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Microenvironments Constrained Early Holocene Pastoralist Occupation in the Arid Eurasian Steppe

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Abstract

The success of pastoralism in the Central Eurasian Steppe poses a longstanding archaeological question: how did mobile societies sustain long-term occupation in a landscape often characterized as arid, open, and environmentally uniform? By identifying and mapping resource-rich and biodiverse steppe microenvironments at the mesoscale, this study shows a contrary scenario whereby fine-scale ecological heterogeneity structured settlement choices across the open steppe at least since the Bronze Age (ca. 3000-800BCE). We identified a pattern of spatial correlation between microenvironments and pastoralist settlements by conducting machine learning land classifications of microenvironments in Kazakhstan's arid steppe, using multispectral satellite images from Planet Labs and Landsat, coupled with archaeological survey data. We offer a user-friendly workflow within Google Earth Engine, capable of performing land classifications on areas upwards of 35,000 square kilometers, allowing us to identify discrete productive microenvironments in the arid Eurasian Steppe that total only 3% of the region. These rich biodiverse ecologies correlate positively with documented prehistoric settlements spanning over 3000 years of human occupation in our study area in Kazakhstan. The analysis of three key spectral indices illustrates that while microenvironments act as consistent thermal refugia and as productive plant communities year-round, they are most distinct from their surrounding landscapes in summer months. By combining archaeological data with quantitative land classification, this study provides a model for evaluating microenvironmental influences on prehistoric settlement behavior in the arid Eurasian steppe.

Introduction

Microenvironments in the Central Eurasian Steppe

Pastoralism represents the most enduring and widespread economic system in the Eurasian steppe. Extending from the Black Sea to Mongolia, the steppe biome has long functioned as a corridor for human mobility, animal dispersal, and technological exchange. The Central Eurasian Kazakh steppe, in particular, served as a key area for the unfolding of ceramic traditions, bronze metallurgy, mortuary practices, wheeled transportation, and horse domestication (Anthony 2010; Bendezu-Sarmiento 2021; Benecke and von den Driesch 2003; Doumani Dupuy 2017; Outram et al. 2009; Librado et al. 2021; Radivojević et al. 2013; Stöllner et al. 2011; Yevdokimov and Varfolomeev 2002; Zaibert 1992). Steppe populations played a key role in facilitating the spread of these major Eneolithic (ca. 4500-3000BCE) and Bronze Age (ca. 3000 – 800 BCE) innovations across the Eurasian continent, while also engaging in complex processes of the adoption and dispersal of southwest and East Asian domesticates. The emergence and spread of pastoralism coupled with agriculture in the Bronze Age (ca. 3000 – 1000 BCE) resulted in a period of regionally diversified socioeconomic changes throughout Central Asia (Akhinzhanov et al. 1992; Benecke 2017; Frachetti 2008; Hermes et al. 2019; Kalieva and Logvin 2011; Kohl 2007; Krader 1955; Motuzaite Matuzeviciute et al. 2021; Spengler, Frachetti, et al. 2014; Ventresca Miller et al. 2014). Compared to the better-studied mountain ecozone that served as one of the major interaction routes north and south (Frachetti 2012; Honeychurch et al. 2021; Hermes et al. 2017; Taylor

et al. 2021), our understanding of pastoralist mobility and settlement choice is constrained by a dearth of archaeological research at open, arid steppe sites. However, recent local-scale research on the Eurasian steppe brings forth several examples that demonstrate varied economic and cultural pasts coupled with greater steppeland diversity in micro regions (Honeychurch 2014; Iovita et al. 2020; Gill et al. 2025; Frachetti et al. 2017). Despite such headway, there remains an overriding emphasis on macro-scale climatic zones and broad ecological gradients (Bendrey 2011; Benecke 2017; Haruda 2014; Outram et al. 2012), often overlooking the fine-grained environmental variability that structured daily settlement and subsistence decisions (Spengler 2014).

A significant part of the Central Eurasian Steppe subregion (CES) is located within the northern latitudes of Kazakhstan, covered by open (treeless) and landlocked grasslands with narrow to no access to major water sources. Characterized by hypercontinental climate regimes, this environmental region exhibits significant annual variation in temperature ranging from hot summers to frigid and dry winters, with rainfall concentrated to late spring and (punctuated) fall precipitation cycles (Werger and van Staalduinen 2012). The CES exhibits a short growing season in summer and climate change continues to cause extreme summer droughts, desertification, and increases in winter snow cover can limit steppe pasture quality for domestic and wild fauna (Mordkovich 2014; Rachkovskaya and Bragina 2012). As our study helps to demonstrate, within the general ecological limitations of the arid grasslands and open geographic character of the CES, there exists a complex mosaic of rich environmental pockets with diverse endemic fauna and flora adapted to tolerate intermittent droughts and harsh winters. The presence of these environments likely helped to facilitate sustainable and successful human occupations from the Paleolithic to the present day.

Ecological studies document discrete productive microenvironments that occur as spring-fed depressions, foothill ecotones, marshes, and vegetated drainages sustained by shallow groundwater systems (Werger and van Staalduinen 2012; Gutman et al. 2020; Bernath-Plaisted et al. 2023; Eisfelder et al. 2014; Kappas et al. 2020; Wesche and Treiber 2012). However, very few archaeological studies focus on the distributed geography and long-term exploitation of these resource-rich micro-regions and their importance in understanding ancient human mobility and settlement choices in the Eurasian steppe. This lack of detailed, micro-environmental research within archaeology is especially notable in the marginal open steppe environment of northeastern Kazakhstan. This gap is compounded by the practical difficulty of locating steppe settlements in the first place, given extensive surface erosion, low-visibility archaeological signatures, and a relatively low density of archaeological sites.

