UAV-Based Remote Sensing, GIS, and Its Application in Archaeology: A Case Study of the Xiongnu Elite Burial Complex at Gol Mod-II, Mongolia

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Abstract

This study presents a spatial analysis of the Xiongnu elite burial complex at the Gol Mod-II site in Arkhangai aimag, Mongolia, using Unmanned Aerial Vehicle (UAV)-based remote sensing and Geographic Information System (GIS). Over 500 burial mounds, classified into square, circular, and satellite types, were documented to generate orthomosaic imagery and Digital Surface Model (DSM). Kernel Density Estimation (KDE) was applied to visualise the spatial distribution and potential hierarchical patterns among the burial types. Despite the limitations due to the absence of Ground Control Points (GCPs) and manual UAV operation, the analysis provided meaningful insights into the organisation of Xiongnu burial landscapes based on relative spatial positioning. This study demonstrates the practical integration of UAV and GIS technologies in Eurasian steppe archaeology and highlights the potential of interdisciplinary approaches to the study of nomadic cemetery landscapes.

1. Introduction

The Xiongnu, a powerful nomadic empire that thrived across East and Central Eurasia from the 3rd century BCE, has been a central subject of archaeological investigation. Their mortuary culture provides critical evidence for reconstructing the social stratification and political organisation of early steppe societies. Previous research has primarily relied on Chinese literature such as the *Shiji*, along with excavated human remains, tomb structures, and artefacts such as grave goods. While these approaches have revealed important insights, they have also constrained interpretations by limiting the spatial scale of analysis and reinforcing textual bias.

In contrast to sedentary societies, the archaeological footprint of nomadic cultures is often sparse and discontinuous. However, the burial mounds remain among the most visible and structurally consistent features, making them vital for understanding elite display and social hierarchy. Despite this, most studies of Xiongnu tombs have focused on select examples through excavation, lacking efforts to investigate the broader landscape arrangement and internal structure of burial fields. Moreover, traditional archaeological fieldwork is resource-intensive, time-consuming, and inherently destructive, necessitating alternative and scalable documentation methods.

Recent advances in digital archaeology have brought attention to the use of Unmanned Aerial Vehicle (UAV)-based remote sensing and Geographic Information System (GIS) for archaeological site analysis. These technologies are particularly suitable for expansive, remote, or inaccessible areas such as the Eurasian steppe. UAVs allow archaeologists to independently acquire high resolution imagery and elevation data, offering new avenues for interpreting the spatial logic and symbolic structure of ancient cemetery landscapes.

This study focuses on the Gol Mod-II site in Arkhangai aimag, Mongolia, known for its concentration of Xiongnu elite burial complex. Using UAV-derived orthomosaic and elevation models, over 500 tombs were categorised into square, circular and satellite types. The Gol Mod-II site occupies a central position in the archaeological study of the Xiongnu. It features the largest known square with stepped terraces, accompanied by a remarkably diverse and ornate assemblage of grave goods, which are clear indicators of elite status. Despite this, the site remains in an early phase of investigation, with less than 10% of the burials excavated. It is widely regarded as a major site in Xiongnu archaeology that remains insufficiently analysed, despite its significance for understanding mortuary organisation and socio-political hierarchy.

To explore spatial clustering and possible hierarchical patterns among the burial types, Kernel Density Estimation (KDE) was applied to the categorised burial dataset. The analysis enables a structured reinterpretation of burial layouts, challenging static typological models and introducing a more dynamic perspective on social organisation. As a pilot study, this work integrates archaeological inquiry with spatial analysis, proposing a methodological shift for future landscape-oriented research on the ancient Eurasian nomadic cultures.

While the absence of Ground Control Points (GCPs) resulted in limited vertical accuracy in the generated models, this study is designed as a qualitative, landscape-level investigation. Its primary aim is to analyse relative spatial patterns among tomb types, rather than to produce metrically precise reconstructions.

