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APPLICATION OF SEED ZONE MAPPING IN MONGOLIA: A CASE STUDY FOR MINE REHABILITATION

Bachelor's Thesis

by

NOMIN-ERDENE Gankhulug

Study Program: Environmental Engineer

Student ID: B2200431

1st Supervisor/Examiner: Prof. Dr. Gantuya Ganbat

2nd Supervisor/Examiner: Prof. Dr. Yong Ho Lee

Ulaanbaatar/Nalaikh

2026

Statutory Declaration

Gankhulug Nomin-Erdene

B2200431

Last Name, First Name

Student ID Number

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Abstract

Land degradation from mining activities represents a critical environmental challenge in Mongolia, where the lack of a systematic framework for native plant material selection has limited the effectiveness of mine rehabilitation. This study addresses this gap by developing the first comprehensive GIS-based seed zone map for Mongolia, delineating 44 discrete seed zones through the integration of natural vegetation zones, plant hardiness zones derived from January minimum temperature, and precipitation zones derived from long-term annual precipitation data.

The delineation followed a hierarchical, ecoregion-first approach implemented in ArcMap 10.8, with statistical validation performed using PERMANOVA, pairwise environmental distance matrix analysis, and Linear Discriminant Analysis (LDA). PERMANOVA results confirmed statistically significant environmental differentiation among the six ecoregion groups ($F = 4.808$, $R^2 = 0.388$, $p = 0.001$), with LDA accounting for 72.8% of between-group variation along the first discriminant axis.

The framework was applied to the Energy Resource LLC (Ukhuaa Khudag coal mine) in Umnugovi province as a case study. The mine was identified within seed zone MZ7 (Dundgovi Desert zone, H5, Semi-dry), and evaluation of current practices revealed that distant seed sourcing introduces a measurable risk of maladaptation. Native species such as *Haloxylon ammodendron* and *Caragana spp.* were identified as the most ecologically suitable for MZ7 conditions.

The developed framework provides a scientifically grounded spatial decision-support tool for guiding seed sourcing in mine rehabilitation and ecological restoration across Mongolia.

Keywords: seed zone mapping; mine rehabilitation; maladaptation; ecological restoration; GIS; local adaptation; Mongolia; plant hardiness zones; ecoregions; PERMANOVA; linear discriminant analysis

1. Introduction

1.1 Background study

Globally, the expansion of extractive industries has made mining one of the leading drivers of land degradation, significantly transforming natural landscapes and disrupting ecosystem functions. Mining operations remove vegetation, topsoil, and geological overburden, leaving behind physically unstable and biologically inactive substrates that are highly vulnerable to erosion and incapable of natural regeneration [1]. As a result, ecological restoration has become a critical component of post-mining land management, aiming to re-establish functional and self-sustaining ecosystems. A key challenge in this process is the successful re-establishment of native vegetation, which depends not only on planting efforts but also on the selection of plant materials that are well adapted to local environmental conditions [2].

To address this challenge, restoration science has long relied on the principle of “local is best,” which assumes that plant materials sourced from nearby locations are most suitable for restoration sites due to local adaptation [3]. While this principle is ecologically valid, its practical application is often inconsistent and poorly defined. In many cases, “local” is determined using arbitrary geographic distances or administrative boundaries that do not reflect true environmental similarity [3]. Such approaches can lead to maladaptation, where plant materials are not suited to the climatic and ecological conditions of the restoration site, resulting in poor survival and reduced restoration success. This limitation highlights the need for a more systematic, scientifically grounded framework to guide seed sourcing decisions.

Seed zone mapping has emerged as a robust solution to this problem by providing a spatial framework that defines areas of environmental and genetic similarity. A seed zone is a geographically delineated region within which plant materials can be transferred with minimal risk of maladaptation [4]. By integrating climatic and ecological variables such as temperature and precipitation, seed zone maps enable practitioners to match plant materials with appropriate environmental conditions. In practice, two main types of seed zones are used: empirical seed zones, derived from genetic and provenance studies, and provisional seed zones, based on climatic data when genetic information is limited [2]. Although empirical zones are considered more precise, provisional seed zones have proven highly effective for large-scale applications. For example, in the United States, generalized provisional seed zones developed by Andrew D. Bower and colleagues have been

successfully applied across diverse ecosystems, demonstrating the capacity for expansion and practical value of climate-based seed transfer frameworks [2].

Mongolia presents a particularly urgent context for applying such approaches due to the combined pressures of mining expansion, climate change, and environmental degradation. The country's economy is heavily dependent on the mining sector, which has led to extensive land disturbance and ecosystem degradation. At the same time, Mongolia's harsh continental climate which is characterized by extreme temperature fluctuations, low precipitation, and fragile steppe ecosystems, limits the natural recovery of disturbed lands [5]. These challenges are further intensified by climate change, with observed temperature increases and increasing frequency of extreme events such as droughts and dzud [6]. In response, Mongolia has committed to reducing greenhouse gas emissions by approximately 22.7% by 2030 under its Nationally Determined Contribution (NDC), highlighting the importance of sustainable land management and ecosystem restoration [7]. In addition, national initiatives such as the Billion Trees National Movement aim to plant one billion trees by 2030, further increasing the demand for effective and scientifically guided reforestation strategies [8].

Despite these urgent needs, Mongolia currently lacks a comprehensive and operational framework for sourcing native plant materials for mine rehabilitation. Existing approaches are limited by the country's vast territory, sparse transportation infrastructure, and the absence of detailed genetic data for most native plant species [5]. Methods used in other regions, such as defining seed collection zones based on road networks or administrative boundaries, are not suitable under Mongolian conditions. While preliminary seed region studies exist for a limited number of forest species, they do not cover the full range of ecosystems or plant types required for large-scale mine rehabilitation [5]. Therefore, there is a clear need for a scientifically grounded, spatially explicit seed zone mapping framework that can guide restoration practices across Mongolia. This study addresses this gap by developing and applying a GIS-based seed zone map tailored to Mongolia's environmental conditions, providing a practical tool to improve the ecological success and long-term sustainability of mine land rehabilitation.

1.2 Objective of the study

The comprehensive aim of this study is to develop a scientifically grounded, spatially explicit seed zone mapping framework for Mongolia to support the ecological rehabilitation of mine

lands across the country's diverse environmental conditions. The Energy Resource mine (Ukhua Khudag) serves as a case study through which the practical applicability of the developed framework is demonstrated and evaluated.

To achieve this aim, the following specific objectives were established:

1. To develop a comprehensive seed zone map for Mongolia by integrating multiple environmental and spatial datasets, including climatic variables such as temperature and precipitation, topographic data, and natural vegetation zone information, using Geographic Information System (GIS) techniques and statistical methods.
2. To examine the key environmental variables driving seed zone differentiation across Mongolia, with particular focus on annual mean temperature, annual precipitation, and elevation, and to assess through statistical validation how these variables define meaningful environmental boundaries between zones.
3. To provide a spatial framework for guiding native plant material selection and seed collection by linking delineated seed zones to their environmental characteristics, thereby supporting ecologically appropriate seed sourcing decisions for restoration practitioners.
4. To evaluate the practical applicability of the seed zone framework for mine rehabilitation through a case study at the Energy Resource mine (Ukhua Khudag), assessing the alignment of current seed sourcing and species selection practices with the developed framework and identifying areas for improvement.

1.3 Literature review

Despite the growing importance of seed zone mapping in ecological restoration worldwide, research on this topic in Mongolia remains extremely limited. At present, only one systematic study has attempted to delineate seed regions within the country, and it is restricted to a small number of forest tree species [5]. This lack of research presents a significant challenge for restoration practices, particularly in the context of mine rehabilitation, where the selection of ecologically appropriate plant materials is critical for long-term success.

To address this gap, it is necessary to draw upon established knowledge from related scientific fields, including restoration ecology, ecological genetics, and spatial environmental analysis. This literature review therefore examines the key concepts and methodologies that underpin seed zone mapping. It begins with the principle of local adaptation, which explains how plant populations become suited to specific environmental conditions, and then

introduces seed zone mapping as a spatial tool for guiding seed transfer. Finally, it reviews existing studies in Mongolia and identifies the limitations that justify the development of a comprehensive, landscape-scale seed zone framework for the country.

1.3.1 Principles of local adaptation of native plant species in restoration

Seed zone mapping is based on the ecological principle of local adaptation, which states that plant populations evolve to become genetically specialized for the environmental conditions of their native locations [2]. This differentiation arises from natural selection acting on traits related to climate, such as frost hardiness and drought tolerance, and edaphic factors like soil chemistry and texture [2]. Numerous studies have demonstrated that transferring seeds far from their point of origin can lead to maladaptation, resulting in poor growth, reduced reproductive success, and high mortality rates, ultimately causing restoration projects to fail [2]. The use of seed zones is therefore a proactive strategy to minimize this risk by ensuring that plant materials are deployed within environments to which they are already adapted [2]. As McKay et al. (2005) argue, ecological distance is often a better predictor of restoration success than simple geographic distance, underscoring the need for tools that delineate areas of true environmental similarity [2].

1.3.2 Seed zone mapping

Seed zone mapping is a spatial approach used to delineate geographic areas within which plant materials can be transferred with minimal risk of maladaptation or loss of fitness. This method is based on the concept of local adaptation, where plant populations are genetically suited to the environmental conditions of their native habitats [2, 9]. As a result, transferring plant materials beyond these adaptive ranges can lead to reduced survival, growth, and reproductive success.

Early seed zone delineation relied on provenance trials, in which plant populations from different geographic origins were evaluated under common environmental conditions [5]. Although this approach provides reliable information on genetic adaptation, it is time-consuming and difficult to apply at large spatial scales. Consequently, modern seed zone mapping increasingly utilizes climate-based methods that incorporate key environmental variables such as temperature and precipitation as proxies for plant adaptation [2].

One widely adopted approach is the development of generalized provisional seed zones, as demonstrated by Bower et al. (2014), which use a limited number of climatic variables to

represent major environmental gradients [2]. This method has proven effective for large-scale applications and is now widely used in restoration planning. In addition to improving restoration success, seed zone mapping supports the conservation of genetic diversity by ensuring that plant materials are matched to ecologically similar environments [9].

1.3.3 Prior seed zone studies in Mongolia and their limitation

Mongolia is characterized by a high degree of ecological and climatic heterogeneity, which strongly influences plant distribution and adaptation. The country is divided into 16 phytogeographical regions, as defined by Grubov (1982), representing distinct combinations of climate, elevation, and vegetation types across the territory [10]. These regions range from mountain taiga and forest-steppe ecosystems in the north to steppe, semi-desert, and desert environments in the south, reflecting pronounced environmental gradients.

Research on seed zone delineation in Mongolia remains limited, with the only systematic effort conducted by Jamyansuren et al., who developed preliminary forest seed-region maps for major coniferous species such as *Larix sibirica*, *Pinus sylvestris*, *Pinus sibirica*, *Abies sibirica*, and *Picea obovata* [5]. In their study, seed regions were defined using a combination of topographic features, Digital Elevation Model (DEM) data, satellite imagery, forest inventory records, and meteorological information. The authors also noted that commonly used delineation approaches in other countries, such as using road or railway networks are not suitable for Mongolia due to its vast territory and limited infrastructure [5].

Despite its importance, this study has several limitations when considered in the context of large-scale ecological restoration. The delineation focuses primarily on a limited number of forest tree species and does not account for the broader range of native shrubs, grasses, and steppe-adapted species that are essential for mine-site rehabilitation. Furthermore, the methodology relies mainly on topographic and meteorological variables, without incorporating a more comprehensive set of bioclimatic factors that are widely used in modern seed zone mapping approaches. In addition, the developed seed regions were intended for forest management and seed supply purposes rather than for the ecological restoration of degraded mining landscapes.

Given the strong environmental gradients and high ecological diversity of Mongolia, these limitations highlight the need for a more comprehensive and spatially explicit seed zone framework. Such a framework should integrate both climatic and ecological variables to better represent the adaptive variation of plant species across the country. Therefore, the

development of a nationwide seed zone map is essential for providing scientifically grounded guidance for seed sourcing and for improving the effectiveness of mine rehabilitation and restoration practices.

2. Methodology

2.1 Study area

The study was conducted across the entire territory of Mongolia, a landlocked country located in Central Asia, bordered by Russia to the north and China to the south, east, and west. It covers an area of approximately 1,566,500 km², spanning latitudes 41°35'–52°09' N and longitudes 87°44'–119°56' E, with a total border length of approximately 8,162 km [11].

Administratively, the country is divided into 21 provinces (aimags) and the capital municipality of Ulaanbaatar, which are further subdivided into 339 district (soums) that serve as the primary units for land management and environmental governance.

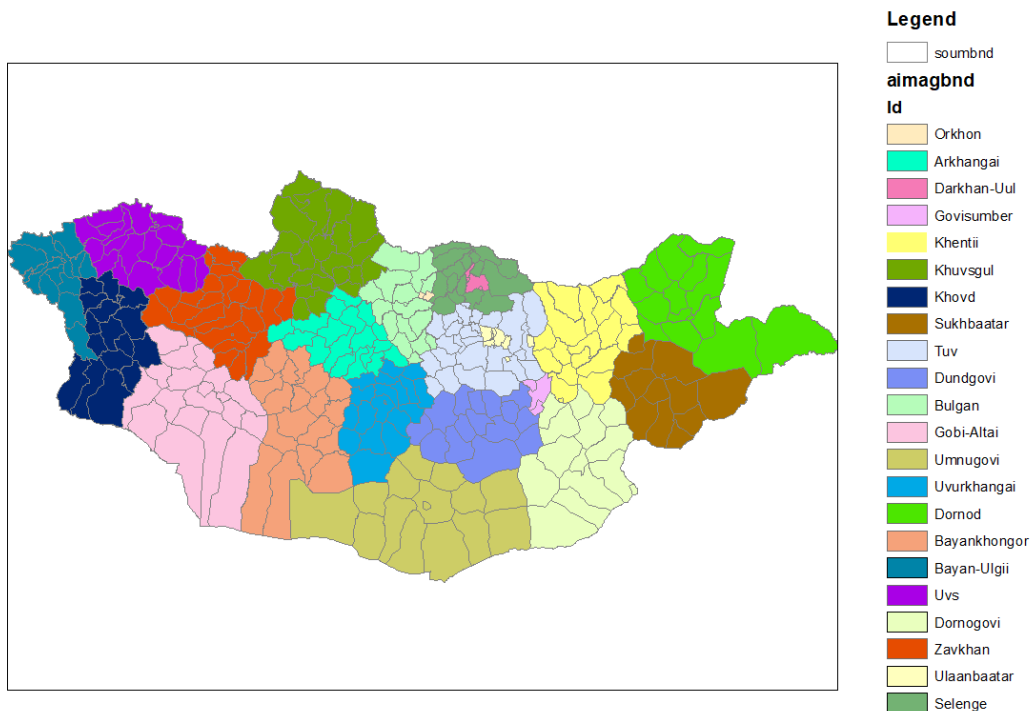


Figure 1 Administrative boundaries of Mongolia showing the 21 aimags and their soum subdivisions.