To address these limitations, our study focuses on productive microenvironments embedded within the open steppe of northeastern Kazakhstan. Our case study centers on the Kokentau–Semeytau region, with particular emphasis on the archaeological sites of Koken and Kenasu (Fig. 1). Archaeological evidence shows repeated occupation of these locations from the late Pleistocene at least through the Bronze Age, suggesting long-term engagement with localized ecological niches (Doumani Dupuy et al. 2021, 2023; Gill et al. 2025). Recent satellite image-based investigations of the Kokentau region offer insights into site selection preferences for pastoralist Bronze Age communities – namely that the

northern slopes of the Kokentau Range acted as refugia from cold winter winds with minimal snowcover (Assylbekov et al. 2025). Accordingly, our survey and remote study exclusively focus on archaeological sites along the Northern Kokentau Range. These sites are situated within distinct vegetated microenvironments characterized by shallow groundwater, marshy depressions, and dense grass cover, despite their distribution within an otherwise arid steppe landscape. Importantly, these microenvironments are not transitional mountain–steppe ecotones but occur irregularly across the geographic core of the steppe, allowing us to isolate microenvironmental effects from broader ecozonal gradients.

We propose that such microenvironments functioned as stable ecological anchors that structured settlement placement, subsistence strategies, and mobility across millennia. Logically, long-term hunter-gatherer familiarity with these productive microniches would have provided an ecological foundation for early pastoralist economies, which emerged during the Bronze Age. Rather than assuming that habitable ecologies were abundant and evenly distributed across a homogeneous grassland landscape, this study quantifies the constrained proportion of productive microenvironments across the steppe and their disproportionate role in shaping settlement ecology throughout the region's prehistory.

Ecology of Microenvironments and Microclimates

Ecological research increasingly shows that grassland microclimates can vary sharply over short distances, which has important consequences for ecosystem function, biodiversity, and climate resilience (Bernath-Plaisted et al. 2023). Even in landscapes often described as low-relief, small differences in microtopography together with soils, vegetation structure, and hydrology can create localized microenvironments that diverge from the surrounding macroclimate by harboring distinct microclimates (Mahrt 2006; Barry and Blanken 2016; Bernath-Plaisted et al. 2023). These fine-scale conditions shape temperature and moisture availability, primary productivity, and the distribution of forage, water, and endemic flora and fauna, which are all factors that operate at spatial scales relevant to animal behavior and human land-use decisions.

Despite growth in microclimate research in forested, montane, and tundra systems, grassland remain comparatively understudied in this field, partly because of assumptions that grasslands are environmentally uniform (Bennie et al. 2008; Loarie et al. 2009). Grasslands are among the most climate-sensitive and least protected biomes, making localized refugia increasingly important under rising aridity and temperature variability (Carroll et al. 2016; Scholtz and Twidwell 2022). Although grassland ecosystems are low-lying and lacking topographic complexity when compared to montane environments, even subtle microtopographic variation can produce strong microclimate variability (Mahrt 2006). Under extreme conditions such as droughts or heat waves, microenvironmental heterogeneity can yield microrefugia that stabilize habitat use, support demographic persistence, and structure movement patterns of grassland-dependent species (Suggitt et al. 2018). Archaeologically, this approach links environmental variability to site-selection choices and long-term patterns of settlement

and resource use. These dynamics are especially pronounced in arid and semi-arid grasslands, where access to water and biomass can determine survival.

Remote Sensing and Microenvironments

In ecological research, microclimates and microenvironments are often defined at very fine spatial resolutions, sometimes on the scale of individual organisms (Zellweger et al. 2019). In contrast, we focus on the concerns of premodern pastoralists and their herd animals, placing our analytical focus on mesoscale microenvironments, such as river valleys, foothill zones, and vegetated depressions. Remote sensing and physical geography provide a well-established methodology for identifying and modeling microenvironments from high resolutions (≤ 3m) to the mesoscale (i.e. river valleys, > 500-meter landscape features). Multispectral satellite, drone, and aerial remote sensing are particularly well-suited to detecting such features through analysis of vegetation indices and surface temperature patterns (Hoffrén and García 2023), and through machine learning based land classifications. In extreme environments where vegetation communities sharply contrast with their surrounding environments spectrally, thermally, and visually, normal resolution imagery has proven quite effective in mapping microenvironments in different areas of the world (Andrew and Warrener 2017; Reinermann et al. 2020; Almalki et al. 2022). Comparable approaches, however, are narrowly applied to the Eurasian steppe, where environmental heterogeneity is subtle and spatially fine-grained (Zellweger et al. 2019; Milling et al. 2018).

Recently, the coalescence of wider access to VHR imagery, across greater temporal resolutions (e.g. Planet Labs), improved computational capacity (e.g. through cloud computing platforms such as Google Earth Engine (GEE), and streamlined pixel classification with GeoAI pipelines has led to a marked increase in fine-grained land classifications in nearly every ecozone (Wulder et al. 2018). Nevertheless, previous studies of landscape structure and ecological variability have largely operated at spatial resolutions of ~ 10–30 m, in spite of available data at finer resolution, which are demonstrably more accurate for capturing small vegetation communities (Peven et al. 2025). The 10m resolution GLC10 land classification, for example, models the vast majority of the arid steppe as “grassland”, effectively overlooking productive microenvironments identified in this study (Gong et al. 2019), while other multivariate approaches more effectively map mosaic ecozones at a coarser spatial resolution, ~5km (Kempf 2026). Additionally, remote sensing in high latitude continental or cold semiarid climate regimes poses the additional challenge of extreme seasonal variation, and obfuscation from snow-cover for nearly 5 months of the year. Few studies have monitored how microenvironments may persist or change seasonally in the steppe, though this is of great importance to herders and their mobility regimes and site selection preferences. This study addresses the above challenges by combining high resolution satellite imagery and in-situ archaeological data.

Results

Land Classification: Correlating Pastoralist Settlements with Microenvironments

In order to map the extent of steppe microenvironments across the Arid Eurasian Steppe (AES) (Fig. 2), and to determine their correlation with ground-truthed archaeological settlements (Supplementary Table 1), we performed a three-class machine learning classification using 3m/px PlanetScope May and August imagery. In our focal model extent, our minimum distance pixel classifier (generated using the workflow in Fig. 6) predicts 97 square kilometers of microenvironments in a 1,700 square kilometer area (5.71% of the total area) for May, and 27 square kilometers (1.59%) for August. Our accuracy assessment (Table 3) yielded a high overall accuracy of .935 and a Kappa coefficient of .927, indicating “almost perfect agreement” (Landis and Koch 1977). Additionally, a simple visual test of known microenvironments indicates that our classifier very accurately captures the shape and contour of each microenvironment with very little omission and fairly low commission error.