2. Literature Review on the Xiongnu Elite Burial Complex

Previous archaeological investigations into Xiongnu burial complexes have primarily focused on quantifying the number of burials at selected sites. To date, approximately 15,000 Xiongnu tombs have been identified, with more than 87% (over 13,000 burials) distributed within present-day Mongolia (Eregzen, 2021). While many of the elite tombs and large elite burial complexes are concentrated in Mongolia and southern Siberia—including Buryatia and Tuva—financial constraints have often hindered comprehensive, large-scale excavations. As a result, most existing studies on Xiongnu burial practices have relied heavily on sample excavations (Han and Eregzen, 2017).

Figure 1. Distribution of Xiongnu burial sites (adapted from Erdenebaatar et al., 2015)

Xiongnu burials are generally categorised into two primary types: square and circular tombs. This typological distinction, which will also be adopted in the present study, was originally proposed by a Mongolian archaeologist Ts. Dorjsuren, who associated the burial structures—such as shape, presence of a dromos, and the architectural features—and excavated grave goods with social hierarchy. According to his interpretation, square tombs were reserved for elites, whereas circular tombs represented commoners (Eregzen, 2010; Han, 2025). In addition to these two primary categories, a third type–satellite tombs–has been identified, often arranged near large square tombs (see figure 2).

Figure 2. Various types of burials in Gol Mod-II (imagery taken on 27 July 2022)

While this classification has been widely accepted and has provided a basic framework for understanding Xiongnu mortuary traditions, it is not without limitations. First, Dorjsuren's binary typological model has remained largely unchallenged for over six decades. However, recent excavations have uncovered examples that deviate from this strict dichotomy, calling into question the reliability of such a framework (Central Institute of Cultural Heritage et al., 2020). Second, as only a small portion of tombs at each site have been excavated—often chosen for their visibility or preservation—there is a significant risk of generalising from non-representative samples. This raises the need to reassess prior interpretations of social stratification and mortuary organisation based solely on limited evidence.

In light of these limitations, the application of remote sensing technologies—particularly UAV-based survey methods—offers a promising alternative. These approaches allow researchers to analyse tombs at the landscape level and overcome the spatial and temporal constraints of traditional excavation. By facilitating large-scale, non-invasive documentation, such methods contribute to a more comprehensive and nuanced understanding of Xiongnu burial culture.

3. Research Methods and Its Object

3.1 Research Methods

To improve the general understanding of the Xiongnu burials, even basic spatial analysis based on UAV remote sensing data is an essential approach. Remote sensing and its application in archaeology are not recent developments; rather, they have been widely adopted for various purposes worldwide (Agapiou and Lysandrou, 2015). Compared to the widespread adoption in European regional studies, archaeological research utilising UAVs in Asia has been steadily increasing. The use of commercial UAVs for archaeological purposes has also become far more common than in previous decades.

The application of UAVs in Eurasian archaeological research has become increasingly standard practice. In particular, the archaeological sites associated with the Xiongnu and other ancient nomadic pastoralist civilisations share several key characteristics: they are transnational and extend across vast areas. Compared to Europe, however, there are relatively fewer studies employing UAV-based methods. For instance, Korean archaeological teams primarily used Ground Penetrating Radar (GPR), with UAV data playing only a supplementary role, such as identifying potential kurgan features in Kazakhstan (National Research Institute of Cultural Heritage, 2019). In contrast, more advanced cases have been reported in Kyrgyzstan, where UAV data was used to create distribution maps and identify potential archaeological features (Sărășan et al., 2020) as well as to analyse ancient nomadic landscape formation through GIS (Rouse et al., 2021). These examples highlight the expanding role of UAV remote sensing in archaeological research.

Building on this foundation, applying remote sensing and GIS technologies to the study of Xiongnu burial culture is a highly promising approach. For this purpose, we selected a Xiongnu burial site, named Gol Mod-II, located in Arkhangai aimag, Mongolia, as the case study for data acquisition. There were numerous options available regarding commercial UAV models. Previous studies frequently employed UAVs from the brand DJI (National Research Institute of Cultural Heritage, 2019; Rouse et al., 2021; Sărășan et al., 2020). After comparing factors such as price, weight, accuracy, and resolution, we

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selected the Mavic 3 model as the primary tool for UAV-based data acquisition.