Mongolia is predominantly a mountainous country with a mean elevation of 1580 m above sea level [12]. As shown in Figure 2, elevation ranges from below 500 m in low-lying basin

areas to above 4,500 m in the high Altai ranges of the west. The dominant elevation classes of 1,000-1,500 m and 1,500-2,000 m cover large parts of central and western Mongolia, reflecting the broadly elevated plateau character of the country. The highest peaks are concentrated in the Mongolian Altai, including Khuiten Peak at 4,374 m, while other major mountain systems such as the Khangai and Khentii ranges further define the country's topographic complexity. These upland regions gradually transition eastward into the lower Eastern Steppe plains and southward into the Gobi Desert basin. Such pronounced altitudinal gradients play a critical role in shaping environmental conditions, driving distinct vertical vegetation belts and serving as a key input variable in the seed zone delineation framework applied in this study [12,13].

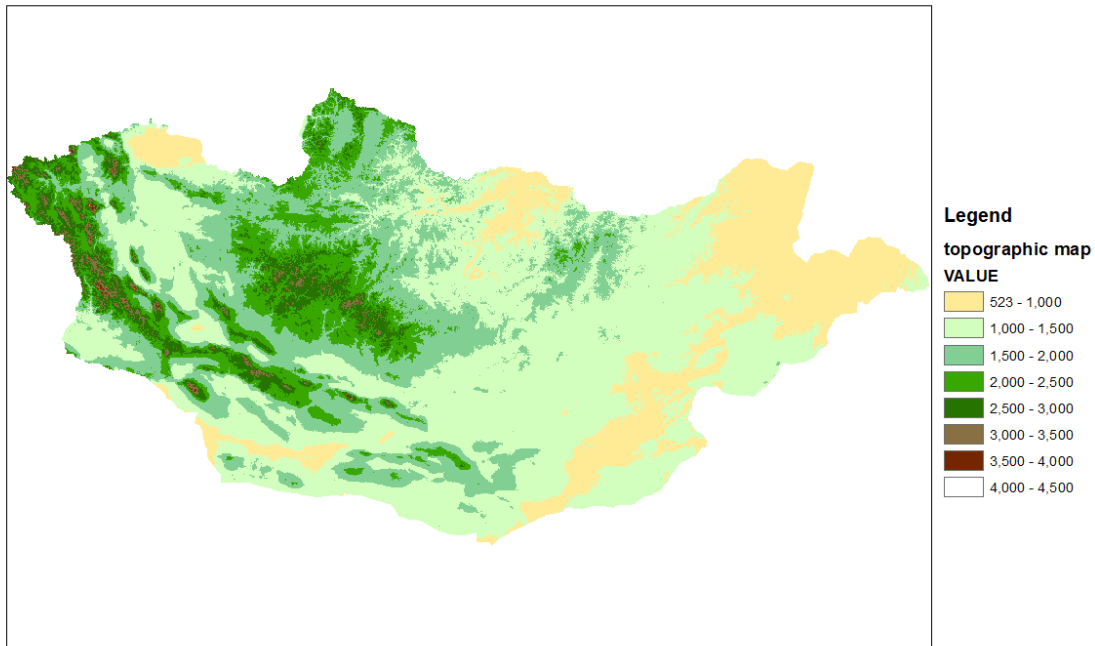


Figure 2 Topographic map of Mongolia showing elevation classes (meters above sea level).

Closely linked to this topographic variability is Mongolia's extreme continental climate, characterised by long, cold winters, short summers, high solar radiation, and generally low annual precipitation [13]. Precipitation exhibits a clear north-to-south gradient: while most of the country receives above 100 mm of mean annual precipitation, the southern and south-western regions are largely corresponding to the Gobi Desert and the Great Lakes Depression, receive below 100 mm, with some areas experiencing virtually no measurable precipitation in certain years [14]. The majority of precipitation occurs during the short summer growing season (June–August), further constraining ecological processes. Mean

annual temperatures range from below -8°C in northern mountainous areas to above 6°C in the southern Gobi, with extreme winter temperatures dropping as low as -53°C in the north [12]. In addition, Mongolia has experienced a mean temperature increase of approximately 2.5°C over the past 80 years, exceeding the global average and intensifying the frequency of extreme climatic events such as dzud and dust storms [14]. These climatic conditions, in combination with the country's complex topography, act as fundamental determinants of plant species distributions and must be explicitly considered in seed sourcing strategies for mine rehabilitation.

As a result of these interacting gradients of elevation, temperature, and precipitation, Mongolia's vegetation is organised into distinct latitudinal and altitudinal natural zones, as presented in Figure 3. The spatial configuration of these vegetation zones provides the ecological foundation for the seed zone mapping approach employed in this study, as it reflects the integrated influence of the country's key environmental gradients.

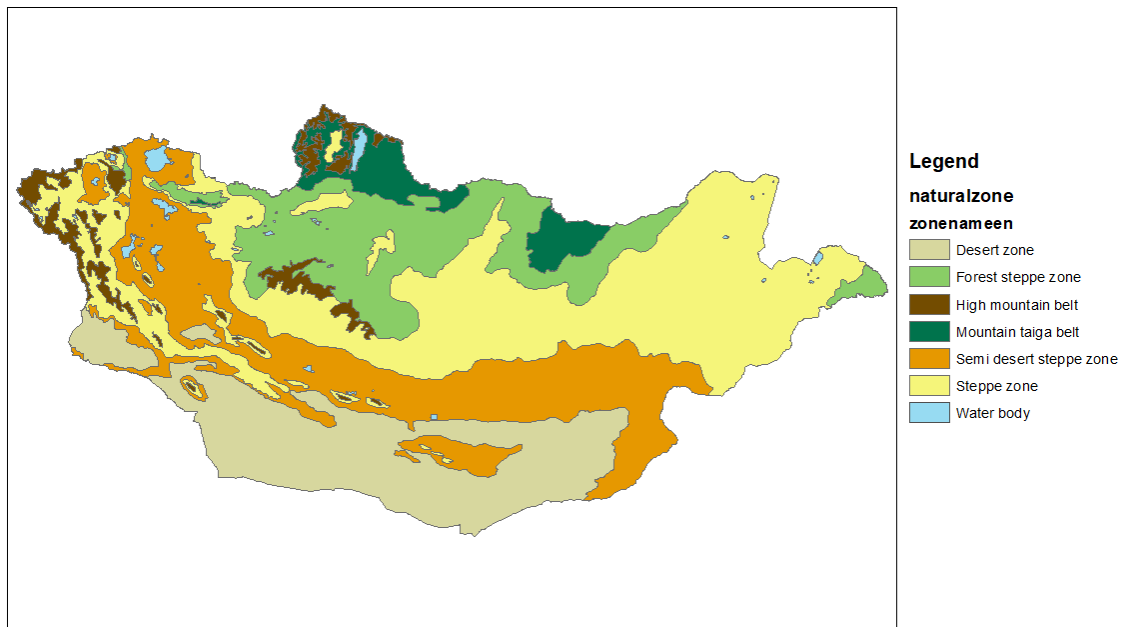


Figure 3 Natural vegetation zones of Mongolia, including the Desert zone, Forest Steppe zone, High Mountain Belt, Mountain Taiga Belt, Semi-desert Steppe zone, and Steppe zone

2.2 Data collection and sources

In this study, several spatial and climatic datasets were collected to support the development of seed zone mapping for mine rehabilitation. The datasets were obtained from both national and international sources and used as input layers for further analysis.

Administrative boundary data at the *soum* level, province level, country boundary and natural zone maps of Mongolia were collected from the Environmental Information Center (EIC), which provides official geospatial data widely used in environmental studies in Mongolia [15]. These datasets were used as base layers for spatial analysis.

Topographic data were obtained from the United States Geological Survey (USGS), which provides digital elevation and terrain-related datasets for global applications [16]. These data were used as a supporting layer for spatial analysis.

Climate-related data were collected from the WorldClim Version 2.1 database, which provides high-resolution global climate data based on long-term historical records for the period 1970-2000 [17]. Specifically, the minimum temperature dataset *wc2.1_2.5m_tmin* with a spatial resolution of 2.5 arc-minutes (~5 km) was used for generating the hardiness zone map. The use of a 30-year climatological period reduces the influence of short-term variability and ensures that the derived zones represent stable environmental conditions relevant for plant adaptation.

Precipitation data were obtained using Google Earth Engine from the WorldClim bioclimatic dataset, which includes variables such as annual precipitation (*bio12*) [18]. This dataset also represents long-term average conditions for the period 1970-2000. The dataset was clipped to the Mongolia boundary and exported as a GeoTIFF file with a spatial resolution of *1 km* for further GIS analysis. The use of long-term average precipitation data ensures that moisture conditions are represented accurately for ecological applications such as seed zone mapping.

The collected datasets include both vector and raster formats. Administrative and natural zone data were used as vector layers, while topographic and climate data were used as raster datasets for spatial analysis.

2.3 Data pre-processing

Prior to spatial analysis, all datasets were subjected to a series of pre-processing procedures to ensure consistency, accuracy, and compatibility within the GIS environment. Pre-processing was carried out using ArcMap 10.8 and Google Earth Engine (GEE), and involved three main stages: (1) climate data preparation for hardiness zone mapping, (2) precipitation data acquisition and processing, and (3) topographic data preparation.

2.3.1 Hardiness zone data preparation

Monthly minimum temperature data for January were obtained from the WorldClim version 2.1 global climate database [17]. WorldClim 2.1 provides globally interpolated climate surfaces derived from weather station records for the period 1970-2000 and is widely used as a standard reference dataset in ecological, biogeographical, and conservation research [17, 19]. Data were downloaded in GeoTIFF format at a spatial resolution of 2.5 arc-minutes (approximately 5 km at the equator) from the WorldClim online repository.

January minimum temperature (tmin1) was selected as the primary input variable because January represents the coldest month in Mongolia due to the country's extreme continental climate regime, characterised by cold, dry winters under the influence of the Siberian High-pressure system [20]. The January minimum temperature therefore serves as the most appropriate single-month proxy for the average annual extreme minimum temperature, which is the key climatic variable used to assess plant cold tolerance and define hardiness zone boundaries [19]. The downloaded raster was loaded into ArcMap 10.8 and its spatial reference was confirmed as the *Geographic Coordinate System WGS 1984*. No unit conversion was required as WorldClim 2.1 temperature values are provided natively in degrees Celsius [17].

For boundary clipping, the country boundary of Mongolia was obtained from the Environmental Information Center (EIC), which provides official geospatial data widely used in environmental studies in Mongolia [15]. The January minimum temperature raster was clipped to the national extent of Mongolia using the *Extract by Mask* tool of ArcMap 10.8 (Spatial Analyst Tools - Extraction - Extract by Mask). The clipped raster yielded temperature values ranging from approximately -38.3°C in the northern mountain regions to -16.1°C in the southern Gobi Desert, consistent with documented climatic conditions in Mongolia [20].

The clipped minimum temperature raster was reclassified into discrete plant hardiness zones using the *Reclassify* tool of ArcMap 10.8 (Spatial Analyst Tools - Reclass - Reclassify). The classification followed a temperature-based plant hardiness zone system adapted to Mongolia's continental climate conditions, using minimum temperature intervals of 5.6°C to define discrete zones [20]. This interval-based approach is widely applied in ecological zoning and seed zone delineation studies to capture meaningful differences in plant cold tolerance across landscapes [19]. Based on the temperature range of the study

area, six hardiness zones were identified within Mongolia, designated as H1 through H6. The temperature thresholds applied in the reclassification are presented in *Table 1*.

Table 1 Plant hardiness zone temperature thresholds applied in the reclassification of January minimum temperature for Mongolia.

Zone Code	Temperature Range (°C)	Temperature Range (°F)	Description
H1	Below – 45.6	Below –50	Extremely cold
H2	– 45.6 to – 40.0	– 50 to – 40	Very extremely cold
H3	– 40.0 to – 34.4	– 40 to – 30	Very cold
H4	– 34.4 to – 28.9	– 30 to – 20	Cold
H5	– 28.9 to – 23.3	– 20 to – 10	Moderately cold
H6	– 23.3 to – 17.8	– 10 go 0	Mild cold

2.3.2 Precipitation data

Data Acquisition via Google Earth Engine

Annual precipitation data were obtained from the WorldClim Version 1 Bioclimatic Variables dataset [11], accessed through the Google Earth Engine (GEE) cloud computing platform [2]. This dataset provides global climatological data interpolated from monthly temperature and rainfall records spanning the period 1970-2000, at a spatial resolution of approximately 1 km (30 arc-seconds). The specific variable extracted was BIO12, representing mean annual precipitation in millimetres. Long-term average precipitation data were selected to ensure that moisture conditions are represented as stable environmental conditions relevant for ecological applications such as seed zone mapping [21].

Data Extraction and Export

A JavaScript script was written and executed in the GEE Code Editor to extract and export the precipitation data for Mongolia. The national boundary of Mongolia was defined using the USDOS Large Scale International Boundary (LSIB) Simple dataset. The annual precipitation layer was clipped to the boundary of Mongolia and exported to Google Drive in GeoTIFF format at a spatial resolution of 1,000 metres. The GEE script used in this study is provided in Appendix B1.

Reclassification into Precipitation Zones

The exported GeoTIFF raster was imported into ArcMap 10.8 for further processing. Annual precipitation values across Mongolia ranged from a minimum of 33 mm in the southern Gobi Desert to a maximum of 714 mm in the northern mountain areas. The continuous precipitation raster was reclassified into two discrete precipitation zones using the *Reclassify tool* in the of ArcMap 10.8 (Spatial Analyst Tools - Reclass - Reclassify), as presented in *Table 2*.

Table 2 Precipitation zone classification thresholds applied in the reclassification of annual precipitation for Mongolia

Zone Value	Precipitation zones	Annual precipitation (mm)
1	Zone 1 - Dry	<100
2	Zone 2 – Semi-dry	≥ 100

The classification threshold of *100 mm* was selected based on its ecological significance as a critical boundary between arid and semi-arid conditions in Central Asian dryland ecosystems [22]. This threshold is widely recognised in the literature as a meaningful distinction for plant community composition, seed adaptation, and land rehabilitation potential in arid regions [22].

Coordinate System Reprojection and Format Conversion

The reclassified precipitation raster was converted from raster to vector polygon format using the *Raster to Polygon* conversion tool in ArcMap 10.8 (Conversion Tools - From Raster - Raster to Polygon). The resulting polygon layer was subsequently reprojected from the Geographic Coordinate System WGS 1984 to the Projected Coordinate System WGS 1984 UTM Zone 48N using the *Project tool*. This reprojection was carried out to ensure spatial consistency with other analytical layers and to enable accurate area calculations in metric units.

2.3.3 Topographic data

Topographic data were obtained from the United States Geological Survey (USGS) [23], which provides globally available digital elevation and terrain datasets. The digital elevation model (DEM) was loaded into ArcMap 10.8 and used as a supporting spatial layer to provide terrain context for the seed zone analysis. The DEM was clipped to the country boundary of Mongolia using the *Extract by Mask tool* (Spatial Analyst Tools - Extraction - Extract by

Mask) with the GADM national boundary layer [10] as the mask input. The clipped DEM was maintained in the Geographic Coordinate System WGS 1984, consistent with the other raster datasets used in the analysis. The topographic layer was used as a supporting reference layer for statistical analysis.