Table 1.

Table 1
Standard confusion matrix for classified August PlanetScope image, dividing our validation data into microenvironment and non-microenvironment classes.

TP	**10**
FP	1
FN	0
TN	19
Cohen's Kappa	0.927
Accuracy	0.935

Most importantly, when buffers are applied around 28 pastoralist settlements identified through survey, they prove to be an accurate predictor of microenvironments, such that when a 300-meter buffer is applied, only a single site (a medieval caravansarai with a double wall enclosure) falls outside the range of classified microenvironments (Fig. 3). Given that all but one of these settlements fall neatly around the borders of predicted microenvironments, it is likely that these green patches were not radically larger or smaller than their present extent at least as far back as the Bronze Age. There is no major statistical pattern in terms of chronological period and distance from a modeled microenvironment (Supplementary Table 2).

Land Classification in the Greater Arid Steppe

We applied our three-class pixel classifier to a 35,000 square kilometer (a 9.3 billion pixel 8-band raster) August image extending far beyond our study area in the Kokentau and Semeytau ranges, encompassing most of the eastern and central AES. Our results show that 3.42% of the arid steppe is occupied by biodiverse microenvironments such as those in our focal study area, indicating a fairly constrained area of the arid steppe was favorable for premodern pastoralist occupation (Fig. 4). This classification provides a marked improvement from global 10-meter resolution landcover schemes such as GLC10, which classifies ground truthed microenvironments as “grassland”, which is modelled as occupying 92% of the equivalent study area (Gong et al. 2019).

Spectral Signatures and Seasonality

Using classified microenvironments converted to polygons, and PlanetScope imagery for August and May, we investigated three primary spectral indices – normalized difference vegetation index (NDVI), chlorophyll index – red edge (CIRE), and Landsat thermal data - to quantify the seasonal and ecological characteristics of arid steppe microenvironments (See Supplementary Table 2). The average August NDVI of classified microenvironments was .70, compared to .32 for terrestrial non-microenvironment areas. Similarly, microenvironments have a 1.93 average August CIRE value compared to .58 for the surrounding terrestrial landscape. Given the comparatively high CIRE values of microenvironments, we argue that they exhibit uncharacteristically high chlorophyll absorption and high internal leaf scattering, implying a much higher access to water/moisture for the plant community (Chang-Hua et al. 2010). Notably, CIRE also provides the sharpest visual contrast for delineating microenvironments against the surrounding steppe (Fig. 5). Based on Landsat thermal imaging, classified microenvironments exhibited a lower temperature than their surroundings across both measured seasons – they are 7.44 K (degrees kelvin) cooler in May, and 6.59 K cooler in August. In January, microenvironments appear to exhibit higher overall temperatures, indicating they could serve as year-round microrefugia for humans and herd animals, though it is harder to delineate their borders under snow cover. Our results confirm previous research by Asylbekov et al. (2025), which demonstrates the importance of winter survivability in Bronze Age pastoralist site selection, as settlements from this period are exclusively found in areas sheltered from harsh SE – NE winds.

Crucially, across all three measured indices, microenvironments are more distinctive in August (Fig. 4), when their NDVI and CIRE values are comparatively higher than the surrounding landscape, potentially indicating that it is especially effective to settle near microenvironments in the hot and dry season of late summer.

Discussion

Although pastoralism has long thrived in the open steppe, pastoralist settlement choices and mobility across this challenging environment remain poorly understood. Archaeological research in Central

Eurasia has traditionally differentiated the region in terms of macroscale environmental contrasts, such as steppe versus mountain or forest-steppe ecotones (the former two are frequently interpreted as hotspots of biodiversity and archaeological investment)(Frachetti 2012; Outram et al. 2012; Spengler et al. 2013). By contrast, the arid steppe interior is frequently treated as a relatively homogeneous and simple ecosystem. This perspective has limited attention to microenvironmental variability within the open steppe, especially in areas distant from major mountain or river systems. Our results suggest that this expansive region was not uniformly available for sustained human occupation, but was instead structured by highly localized ecological contexts that constrained where people and animals could reliably live. By combining high-resolution multispectral imagery and geolocated survey points, we provide quantitative confirmation that AES microenvironments are meaningful predictors of prehistoric and historic settlement placement within the open steppe. The resolution of our land classification allows for a more fine-grained identification of microenvironments in an ecoregion otherwise classified entirely as “grassland” by other studies (e.g. Gong et al. 2019). Our regional analysis shows that only 1,050 km² within a 35,000 km² landscape (~ 3%) provides the ecological conditions necessary for sustained human occupation and animal management. These findings effectively reframe the steppe as as an archipelago of discrete, resource-rich microenvironments—ecological niches that structured movement, settlement, and interaction.

In the Kokentau–Semeytau region, our case-study demonstrates that steppe microenvironments have distinctive spectral signatures, with high vegetative indices (particularly in the red-edge and NIR ranges), and comparatively favorable year-round temperatures that directly overlap with long histories of hunter-gatherer and pastoralist occupations. While grass cover within these micro-regions remains relatively stable, the surrounding arid steppe fluctuates significantly in plant productivity. The CIRE index isolates microenvironments with notable clarity, both visually and quantitatively, meaning that satellite platforms incorporating red-edge bands (~ 680–750 nm) can support more accurate identifications with fewer spurious detections than approaches relying on NDVI alone. This is methodologically significant for steppe archaeology because it provides a targeted way to map the ecological features most relevant to herd ecology and site selection. The seasonal comparisons demonstrate that in May, vegetation signals appear more similar to the surrounding steppe, while in late summer (August) productive patches become much more distinct as the broader landscape dries and biomass declines. This seasonal divergence is archaeologically meaningful as late summer and early fall are periods when reliable grazing and water become especially valuable as herders prepare for winter, manage herd condition, and anticipate increased climatic stress (Masanov 1995; Ventresca Miller et al. 2020). Thermal data further support this interpretation, as microenvironments are comparatively cooler than their surrounding landscapes in August, providing shelter during hot arid summers. Furthermore, the model also reveals that archaeological settlements tend to occur close to the margins of microenvironments rather than directly within them. The most waterlogged or marshy core areas are likely unsuitable for construction, while the edges provide immediate access to water and high biomass without the costs of unstable ground. Settlements consistently align with these boundaries, suggesting that the overall shape and position of microenvironments may persist over long timescales, even if their precise extent fluctuates

seasonally. Testing this persistence explicitly will require integrating topography, hydrological context, and stratified paleoenvironmental proxies, but the observed edge-settlement pattern provides a strong hypothesis for future work.

