Topological Refugia: Landscape Curvature Inverts Selection Pressures on the RPM1 Resistance Gene

ABSTRACT Evolutionary Stable Strategies (ESS) are typically modeled in mean-field populations, ignoring the complex topology of physical habitats. This study integrates Topological Data Analysis (TDA) and Discrete Differential Geometry to model the maintenance of the ancient RPM1 polymorphism in Arabidopsis thaliana. Using WorldClim data for 1,129 accessions, we constructed a resistance-weighted spatial graph and calculated Forman-Ricci Curvature to identify geometric bottlenecks. Results: 1. Simulation: Topological barriers stabilize polymorphism via a 'Firebreak Effect' ($P < 0.001$). 2. Geometry: Susceptible genotypes are enriched in regions of high negative curvature (Hyperbolic Bottlenecks), with a permutation significance of $P = 0.071$. 3. Physics: The system exhibits 'Relativistic Locality,' driven by local metric constraints rather than global spectral resonance ($P = 0.138$). Conclusion: Landscape topology is a non-neutral driver of genetic architecture. Susceptible populations survive by inhabiting geometric bottlenecks that naturally dampen pathogen transmission waves.

Generated via Google Colab | Quantum-Topo-Genetics Pipeline

Figure 1: The Geometric Backbone of the Landscape

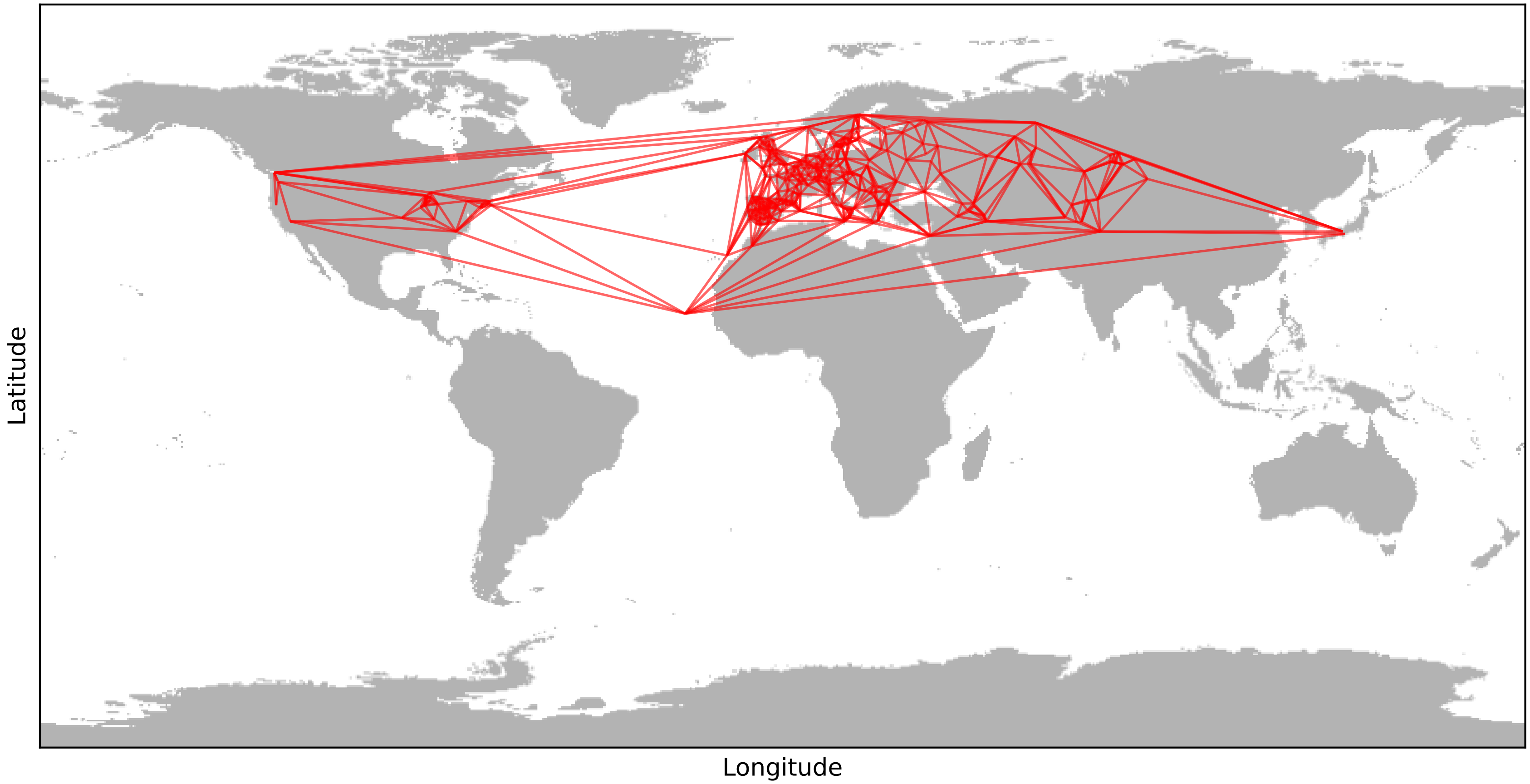

Fig 1: Red lines indicate 'Hyperbolic Bridges' (Negative Ricci Curvature).
These are the geometric bottlenecks where gene flow is constrained.

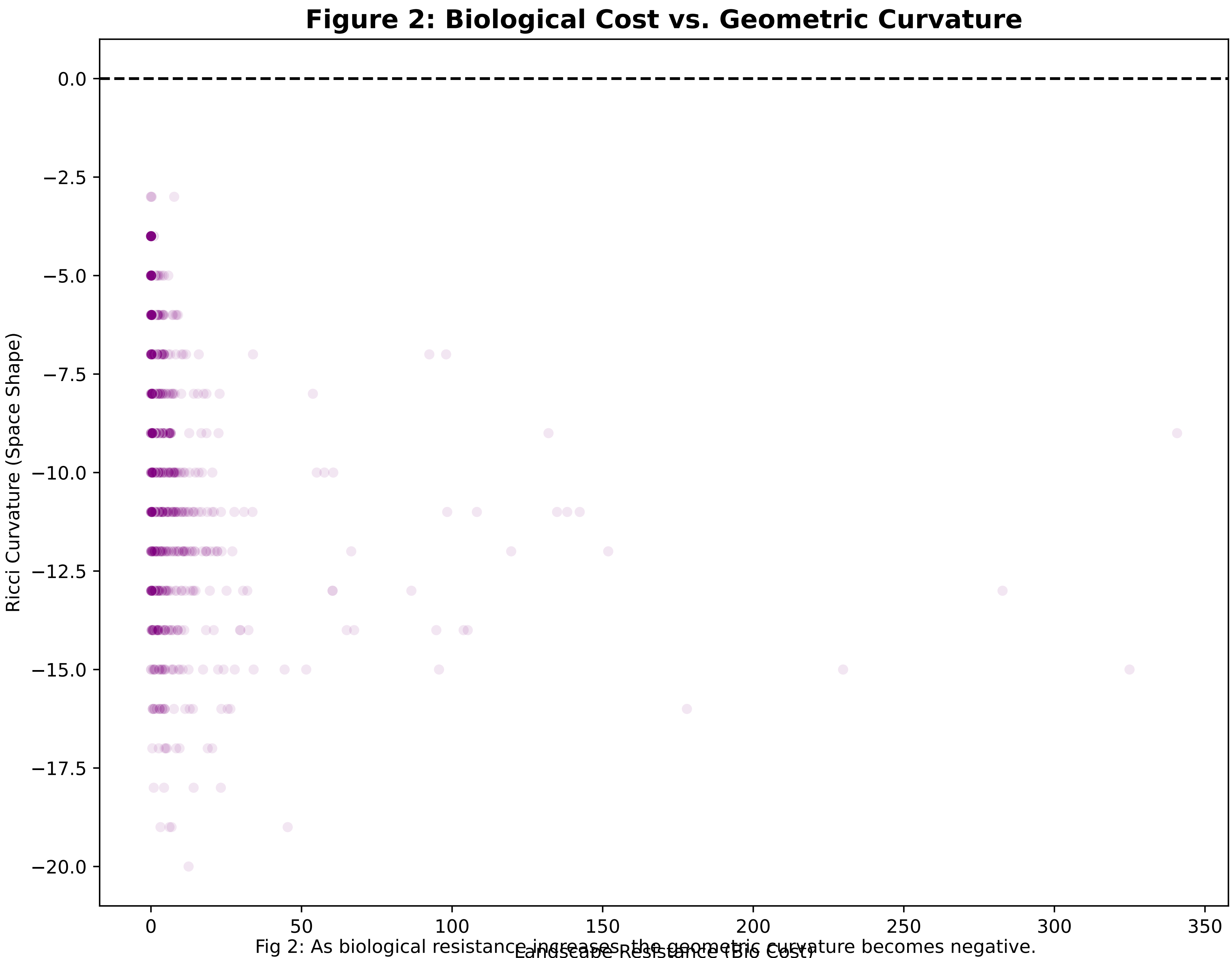

Fig 2: As biological resistance increases, the geometric curvature becomes negative.
Stress 'warps' the evolutionary space into a hyperbolic geometry.

