

Predicting Hazard Risk in Northern Mongolia: A Multimodal Geospatial Analysis Integrating Satellite Remote Sensing and Socio-Economic Vulnerability

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Climate change is accelerating rapidly in Northern Mongolia, with air temperatures in high-mountainous regions increasing by 2.5C to 3C over the last 82 years. This warming trend drives a critical "cryosphere-pasture feedback loop," where permafrost degradation causes upland desiccation, significantly increasing the vulnerability of nomadic pastoral systems to **dzud**—a complex cold-season disaster resulting in mass livestock mortality. Effectively adapting to these shifts requires high-resolution prediction modeling that can distinguish between the diverse physical mechanisms of dzud.

Scientifically, dzud is categorized into five distinct types based on the prevailing physical constraints: (1) White Dzud (deep snow burial of pasture); (2) Black Dzud (extreme cold and lack of snow for water supply, often following summer drought); (3) Iron (Tumur) Dzud (impenetrable ice crust from refrozen snow); (4) Cold (Khuiten) Dzud (prolonged extreme cold surges and freezing winds); and (5) Drought-Induced (Gan) or Hoofed Dzud (pasture depletion from summer desiccation or livestock over-concentration). Currently, the Mongolian National Agency for Meteorology and Environmental Monitoring (NAMEM) produces risk maps using 11 parameters—including MODIS-derived snow cover and drought indices—processed through multi-criteria decision analysis (MCDA) in a GIS environment. This system suffers from a "resolution mismatch" that fails to account for micro-scale pasture stress and the specific pre-conditioning signatures of different dzud types.

This study proposes a **Signature Multi-Modal Classifier** for provincial-level prediction that utilizes a two-stage predictive logic. The pre-conditioning phase reanalyzes historical atmospheric data and summer pasture health indicators—Normalized Difference Vegetation Index (NDVI) and Soil-Adjusted Vegetation Index (SAVI)—alongside precipitation anomalies (P_{6-8}) to predict the initial likelihood of Black vs. Drought-Induced dzuds. The real-time update phase incorporates winter snow depth (SD) and temperature (T_{11-2}) anomalies to distinguish the onset of White or Iron dzuds. The primary innovation lies in the use of reanalyzed impact assessments to establish specific parameter thresholds for each disaster type. By integrating National Statistical Office (NSO) socio-economic data, including livestock density (POP_{pre}) and herders' lived experiences, this model provides a foundation for more quantifiable dynamical system analysis using deep learning algorithms and enhances the diagnostic capabilities of early warning systems in the face of Northern Eurasia's changing climate.

Keywords: Disaster Prediction Modeling, Atmospheric Reanalysis, Socio-Economic data, multi-modal classifier