Methodologically, we contribute a reproducible workflow for producing land cover maps highlighting steppe microenvironments using cloud computing in GEE. In addition, our land cover map, with its high overall accuracy, provides an efficient means of narrowing future survey areas. In future work, leveraging the daily temporal resolution of PlanetScope imagery will allow us to track intra-seasonal variation in microenvironment dynamics. Integrating faunal datasets alongside ethnographic case studies could further develop this framework into a powerful tool for modeling seasonal shifts in pastoralist decision-making, mobility, land-use strategies, and social connectivity across the Eurasian steppe. If microenvironments functioned as recurring ecological anchors, then pastoralist networks of movement may have been structured by predictable chains of productive patches, helping explain how long-term occupation was sustained in landscapes often characterized as marginal. We suggest that site selection and mobility since the Bronze Age likely depended on detailed ecological knowledge of these patchy refugia, which played a critical role in supporting human adaptation in the arid Eurasian steppe.

Materials and Methods

Kokentau-Semeytau Survey

In 2018, researchers from Nazarbayev University conducted a stratified, non-random archaeological survey of the Kokentau and Semeytau foothills (Fig. 2). Based on surface artifacts and architectural remains, a total of 68 sites were documented in the Kokentau and Semeytau regions, including 28 settlements (Supplementary Table 1). The remaining sites comprise of corrals, burials, rock art localities, standing stones, and artifact scatters, attributed to the Stone Age, Bronze Age, Iron Age, Turkic, Medieval, and Ethnographic periods. Survey design combined consultation of Soviet-era topographic maps with systematic pedestrian and vehicle-based ground coverage. Field investigations targeted riverine valleys, alluvial fans, and areas surrounding contemporary homesteads, alongside systematic coverage of multiple elevation zones, particularly in Kokentau, from the highest peaks (c. 800 m asl) to the foothill bases and adjacent plains. This approach aimed to capture potential seasonal or occupational variability in site distribution. Arid zones beyond recognized microenvironments were also surveyed to assess the representativeness of site patterning across the broader landscape. The Kokentau mountain range was surveyed almost in its entirety, with most effort concentrated on the northern slopes; coverage of the southern slopes was more limited due to extensive swampland and dense reed growth. In contrast, survey coverage in the Semeytau range was partial, focusing primarily on its central, eastern, and southeastern sectors. When surface materials or architectural features were identified, transect walking was employed to locate diagnostic artifacts that could inform site chronology or function. In order to generate ground-truthed microenvironment locations for our land classifications, we used geolocated points within heavily vegetated areas, which were also documented using UAV and surface photography.

Imagery

To calculate vegetation indices and conduct machine learning pixel classifications, we ordered Planetscope Superdove (PSB.SD - access provided by an education and research package at Planet Labs) imagery from mid-May and late August for 2024 and 2025. We clipped these orders to a 1,700 square kilometer area encompassing the Kokentau and Semeytau ranges (Fig. 1), and the expanses of foothills and steppe between them. We also ordered a discontinuous (to avoid cloud obfuscation) 35,000 square kilometer August image covering a large percentage of Kazakhstan's arid steppe to roughly estimate the areal extent of microenvironments using our GEE classifier. All Superdove pixel values are expressed in surface reflectance, across 8 spectral bands that also correspond to Sentinel-2 values, from Coastal Blue (443nm) to NIR (865nm). These surface reflectance values were harmonized/normalized to Sentinel-2 values for radiometric consistency. The ground sampling distance for all Superdove imagery used in this project is 3m/pixel. Once ordered, clipped, and harmonized, all imagery was uploaded as assets to GEE and processed therein using a JavaScript API.

Using GEE, we also processed an equivalent GLC10 global land class of this study area to compare our classified landscape to a lower-resolution alternative.

For thermal imaging, we utilized USGS Landsat 8 and 9 thermal band10 values as a measure of surface temperature. These assets were added as image collections within GEE for mid-May and late-August of 2022. Level-2 surface reflectance bands (SR_B*) were converted to reflectance using the Collection 2 linear scale factors (reflectance = DN × 0.0000275 − 0.2). The surface temperature raster was converted to Kelvin using published scale factors.

Calculating Indices

Using the Planetscope imagery, we calculated a series of vegetation indices using published Sentinel-2 formulae from ArcGIS documentation. Ultimately, the normalized difference vegetation index (NDVI) and the Chlorophyll Index - Red-Edge (CIRE) provided the sharpest visual distinction between the edges of densely vegetated microenvironments and surrounding arid steppeland. (For full GEE script of indices, see Supplementary Text 1). To calculate NDVI in GEE, we calculated the normalized difference between B6 and B8: var ndvi = PLANET.normalizedDifference([B8, B6]).rename('NDVI'); To calculate CIRE in GEE, we followed published methods for Sentinel-2 (Gitelson et al. 2003) and CHL-RED-EDGE (Chlorophyll Red-Edge) in Sentinelhub/ESRI documentation, using B7 and B8.

Performing Minimum Distance Pixel Classification

To determine the count, placement, and extent of microenvironments in our study area, we produced a 3-class landcover map using a minimum distance pixel classifier (for GEE code see Supplementary Text 1). We conducted one classification on a PlanetScope May 29th 8-band composite, and a second classification on an August 13th composite (Fig. 6). In order to extrapolate beyond our study area, and roughly estimate the extent of microenvironments in the arid steppe of eastern Kazakhstan, we

conducted our minimum distance pixel classification on a ~ 35,000 square kilometer PlanetScope image from August 14th, 2024.

