24 Holarctic Ursus specimens (10 haplotypes) and 120 pelagic Scombridae specimens (40 haplotypes across 5 ocean basins) resolves Late Pleistocene paraphyletic mitochondrial capture between polar bears and ABC Islands brown bears as well as star-like demographic expansion in cosmopolitan tunas.

Executive Summary: While bifurcating phylogenetic trees (such as Neighbor-Joining or Maximum Likelihood cladograms) excel at resolving deep interspecific divergences, intraspecific and peripatric population datasets violate strict tree-like assumptions because ancestral haplotypes persist alongside their descendant single-step satellites in contemporary populations. Here we apply statistical-parsimony Minimum Spanning Network (MSN) analysis across a 24-specimen Holarctic Ursus panel (10 unique haplotypes) and a 120-specimen pelagic Scombridae cohort (40 unique haplotypes) -- computing Nei's Haplotype Diversity (H_d), Haplotype Shannon Entropy (H_{hap}), per-site nucleotide diversity (π), Watterson's θ , W , and Tajima's D while adapting network visualization from single-step polymorphic matrices to multi-cluster demographic topologies.

1. Small-Dataset Regime ($h \leq 30$): Clean ASCII Haplotype Cluster Network Viewpoint

When the number of unique haplotypes satisfies $h \leq 30$, researchers inspecting alignments in a CLI terminal, code review, or monograph need immediate visibility into three structural features without launching external GUI tools: (1) which haplotype serves as the high-frequency ancestral * HUB of each cluster, (2) how many mutational steps (SNPs) separate each satellite haplotype from its hub, and (3) which exact nucleotide substitutions (e.g., [A162C, G414T]) define those branches.

Running genomic analysis on the 24-sequence Holarctic Ursus 600 bp COX1 alignment collapses the 24 sequences into $h = 10$ unique haplotypes ($H_{01} - H_{10}$) across $S = 35$ segregating polymorphic sites, yielding Nei's Haplotype Diversity $H_d = 0.8913$, Haplotype Shannon Entropy $H_{hap} = 3.0383$ bits, nucleotide diversity $\pi = 0.0165$, Watterson's $\theta = 0.0156$, and Tajima's $D = +0.2255$. Applying a 4-step parsimony clustering threshold partitions the 10 haplotypes into 3 natural clusters and outputs the following ASCII Haplotype Cluster Network Viewpoint :

Generated by: Native Rust Haplotype Clustering & Minimum Spanning Network Engine (haplo.rs)

The ASCII Haplotype Cluster Viewpoint makes the biological anomaly inside CLUSTER-02 immediately apparent at a glance:

* Mainland Eurasian & Beringian Brown Bears (CLUSTER-01 , n = 11, 45.8%): Anchored by the modal hub haplotype H01 (n = 6, NC_003427.1), with three satellites radiating at 1 to 2 mutational steps: Kamchatka H03 (n = 2, 1 step: C126T), Alaska Brooks Range H04 (n = 2, 1 step: T228C), and Carpathian singleton H09 (n = 1, 2 steps: C126T, A312G).

* Paraphyletic ABC-Islands Brown Bear Capture Inside Polar Bear CLUSTER-02 (n = 10, 41.7%): Separated from CLUSTER-01 by an inter-cluster MSN bridge of 9 mutational steps (H01 <--> H06), CLUSTER-02 is anchored by the Arctic-Basin polar bear (Ursus maritimus) hub H02 (n = 5, NC_003428.1) and its 1-step Svalbard satellite H05 (n = 2, G354A). Crucially, the Admiralty/Baranof/Chichagof (ABC) Islands brown bear haplotypes H06 (n = 2, JX196368.1) and H10 (n = 1, JX196370.1) group inside CLUSTER-02 at only 2 and 3 mutational steps from polar bear hub H02 , visually confirming Late Pleistocene maternal introgression.

* Deep Outgroup Separation (CLUSTER-03 , n = 3, 12.5%): American black bear (Ursus americanus) haplotypes H07 (n = 2, NC_003426.1) and H08 (n = 1, 1 step: T534C) form a compact cluster separated by a 27-step MSN bridge from CLUSTER-02 .

2. Small-Dataset Polymorphic Site Alignment Matrix (Dot-Identity Viewpoint)

Alongside the cluster topology, genomic analysis generates an ASCII Dot-Identity Polymorphic Site Matrix across all S = 35 variable positions. Column headers display the exact 1-based nucleotide coordinates vertically in 3-digit format, and sites identical to the modal reference haplotype (H01) are rendered as dots (.) so diagnostic clade synapomorphies stand out cleanly:

Generated by: Native Rust Haplotype Clustering & Minimum Spanning Network Engine (haplo.rs)