Data processing was conducted using Agisoft Metashape (formerly known as PhotoScan), which converts aerial photographs into 3D models, Digital Surface Models (DSM), and orthomosaic imagery. The effectiveness of 3D modelling, DSM, and orthomosaic in preserving and analysing archaeological contexts has been previously demonstrated (National Research Institute of Cultural Heritage, 2019; Trizio et al., 2018). Following this, the primary archaeological dataset and distribution maps were created by using QGIS software, incorporating basic spatial analysis.

Although the Ground Control Points (GCPs) were not employed, aerial imagery processing was conducted using Agisoft Metashape, ensuring a satisfactory level of internal alignment. According to the processing report, the average reprojection error was 1.14 pixels, and a total of 2,502,578 tie points were generated, with an average tie point multiplicity of 5.95. Despite limitations in absolute geolocation—especially vertical accuracy due to manual UAV operation and vegetation cover—the generated orthomosaic and DSM data were sufficiently accurate for typological classification and spatial clustering analysis. The average vertical (Z-axis) error was measured at 17.12 meters, and the total camera alignment error was 17.40 meters, which limits metric-level modelling but remains suitable for relative spatial analysis.

The use of commercial UAV (DJI Mavic 3) and QGIS software allowed for cost-effective non-destructive spatial documentation. However, we acknowledge the lack of RTK, GNSS, or GCP integration as a limitation for metric-level analysis. Future research should aim to incorporate georeferencing strategies and collaborate with geomatics experts to improve reproducibility and spatial precision.

To enhance the visualisation of tomb distribution by type, Kernel Density Estimation (KDE) was employed. KDE has been evaluated as an effective method for analysing regional events and spatial phenomena (O'Sullivan and Unwin, 2010). Accordingly, we expect that applying KDE will clarify the spatial distribution patterns of the Xiongnu elite burial complex. While the KDE results are qualitative, they reveal meaningful patterns in the burial complex layout, offering new insights into Xiongnu burial organisation. This approach demonstrates the potential of UAV-based survey and GIS methods to contribute to archaeological interpretation even in data-scarce or logistically constrained environments.

3.2 Research Object

Using the tools outlined above, this study selected the representative Xiongnu burial site known as Gol Mod-II as its research object. This site was first identified by a joint research team from the Department of Archaeology at Ulaanbaatar State University and the University of Pittsburgh, USA, in 2001 (Allard et al., 2002; Miller et al., 2006). Subsequently, a Chinese joint research team also conducted joint investigations at the site (Zhou et al., 2020, 2022). Over nearly two decades, the largest square tomb was excavated, and approximately 500 tombs were identified during field surveys. However, the precise number and detailed archaeological characteristics of the site remain unclear (see Figure 3).

At Gol Mod-II, only a small portion of the tombs have been excavated: specifically, 4 square tombs and 43 satellite tombs. Notably, no circular tombs have been excavated to date. Furthermore, previous archaeological researches at this site have exclusively focused on tombs from the Xiongnu period, neglecting the possibility of longer-term site formation processes extending from the Bronze Age to the Mongol Empire period. Thus, previous excavations have primarily taken a microscopic approach, focusing solely on the Xiongnu period and investigating less than 10% of the total burials. This limited scope makes it insufficient to generalise or fully understand the burial site's social structure based on earlier hierarchical typologies.

Given these circumstances, it is necessary to re-examine Gol Mod-II through comprehensive field surveys and UAV-based remote sensing. As mentioned earlier, Xiongnu burials are typically classified into three types based on their external structures and spatial distributions: square tombs, circular tombs, and satellite tombs. We argue that these typologies and attributes provide a more intuitive and practical framework for describing the Xiongnu burial culture. Relying solely on hierarchical interpretations—such as categorising tombs into elite and commoner burials—is inadequate to explain previous excavation results and fails to address typological misunderstandings not only at Gol Mod-II but also at other so-called Xiongnu elite burial complexes. Thus, the Gol Mod-II site offers sufficient grounds to propose new hypotheses and perspectives through UAV-based remote sensing analysis.