Reference Data

Reference data for the **microenvironment** class was generated by drawing 50 4x4 pixel boxes within ground-truthed microenvironments from the Kokentau-Semeytau survey, intentionally avoiding areas within a 300m buffer of archaeological sites, to avoid contaminating training and validation datasets. For the **terrestrial non-microenvironment** class, an independent expert scanned a gridded google composite satellite image of our study area, annotating 100 terrestrial objects that categorically could not be characterized as microenvironments (i.e. bare land, rocky outcrops, expansive salt flats). A 4x4 pixel square was drawn around all of these user-generated points. Finally, this annotation process was repeated for the **water** class, for a total of 20 4x4 pixel boxes. All of these reference data were divided into an 80/20 training/validation split and imported into GEE and utilized with a minimum distance pixel classifier (pixel boxes were only used for training, and not validation).

Conducting Accuracy Assessments

We conducted an accuracy assessment, using validation points from each class, calculating Cohen's Kappa coefficient as a measure of model performance. We chose to measure our model accuracy on our August image classification, because that is when microenvironments are most constrained, and occupy the smallest percentage of the study area. We conducted a second accuracy assessment to determine the correlation between premodern pastoralist settlements and identified microenvironments. This correlation can either be expressed in terms of "hit-rate" (overall accuracy) or archaeological settlements themselves can be used as validation points (i.e. testing whether the presence of an archaeological site effectively predicts the co-presence of a microenvironment). In order to produce the latter form of accuracy assessment, we must consider that archaeological sites are rarely (if ever) located on microenvironments themselves, but rather on their periphery. Therefore, we drew a 100m buffer around each site, and considered any overlap between these buffers and a classified microenvironment as being positive hits. We repeated this process with 200m and 300m buffers.

Declarations

Competing Interests Statement

The authors declare no competing interests.

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Author Contribution

Z.T., J.B., and M.D.F. designed the study. Z.T. and J.B. conducted the analyses and wrote the original draft of the manuscript. M.D.F. supervised the study. P.D.D. and A.Z. directed the Kokentau and Semeytau archaeological survey. All authors contributed to manuscript revisions and approved the final version.

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Data Availability

All data generated or analyzed during this study are included in this published article and its Supplementary Information file. Supplementary materials include 1) the full list of surveyed archaeological settlements and their spatial relationship to modeled microenvironments (Supplementary Table 1), 2) complete spectral statistics for microenvironment and non-microenvironment classes (Supplementary Table 2), and 3) the full Google Earth Engine (GEE) scripts used for vegetation index calculation, minimum distance classification, and land surface temperature modeling (Supplementary Text 1). PlanetScope imagery was accessed under an educational and research license from Planet Labs and is therefore not publicly redistributed; Landsat Collection 2 Level-2 products are publicly available through the USGS Earth Explorer and Google Earth Engine platforms. All classification workflows are fully reproducible using the provided scripts.

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Figures

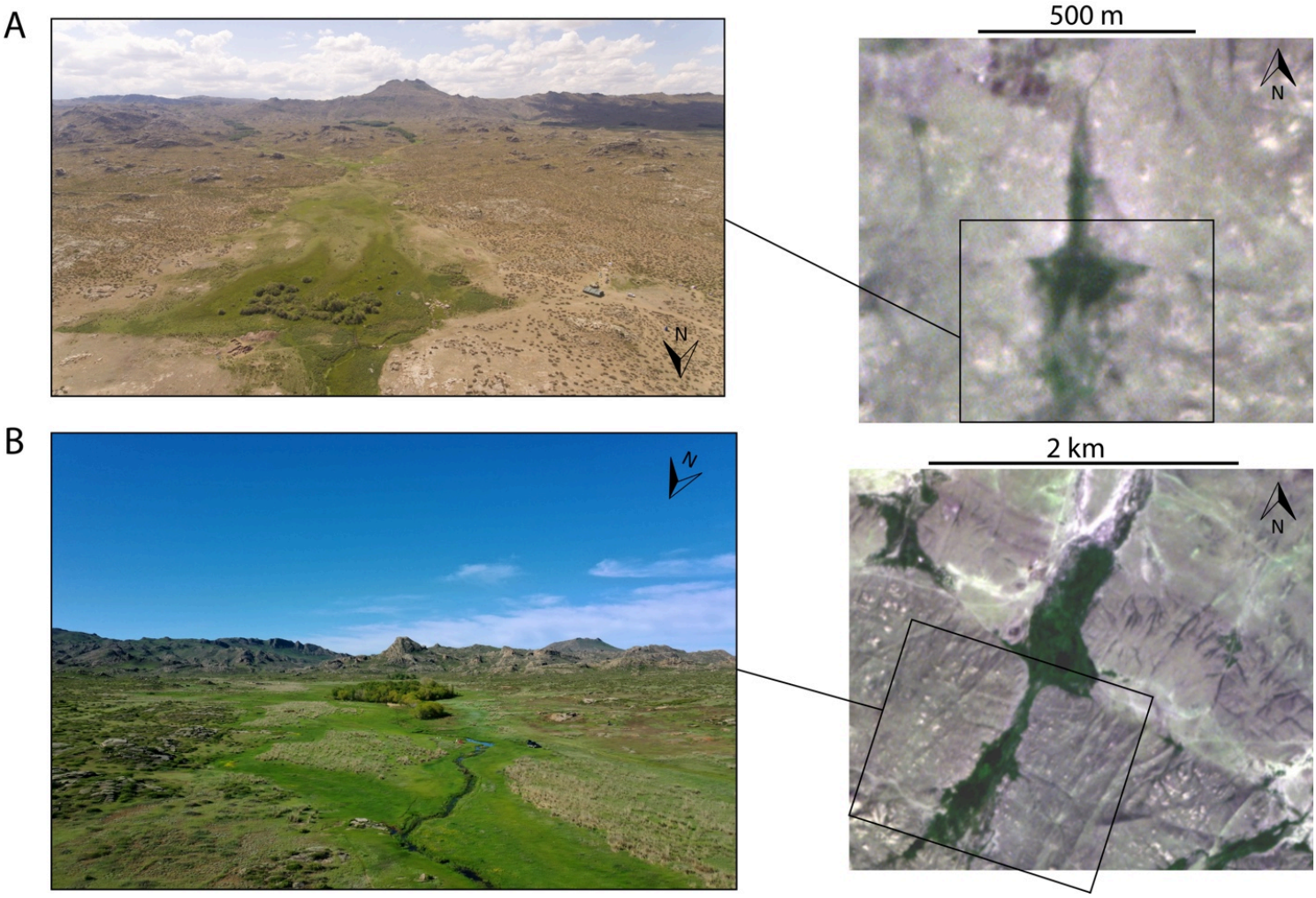


Figure 1

Drone photographs and true-color PlanetScope images of Koken (A) and Kenasu (B), multi-period settlements located on the edges of microenvironments.