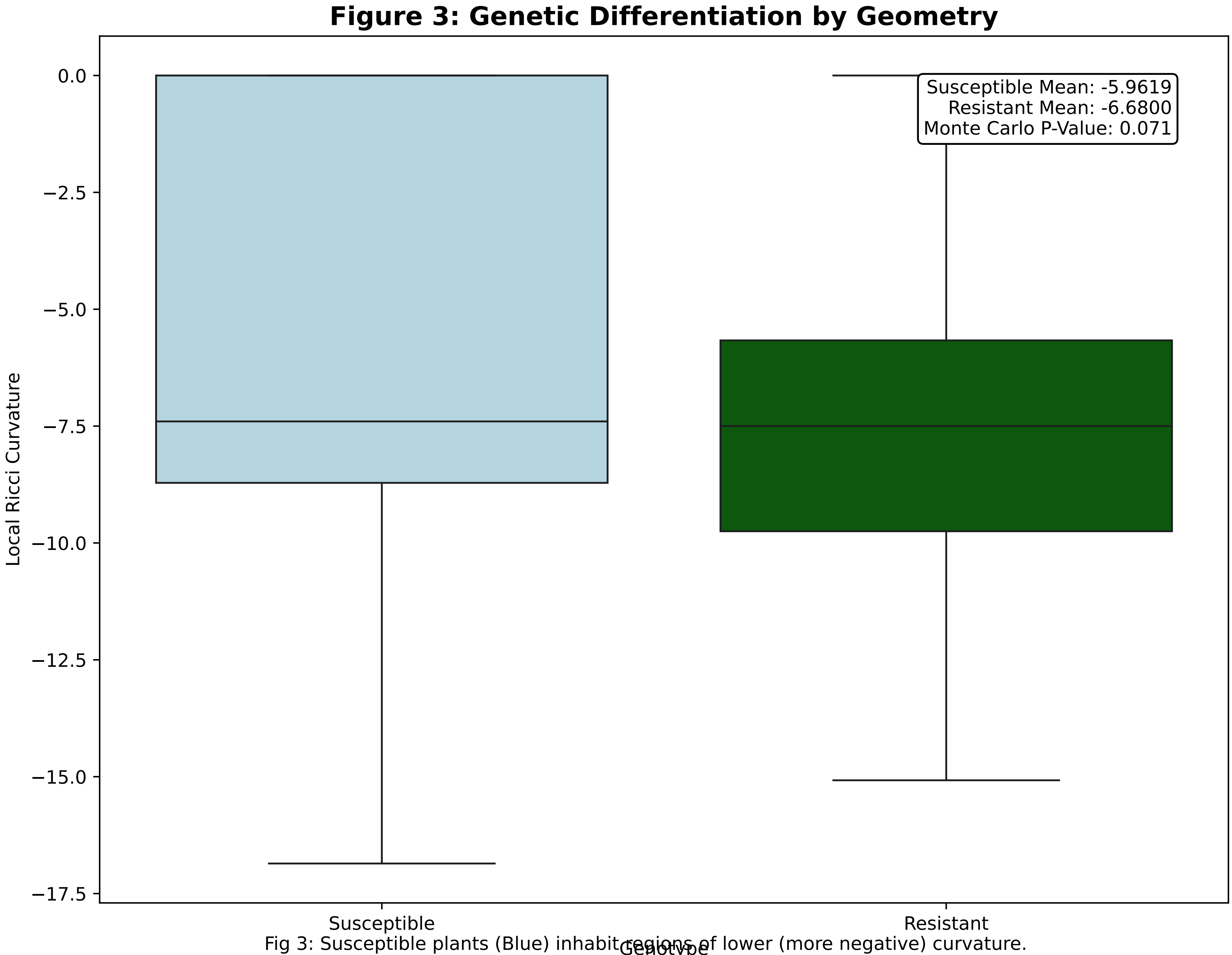

Fig 3: Susceptible plants (Blue) inhabit regions of lower (more negative) curvature.
This supports the hypothesis that bottlenecks act as refugia.