Fluctuations of glacier extent in Lake Nam Co and Nyenchen Tanglha Mountains within a decade as detected by machine learning methods of image analysis for monitoring Lhasa terrane, Tibetan Plateau

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Abstract
Machine learning (ML) methods of satellite image analysis were applied in this study for geological-environmental analysis of glacier extent in Tibetan Plateau, China. The purpose of this work is to map the changes in glacier extent as a hydrological resource and its effects on land cover types using remote sensing data. A quantitative cartographic method of image analysis has been developed using ML algorithms and GRASS GIS scripts. Fluctuations of glacier extent are a key trigger for landscape dynamics in Tibetan Plateau. However, the links between spatio-temporal changes in snow and glacier, and associated land cover changes remain elusive. Six Landsat 8-9 multispectral satellite images covering Lhasa were evaluated. The images show fluctuation in glacier coverage from 2013 to 2023 with a 2-year gap between the observations, characterized by strong heterogeneities caused by climate changes. Glacier dynamics was evaluated for northern range of Nyenchen Tanglha Mountains and Lhasa Terrane, Tibetan Plateau, China. The results present an exploratory analysis of six images (on 2013, 2015, 2017, 2019, 2021 and 2023) for glaciological modelling using ML.

Key words: machine learning, environment, Earth, China, cartography, mapping, GIS

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Introduction

Cartographic visualization of land cover classification is often used in a variety of environmental applications. It is important for *e.g.* mapping land cover changes and evaluation of landscape dynamics (Zhai et al. 2023). Recently, mapping of agricultural land is extremely useful for landscape monitoring and sustainable land

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development (Cheng et al. 2023, Lemenkova 2025a), and/or analysis of urban sprawl (Zhang et al. 2022). Other examples include modelling habitats in reserved landscapes, applied geologic analysis, analysis of vegetation in context with topographic variability, biodiversity conservation and segmentation (Lemenkova 2024a). Land cover mapping is also frequently used to visualise the expansion or retreat of lakes as a response to seasonal fluctuations, assess ecosystem services and assist in the land development, planning and policy. In all these and similar cases, the general aim is to accurately represent the landscapes and features on the Earth's surface visible from space. The challenge of this task is how to effectively evaluate the satellite data and extract meaningful informations that can be used in landscape analysis for the thematic representation of the Earth's ecosystems.

Remote sensing data has proved to be a valuable tool for cartographic visualization and environmental monitoring of landscapes as a spatiotemporal dynamics (Wang et al. 2016) and detecting land cover changes in particular (Kulkarni and Bahuguna 2002, Lemenkova 2024b). They allow for rapid and effective data extraction for monitoring and mapping changes in land cover types across diverse areas worldwide. The key approach to processing satellite images is a classification of land cover types based on analysis of spectral reflectance of pixels which can be performed using unsupervised (automatic) and supervised methods (Li et al. 2023a).

The main idea behind these methods lies in grouping pixels with similar properties of spectral reflectance on the satellite images.

The machine algorithms recognize similarities in spectral signatures of these pixels across all the bands and assigns them into classes during classification process (Li et al. 2023b, Lemenkova 2025b). Classes may be categorized into the predefined land cover types identified in the study area. Once the classification is achieved and the accuracy assessment is completed, the maps obtained on the basis of the classified images are used for comparative analysis to evaluate the changes that take place for each land cover type between certain time periods (Liu et al. 2021, Lemenkova 2023).

One of the most widely used methods is the supervised and non-supervised classification of satellite images. The land cover change analysis is then based on the comparative analysis of the classified several multi-temporal images. This method allows to analyse changes, to visualise and estimate the boundary expansion or contraction of selected landscape parcels which indicate landscape dynamics over time and space or get insights into the vegetation patterns. The application of novel machine learning (ML) approaches has been proposed recently in environmental studies with the aim to increase the accuracy and automation of remote sensing data processing (Xiao et al. 2024, Lemenkova 2024e, 2024c; Chen et al. 2023, Luo et al. 2022). These methods are based on the use of scripting algorithms that enable to process, classify and analyse data using advanced syntax of proramming languages (Lemenkova 2021a, 2022a).

The use of ML in cartography enables to extensively use computer-based tools to assess the raster data and evaluate landcape changes accurately and automatically. The ML methods use a variety of computer vision algorithms for image processing, for instance, extra trees, random forest, logistic regression, support vector machine and many more. In this study, we focus on the frequently used method of Random Forest (RF) which provides an overall classification of satellite images for any change detection on satellite images as the product of ML techniques (Chen et al. 2022, Wang et al. 2022, Ma et al. 2022, 2024; Hu et al. 2024).