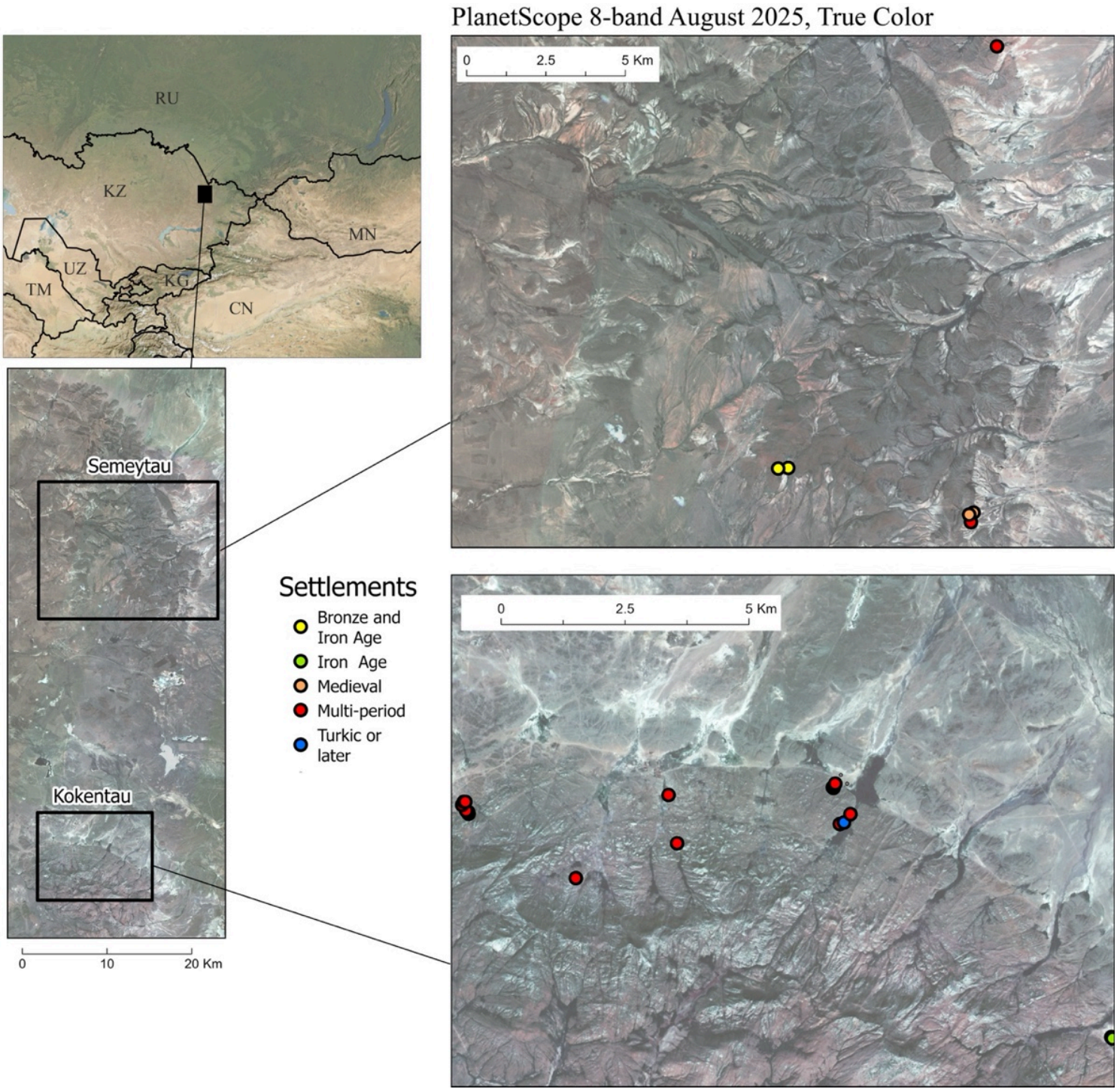
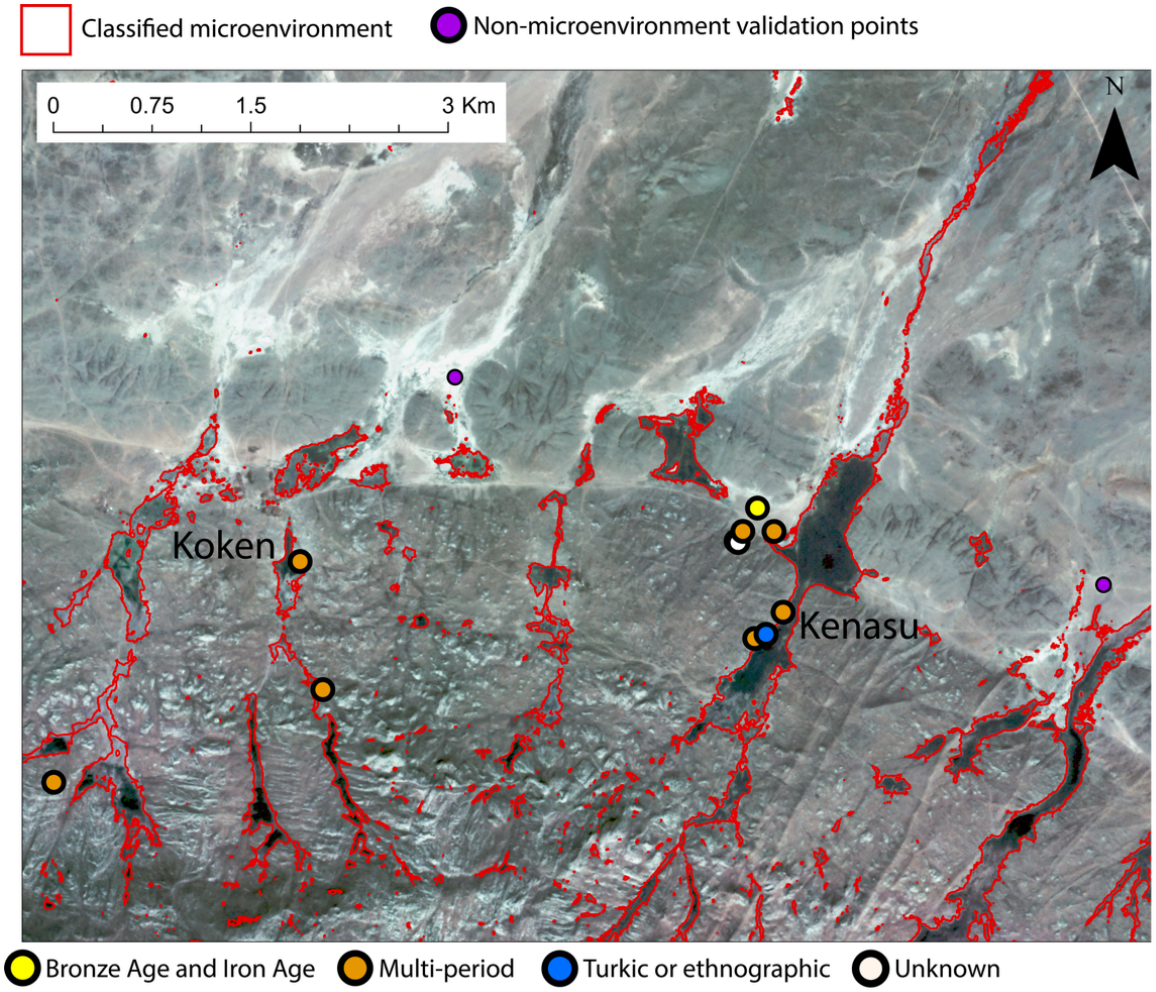