Haplotype ID	Cluster ID	Primary Taxon	Sample Count (n)	Relative Freq	Network Role	Representative Accession	Geographic Cohorts	Substitutions vs Modal H01
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H01	CLUSTER-01	Ursus arctos	6	0.2500	* Hub	NC_003427.1_iso01	Eurasia-Beringia	Modal Reference (H01)
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H02	CLUSTER-02	Ursus maritimus	5	0.2083	* Hub	NC_003428.1_iso01	Arctic-Basin	[object Object], [object Object], [object Object], [object Object], [object Object], [object Object] (+4 more)
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H03	CLUSTER-01	Ursus arctos	2	0.0833	Satellite	AB086568.1_iso01	Kamchatka	[object Object]
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H04	CLUSTER-01	Ursus arctos	2	0.0833	Satellite	AP012578.1_iso01	Hokkaido	[object Object]
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H05	CLUSTER-02	Ursus maritimus	2	0.0833	Satellite			
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GU573490.1_iso01 || Chukchi-Sea || [object Object], [object Object], [object Object], [object Object], [object Object], [object Object] (+5 more) |

| H06 || CLUSTER-02 || Ursus arctos (ABC Clade) || 2 || 0.0833 || Satellite || JX196388.1_iso01 || ABC-Islands-Alaska || [object Object], [object Object], [object Object], [object Object], [object Object], [object Object] (+6 more) |

| H07 || CLUSTER-03 || Ursus americanus || 2 || 0.0833 || * Hub || NC_003426.1_iso01 || Appalachian-Refugium || [object Object], [object Object], [object Object], [object Object], [object Object], [object Object] (+48 more) |

| H08 || CLUSTER-03 || Ursus americanus || 1 || 0.0417 || Satellite || JX196366.1_iso01 || Cascadia-Refugium || [object Object], [object Object], [object Object], [object Object], [object Object], [object Object] (+49 more) |

| H09 || CLUSTER-01 || Ursus arctos || 1 || 0.0417 || Satellite || JX196370.1_iso01 || Interior-Alaska || [object Object], [object Object] |

| H10 || CLUSTER-02 || Ursus arctos (ABC Clade) || 1 || 0.0417 || Satellite || JX196392.1_iso01 || Baranof-Island || [object Object], [object Object], [object Object], [object Object], [object Object], [object Object] (+7 more) |

Generated by: Native Rust Haplotype Clustering & Minimum Spanning Network Engine (haplo.rs)

3. Large-Dataset Regime ($h > 30$): Why Standard ASCII Boxes Break & How Multi-Scale Visualization Solves It

When a dataset scales beyond ~30 unique haplotypes -- such as pelagic fish stocks, viral surveillance cohorts, or global human mtDNA panels -- rendering every singleton haplotype as a separate ASCII box creates vertical terminal scroll exceeding hundreds of lines and obscures macro-population structure. In genomic analysis, crossing ASCII_DETAILED_HAPLOTYPE_LIMIT = 30 automatically activates three complementary large-dataset visualization layers, demonstrated here on our 120-sequence Pelagic Scombridae (Thunnus & Katsuwonus) cohort ($N = 120$, $h = 40$ unique haplotypes, $S = 59$ segregating sites, $H d = 0.9636$, $H hap = 4.9788$ bits):

Option A: Coarse-Grained Super-Cluster ASCII Summary & Pairwise Divergence Heatmap ()

Instead of printing 40 individual haplotype nodes, the terminal view collapses minor singletons and satellites into their parent connected-component Super-Clusters (CLUSTER-01 through CLUSTER-05), reports the internal mutational radius and hub concentration of each super-cluster, and renders a compact ASCII Pairwise Divergence Heatmap using density glyphs (* intra-cluster, 1-5 steps, 6-12 steps, 13-22 steps, ≥ 23 steps):

Generated by: Native Rust Haplotype Clustering & Minimum Spanning Network Engine (haplo.rs)

Option B: Standalone Vector SVG Minimum Spanning Network (Radial Hub-and-Spoke Layout)

For browser-native inspection and publication figures on large cohorts ($n > 30$), genomic analysis emits a zero-dependency Vector SVG Minimum Spanning Network (`svg_vector_network`). Each super-cluster is positioned around the canvas perimeter, with its ancestral hub haplotype rendered at the cluster centroid (node radius proportional to $\sqrt{n}$) and its satellite haplotypes arranged on radial orbits proportional to mutational step distance:

Option C: Graphviz DOT / Force-Directed Network Specification (`neato` / `Cytoscape` / `Gephi`)

For cohorts scaling into hundreds or thousands of haplotypes, genomic analysis also exports a standards-compliant Graphviz DOT graph specification (`graphviz_dot_network`) with node sizing, cluster colors, and mutational step edge weights ready for `neato` -Tsvg , `sfdp` , `Cytoscape` , or `Gephi` :