2.4 Methodology

The present study addresses the identified research gap by developing a comprehensive, landscape-scale GIS-based seed zone map for Mongolia. The analysis integrates multiple environmental datasets, including WorldClim bioclimatic variables, Google Earth Engine-derived precipitation data, Digital Elevation Model (DEM) topographic layers, and national geospatial data obtained from the Environmental Information Center of Mongolia. Statistical techniques, including descriptive statistical analysis, Permutational Multivariate Analysis of Variance (PERMANOVA), pairwise environmental distance matrix, and Linear Discriminant Analysis (LDA), were applied within the ArcGIS environment to delineate zones of environmental similarity. The resulting framework is further demonstrated through its application to a mine rehabilitation case study, providing a practical spatial decision-support tool for restoration practitioners, environmental engineers, and policymakers.

The seed zone delineation framework follows a hierarchical, ecoregion-first approach implemented within a Geographic Information System (GIS) environment. This approach is based on the principle that ecological and genetic similarity between plant populations is primarily determined by broad climatic and vegetation gradients, and that seed transfer boundaries should reflect these environmental patterns [2,24].

Historically, seed zone delineation was based on provenance trials, in which plant populations from different geographic origins were evaluated under common environmental conditions. Although these experiments provide robust insights into genetic adaptation, they are resource-intensive and difficult to implement at large spatial scales, particularly in regions with limited research infrastructure such as Mongolia [2,24]. Consequently, modern methodologies increasingly rely on spatial and climate-based approaches.

In this study, the delineation process was carried out in three sequential stages. First, Mongolia's natural vegetation zones (ecoregions) were used as the primary spatial framework to define initial candidate seed zones. Administrative district (soum) boundaries were incorporated to ensure that the resulting zones are operationally practical for land management and seed collection. Second, climatic variables, specifically plant hardiness

zones derived from minimum temperature and precipitation zones derived from annual precipitation, were applied as secondary criteria to refine the ecoregion-based zones, introducing subdivision only where significant climatic variation exists. Finally, the resulting zones were spatially processed through overlay, cleaning, and consolidation procedures to produce the final seed zone map.

This methodology follows the guidance of Bower et al. (2014), which emphasizes the use of a limited number of key environmental variables to capture dominant ecological gradients while maintaining methodological simplicity [2]. It also aligns with the findings of Jamyansuren et al. (2019), who highlighted the limitations of infrastructure-based delineation methods in Mongolia and recommended environmentally and administratively grounded approaches [5]. All spatial analyses were conducted using ArcMap 10.8, utilizing the *Spatial Analyst, Data Management, and Analysis* toolboxes.

2.5 Seed zone delineation

The seed zone delineation framework follows a hierarchical, ecoregion-first approach implemented within a Geographic Information System (GIS) environment using ArcMap 10.8. This approach is based on the principle that ecological and genetic similarity between plant populations is primarily determined by broad climatic and vegetation gradients, and that seed transfer boundaries should reflect these environmental patterns.

The delineation process was carried out in four sequential stages: (1) ecoregion-based zone construction using administrative boundaries (soum boundary), (2) climate-based refinement using hardiness and precipitation zones, (3) spatial integration through overlay analysis, and (4) zone consolidation, fragment removal, and naming.

2.5.1 Ecoregion-based zone construction

The natural vegetation zone map of Mongolia, obtained from the Environmental Information Center (EIC) [15], was used as the primary spatial framework for seed zone delineation. This layer defines six major ecological zones across Mongolia: Mountain Taiga Belt, High Mountain Belt, Forest Steppe, Steppe, Semi-desert Steppe, and Desert zones. These zones reflect the combined effects of elevation, temperature, and precipitation and provide ecologically meaningful units for guiding seed transfer [2,5].

In order to make the resulting seed zones operationally practical for land managers and seed collectors, the soum-level administrative boundary layer (also obtained from EIC [15])

was used to align zone boundaries to administrative units. Each *soum* was assigned a dominant ecoregion based on spatial overlay analysis. The *Intersect* tool (Analysis Tools - Overlay - Intersect) was used to overlay the *soum* boundary layer with the ecoregion layer. The area of each ecoregion within each *soum* was then calculated using the *Calculate Geometry* function. The dominant ecoregion was defined as the one with the largest area within each *soum*. This information was obtained using the *Summary Statistics* tool (Analysis Tools - Statistics - Summary Statistics) and joined back to the *soum* boundary layer.

Neighbouring *soums* with the same dominant ecoregion were then grouped using the *Dissolve* tool (Data Management Tools - Generalization - Dissolve) to form larger candidate seed zones. The resulting zones are shown in Figure 4, where administrative boundaries are consolidated into ecologically consistent regions. This step reduces fragmentation and produces a more manageable set of zones for practical use in seed transfer and land management.

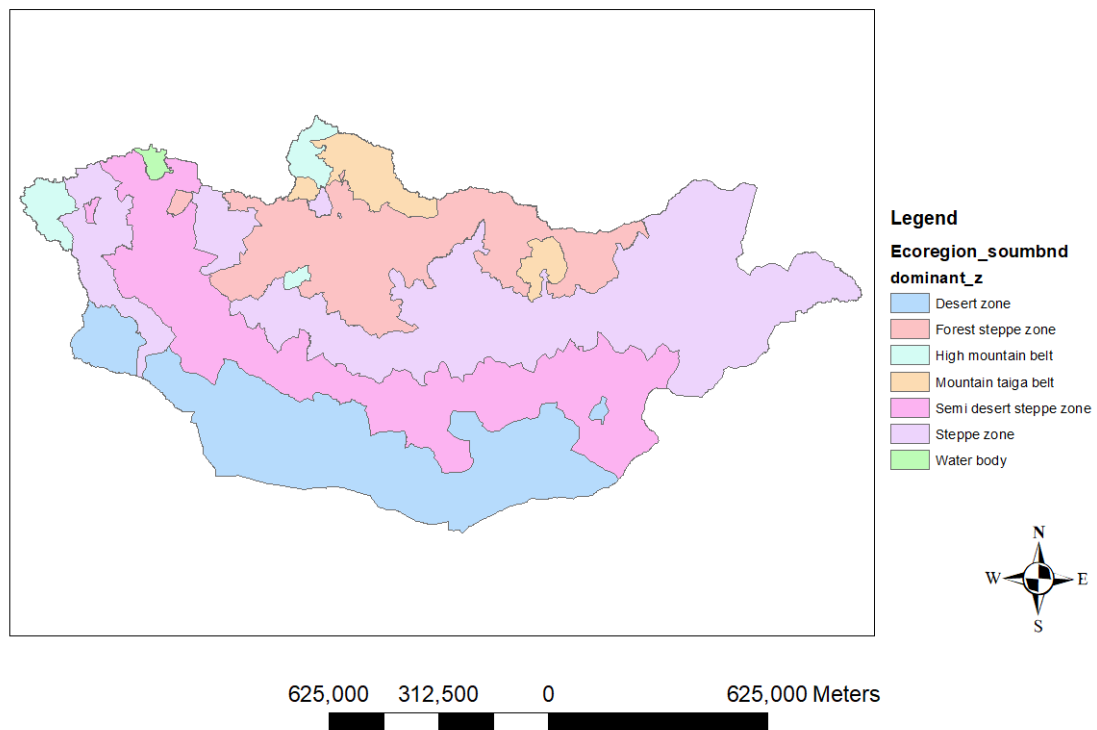


Figure 4 Candidate seed zones derived from dominant ecoregion assignment and subsequent dissolution of neighbouring *soums*

2.5.2 Climate-based refinement

Following the construction of ecoregion-based candidate zones, climatic layers were applied as secondary refinement criteria to subdivide zones where significant climatic differentiation was identified. Two climatic variables were used for this purpose: the plant hardiness zone layer (derived from January minimum temperature; see Section 2.3.1) and the annual precipitation zone layer (derived from WorldClim BIO12; see Section 2.3.2).

The dominant hardiness zone and precipitation zone for each soum were determined using the *Zonal Statistics as Table* tool (Spatial Analyst Tools - Zonal - Zonal Statistics as Table). The *MAJORITY* statistic was used so that each soum was assigned a single hardiness zone value and a single precipitation zone value based on the most common raster value within its boundary. These values were then joined back to the soum boundary layer, creating a single attribute table that includes ecoregion, hardiness zone, and precipitation zone for each soum.

The hardiness zone layer divides Mongolia into six zones (Zones 1 to 6) based on minimum winter temperature. The precipitation layer divides the country into two zones: Dry (annual precipitation below 100 mm) and Semi-dry (100 mm or above). The 100 mm threshold was used because it represents an important boundary between arid and semi-arid conditions in Central Asian dryland environments [22].

2.5.3 Spatial integration through overlay analysis

The three spatial layers, namely the ecoregion-based candidate zones, the hardiness zone layer, and the precipitation zone layer, were combined within the soum boundary layer. The soum boundary layer was then dissolved using the *Dissolve* tool (Data Management Tools - Generalization - Dissolve) based on the three attribute fields: the ecoregion zone name, the hardiness zone code, and the precipitation zone code. This consolidation merged spatially adjacent soums sharing identical combinations of all three attributes into single, continuous zone polygons, producing the preliminary seed zone layer.

2.5.4 Zone consolidation, fragment removal, and naming

Following the dissolve process, the preliminary seed zone layer was converted from multipart to singlepart polygons using the *Multipart to Singlepart* tool (Data Management Tools - Features - Multipart to Singlepart) to enable individual polygon area calculations and to ensure that geographically separated polygons with identical environmental attributes

were treated as distinct seed zones, consistent with the principle that seed transfer should occur within spatially contiguous areas to maintain adaptation and avoid maladaptation [2].

The area of each polygon was calculated in square kilometres using the Calculate Geometry function. Polygons with an area of less than 5000 km² were identified using the *Select by Attributes* function and removed using the *Eliminate* tool (Data Management Tools - Generalization - Eliminate), which merged each small fragment into the adjacent zone polygon with which it shared the longest common boundary.

Each seed zone represents a unique combination of natural vegetation zone, plant hardiness zone, and precipitation zone, and aligned to soum-level administrative boundaries. Zones were assigned descriptive names combining the dominant province (aimag) name, the ecoregion type, the hardiness zone code, and the precipitation class.

2.6 Statistical Validation of Seed Zones

To evaluate whether the delineated seed zones represent environmentally distinct and internally coherent units, a multi method statistical validation framework was applied. The validation integrated three approaches: (1) descriptive statistical analysis, (2) Permutational Multivariate Analysis of Variance (PERMANOVA), (3) Pairwise environmental distance matrix, and (4) Linear Discriminant Analysis (LDA). Three environmental variables were used as the basis for all analyses: BIO1 (annual mean temperature), BIO12 (annual precipitation), and elevation derived from the Digital Elevation Model (DEM). For each of the 44 seed zones, zonal statistics, including mean, standard deviation, minimum, maximum, and range, were extracted using the *Zonal Statistics as Table* tool in ArcMap 10.8. All statistical analyses were conducted in Python using the pandas [25], NumPy [26], SciPy [27], and scikit-learn [28] libraries.

2.6.1 Descriptive statistical analysis

As a first step, descriptive statistics were computed for each of the 44 seed zones and summarised by ecoregion group to characterise the environmental conditions represented by the delineated zones. For each zone, the mean, standard deviation, minimum, and maximum values of BIO1, BIO12, and elevation were calculated from the zonal statistics extracted in ArcMap 10.8. Summary statistics were then aggregated by ecoregion to assess inter-group environmental differentiation. This approach follows standard practice in seed zone validation studies, where descriptive characterisation of climatic variables provides the

empirical foundation for interpreting inferential test results. The results are presented as bar charts showing the mean value and range (minimum-maximum) of each environmental variable across all 44 zones, with zones coloured by their respective ecoregion.

2.6.2 Permutational multivariate analysis of variance (PERMANOVA)

A one-way Permutational Multivariate Analysis of Variance (PERMANOVA) was conducted to test whether the 44 seed zones, when grouped by six ecoregion classes, are statistically distinguishable based on their combined environmental characteristics. PERMANOVA is a non-parametric multivariate test that partitions the total multivariate variation among observations into between-group and within-group components, producing an F-statistic, an R^2 value representing the proportion of total variation explained by group membership, and a p-value derived from permutation [29]. Unlike univariate ANOVA, PERMANOVA operates on a distance matrix and makes no assumptions about the normality of the data, making it suitable for environmental data with complex distributions [29].

The analysis was conducted using 15 standardised environmental features derived from BIO1, BIO12, and elevation for each seed zone. Prior to analysis, all variables were standardised to have a mean of zero and a unit variance using z score normalisation. This step was applied to ensure that all variables contributed equally to the analysis despite differences in their units and scales.

Pairwise Euclidean distances were then calculated between all seed zones to construct a distance matrix representing environmental similarity. The 44 seed zones were grouped into six ecoregion classes, namely Desert zone, Semi desert steppe zone, Steppe zone, Forest steppe zone, High mountain belt, and Mountain taiga belt. These classes were used as grouping factors, while individual seed zones were treated as replicates within each group.

Statistical significance was evaluated using 999 permutations, following approaches commonly used in ecological multivariate analysis [2, 24]. The null hypothesis assumed that there is no significant difference in the multivariate environmental characteristics among the six ecoregion groups beyond what would be expected by chance.

In addition to the overall PERMANOVA results, a pairwise environmental distance matrix was calculated among all seed zones. For each pair, the Euclidean distance was computed based on the standardised environmental variables and then scaled between 0 and 1, where

0 represents identical environmental conditions and 1 represents the highest level of dissimilarity.

The resulting matrix was visualised as a heatmap to illustrate the degree of environmental variation between seed zones. Zones were grouped according to their ecoregion affiliation, allowing patterns of similarity and separation to be clearly identified. This approach is consistent with methods used to assess environmental differentiation in spatial ecological zoning studies [24].

2.6.3 Pairwise environmental distance matrix

To further examine the degree of environmental similarity and dissimilarity between individual seed zones, a pairwise environmental distance matrix was calculated for all 44 zones. For each pair of zones, the Euclidean distance was computed based on the same standardised environmental variables used in the PERMANOVA, BIO1, BIO12, and elevation, and then scaled to a range between 0 and 1, where 0 represents identical environmental conditions and 1 represents the maximum level of dissimilarity observed among all zone pairs.

This scaling approach facilitates direct visual interpretation of the resulting matrix, enabling clear identification of both closely similar and strongly contrasting zone pairs. The resulting distance matrix was visualised as a heatmap in which darker colours indicate greater environmental dissimilarity between zone pairs, while lighter colours indicate higher similarity. Zones were ordered and grouped according to their ecoregion affiliation along both axes of the heatmap, allowing block-level patterns of within-ecoregion similarity and between-ecoregion contrast to be readily identified.