Material and Methods

Study background

This study investigates a glacier retreat in the region of the Tibetan Plateau, China, with the special focus on the Lake Nam Co area and Nyenchen Tanglha Mountains (Fig. 1).

Himalayan glaciers are important global water reservoirs which are essential factors for richness of biodiversity and ecosystems (Körner et al. 2017, Liu et al. 2022). The extended region of Hindu Kush Himalaya which includes the Pamirs, Tien Shan and Alatau Mountains plays a crucial role in the hydrology of Central Asia. At the same time, they are highly sensitive to climate change and demonstrated shrinkage over the past decades.

However, the site-related rates and character of glacier retreat are still not well known with regard to regional differences. Although the most essential reason for glacier melt is caused by global warming, however, the responses to the increase in temperatures differ by regional glaciers (Yang et al. 2013, Wu et al. 2015, Zhang et al. 2023). For example, while Himalayan glaciers are retreating in general, those located in the Karakorum, in contrast, advancing (Gardelle et al. 2012, Wang et al. 2014, Barandun et al. 2021). The glaciers in Nyenchen Tanglha Mountains are fluctuating since recent decades (Li and Lin 2017, Li et al. 2021, Lu et al. 2022). Moreover, strong effects of local topography on glacial and catchment morphology are reported by Loibl et al. (2014).

Regional scale studies on comparative analysis of land cover changes caused by glacier retreat and snowmelt are still scarce for Nyenchen Tanglha Mountains, despite the fact that the necessary environmental and geographical conditions exist for the catastrophic potential of glacier retreat across the Lake Nam Co area. There are also many lacustrine basins in the region of Lhasa terrain region, that do not have received attention to monitor the size or rate of glacier retreat with regard to land cover change analysis. At the same time, investigating changes in river and lake hydrology over Tibetan Plateau is in perspective using satellite remote sensing data by ML methods to analyse basin-wide land cover changes. Using remote sensing imagery processed. This paper examines the changes in land cover types in Lake Nam Co and Nyenchen Tanglha Mountains, Tibetan Plateau, China, Fig. 1. The whole study period covers a decade (2013-2023) with 6 individual images and a gap between each pair of 2 years: 2013, 2015, 2017, 2019, 2021 and 2023.

Recent climate change in short-term dynamics (2013-2023) and the effects on permafrost, glacier extent, and ecosystems on the Lake Nam Co and Nyenchen Tanglha Mountains, Tibetan Plateau are investigated. The study is performed by processing remote sensing data such as satellite images using ML methods through GRASS GIS and the use of Random Forest classifier approach to image analysis. Moreover, the results with topographic, geologic and tectonic data are related to source compilation (literature review analysis) using numerous resources documenting landscape dynamics in southern part of the Tibetan Plateau.

The emphasis of this research is given to the evaluation of 10-year trend in the dynamics of land cover types and glacier extent over the region of Nyenchen Tanglha Mountains and Lake Nam Co. The objective is to map how highland ecosystems in Lhasa terrain surroundings have changed under the effects of the fluctuations of warmer and wetter periods in the past decade.