Figure 2

Map of the distribution of archaeological settlements in the surveyed areas of the Kokentau and Semeytau ranges. Basemap from PlanetScope August image, 2024.



300 meter buffer

TP	26
FP	1
FN	1
TN	19
Cohen's Kappa	0.913
Accuracy	0.938

200 meter buffer

TP	22
FP	1
FN	5
TN	19
Cohen's Kappa	0.745
Accuracy	0.854

100 meter buffer

TP	14
FP	1
FN	13
TN	19
Cohen's Kappa	0.435
Accuracy	0.688

Figure 3

Sub-section of classified landcover map highlighting the model's efficacy in precisely identifying steppe microenvironments. Three confusion matrices to the right show the correlation between pastoralist settlements and green patches when placed within a 300, 200, and 100 meter buffer. Basemap from Planetscope August image, 2024.

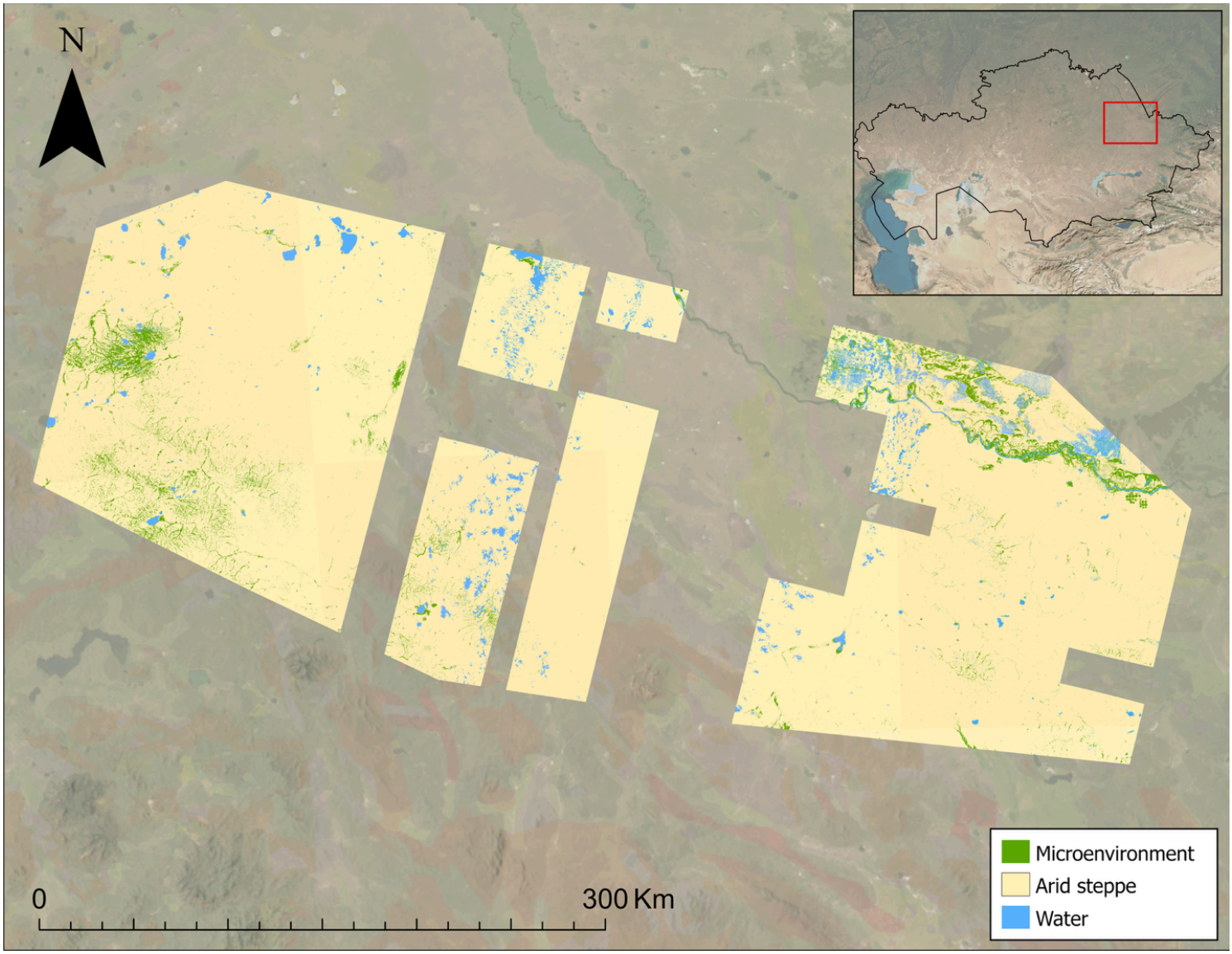


Figure 4

Microenvironment classification of the Greater Arid Eurasian steppe. Map illustrating the distribution of ecologically productive microenvironments across the Greater Arid Steppe (in green); beige denotes the surrounding arid steppe; and blue indicates water.