2.6.4 Three-dimensional linear discriminant analysis (LDA)

Linear Discriminant Analysis (LDA) was applied to visualise the degree of environmental separation among the 44 seed zones in multivariate environmental space. LDA is a supervised dimensionality reduction technique that identifies linear combinations of input variables, referred to as linear discriminants, which maximise the ratio of between group to within group variance. This allows the data to be projected onto axes that best separate predefined groups [30].

In the context of seed zone validation, LDA has been used to demonstrate the environmental distinctiveness of delineated zones in ordination space, as shown in previous studies, including Lee et al. (2025) for seed zones in South Korea [24].

To represent environmental variation within each zone, a Monte Carlo sampling approach was applied prior to the LDA. For each of the 44 seed zones, 80 synthetic data points were generated by sampling from a normal distribution defined by the zonal mean and standard deviation of each environmental variable, including *BIO1*, *BIO12*, and elevation. This resulted in a total of 3,520 observations. This approach preserves the statistical characteristics of each zone while allowing the internal variability of zones to be visualised in the ordination space.

All variables were standardised before applying LDA to ensure equal contribution of each variable. The analysis was performed using the seed zones as group labels, and the results were projected onto the first three linear discriminant axes, namely LD1, LD2, and LD3. The proportion of variance explained by each axis was reported using the explained variance ratio.

The resulting three-dimensional ordination plot was used to evaluate the degree of environmental separation among seed zones. Each zone was represented as a cluster of points, with colours indicating ecoregion affiliation, allowing patterns of similarity and separation to be clearly identified.

2.7 Workflow diagram

The overall workflow used in this study is shown in *Figure 5*. It summarizes the main steps from data collection to the final seed zone map.

First, spatial and climate data were collected from different sources, including the Environmental Information Center, WorldClim, and Google Earth Engine. These datasets provided the base information for the analysis.

Next, all datasets were pre-processed in ArcMap 10.8. This included clipping the data to the boundary of Mongolia, reclassifying temperature and precipitation layers into zones, and ensuring that all layers had the same coordinate system.

In the first stage, the natural vegetation zone map was combined with soum boundaries to assign each soum a dominant ecoregion. Soums with the same dominant ecoregion were grouped to form initial candidate zones.

In the second stage, climate information was added. Hardiness zones and precipitation zones were used to further divide the candidate zones where there were clear climatic differences.

In the third stage, all layers were combined using spatial overlay. This step created zones based on the combination of ecoregion, temperature, and precipitation.

Finally, the zones were cleaned and simplified. Small fragments were removed, and neighbouring areas were merged to produce the final seed zone map of Mongolia.

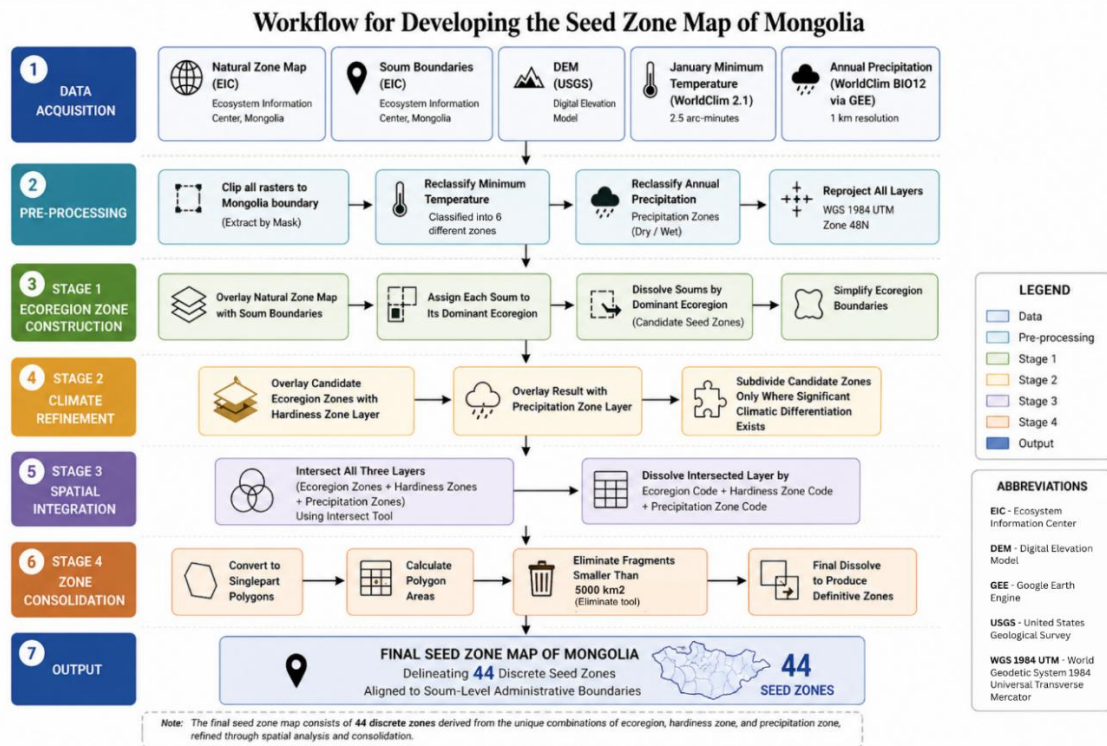


Figure 5 Workflow for Developing the Seed Zone Map of Mongolia /generated by chatgpt/

2.8 Case Study

The case study was conducted at the Ukhaa Khudag coal mine, which is operated by Energy Resources LLC, a subsidiary of the Mongolian Mining Corporation. The mine is located in Tsogttsetsii soum, Umnugovi province, within the South Gobi region of Mongolia, approximately 560 km south of Ulaanbaatar and about 240 km from the Mongolian–Chinese border [31].

The mine primarily produces high-quality coking coal [32], which is widely used in steel production and represents a major export commodity for Mongolia [33].

Mining operations at Energy Resource are conducted using open-pit mining methods, and commercial production began in 2009 [33]. The mining license area covers approximately 2,960 hectares, and the deposit contains hundreds of millions of tonnes of coal resources and reserves [31].

This site was selected as a case study because it represents the typical conditions of mining in Mongolia, especially in desert-steppe environments where the rehabilitation process is difficult. In addition, the mine has ongoing rehabilitation activities, which makes it more suitable for evaluating how seed zone mapping can be applied in practice.

The data used in this case study were collected from several sources. These include company records, available operational information from Energy Resources LLC, and existing records related to rehabilitation activities such as seed sourcing, planting practices, and vegetation performance. These data were used to understand the current practices at the site and to assess how they relate to environmental conditions.

3. Result and Discussion

3.1 Development of seed zone map of Mongolia

The seed zone delineation process resulted in a total of 44 distinct seed zones across Mongolia, each representing a unique combination of ecoregion type, plant hardiness zone, and precipitation class. The integration of these variables enabled the identification of ecologically meaningful zones that reflect the major environmental gradients of the country.

The spatial distribution of seed zones shows a clear pattern corresponding to Mongolia's geographic and climatic conditions. Arid and semi-arid zones, including desert and semi-desert steppe regions, are primarily concentrated in the southern and southwestern parts of

Mongolia, particularly in Umnugovi, Dundgovi, and Govi-Altai provinces. These areas are characterized by low precipitation and relatively warmer conditions compared to the rest of the country.

In contrast, the northern regions are dominated by forest steppe, high mountain, and mountain taiga zones, which are associated with higher precipitation and lower temperature regimes. These zones are mainly located in provinces such as Khuvsgul, Khentii, and Bayan-Ulgii, reflecting the influence of elevation and cooler climatic conditions.

This distribution highlights a strong north–south environmental gradient, where temperature decreases and precipitation increases toward the north. Such gradients play a key role in determining plant adaptation and are therefore critical for defining appropriate seed transfer zones.

3.1.1 Hardiness zone distribution

The hardiness zone map shows that Mongolia is dominated by cold climate conditions, with most areas falling within Zones H1 to H6. Extremely cold zones are mainly concentrated in the northern mountainous regions, where winter temperatures reach very low levels.

In contrast, relatively milder zones are observed in the southern and southeastern parts of the country. This distribution reflects the strong influence of Mongolia’s continental climate, where temperature decreases significantly with increasing latitude and elevation.

The variation in hardiness zones is important for seed zone mapping, as it directly affects plant survival under extreme winter conditions. Therefore, incorporating hardiness zones into the analysis helps ensure that selected plant materials are adapted to local temperature regimes.

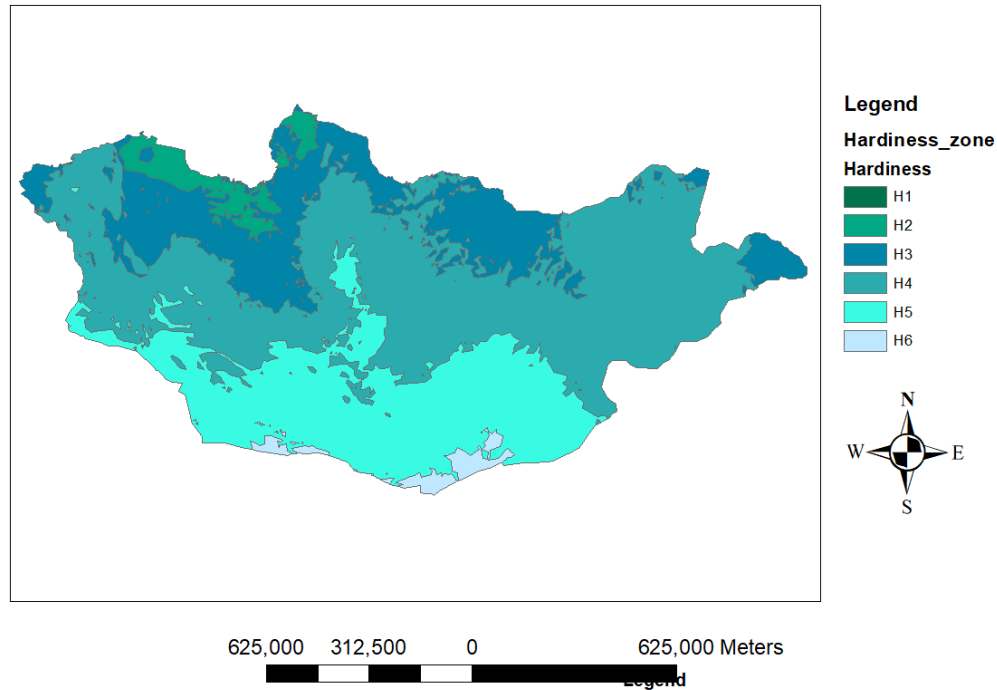


Figure 6 Plant hardiness zone distribution of Mongolia based on January minimum temperature (WorldClim 2.1, 1970–2000).

3.1.2 Precipitation zone distribution

The precipitation zone map indicates a clear division between dry and semi-dry regions across Mongolia. Areas receiving less than 100 mm of annual precipitation are primarily located in the southern Gobi region, while regions with higher precipitation are found in the northern and central parts of the country.

This distribution reflects the well-known north-to-south precipitation gradient in Mongolia, where moisture availability decreases significantly toward the south. Since water availability is one of the most limiting factors for plant growth in arid environments, this variable plays a critical role in defining seed zones.

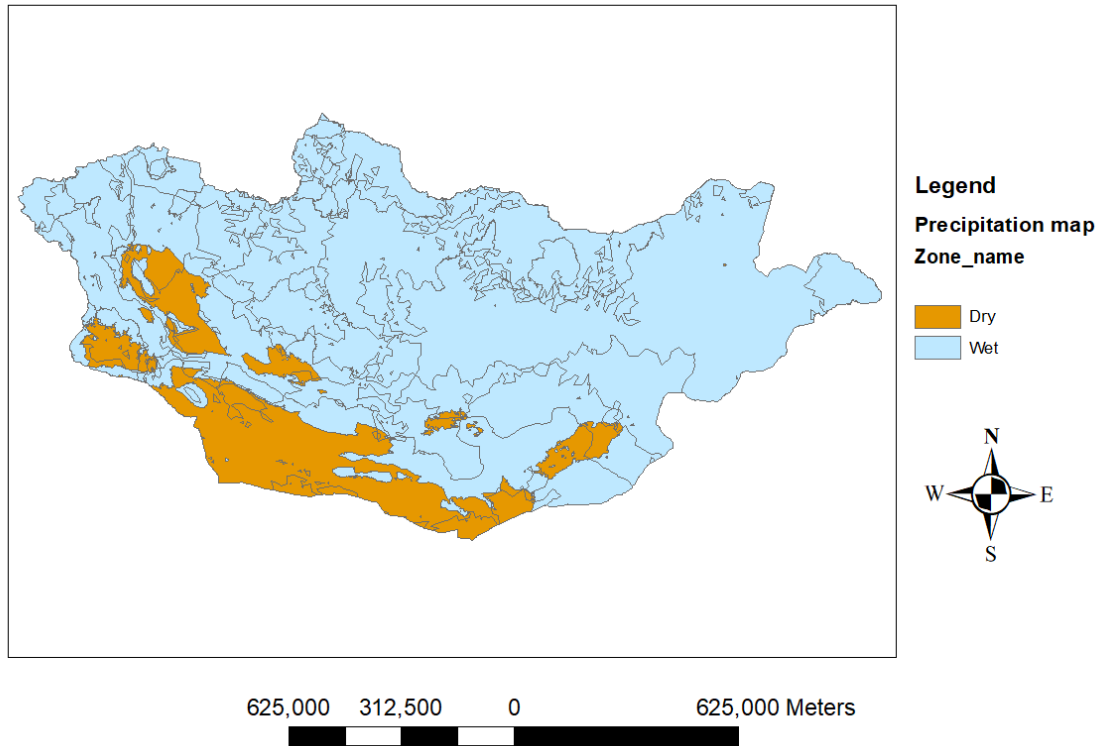


Figure 7 Annual precipitation zone distribution of Mongolia classified into dry (<100 mm) and semi-dry (≥ 100 mm) zones (WorldClim BIO12, 1970–2000).

3.2 Final seed zone map

The final seed zone map of Mongolia (Figure 8) consists of 44 discrete seed zones (MZ1–MZ44), each defined by a unique combination of natural vegetation zone, plant hardiness zone, and precipitation class. The naming convention for each zone incorporates the dominant province (aimag) name, ecoregion type, hardiness zone code, and precipitation classification, providing a clear and practical identification system for use in field operations and policy documentation. The complete list of delineated zones, including zone ID, full name, total area (km²), and mean elevation (m above sea level), is presented in Table 3.