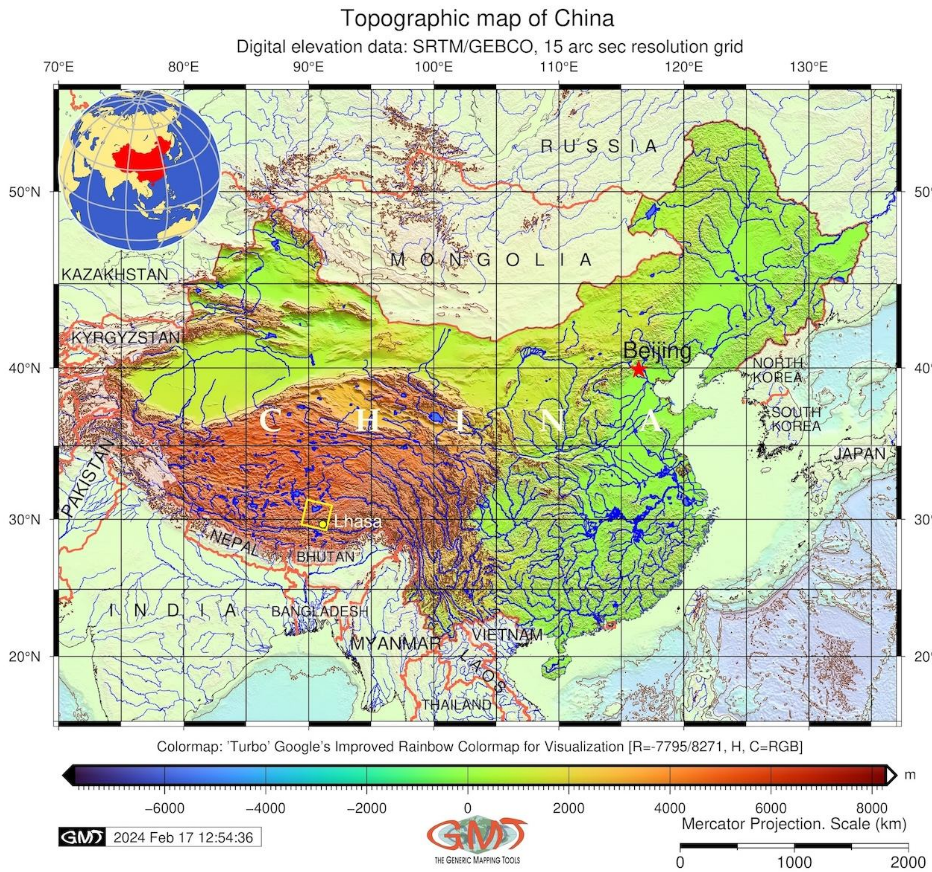

Fig. 1. Topographic map of China with indication of the study area (yellow rotated square indicating location of the Landsat satellite images): Lake Nam Co and Nyenchen Tanglha Mountains, Tibetan Plateau. *Software*: GMT. *Map source*: the author.

Study area (geological overview)

Lake Nam Co is the highest (altitude of 4,718 m a.s.l.) and the largest (area of 1,900 km^2) salt high-altitude lake (Dagang et al. 2002, 2004) among the thousands of lakes located on the Tibetan Plateau, China, which is why it is sometimes referred to as Qinghai-Tibet Plateau (Fig. 2).

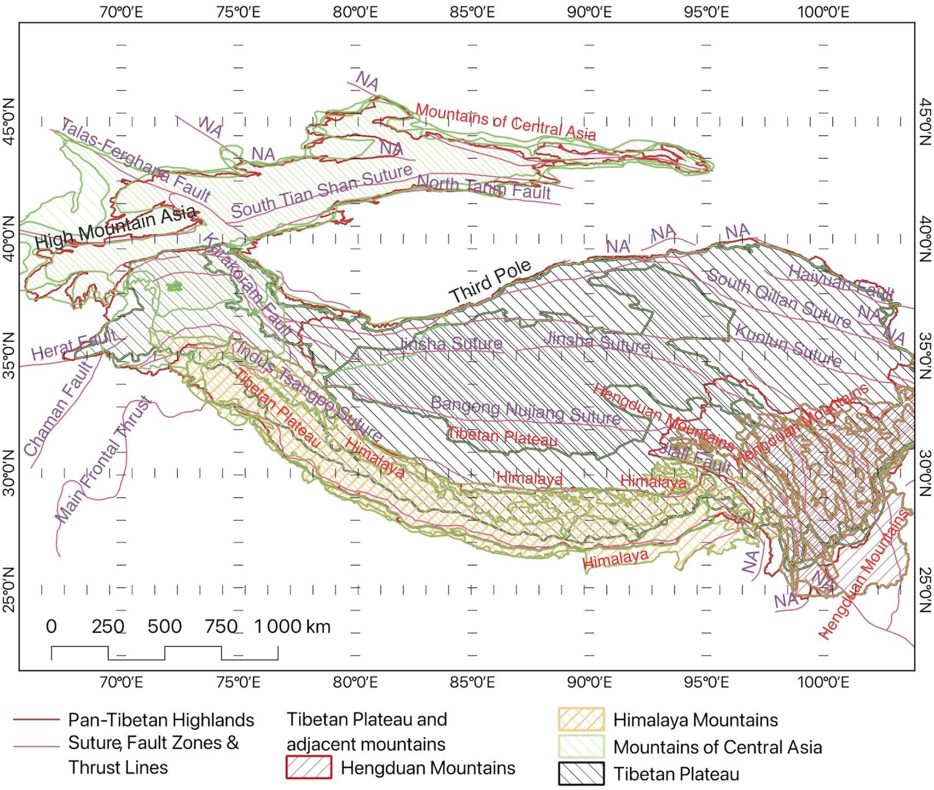

Fig. 2. Tectonic map of Western China showing main structures within the Himalaya Mountains and Tibetan Plateau (Qinghai-Tibet Plateau). *Software*: QGIS. *Map source*: author.