Accordingly, this study conducted a heatmap analysis as a case study in basic spatial analysis, applying remote sensing data within an archaeological theoretical framework. After classifying each tomb by archaeological type, the data were first digitised into polygons and subsequently converted into point shapefiles. This process allows for direct comparison of KDE heatmaps across different tomb types, enabling an evaluation of whether each type was evenly distributed or spatially clustered. Furthermore, the relationship among the tomb types can be identified and interpreted from an archaeological perspective, shedding light on broader patterns within the Xiongnu burial practices.

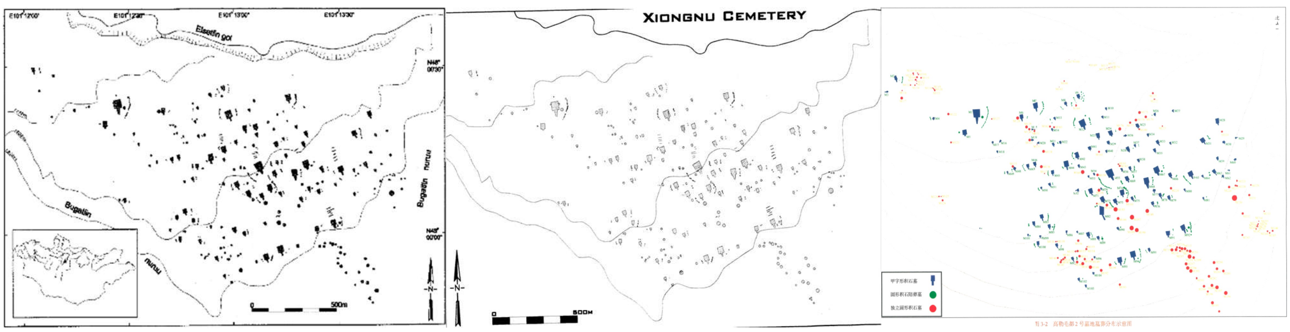

Figure 3. Burial distribution map of Gol Mod-II site (left: Allard et al., 2002; middle: Erdenebaatar et al. 2015; right: Zhou et al., 2022

4. Data Collecting and Processing Procedures

4.1 UAV based Image Acquisition

From July 24 to 28, 2022, the main field survey was conducted at the Gol Mod-II to identify tombs that had been missed during previous investigations. To ensure optimal conditions for remote sensing with minimal errors, we carefully scheduled the survey based on time and weather conditions. Additionally, to address legal and ethical considerations regarding UAV flights, Baasandorj from the National Center for Cultural Heritage of Mongolia participated in the entire filming process, with official authorisation granted by Dr. G. Eregzen of the Institute of Archaeology, Mongolian National Academy of Sciences.

Prior to beginning image acquisition, Baasandorj evaluated the suitability of the site and the expected data accuracy. Given limitations such as storage capacity and the UAV’s available flight time, it was necessary to plan flights at regular intervals and set appropriate altitudes (see figure 4). However, due to the limitations of the DJI Mavic 3 model and its controller, automatic flight planning was unavailable. Thus, all flights were manually operated. Images were acquired starting approximately 300 meters from Tomb No. 1, the largest and tallest structure at the site—with a width of 5–10 meters and a length of 10–20 meters.

Figure 4. Comparison of filming altitude from 200m to 500m (imagery taken on 25 July 2022)

While the average flight altitude was approximately 300 metres above ground level (AGL), the flight was conducted manually due to the absence of automated waypoint planning. The estimated forward overlap was approximately 70%, and the sidelap ranged between 40 to 50%. Terrain variations and vegetation density led to minor inconsistencies in flight altitude and alignment, which likely contributed to uneven reconstruction quality. Through the image acquisition process, a total of 1,810 images were collected. Among these, 1,605 images, which are free from significant accuracy issues, were selected for processing. Data processing using Agisoft Metashape followed a standard workflow, including photo alignment, dense point cloud generation, and the production of a DSM and orthomosaic imagery. The resulting data had a ground resolution of 8.11 cm/pixel, with the following estimated average positional errors: 1.68 m (X error), 2.30 m (Y error), 17.10 m (Z error), and 17.34 m. (total error) Among these, the Z-axis error was the largest, largely due to the manual flight operations during image acquisition. Furthermore, tree and forest coverage obscured many archaeological features, contributing to the higher vertical error (see figure 5).