Seed Zone Map of Mongolia

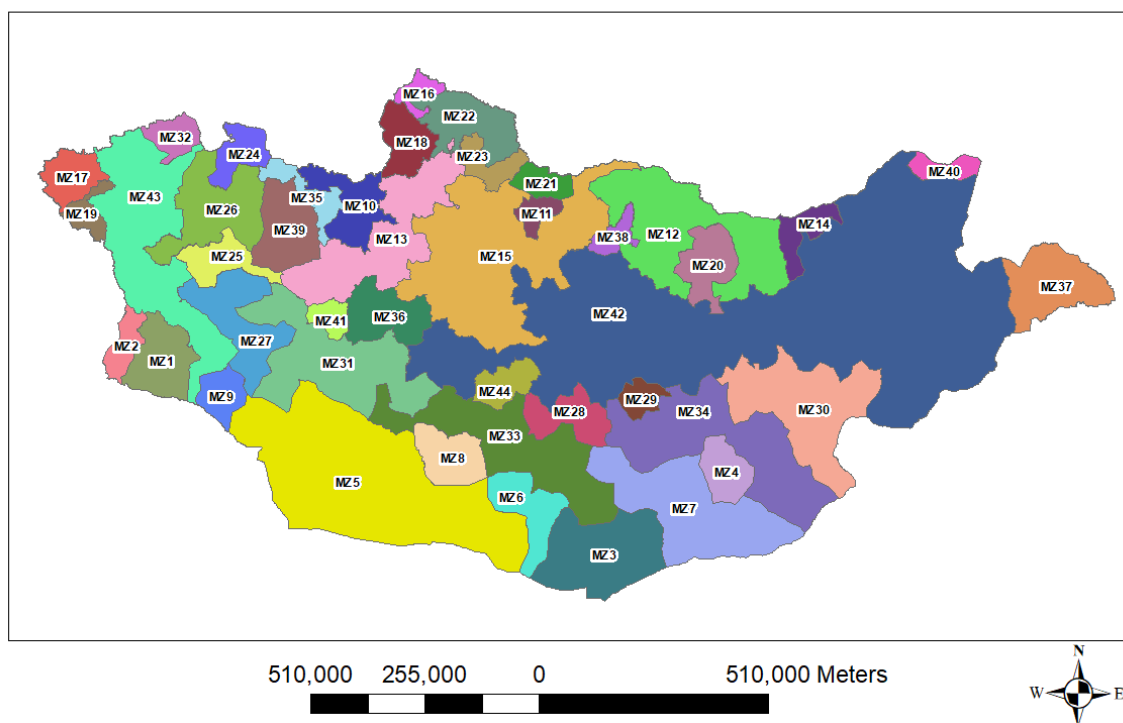


Figure 8 Final seed zone map of Mongolia

Zone areas vary considerably across the map, ranging from approximately 5,880 km² in MZ38 (Darkhan-Uul Steppe zone, H3, semi-dry) to 353,768 km² in MZ42 (Arkhangai Steppe zone, H4, semi-dry), reflecting the uneven spatial distribution of environmental conditions across Mongolia's territory. Mean elevation across zones ranges from 680.6 m in MZ40 (Dornod Steppe zone, H3, semi-dry) to 2,550.7 m in MZ36 (Arkhangai Steppe zone, H3, semi-dry), further illustrating the topographic diversity captured within the framework.

The spatial distribution of seed zones shown in Figure 8 reveals a clear north–south environmental gradient consistent with Mongolia's well-documented latitudinal vegetation zonation. Desert and semi-desert steppe zones dominate the southern and southwestern regions, particularly across Umnugovi, Dundgovi, and Govi-Altai provinces, where low precipitation and relatively warmer temperatures prevail. In contrast, forest steppe, high mountain, and mountain taiga zones characterise the northern provinces of Khuvsgul, Khentii, and Bayan-Ulgii, reflecting the influence of higher elevation and cooler, wetter conditions. The subdivision of zones into dry and semi-dry precipitation categories further highlights the role of moisture availability as a critical limiting factor for vegetation, with dry zones concentrated in desert and semi-desert regions and semi-dry zones predominating

across steppe and forested areas. The relatively high number of 44 discrete zones reflects the considerable environmental heterogeneity across Mongolia, confirming that region-specific seed sourcing strategies are essential for successful mine rehabilitation and ecological restoration.

Table 3 Summary of delineated seed zones in Mongolia including zone ID, zone name, area (km²), and mean elevation (m)

Zone ID	Zone Name	Area (km²)	Mean elevation (m)
MZ1	Khovd Desert zone, H4, Dry	21029.78	1705.765
MZ2	Khovd Desert zone, H4, Semi-dry	8335.712	1529.508
MZ3	Umnugovi Desert zone, H5, Dry	42256.52	1314.098
MZ4	Dundgovi Desert zone, H5, Dry	12687.75	1023.022
MZ5	Govi-Altai Desert zone, H5, Dry	134722.7	1470.419
MZ6	Umnugovi Desert zone, H5, , Semi-dry	18834.49	1533.158
MZ7	Dundgovi Desert zone, H5, Semi-dry	59912	1166.102
MZ8	Umnugovi Desert zone, H5, Semi-dry	16665.61	1538.434
MZ9	Govi-Altai Desert zone, H5, Semi-dry	10124.51	1790.903
MZ10	Khuvsgul Forest steppe zone, H2, Semi-dry	18662.49	1930.524
MZ11	Khuvsgul Forest steppe zone, H3, Semi-dry	5628.438	1268.432
MZ12	Darkhan-Uul Forest steppe zone, H3, Semi-dry	63668.62	1237.934
MZ13	Arkhangai Forest steppe zone, H3, Semi-dry	41906.11	2089.242
MZ14	Khentii Forest steppe zone, H4, Semi-dry	10365.73	1165.459
MZ15	Orkhon Forest steppe zone, H4, Semi-dry	90350.38	1723.525
MZ16	Khuvsgul High mountain belt, H2, Semi-dry	5642.708	2148.534
MZ17	Bayan-Ulgii High mountain belt, H3, Semi-dry	12890.84	2533.327
MZ18	Khuvsgul High mountain belt, H3, Semi-dry	10115.96	2108.089
MZ19	Bayan-Ulgii High mountain belt, H4, Semi-dry	6575.669	2524.809
MZ20	Khentii Mountain taiga belt, H3, Semi-dry	14833.94	1700.925
MZ21	Khuvsgul Mountain taiga belt, H3, Semi-dry	7739.572	1424.728
MZ22	Khuvsgul Mountain taiga belt, H3, Semi-dry	22761.63	1850.647
MZ23	Khuvsgul Mountain taiga belt, H4, Semi-dry	9405.841	1613.306

MZ24	Uvs Semi desert steppe zone, H2, Semi-dry	11327.01	1043.808
MZ25	Khovd Semi desert steppe zone, H3, Dry	13510.25	1395.49
MZ26	Khovd Semi desert steppe zone, H3, Semi-dry	30437.49	1369.61
MZ27	Khovd Semi desert steppe zone, H4, Dry	29472.56	1666.489
MZ28	Dundgovi Semi desert steppe zone, H4, Semi-dry	15717.89	1335.338
MZ29	Dundgovi Semi desert steppe zone, H4, Semi-dry	6506.317	1402.846
MZ30	Govisumber Semi desert steppe zone, H4, Semi-dry	54989.46	1033.603
MZ31	Khovd Semi desert steppe zone, H4, Semi-dry	54729.35	1881.746
MZ32	Uvs Semi desert steppe zone, H4, Semi-dry	6136.363	1650.653
MZ33	Dundgovi Semi desert steppe zone, H5, Semi-dry	57773.26	1514.882
MZ34	Govisumber Semi desert steppe zone, H5, Semi-dry	64707.66	1097.8
MZ35	Khuvsgul Steppe zone, H2, Semi-dry	10081.65	1642.511
MZ36	Arkhangai Steppe zone, H3, Semi-dry	20106.64	2550.669
MZ37	Dornod Steppe zone, H3, Semi-dry	28686.25	788.5736
MZ38	Darkhan-Uul Steppe zone, H3, Semi-dry	5879.552	942.9991
MZ39	Uvs Steppe zone, H3, Semi-dry	18954.29	1826.878
MZ40	Dornod Steppe zone, H3, Semi-dry	6499.534	680.6032
MZ41	Govi-Altai Steppe zone, H4, Semi-dry	5684.719	2208.553
MZ42	Arkhangai Steppe zone, H4, Semi-dry	353768.2	1213.062
MZ43	Khovd Steppe zone, H4, Semi-dry	65006.44	2249.65
MZ44	Uvurkhangai Steppe zone, H5, Semi-dry	10389.23	1929.034

3.3 Statistical analysis of seed zones

The statistical validation of the 44 delineated seed zones was carried out using four approaches: descriptive statistical analysis, Permutational Multivariate Analysis of Variance (PERMANOVA), Pairwise environmental distance matrix, and Linear Discriminant Analysis (LDA). The analysis was based on three key environmental variables: BIO1 (annual mean temperature), BIO12 (annual precipitation), and elevation derived from the Digital Elevation Model (DEM).

These methods were used to evaluate whether the seed zones represent meaningful environmental differences across Mongolia and whether they can be reliably used for seed sourcing in mine rehabilitation.

3.3.1 Descriptive statistical analysis

Descriptive statistics were first used to examine the overall environmental variation across the 44 seed zones. The results are summarised in Appendix A1 and visualised in Figure 9.

Across all zones, BIO1 ranged from -9.22°C to 6.48°C , BIO12 ranged from 70.61 mm to 461.35 mm, and elevation ranged from 680.6 m to 2,550.7 m above sea level. These values confirm that Mongolia has strong environmental gradients.

Figure 9 shows clear differences between ecoregions. Precipitation increases from the Desert zone to the Mountain taiga belt, while temperature generally decreases from south to north. Elevation is highest in the High mountain belt and lowest in the Desert and Semi desert steppe zones.



Figure 9 Environmental characteristics of 44 seed zones across Mongolia.

The variation within zones is also visible through the error bars. Some zones, especially in mountainous areas, show large internal variation. This is expected because these regions have more complex terrain.

Overall, the descriptive analysis shows that the seed zones reflect clear differences in temperature, precipitation, and elevation. These variables are important for plant adaptation, which supports the logic of the seed zone classification.

3.3.2 PERMANOVA results

The results of the PERMANOVA are presented in Table 4. The analysis revealed a statistically significant difference in multivariate environmental composition among the six ecoregion groups ($F= 4.808$, $df=5$, $R^2=0.388$, $P= 0.001$, 999 permutations). The R^2 value of 0.388 indicates that ecoregion group membership explains 38.8% of the total multivariate environmental variation among the 44 seed zones, with the remaining 61.2% attributable to within-group variation. This result is statistically significant at the $\alpha = 0.001$ level and confirms that the delineated seed zones are not randomly distributed in environmental space but reflect real environmental structure across Mongolia's territory.

The R^2 value of 0.388 is consistent with findings from comparable seed zone validation studies. Lee et al. (2025) reported PERMANOVA R^2 values of similar magnitude for seed zones in South Korea using a multi-variable approach [24], while Bower et al. (2014) demonstrated significant multivariate differentiation among provisional seed zones in North America [2]. The moderate R^2 observed in the present study is attributable to two factors. First, Mongolia's large territory means that individual zones necessarily encompass wide internal environmental ranges, particularly in the High mountain belt and Mountain taiga belt zones as evidenced by the large error bars in Figure 9. Second, the analysis used zonal summary statistics rather than pixel-level observations, which reduces the apparent between-group separation relative to studies employing full raster sampling. Despite these constraints, the highly significant p-value ($p = 0.001$) confirms that the environmental differences among ecoregion groups are not attributable to chance.

Table 4 PERMANOVA results for multivariate environmental differentiation among 44 seed zones grouped by ecoregion

Source	df	F-statistic	R ²	p-value	Permutations
Seed zone (ecoregion group)	5	4.808	0.388	0.001	999
Residuals	38	-	0.612	-	-
Total	43	-	1.000	-	-

3.3.3 Pairwise environmental distance matrix

To further examine the similarity between zones, a pairwise environmental distance matrix was calculated and visualised as a heatmap (Figure 10). The heatmap reveals a clear block pattern, where zones belonging to the same ecoregion group are generally more similar to each other, while zones from different ecoregions show greater environmental differences. This pattern confirms that zones within the same ecoregion group are more environmentally similar to each other than to zones in other ecoregion groups, consistent with the PERMANOVA result.

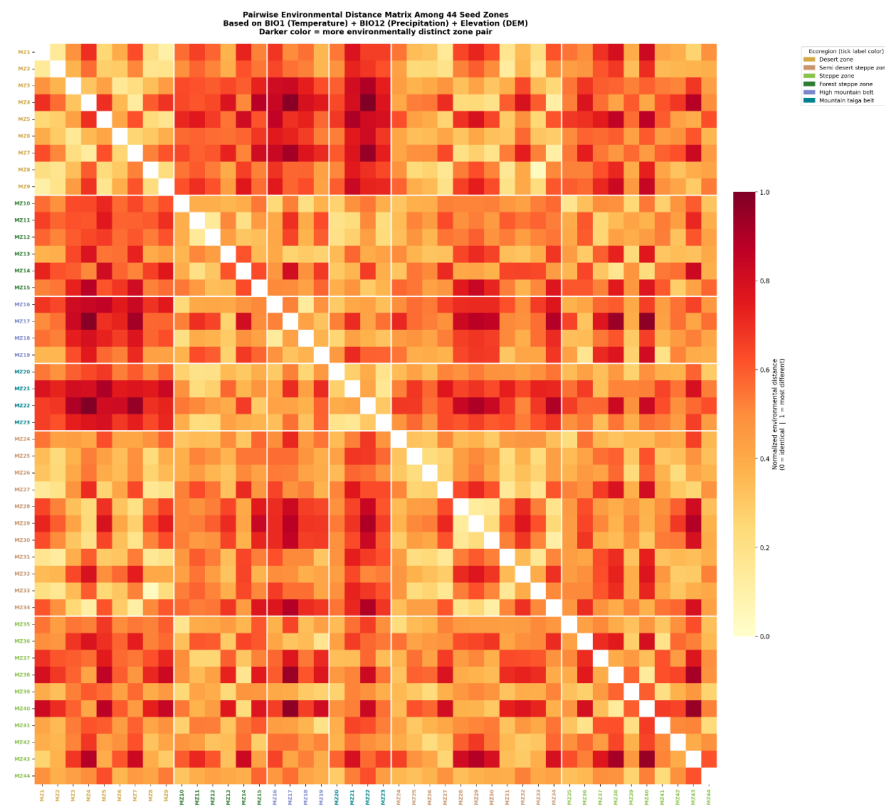


Figure 10 Pairwise environmental distance matrix of 44 seed zones based on BIO1, BIO12, and elevation

A strong contrast is observed between the Desert zone and the Mountain taiga belt, which represent two extreme environmental conditions in Mongolia. The Desert zone is characterised by high temperature and low precipitation, whereas the Mountain taiga belt represents cold and relatively wet environments. This large environmental difference is reflected by the highest distance values in the matrix.

In contrast, the Forest steppe zone and Mountain taiga belt show lower distance values, indicating more similar environmental conditions. This can be explained by their relatively higher precipitation levels and cooler temperatures compared to other regions.

The heatmap also shows gradual transitions between neighbouring ecoregions. For example, the Semi desert steppe and Steppe zones display intermediate similarity, reflecting their transitional position between arid and more humid environments. This indicates that environmental changes across Mongolia are not abrupt but occur gradually along climatic gradients.