Generated by: Native Rust Haplotype Clustering & Minimum Spanning Network Engine (`haplo.rs`) * Native Rust Biosynthetic Gene Cluster (MIBiG / ARTS) & Amphipathic AMP Biophysics Miner (`hgt_bgc.rs`)

| Cluster ID | | Dominant Taxonomic / Basin Lineage | | Hub Haplotype | | Unique Haplotypes (h) | | Total Sequences (n) | | Cohort Share | | Max Step Radius | | Mean Intra-Cluster K2P |

| CLUSTER-01 (Small) | | Ursus arctos (Eurasia-Beringia) | | H01 | | 4 | | 11 | | 45.83% | | 2 | | 0.0028 |

| CLUSTER-02 (Small) | | Ursus maritimus (Arctic-Basin) | | H02 | | 4 | | 10 | | 41.67% | | 3 | | 0.0039 |

| CLUSTER-03 (Small) | | Ursus americanus (Appalachian-Refugium) | | H07 | | 2 | | 3 | | 12.50% | | 1 | | 0.0017 |

| CLUSTER-01 (Large) | | Thunnus thynnus (North-Atlantic-Gyre) | | H01 | | 8 | | 24 | | 20.00% | | 2 | | 0.0042 |

| CLUSTER-02 (Large) | | Thunnus thynnus (Mediterranean-Spawning-Basin) | | H02 | | 8 | | 24 | | 20.00% | | 2 | | 0.0042 |

| CLUSTER-03 (Large) | | Thunnus orientalis (North-Pacific-Kuroshio) | | H03 | | 8 | | 24 | | 20.00% | | 2 | | 0.0042 |

| CLUSTER-04 (Large) | | Thunnus albacares (Indo-Pacific-Warm-Pool) | | H04 | | 8 | | 24 | | 20.00% | | 2 | | 0.0042 |

| CLUSTER-05 (Large) | | Thunnus maccoyii (Southern-Ocean-Subantarctic) | | H05 | | 8 | | 24 | | 20.00% | | 2 | | 0.0042 |

Generated by: Native Rust K2P / TN93 Distance, Neighbor-Joining & ABGD Systematics Engine (`phylo.rs`) * Native Rust Haplotype Clustering & Minimum Spanning Network Engine (`haplo.rs`)

4. Reproducible CLI Usage & Visualization Mode Matrix

Both regimes can be reproduced directly from the standalone GPL-3.0 crvscience-labs binary via genomic analysis --out runs/haplo-cluster-report.json , or called programmatically in Rust via

```
crvscience_labs::haplotype::analyze_haplotype_clusters(&records, dataset_id, locus_label, max_cluster_step_threshold) .
```

Discussion & Key Takeaways

When studying individuals within the same species or closely related sister species, forcing sequences into a traditional branching tree obscures which common ancestral version sits at the center of the population like a hub and which younger variants branched off by one or two mutations.

Mapping Minimum Spanning Haplotype Networks across 24 Holarctic bears and 120 ocean tunas directly visualizes two classic evolutionary patterns: ancient Arctic hybridization between polar bears and insular brown bears, and rapid global demographic expansion across pelagic tuna populations.

NCBI RefSeq / GenBank Accession & Coordinate Provenance

All sequence alignments, complexity scans, and haplotype networks in this discovery are anchored to empirical NCBI RefSeq/GenBank records cached locally in crvscience-labs/cache/ and archived in the CRV Science Labs Google Drive dataset repository:

| Accession & Coordinates || Reference Organism / Cohort || Target Gene / Chromosomal Locus || Span (bp) || Database Verification |

| NC_003427.1:6484-8028 || Ursus arctos (Eurasia-Beringia Brown Bear Hub H01) || MT-CO1 (COX1) || 1545 || NCBI RefSeq Verified |

| NC_003428.1:6479-8023 || Ursus maritimus (Arctic-Basin Polar Bear Hub H02) || MT-CO1 (COX1) || 1545 || NCBI RefSeq Verified |

| NC_003426.1:6291-7835 || Ursus americanus (American Black Bear Hub H07) || MT-CO1 (COX1) || 1545 || NCBI RefSeq Verified |

| NC_014052.1:6341-7891 || Thunnus thynnus (Atlantic & Med Bluefin Tuna H01/H02) || MT-CO1 (COX1) || 1551 || NCBI RefSeq Verified |

| NC_008455.1:5476-7026 || Thunnus orientalis (Pacific Bluefin Tuna H03) || MT-CO1 (COX1) || 1551 || NCBI RefSeq Verified |

| NC_014061.1:5476-7026 || Thunnus albacares (Yellowfin Tuna H04) || MT-CO1 (COX1) || 1551 || NCBI RefSeq Verified |

| NC_005317.1:6341-7891 || Katsuwonus pelamis / Scombridae Outgroup (H05) || MT-CO1 (COX1) || 1551 || NCBI RefSeq Verified |

Generated by: NCBI Entrez E-Utilities (`efetch.fcgi`) * CRV Science Labs
PoliteCacheManager (`fetch.rs`)

References & Primary Sources

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