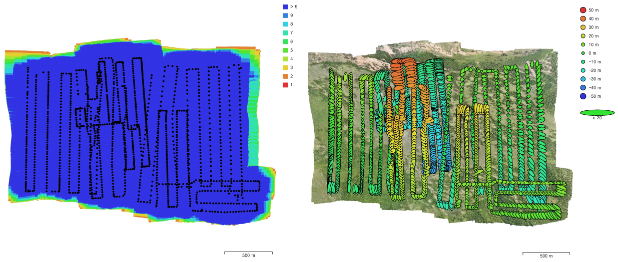

Figure 5. Image overlap (left) and error estimates (right)

Despite these challenges, several significant findings emerged from the remote sensing process, particularly regarding ditches and ritual site remains around the tombs. First, ditches were identifiable through both hillshading and orthomosaic imagery (see figure 6). This finding is noteworthy not only for confirming the locations of tombs but also for providing insights into construction behaviours associated with the tombs.

Second, previous studies at Gol Mod-II had reported visible straight-line features to the north of some square tombs. Our survey confirmed these features on the surface. Excavations at square Tomb No. 1 and No. 189 revealed the absence of artefacts but the presence of burned animal bones and fragments of wood. In addition, further ritual site remains were discovered near some of the square tombs (see figure 7), suggesting complex ritual practices associated with mortuary behaviours of the Xiongnu society.

Figure 6. Example of ditches of square tombs from No.70 to No.75 from Gol Mod-II cemetery

4.2 3D GIS Data Processing

The next step involved GIS-based data processing, using the open-source software QGIS. After completing the photogrammetric processing in Metashape, both the DSM and the orthomosaic imagery were exported as GeoTIFF files. These GeoTIFF files served as the foundational data for mapping in QGIS.

From the DSM file, contour lines and hillshade imagery were generated to better visualise the site's overall topography (see Figure 8, left and right). In addition, previous distribution maps of archaeological features (e.g., figure 4) that were created using georeferencing tools needed to be reassessed for potential inaccuracies or discoveries. Following the georeferencing and the generation of shapefiles for each burial, an updated and geographically corrected distribution map of the site was produced (see figure 7).