At the level of individual zones, some pairs show very low distance values, meaning they have nearly identical environmental characteristics, while others show very high distances, indicating strong environmental contrast. This confirms that the seed zone classification captures both local similarities and large-scale environmental differences.

Overall, the results demonstrate that the delineated seed zones effectively represent the main environmental gradients across Mongolia and provide a meaningful basis for distinguishing ecologically similar and different areas.

3.3.4 Three-Dimensional linear discriminant analysis

The LDA results are shown in Figure 11. The first three axes explain 100% of the variation between groups, with LD1 accounting for 72.8% of the variation, LD2 for 23.4%, and LD3 for 3.8%. The strong dominance of LD1 indicates that a single primary environmental gradient drives the major separation among the seed zones.

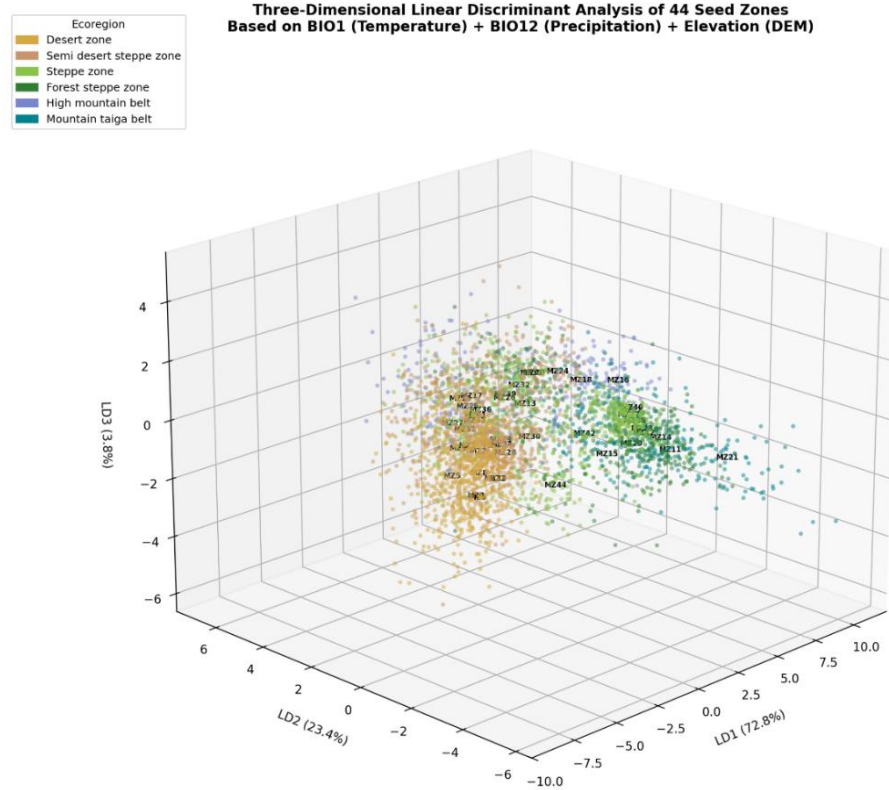


Figure 11 Three-dimensional Linear Discriminant Analysis of 44 seed zones based on BIO1, BIO12, and elevation

The plot shows clear separation between major ecoregions. Desert zones are located on one side of the plot, representing warm and dry conditions, while Forest steppe and Mountain taiga zones are located on the opposite side, representing cooler and wetter environments. Steppe and Semi desert steppe zones appear between these extremes, reflecting their transitional nature.

Some overlap is observed between Forest steppe and Mountain taiga zones, which is consistent with their shared high-precipitation regime identified in the descriptive statistics and pairwise distance matrix. High mountain belt zones show more spread, indicating higher internal variability.

Overall, the three-dimensional LDA confirms that the 44 delineated seed zones are environmentally distinguishable in multivariate space and that the ecoregion-based grouping structure captures the dominant gradients of temperature, precipitation, and elevation across Mongolia. Together with the PERMANOVA and descriptive results, these findings support the conclusion that the seed zone delineation framework provides a scientifically

grounded spatial basis for guiding seed sourcing decisions in mine rehabilitation and ecological restoration across Mongolia.

3.4 Case Study

The Energy Resource LLC (Ukhaa Khudag mine) was used to examine how the developed seed zone map can be applied in a real rehabilitation context. The focus of this case study is on current practices at the site, including how seeds are sourced, what species are used, and how vegetation performs after planting.

3.4.1 Seed sourcing practices

Seed sourcing practices at the Energy Resource LLC (Ukhaa Khudag mine) are based on a combination of externally procured seeds and locally collected plant materials. A considerable proportion of the seeds used in rehabilitation activities is purchased, and therefore their precise geographic origin is not always clearly defined [34]. This lack of traceability can increase the risk of maladaptation, as plant materials may not be optimally adapted to the environmental conditions of the restoration site [9].

In addition to purchased seeds, local seed collection is actively practiced for several native species, including *Allium polyrhizum* (taana), *Allium mongolicum* Regel (khomul), *Salsola saltwort* (budargana), *Caragana* spp. (khargana), and other common desert-steppe plants [34]. These seeds are collected from locations in the vicinity of the mine, such as the Maiga Mountain reservoir, Baruun Naran mining area, forest shelterbelts, and previously rehabilitated sites [34]. Most local seed collection activities are conducted within a radius of approximately 35 km from the mine site, indicating an effort to use plant materials from environmentally similar conditions [34].

However, in some cases, seeds are also sourced from more distant locations, for example Ekhiin Gol in Bayankhongor province, Tsogt-Ovoo soum, Khankhongor soum in Umnugovi province and Khatanbulag soum in Dornogovi province [34]. While this approach may be influenced by species availability and climatic considerations, long-distance seed transfer can introduce ecological risks if environmental conditions differ significantly between source and planting sites [9].

Since 2019, the mine has adopted the practice of collecting seeds from vegetation established in previously rehabilitated areas [28]. This represents a shift toward more localized and potentially adaptive seed sourcing, as plants that have already survived under

site-specific conditions may provide more suitable genetic material for future restoration efforts.

The selection of seed collection sites is generally based on environmental similarity, including vegetation type, climate conditions, precipitation patterns, and soil characteristics. Nevertheless, the process is not fully standardized and may rely partially on observational judgment and practical experience [34]. Such approaches, while useful, may lack the consistency and scientific basis required for large-scale restoration planning.

Seeds are typically collected manually during the autumn season. Different techniques are used depending on the plant species; for example, tools are used to collect flowering heads of certain species, while others are collected by hand [34]. After collection, seeds are stored in breathable containers under controlled conditions with approximately 5% moisture content to maintain viability and prevent fungal growth [34].

Overall, the seed sourcing strategy at the mine reflects a combination of practical constraints and adaptive practices. While the increasing use of locally sourced and site-adapted seeds is a positive development, the absence of a systematic, spatially defined framework highlights the need for approaches such as seed zone mapping to improve the ecological suitability and long-term success of rehabilitation efforts.

3.4.2 Plant species and plant practices

Plant species used at the Ukhaa Khudag mine are mainly selected based on their ability to survive in dry and harsh desert-steppe conditions. Most of the species are native or well adapted to arid environments, which helps improve the success of rehabilitation.

The mine operates a 2.5-hectare plant nursery, established in 2009, where plant species adapted to arid conditions are cultivated for rehabilitation purposes [34]. The main species used in rehabilitation activities are summarized in Table 5.

Table 5 Major plant species used in rehabilitation at Ukhaa Khudag mine [34]

Species	Local name	Type	Purpose
<i>Haloxylon ammodendron</i>	Zag	Shrub	Drought resistance, sand stabilization
<i>Ulmus pumila</i>	Khailaas	Tree	Wind protection, shade
<i>Elaeagnus spp.</i>	Jigd	Shrub	Soil improvement

<i>Populus spp.</i>	Tooroi / Ulias	Tree	Fast growth, biomass
<i>Caragana spp.</i>	Khargana	Shrub	Nitrogen fixation, soil stabilization
<i>Prunus spp.</i>	Buils	Shrub/tree	Ecological and landscape value

The selected species include both woody plants (trees and shrubs) and herbaceous vegetation. Woody species are mainly used for wind protection, shading, and long-term stabilization, while grasses and other herbaceous plants help reduce soil erosion and improve surface stability. Common species used at the site include *Haloxylon ammodendron* (zag), *Ulmus pumila* (khailaas), *Caragana* species (khargana), *Elaeagnus* species (jigd), and *Populus* species (tooroi) [34].

During the field visit, some of these species were directly observed in the rehabilitation areas. For example, *Ulmus pumila* (khailaas) is used as a drought-tolerant species suitable for local environmental conditions.



Figure 12 Example of planted native species (*Ulmus pumila*) used in rehabilitation areas (photo taken during field visit).

Plant production has increased significantly over time, reflecting the expansion of rehabilitation efforts. Approximately 10,100 seedlings were produced in 2020, 10,000 seedlings in 2023, and 48,760 seedlings in 2024. In 2025, around 35,000 seedlings were

cultivated, with 14,965 seedlings supplied for planting activities [34]. This trend indicates a growing capacity for in-house plant propagation and a shift toward more self-sustained rehabilitation practices.

Planting practices involve the use of both container seedlings (bortogotoi suulgats) and direct seeding techniques, depending on the species and site conditions. In some cases, a combination of shrub seedlings and native seed mixtures is applied to enhance vegetation establishment and increase biodiversity. Herbaceous species such as perennial grasses are also used to improve soil stabilization and reduce erosion.

Planting is typically carried out during two main seasons: spring (late May to early June) and autumn (September to October), which correspond to relatively favorable moisture and temperature conditions for plant establishment [34]. Seasonal timing is an important factor in improving survival rates, particularly in arid environments where water availability is limited.

In addition to mine rehabilitation areas, planting activities are also implemented in surrounding zones such as roadside greenbelts, worker residential areas, and industrial facility surroundings. These activities contribute not only to ecological restoration but also to environmental improvement and landscape stabilization in the broader mining region.



Figure 13 Spatial distribution of planted trees and greening areas

As shown in Figure 13, planting activities are distributed across multiple functional areas, including infrastructure corridors and residential zones. The variation in planting quantities reflects differences in site conditions, land use, and rehabilitation objectives.

Overall, plant species selection and planting practices at the mine demonstrate a strong emphasis on native species and adaptive strategies suitable for harsh environmental conditions. However, while species selection is generally appropriate, the effectiveness of these practices could be further improved through more systematic alignment with environmental conditions, such as those defined by seed zone mapping.

3.4.3 Survival growth rate

The survival and growth performance of planted vegetation is a key indicator of the effectiveness of rehabilitation practices at the Energy Resource LLC (Ukhua Khudag mine). Based on available monitoring data, the overall survival rate of planted vegetation is reported to exceed 85 %, indicating relatively successful establishment under the harsh environmental conditions of the South Gobi region [34].

Despite this relatively high survival rate, vegetation growth performance varies across different areas within the mine site. In general, better growth is observed in locations where maintenance and protection measures are more effectively implemented, while relatively poorer growth occurs in areas exposed to harsher environmental conditions or where maintenance activities are limited. This spatial variability suggests that post-planting management practices, such as watering, protection from grazing, and site-specific care, play a critical role in determining plant development.

In addition to artificial planting, natural regeneration has been observed in certain rehabilitation areas. Rehabilitation activities have contributed to improved soil moisture and micro-environmental conditions, which in turn have supported the spontaneous establishment of vegetation. This indicates that artificial rehabilitation efforts can facilitate natural ecological recovery processes.

Overall, while the high survival rate demonstrates that current planting practices are generally effective, the observed variability in growth performance and the limited availability of systematic monitoring data highlight the need for more consistent evaluation methods.

Improving monitoring practices and aligning species selection with environmental conditions could further enhance the long-term success of vegetation establishment in the mine area.

3.4.4 Soil conditions

Soil conditions at the Ukhaa Khudag mine are significantly affected by mining activities and represent one of the main challenges for successful ecological rehabilitation. The dominant soil types in the project area include desert-steppe brown soils, sandy and gravelly soils, and saline-affected soils, which are characteristic of arid regions in southern Mongolia [34]. These soils generally have a heavy texture and are often composed of coarse materials such as gravel and sand, resulting in low water retention capacity and limited fertility [34].

Compared to natural soils in nearby undisturbed areas, mine soils are highly degraded. Mining operations disturb the original soil profile, remove topsoil layers, and alter the physical and chemical properties of the substrate. As a result, the soil structure becomes compacted or loosely aggregated, organic matter content is reduced, and nutrient availability is limited. In contrast, soils in natural seed collection areas are relatively more fertile, better structured, and more suitable for plant growth [34].

To improve soil conditions prior to planting, several preparation measures are applied. These include soil loosening, the addition of sand and fertilizers, and the use of moisture-retaining techniques, particularly in nursery and planting areas. Such interventions aim to enhance soil structure, improve aeration, and increase the capacity of the soil to retain moisture, which is essential for plant establishment in arid environments.

Overall, while current soil preparation practices contribute to improving site conditions, the degraded nature of mine soils remains a limiting factor for long-term ecological restoration. Therefore, integrating soil management strategies with appropriate species selection and seed sourcing approaches is essential for achieving sustainable rehabilitation outcomes.

3.5 Application of seed zone map to case study

3.5.1 Identification of the mine's seed zone

As shown in Figure 14, the Ukhaa Khudag mine operated by Energy Resources LLC is located within seed zone MZ7 (Dundgovi Desert zone, H5, Semi-dry). This zone is characterised by desert ecoregion conditions, a plant hardiness class of H5 (mean annual

extreme minimum temperature between -28.9°C and -23.3°C), and an annual precipitation exceeding 100 mm. The mean elevation of MZ7 is approximately 1,166 m above sea level, covering an area of 59,912 km².

This zonal classification provides a spatially explicit environmental reference framework for evaluating the ecological appropriateness of current seed sourcing and species selection practices at the mine site.