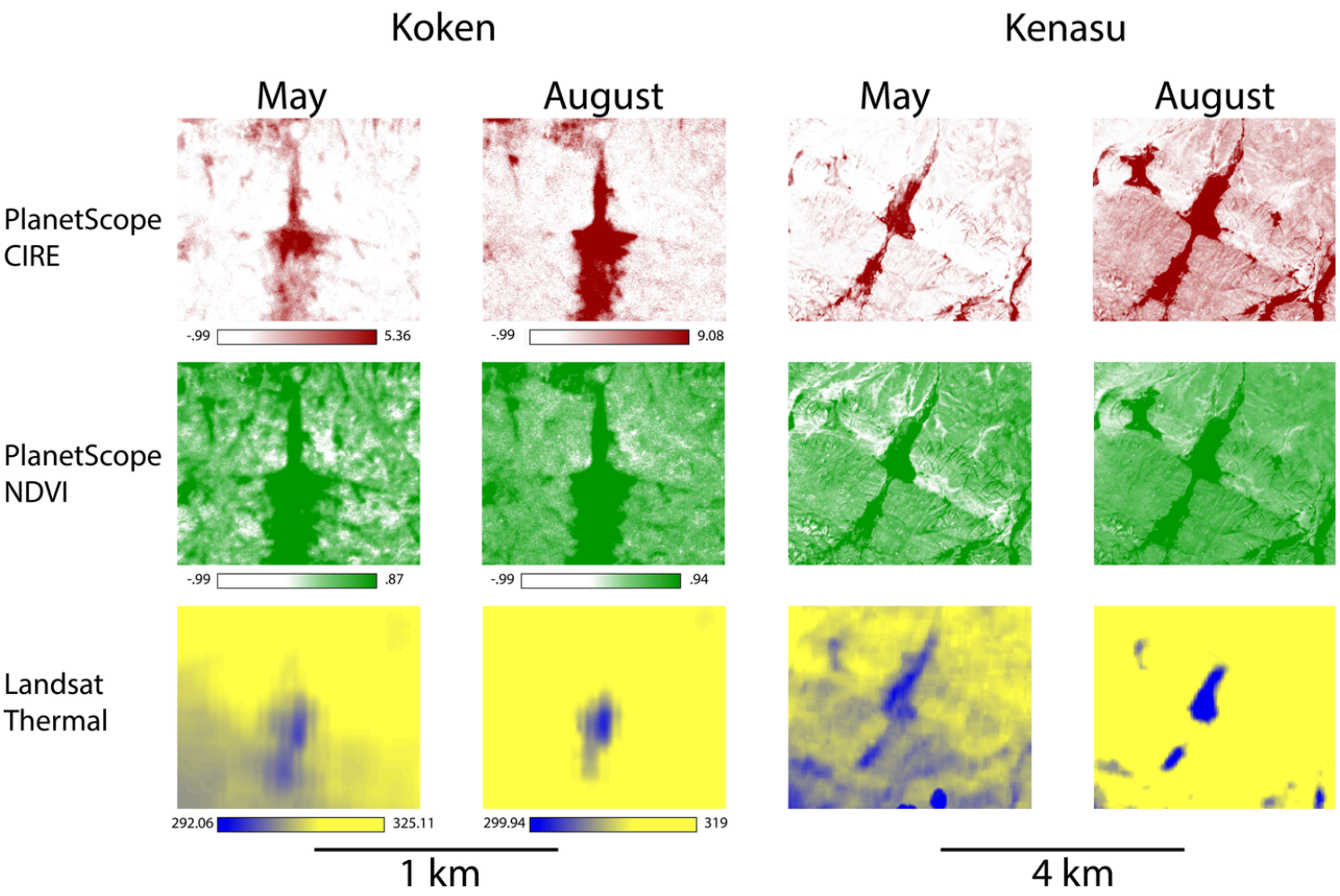


Figure 5

Three microenvironmental indices (CIRE, NDVI, and thermal, expressed in digital numbers, and degrees kelvin respectively) in May and August for the local green patches near Koken and Kenasu. August and May color value stretches are the same for both sites within each season.

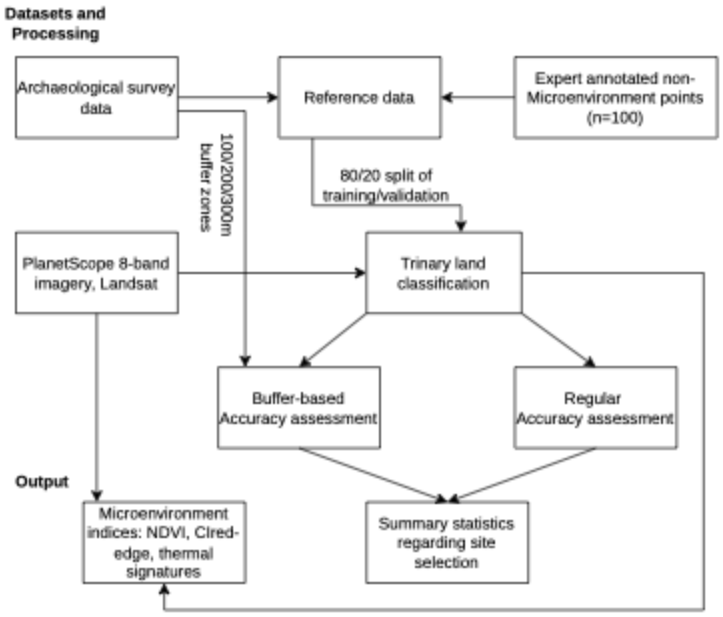


Figure 6

Remote sensing classification workflow.

Supplementary Files

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- SupplementaryTashmanbetovaEtal.pdf