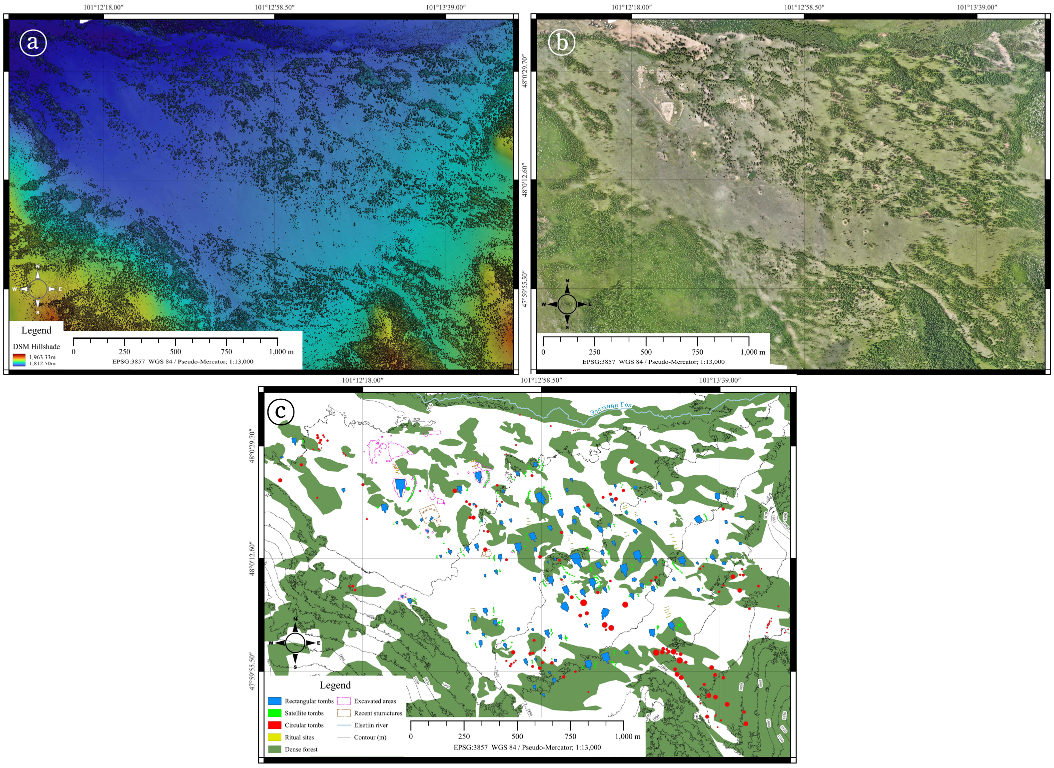

Figure 7. DSM hillshade (ⓐ), orthomosaic (ⓑ) and distribution map of archaeological features (ⓒ) of Gol Mod-II