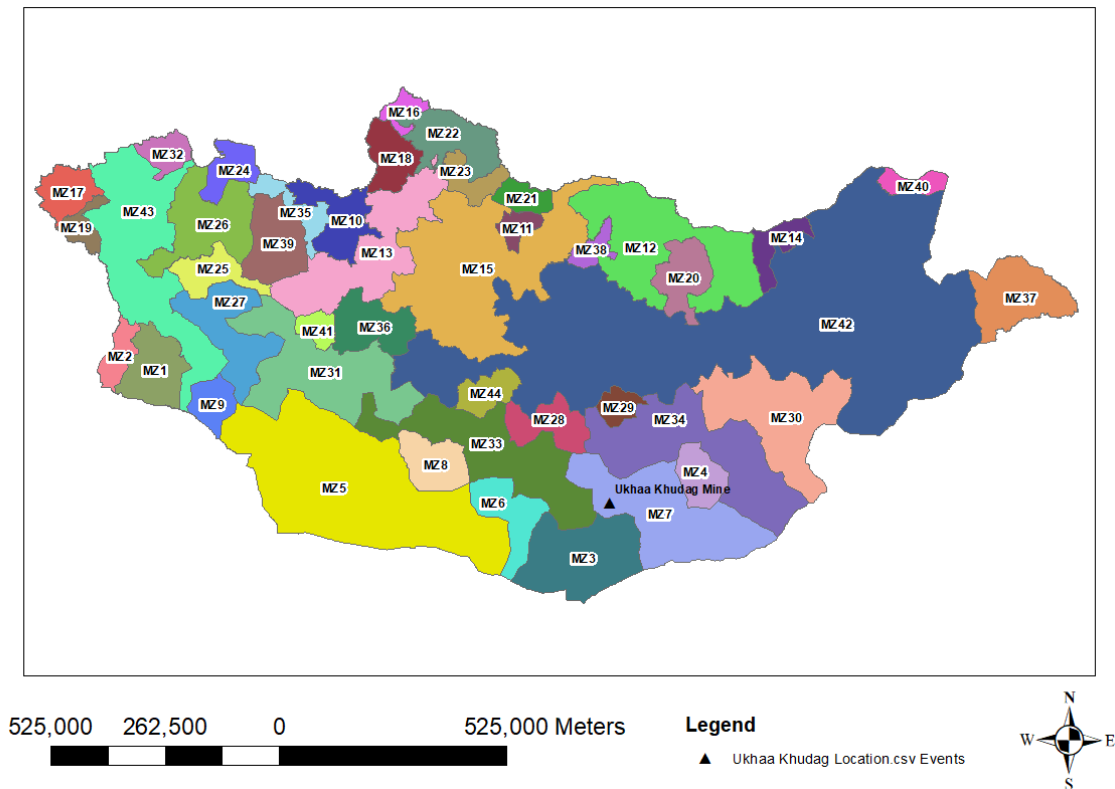


Figure 14 Location of the Ukhaa Khudag Mine within the Seed Zone Map of Mongolia

3.5.2 Evaluation of current seed sourcing against MZ7

Based on the seed sourcing information presented in Section 3.4.1, seed collection locations were assessed against the boundaries of MZ7. The results are summarised in Table 6 below.

Table 6 Assessment of current seed collection locations at the Ukhaa Khudag mine against seed zone MZ7 boundaries [9, 34]

Seed Source Location	Distance from Mine	Seed Zone	Risk level
Maiga Mountain reservoir	~15 km	MZ7	Low
Baruun Naran mining area	~30 km	MZ7	Low
Previously rehabilitated area	On-site	MZ7	Low
Khankhongot soum, Umnugovi	~60 km	MZ6/MZ7	Low-medium
Tsogt-Ovoo soum, Umnugovi	~80 km	MZ6	Medium
Ekhiin Gol, Bayankhongor	~400 km	MZ5/MZ9	High
Khatanbulag soum, Dornogovi	~300 km	MZ30	High

Seeds collected from local sources within approximately 35 km of the mine, such as the Maiga Mountain reservoir and Baruun Naran area, fall within or very close to MZ7 boundaries. This indicates that the mine's local collection practices are broadly consistent with the seed zone framework and represent a low risk of maladaptation.

However, seeds sourced from Ekhiin Gol in Bayankhongor province and Khatanbulag soum in Dornogovi province originate from zones with distinctly different environmental characteristics. These distant sources represent a higher risk of maladaptation, as plant materials may not be genetically adapted to the specific temperature and precipitation conditions of MZ7.

3.5.3 Evaluation of planted species against MZ7 conditions

In order to determine whether the species selection at the Ukhaa Khudag mine aligns with the delineated seed zone framework, each species was evaluated for its ecological suitability under MZ7 conditions; the results of this assessment are summarised in Table 7. Given that MZ7 is defined by harsh desert-steppe conditions, including low annual precipitation and severe winter temperatures, the suitability criteria prioritised native range overlap, drought resistance, and cold tolerance as the principal indicators of long-term establishment potential.

Table 7 Suitability assessment of plant species used in rehabilitation at the Ukhaa Khudag mine for seed zone MZ7 conditions [10, 34]

Species	Local Name	MZ7 Suitability	Reason
<i>Haloxylon ammodendron</i>	Zag	High	Native desert species, drought and cold tolerant
<i>Caragana spp.</i>	Khargana	High	Native desert-steppe shrub, well adapted to H5 conditions
<i>Allium polyrhizum</i>	Taana	High	Native steppe species common in desert-steppe zones
<i>Salsola spp.</i>	Budargana	High	Pioneer desert species, highly tolerant of arid conditions
<i>Ulmus pumila</i>	Khailaas	Medium	Steppe-forest species, tolerant but not native to desert zone
<i>Elaeagnus spp.</i>	Jigd	Medium	Requires more moisture than typical MZ7 dry conditions
<i>Populus spp.</i>	Tooroi	Low-medium	Riparian species, requires significantly more water than MZ7 provides

Species such as *Haloxylon ammodendron*, *Caragana spp.*, and native steppe herbs are well suited to MZ7 environmental conditions and represent ecologically appropriate choices for rehabilitation. In contrast, *Populus spp.* And *Elaeagnus spp.* Are typically associated with riparian or wetter environments and may require additional irrigation and maintenance to survive in MZ7, which is consistent with the observed spatial variability in plant growth performance reported in section 3.4.3.

3.5.4 Recommended seed collection zones

Based on the seed zone map, seed collection zones for mine rehabilitation at the Ukhaa Khudag mine should be prioritised within MZ7 and its environmentally adjacent zones. Table 8 presents the recommended seed collection zones for each major species used at the site.

Table 8 Recommended seed collection zones for major rehabilitation species used at the Energy Resource based on the seed zone map of Mongolia.

Species	Recommended seed zone	Rationale
<i>Haloxylon ammodendron</i>	MZ7, MZ3, MZ6	Same desert ecoregion and hardiness class
<i>Caragana spp.</i>	MZ7, MZ4, MZ6	Desert and semi-desert steppe zones with H5 conditions
<i>Ulmus pumila</i>	MZ7, MZ34, MZ30	Semi-desert steppe zones with similar temperature regime
<i>Salsola spp.</i>	MZ7, MZ3, MZ5	Dry desert zones with matching arid conditions

The application of the seed zone map to the Energy Resource LLC demonstrates that the framework provides a practical and spatially explicit tool for improving seed sourcing decisions. While current practices show some alignment with the seed zone framework through local collection, the systematic adoption of MZ7 boundaries as a guide for seed sourcing would reduce ecological risk and improve the long-term success of vegetation establishment.

3.6 Discussion

3.6.1 Key findings

This study developed the first comprehensive GIS-based seed zone map for Mongolia, delineating 44 discrete seed zones based on the integration of natural vegetation zones, plant hardiness zones, and precipitation zones. The resulting map reveals a strong north-south environmental gradient, with desert and semi-desert steppe zones dominating the south and forest steppe, high mountain, and mountain taiga zones characterising the north. This pattern is consistent with Mongolia's well-documented latitudinal and altitudinal vegetation zonation [13, 14].

The statistical validation confirmed the environmental meaningfulness of the delineation. The PERMANOVA results demonstrated statistically significant differentiation among the six ecoregion groups ($F = 4.808$, $R^2 = 0.388$, $p = 0.001$), confirming that the seed zones reflect real ecological structure across Mongolia's territory. The three-dimensional LDA further confirmed clear separation among ecoregion groups, with LD1 explaining 72.8% of the total between-group variation. These results are consistent with comparable seed zone validation

studies in other regions, including Lee et al. (2025) in South Korea [24] and Bower et al. (2014) in North America [2].

3.6.2 Implications for mine rehabilitation

The application of the seed zone map to the Ukhaa Khudag mine demonstrated its practical value for guiding rehabilitation practices. The mine was identified as falling within seed zone MZ7 (Dundgovi Desert zone, H5, Semi-dry), providing a clear spatial reference for seed sourcing that was previously unavailable to practitioners at the site.

Evaluation of current practices revealed that local seed collection within approximately 35 km of the mine is broadly consistent with MZ7 boundaries, representing a low risk of maladaptation. However, seeds sourced from distant locations such as Ekhiin Gol in Bayankhongor province originate from environmentally distinct zones, introducing a higher risk of maladaptation [9]. This highlights the key limitation of relying on practical availability rather than a systematic spatial framework for seed sourcing decisions.

The species suitability assessment showed that native desert species such as *Haloxylon ammodendron* and *Caragana* spp. are well suited to MZ7 conditions, while riparian species such as *Populus* spp. require additional maintenance to survive in the desert zone environment [10, 34]. This ecological mismatch is consistent with the observed spatial variability in plant growth performance at the mine [34]. While the overall survival rate exceeding 85% is encouraging, long-term ecological sustainability depends not only on initial survival but also on the genetic adaptation of plant materials to local environmental conditions [2, 9]. The seed zone map therefore provides a valuable complementary tool for improving both short-term establishment success and long-term rehabilitation outcomes.

These findings highlight the importance of integrating seed zone mapping into Mongolia's mine rehabilitation framework, particularly in the context of national commitments such as the Billion Trees National Movement [8] and greenhouse gas emission reduction targets [7].

3.6.3 Limitation and future research

Several limitations should be acknowledged. The delineation relies on a limited number of environmental variables, and the inclusion of additional bioclimatic factors such as growing season length and soil moisture could further refine zone boundaries. The absence of

genetic data for most native Mongolian plant species means the current framework should be regarded as a provisional seed zone map, to be refined as genetic and ecological data become available [2, 4]. Additionally, the case study was limited by the availability of systematic quantitative monitoring data, preventing a full empirical evaluation of the relationship between seed sourcing practices and rehabilitation outcomes.

Future research should prioritise the incorporation of species-specific genetic data through provenance trials, the integration of climate change projections to improve long-term relevance, and the development of structured long-term vegetation monitoring programs at mine rehabilitation sites across Mongolia.

4. Conclusion

This study developed and applied the first comprehensive GIS-based seed zone map for Mongolia, delineating 44 discrete seed zones across the country's diverse environmental landscape. The framework integrates natural vegetation zones, plant hardiness zones derived from January minimum temperature, and precipitation zones derived from long-term annual precipitation data, providing a spatially explicit and operationally practical tool for guiding seed sourcing decisions in mine rehabilitation and ecological restoration.

The statistical validation confirmed that the delineated seed zones represent environmentally meaningful and distinct units. The PERMANOVA results demonstrated statistically significant multivariate differentiation among the six ecoregion groups ($F = 4.808$, $R^2 = 0.388$, $p = 0.001$), while the three-dimensional LDA revealed clear separation among ecoregions in multivariate environmental space. Together, these results confirm that the seed zone framework provides a scientifically grounded spatial basis for guiding seed transfer decisions across Mongolia.

The application of the seed zone map to the Energy Resource LLC (Ukhuaa Khudag mine) case study demonstrated the practical value of the framework. The mine was identified as falling within seed zone MZ7 (Dundgovi Desert zone, H5, Semi-dry), providing a clear environmental reference for seed sourcing that was previously unavailable. Evaluation of current practices revealed that while local seed collection within 35 km of the mine is broadly consistent with the seed zone framework, seeds sourced from distant locations introduce a risk of maladaptation that could compromise long-term rehabilitation success. Native desert species such as *Haloxylon ammodendron* and *Caragana* spp. were identified as the most ecologically appropriate species for MZ7 conditions, while the use of riparian species such

as *Populus* spp. without supplementary irrigation poses ecological risks in the desert zone environment.

Overall, this study demonstrates that seed zone mapping is a scientifically sound and practically applicable approach for improving mine rehabilitation in Mongolia. The developed framework addresses a critical gap in Mongolia's restoration practice by providing rehabilitation practitioners, environmental engineers, and policymakers with a systematic, evidence-based tool for seed sourcing decisions. In the context of Mongolia's national commitments to the Billion Trees National Movement [8] and greenhouse gas emission reduction targets [7], the adoption of seed zone mapping as a standard practice in mine rehabilitation represents an important step toward more effective and ecologically sustainable land restoration across the country.

Future refinement of the framework through the incorporation of genetic data, additional bioclimatic variables, and climate change projections will further strengthen its scientific basis and long-term applicability. It is hoped that this study will serve as a foundation for future research and policy development in ecological restoration and sustainable land management in Mongolia.

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Appendix

Annex A1 Descriptive statistic data

BIO1 Min (°C)	BIO1 Max (°C)	BIO12 Mean (mm)	BIO12 Min (mm)	BIO12 Max (mm)	DEM Mean (m)	DEM Range (m)
-8.1012	5.3597	117.2513	82	273	1705.7649	1042 to 3888
-7.2045	4.3578	124.2356	89	242	1529.5076	1024 to 3496
0.2532	9.5310	90.0487	61	177	1314.0976	785 to 2794
2.0545	5.9613	101.3143	87	123	1023.0222	743 to 1428
-7.0020	9.0515	70.6129	26	235	1470.4190	523 to 3800
0.0645	8.0745	105.7296	57	179	1533.1584	1012 to 2814
3.0640	8.3230	110.7562	85	164	1166.1017	800 to 1782
-6.2037	6.6088	112.0275	66	282	1538.4336	943 to 3950
-6.9543	7.3622	105.1982	56	239	1790.9026	816 to 3738
-9.8938	-4.3012	239.9925	186	330	1930.5237	1176 to 2843
-4.0855	0.2935	365.9900	300	505	1268.4318	821 to 2171
-5.3538	0.1672	336.4517	260	494	1237.9337	591 to 2473
-9.4188	-0.1608	238.7694	106	401	2089.2425	1210 to 3969
-3.6463	-0.2512	352.4993	302	410	1165.4590	851 to 1745
-8.4015	0.7335	310.4994	205	584	1723.5249	588 to 3540
-11.3560	-6.1367	377.0352	283	465	2148.5339	1190 to 3243
-12.5510	-0.8453	203.8490	110	432	2533.3270	1730 to 4318
-11.3475	-4.4428	319.8562	240	425	2108.0888	1117 to 3330
-9.9325	0.6473	169.2176	109	261	2524.8092	1524 to 3867
-6.1642	0.1527	349.9484	241	442	1700.9247	1042 to 2793
-5.0337	-1.7683	461.3459	347	582	1424.7280	906 to 2153
-10.9200	-2.8295	374.3832	261	625	1850.6467	1075 to 3462
-6.9193	-1.6638	363.3131	293	568	1613.3064	1024 to 2524

-5.3675	-0.4190	210.3155	133	259	1043.8083	743 to 2298
-7.4573	1.5815	100.9353	74	251	1395.4900	1096 to 3777
-6.5958	1.7353	142.6735	89	288	1369.6098	757 to 3197
-8.7000	4.1392	98.9532	58	290	1666.4894	959 to 4201
1.4723	4.9530	138.3820	104	225	1335.3376	1100 to 1902
0.7680	3.0132	141.2009	110	176	1402.8464	1207 to 1612
-0.2508	4.8377	155.9494	112	224	1033.6029	729 to 1599
-6.6822	5.0497	117.7932	53	229	1881.7462	1007 to 3768
-10.4312	-0.8908	203.3231	146	348	1650.6535	756 to 4023
-6.6678	6.4232	134.4285	81	286	1514.8821	978 to 3952
0.3902	5.5855	116.7960	90	180	1097.7998	689 to 1700
-7.8182	-3.0397	219.0903	184	263	1642.5112	969 to 2755
-9.5207	-1.6175	193.5326	114	291	2550.6695	1817 to 3974
-3.5167	0.8845	284.9645	213	442	788.5736	571 to 1501
-1.6665	-0.2473	301.3639	281	339	942.9991	654 to 1460
-7.9238	-0.4318	188.0204	112	320	1826.8780	1268 to 2927
-1.4057	0.2228	278.1041	245	331	680.6032	568 to 1043
-8.4010	0.0568	166.5614	121	268	2208.5529	1570 to 3377
-7.9302	2.3933	242.0191	108	386	1213.0624	551 to 3540
-11.2428	2.7343	159.7836	74	354	2249.6503	757 to 4203
-3.6570	2.6238	245.3561	173	322	1929.0340	1495 to 2981

Annex B1 GEE script

```
var mongolia = ee.FeatureCollection("USDOS/LSIB_SIMPLE/2017")
    .filter(ee.Filter.eq('country_na', 'Mongolia'));
var precip = ee.Image("WORLDCLIM/V1/BIO").select('bio12');
var precipMongolia = precip.clip(mongolia);
Export.image.toDrive({
  image: precipMongolia,
  description: 'Mongolia_Annual_Precipitation',
  scale: 1000,
  region: mongolia,
  fileFormat: 'GeoTIFF',
  maxPixels: 1e13
});
```

Required libraries (install once using pip):

```
pip install pandas numpy matplotlib seaborn scipy scikit-learn openpyxl
```

Annex B.2 Import Libraries

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import matplotlib.patches as mpatches
import seaborn as sns
from scipy.spatial.distance import pdist, squareform
from sklearn.preprocessing import StandardScaler, LabelEncoder
from sklearn.discriminant_analysis import LinearDiscriminantAnalysis
import warnings
warnings.filterwarnings('ignore')
np.random.seed(42)
```

Annex B.3 Load and Prepare Data

```
# Load the statistic sheet from the descriptive statistics Excel file
df = pd.read_excel('descriptive_statistic.xlsx', sheet_name='statistic')

# Rename columns to shorter variable names
df = df.rename(columns={
    'Mean Precipitation' : 'Precip_Mean',
    'Min Precipitation'   : 'Precip_Min',
    'Max Precipitation'   : 'Precip_Max',
    'STD Precipitation'   : 'Precip_Std',
    'Mean Temperature'    : 'Temp_Mean',
    'Min Temperature'     : 'Temp_Min',
    'Max Temperature'     : 'Temp_Max',
    'STD Temperature'     : 'Temp_Std',
    'Mean Elevation'      : 'Elev_Mean',
    'Min Elevation'       : 'Elev_Min',
    'Max elevation'       : 'Elev_Max',
    'STD Elevation'       : 'Elev_Std',
})
```

```
# Convert precipitation to numeric (MZ42 and MZ43 have missing values)
for col in ['Precip_Mean', 'Precip_Min', 'Precip_Max', 'Precip_Std']:
    df[col] = pd.to_numeric(df[col], errors='coerce')

# Sort zones correctly: MZ1, MZ2, ..., MZ44
df['Zone_num'] = df['Zone'].str.extract(r'(\d+)').astype(int)
df = df.sort_values('Zone_num').reset_index(drop=True)
```

Annex B.4 Define Ecoregion Colors

```
eco_order = [
    'Desert zone', 'Semi desert steppe zone', 'Steppe zone',
    'Forest steppe zone', 'High mountain belt', 'Mountain taiga belt',
]

eco_colors = {
    'Desert zone' : '#D4A843',
    'Semi desert steppe zone': '#C8956C',
    'Steppe zone' : '#8BC34A',
    'Forest steppe zone' : '#2E7D32',
    'High mountain belt' : '#7986CB',
    'Mountain taiga belt' : '#00838F',
}

df['Color'] = df['Ecoregion'].map(eco_colors)
legend_patches = [
    mpatches.Patch(color=eco_colors[e], label=e)
    for e in eco_order if e in df['Ecoregion'].values
]
```

Annex B.5 Descriptive Statistics

```
grouped = df.groupby('Ecoregion').agg(
    N_zones = ('Zone', 'count'),
```

```

Precip_Mean = ('Precip_Mean', 'mean'),
Precip_SD   = ('Precip_Mean', 'std'),
Precip_Min  = ('Precip_Mean', 'min'),
Precip_Max  = ('Precip_Mean', 'max'),
Temp_Mean   = ('Temp_Mean',   'mean'),
Temp_SD     = ('Temp_Mean',   'std'),
Temp_Min    = ('Temp_Mean',   'min'),
Temp_Max    = ('Temp_Mean',   'max'),
Elev_Mean   = ('Elev_Mean',   'mean'),
Elev_SD     = ('Elev_Mean',   'std'),
Elev_Min    = ('Elev_Mean',   'min'),
Elev_Max    = ('Elev_Mean',   'max'),
).round(2)

grouped = grouped.reindex(eco_order)
grouped.to_excel('descriptive_stats_output.xlsx')
print(grouped.to_string())

```

Annex B.6 PERMANOVA

```

# Features used: mean and std of precipitation, temperature, and elevation
features =
['Precip_Mean', 'Precip_Std', 'Temp_Mean', 'Temp_Std', 'Elev_Mean', 'Elev_Std']

df_clean = df.dropna(subset=features).copy()

X_raw     = df_clean[features].values
X         = StandardScaler().fit_transform(X_raw)

eco_labels = df_clean['Ecoregion'].values
zone_list  = list(df_clean['Zone'])

unique_groups = np.unique(eco_labels)
k = len(unique_groups)
n = len(X)

dist_sq = squareform(pdist(X, metric='euclidean'))**2

```

```

def compute_f(dist_sq, labels):
    n = len(labels)
    SS_total = dist_sq.sum() / (2 * n)
    SS_within = 0
    for g in np.unique(labels):
        idx = np.where(labels == g)[0]
        n_g = len(idx)
        if n_g > 1:
            SS_within += dist_sq[np.ix_(idx, idx)].sum() / (2 * n_g)
    SS_between = SS_total - SS_within
    if (n - k) == 0: return np.nan, np.nan
    F = (SS_between / (k-1)) / (SS_within / (n-k))
    R2 = SS_between / SS_total
    return F, R2

F_obs, R2_obs = compute_f(dist_sq, eco_labels)
count = 0
for _ in range(999):
    F_p, _ = compute_f(dist_sq, np.random.permutation(eco_labels))
    if not np.isnan(F_p) and F_p >= F_obs:
        count += 1
p_val = (count + 1) / 1000

print(f'F = {F_obs:.4f}, R2 = {R2_obs:.4f}, p = {p_val:.4f}')

```

Annex B.7 Pairwise Environmental Distance Matrix

```

dist_matrix = squareform(pdist(X, metric='euclidean'))
dist_norm = dist_matrix / dist_matrix.max()
np.fill_diagonal(dist_norm, np.nan)

# Build full 44x44 matrix (including MZ42 and MZ43 as NaN)
dist_full = np.full((len(df), len(df)), np.nan)
zone_idx = {z: i for i, z in enumerate(df['Zone'])}

```

```

clean_idx = [zone_idx[z] for z in zone_list]
for i, ci in enumerate(clean_idx):
    for j, cj in enumerate(clean_idx):
        dist_full[ci, cj] = dist_norm[i, j]

zone_label_colors = [eco_colors.get(eco, '#AAAAAA') for eco in df['Ecoregion']]

fig, ax = plt.subplots(figsize=(20, 18))
sns.heatmap(dist_full, annot=False, cmap='YlOrRd',
            xticklabels=df['Zone'], yticklabels=df['Zone'],
            linewidths=0.0, vmin=0, vmax=1,
            cbar_kws={'label': 'Normalised environmental distance',
                    'shrink': 0.6}, ax=ax)

for tick, color in zip(ax.get_xticklabels(), zone_label_colors):
    tick.set_color(color); tick.set_fontweight('bold')
for tick, color in zip(ax.get_yticklabels(), zone_label_colors):
    tick.set_color(color); tick.set_fontweight('bold')

ax.set_xticklabels(ax.get_xticklabels(), rotation=90, fontsize=8)
ax.set_yticklabels(ax.get_yticklabels(), rotation=0,  fontsize=8)
ax.set_title('Pairwise Environmental Distance Matrix Among 44 Seed Zones',
            fontsize=12, fontweight='bold', pad=15)
ax.legend(handles=legend_patches, fontsize=9, title='Ecoregion',
        loc='upper left', bbox_to_anchor=(1.12, 1.0))

# White lines between ecoregion blocks
current_eco, boundaries = None, []
for i, eco in enumerate(df['Ecoregion']):
    if eco != current_eco:
        boundaries.append(i); current_eco = eco
for b in boundaries[1:]:
    ax.axhline(b, color='white', linewidth=2)

```

```

ax.axvline(b, color='white', linewidth=2)

plt.tight_layout()

plt.savefig('Figure2_distance_heatmap.png', dpi=200, bbox_inches='tight')

plt.close()

```

Annex B.8 Three-Dimensional Linear Discriminant Analysis (LDA)

```

# Generate 80 synthetic observations per zone using mean and std
# This enables cloud-like visualisation of intra-zone variability
rows = []
for _, zrow in df_clean.iterrows():
    for _ in range(80):
        rows.append({
            'Zone'      : zrow['Zone'],
            'Ecoregion': zrow['Ecoregion'],
            'Precip'    : np.random.normal(zrow['Precip_Mean'],
                                           max(zrow['Precip_Std'], 0.01)),
            'Temp'      : np.random.normal(zrow['Temp_Mean'],
                                           max(zrow['Temp_Std'], 0.01)),
            'Elev'      : np.random.normal(zrow['Elev_Mean'],
                                           max(zrow['Elev_Std'], 0.01)),
        })
df_sim = pd.DataFrame(rows)
Xs      = StandardScaler().fit_transform(df_sim[['Precip', 'Temp', 'Elev']].values)
y_sim   = LabelEncoder().fit_transform(df_sim['Zone'].values)

lda_vis = LinearDiscriminantAnalysis(n_components=3)
X_lda   = lda_vis.fit_transform(Xs, y_sim)
exp_vis = lda_vis.explained_variance_ratio_ * 100
print(f'LD1={exp_vis[0]:.1f}% LD2={exp_vis[1]:.1f}% LD3={exp_vis[2]:.1f}%')

fig = plt.figure(figsize=(14, 10))
ax   = fig.add_subplot(111, projection='3d')

```

```

for eco in eco_order:
    if eco not in df_sim['Ecoregion'].values: continue
    mask = df_sim['Ecoregion'].values == eco
    coords = X_lda[mask]
    ax.scatter(coords[:,0], coords[:,1], coords[:,2],
               c=eco_colors[eco], label=eco, s=12,
               alpha=0.5, edgecolors='none')

# Add zone centroid labels
for zone in zone_list:
    mask = df_sim['Zone'].values == zone
    coords = X_lda[mask]
    ax.text(coords[:,0].mean(), coords[:,1].mean(), coords[:,2].mean(),
            zone, fontsize=6, color='black', fontweight='bold')

ld_ax = [f'LD{i+1} ({exp_vis[i]:.1f}%)' for i in range(3)]
ax.set_xlabel(ld_ax[0], fontsize=10, labelpad=10)
ax.set_ylabel(ld_ax[1], fontsize=10, labelpad=10)
ax.set_zlabel(ld_ax[2], fontsize=10, labelpad=10)
ax.set_title('Three-Dimensional LDA of 44 Seed Zones',
             fontsize=12, fontweight='bold', pad=15)
ax.legend(fontsize=8, loc='upper left',
          bbox_to_anchor=(-0.15, 1.05), ncol=1)
ax.view_init(elev=20, azimuth=225)

plt.tight_layout()
plt.savefig('Figure3_LDA_3D.png', dpi=200, bbox_inches='tight')
plt.close()

```

Annex B.9 Environmental Characteristics Bar Charts (Figure 1)

```

x = np.arange(len(df))

```

```

def draw_panel(ax, mean_col, std_col, min_col, max_col, ylabel, title, hline=None):
    means = df[mean_col].values.astype(float)
    stds = df[std_col].fillna(0).values.astype(float)
    mins = df[min_col].values.astype(float)
    maxs = df[max_col].values.astype(float)
    colors = df['Color'].values

    ax.bar(x, means, color=colors, edgecolor='white',
           linewidth=0.4, width=0.8, zorder=2)

    for i in range(len(df)):
        if not np.isnan(means[i]):
            ax.plot([x[i], x[i]], [mins[i], maxs[i]],
                    color='#333', lw=1.0, zorder=3)
            ax.plot(x[i], mins[i], '_', color='#333',
                    markersize=7, markeredgewidth=1.5, zorder=4)
            ax.plot(x[i], maxs[i], '_', color='#333',
                    markersize=7, markeredgewidth=1.5, zorder=4)
            ax.plot(x[i], means[i]+stds[i], 'd', color='white',
                    markersize=4, markeredgewidth=0.8, zorder=5)
            ax.plot(x[i], means[i]-stds[i], 'd', color='white',
                    markersize=4, markeredgewidth=0.8, zorder=5)

    ax.set_xticks(x)
    ax.set_xticklabels(df['Zone'], rotation=90, fontsize=8)
    ax.set_ylabel(ylabel, fontsize=10)
    ax.set_title(title, fontsize=11, fontweight='bold', pad=6)
    ax.set_xlim(-0.8, len(df)-0.2)
    ax.grid(axis='y', linestyle='--', alpha=0.3, zorder=1)

    if hline:
        ax.axhline(hline, color='red', linestyle='--', lw=1.2, alpha=0.7)

    current_eco = None
    for i, eco in enumerate(df['Ecoregion']):
        if eco != current_eco and i > 0:
            ax.axvline(i-0.5, color='gray', lw=1,

```

```

        linestyle='--', alpha=0.4, zorder=1)

    current_eco = eco

    ax.legend(handles=legend_patches, fontsize=7,
              loc='upper right', ncol=2, framealpha=0.9)

fig, axes = plt.subplots(3, 1, figsize=(22, 20))
fig.suptitle('Environmental Characteristics of 44 Seed Zones',
            fontsize=13, fontweight='bold', y=1.01)

draw_panel(axes[0], 'Precip_Mean', 'Precip_Std', 'Precip_Min', 'Precip_Max',
            'Annual Precipitation (mm)',
            'A. BIO12 - Annual Precipitation per Seed Zone', hline=100)
draw_panel(axes[1], 'Temp_Mean', 'Temp_Std', 'Temp_Min', 'Temp_Max',
            'Annual Mean Temperature (°C)',
            'B. BIO1 - Annual Mean Temperature per Seed Zone')
draw_panel(axes[2], 'Elev_Mean', 'Elev_Std', 'Elev_Min', 'Elev_Max',
            'Elevation (m a.s.l.)',
            'C. Elevation (DEM) per Seed Zone')

plt.tight_layout()
plt.savefig('Figure1_all_variables.png', dpi=200, bbox_inches='tight')
plt.close()
print('All figures saved.')

```