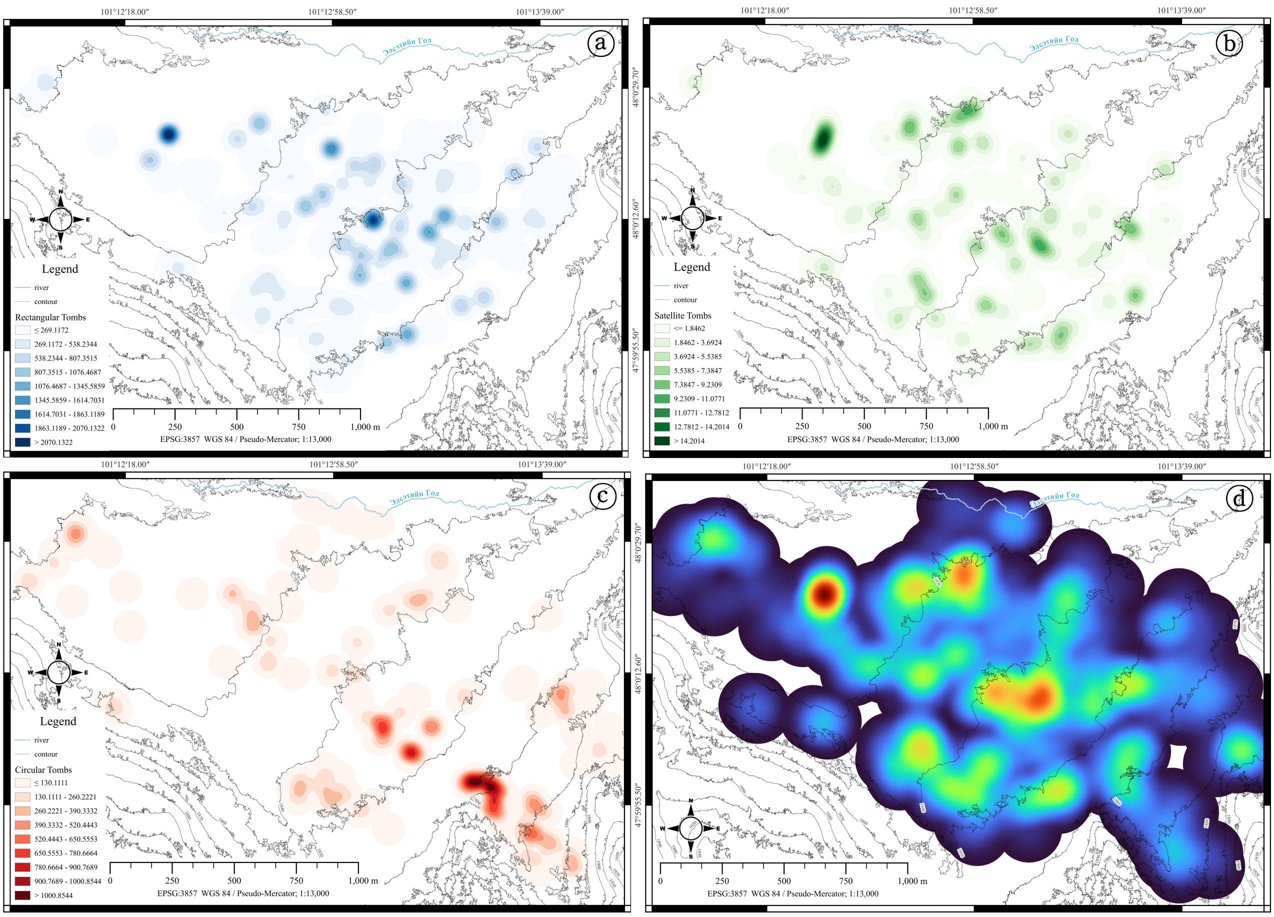

Figure 8. KDE heatmap of burial types: square tombs (ⓐ), satellite tombs (ⓑ), circular tombs (ⓒ), and all tombs combined (ⓓ).
[QGIS-based; ⓐ to ⓒ 100m bandwidth and ⓓ 200m bandwidth; 5m cell size; UTM zone 48N]

4.3 KDE Analysis and Spatial Interpretation

After the completion of the site mapping, spatial analysis was conducted. Within QGIS’s Processing Toolbox, the heatmap generator, an interpolation function was utilised. Because KDE is a point-based analysis, it was necessary first to convert the polygon shapefiles representing each tomb into centroid-based point shapefiles.

Each type of tomb exhibited different size distributions and quantities. For example, both the square and circular tombs showed a wide range of sizes between the largest and smallest structures, whereas the satellite tombs generally had relatively static size, with a few notable outliers (e.g., the largest satellite tomb No. 30, which is associated with square tomb No. 1).

To properly contrast each type:

1) For square and circular tombs, weighting based on the spatial extent (size) was applied to highlight their relative magnitudes.
2) For satellite tombs, no size-based weighting was applied; only the quantity was considered when generating the KDE heatmap raster layers.

The spatial analysis revealed notable distribution patterns:

1) Square tombs and satellite tombs tended to cluster together, showing almost identical distribution patterns. Even with size weighting, the density of satellite tombs appeared proportional to the size of nearby square tombs.
2) In contrast, circular tombs showed a tendency to distribute independently or to cluster along the edges of the site. Thus, it is reasonable to interpret that circular tombs were more irregularly distributed compared to square and satellite tombs.

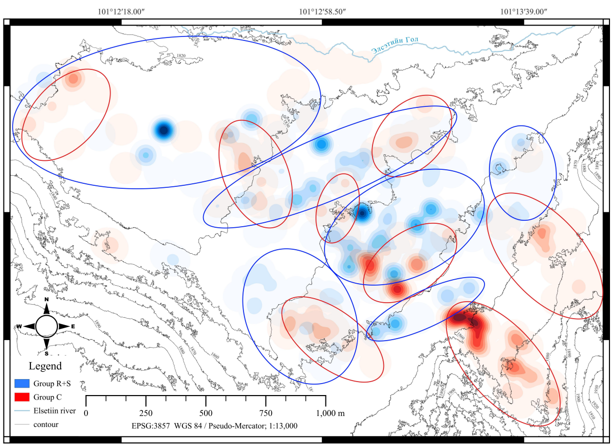

Figure 9. Group Separation of the burial types

5. Discussion and Conclusion

The application of UAV-based methodologies for the remote assessment of archaeological features, as demonstrated in this study of the Gol Mod-II site, offers significant advantages over traditional ground-based survey techniques. The ability to rapidly acquire high-resolution spatial data across extensive areas enables a more comprehensive and efficient documentation of archaeological landscapes. While the inherent limitations of relying solely on aerial imagery—particularly in detecting subsurface features, determining artefact typologies, and achieving precise dating—must be acknowledged, the integration of UAV-derived data with GIS and advanced photogrammetric processing has yielded novel insights into the spatial organisation and topographic characteristics of this important Xiongnu elite burial complex.

Our findings underscore the efficiency and utility of UAV-based imaging and remote sensing in archaeological research. Detailed mapping of the Gol Mod-II site has revealed intricate topographic variations and subtle surface features that were previously undocumented through conventional methods. Notably, the high-resolution DSM generated in this study have enabled a more nuanced understanding of the spatial distribution and arrangement of the Xiongnu tombs, particularly the elite burial mounds. This enhanced visualisation capability establishes a crucial foundation for future ground-based investigations and targeted excavations. Furthermore, the integration of multispectral imagery could contribute to the identification of soil anomalies and vegetation patterns indicative of buried archaeological features, thereby further enhancing the effectiveness of UAV-based surveys.

The integration of UAV-based remote sensing with kinematic surveying (KS) and GIS analysis represents a significant methodological advancement in Xiongnu archaeological studies. Precise georeferencing and orthorectification of aerial imagery, combined with the analytical capabilities of GIS, allow for more rigorous spatial analyses of the archaeological landscape. This approach not only improves the accuracy of site mapping and feature identification but also establishes a robust framework for investigating the spatial relationships among different archaeological elements and their surrounding environments. The detailed topographic models generated in this study provide a valuable resource for understanding how landscape features may have influenced the placement and orientation of the Xiongnu burial complexes, offering potential insights into the socio-political and cosmological beliefs of the nomadic society.

While the study is limited by the absence of high-precision georeferencing data and a lack of excavation data for circular tombs, it nevertheless presents a scalable and replicable model for landscape archaeology in steppe regions. One of the technical limitations of this study stems from the lack of GCPs and RTK-based ground control, which could have improved absolute geolocation accuracy. Due to on-site constraints, including limited accessibility, dense forest cover, and manual UAV operation without consistent altitude control, the vertical (Z-axis) error reached an average of 17.10 meters according to the photogrammetric report. While this level of inaccuracy restricts precise metric modelling—particularly in elevation-dependent interpretations—it had minimal impact on the interpretive outcomes of this study, which focused primarily on typological classification and relative spatial clustering patterns.

The methodology introduced here offers a valuable alternative to traditional excavation by enhancing the efficiency of fieldwork and enabling comparative, data-rich interpretations. Future research integrating geomatics, historical sources, and targeted excavation could further refine our understanding of the spatial structure of Xiongnu burial complexes and their significance within Eurasian steppe civilisation.

Despite the considerable potential of UAV-based methods demonstrated here, it is crucial to recognise their limitations. The interpretation of remotely sensed data requires careful validation through ground-truthing and integration with existing archaeological knowledge. Future research should prioritise combining UAV-based surveys with geophysical prospection, targeted excavations, and artefact analyses to develop a more holistic understanding of the Gol Mod-II site and the broader burial culture of the Xiongnu. Moreover, the application of advanced image analysis techniques, such as object-based image analysis (OBIA) and machine learning algorithms, holds promise for further enhancing the extraction of archaeological information from UAV-derived imagery.

In conclusion, our multidisciplinary approach to the topographic modelling of the Gol Mod-II site—integrating UAV remote sensing, kinematic surveying, and GIS analysis—highlights the transformative potential of these technologies in archaeological research. This study not only provides the most detailed spatial documentation of the Gol Mod-II site to date but also offers valuable methodological insights for applying UAV-based approaches to other archaeological contexts, particularly complex burial landscapes. Future research building upon these findings will undoubtedly contribute to a more comprehensive understanding of Xiongnu archaeology and the broader cultural heritage of the Eurasian steppes.

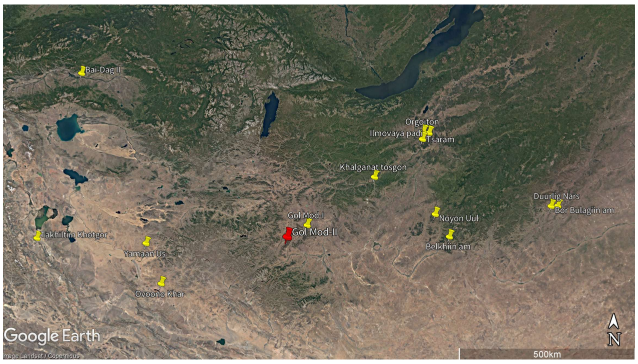

Figure 10. Satellite view of Xiongnu elite burial complexes on Google Earth

Acknowledgements

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