Precise description on the extent and names of the geographic entities reports that the Tibetan Plateau occupies the area of 1.82×106 km^2 with mean elevation of 4465 m, forming a part of the Pan-Tibetan Highlands. The formation of the Nyenchen Tanglha Mountains, a southern entity of the Tibetan Plateau is deeply connected to the geologic history of the Himalayan-Tibetan orogen which experienced the Indo-Asian collision at ca. 70 Ma (Yin and Harrison 2000). Formed as a result of complex tectonic movements in the Himalaya during Tertiary period, it presents now a slightly saline basin located at the elevation of 4,718 m a.s.l. with an average depth of 100 m (Wang et al. 2009). The Tibetan Plateau is the highest and greatest plateau on the Earth to elevation surface above 4000 m a.s.l. It is located in the Tibet Autonomous Region and the Qinghai province, China. Its eastern boundary correlates with the extent of the Hengduan Mountains. The NE corner is delimited by the Qilian Mountains, the southern boundary is situated on the south foot of the Himalayas, the northern one – on the northern foot of western Kunlun Mountains and Altyn Tagh fault and Qilian Mountains, and the western boundary merges with Pamir (*see* Fig. 3).

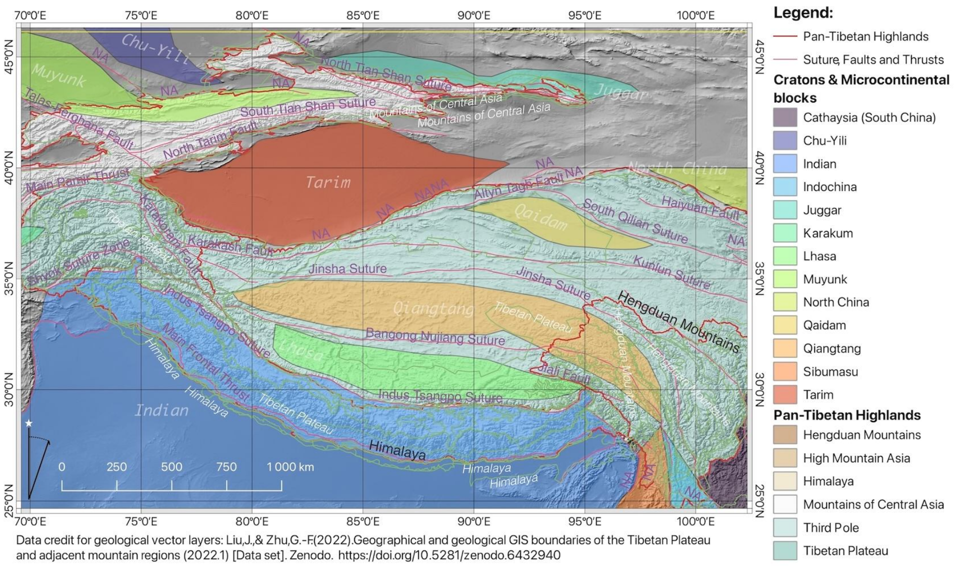

Fig. 3. Geologic map of Western China showing general settings of the Himalaya and Tibetan Plateau. *Software*: QGIS. *Map source*: author.

Complex interactions between the tectonic development and geologic structure, glacial and hydrological changes as a response to climate change and atmospheric processes, and finally, are reflected in the ecosystems over the Tibetan Plateau (Ehlers et al. 2022). For example, the interaction between geomorphology, sediment distribution and soil types in highland regions of Tibetan Plateau are reflected in soil development which has distinct distribution patterns as a function of sediment types and geomorphic settings (Yang et al. 2020). Soil types vary in response to the local climatic settings, geomorphic units and their structural components such as floodplains, hillslopes or alluvial fans, *etc*. In turn, various soil types necessarily determine the distribution of vegetation types. Changes in one or more of these domains trigger related processes throughout the ecosystem of the Tibetan Plateau in regional scales. Nevertheless, the links between these systems are often poorly understood.

Tectonic history briefly outlined above is schematically represented in the map in Fig. 2 showing current distribution of active faults and folds in the Himalayan-Tibetan orogen. During the late Quaternary period, Lake Nam Co had a vast area and was connected to other small basins surrounding its surface. Old lake terraces elevated up to 28 m above the current lake level evidence that Lake Nam Co gradually decreased in size since the Holocene due to the starting drying climate. The 'Third Pole' indicated in the tectonic scheme of Fig. 2 refers to the Himalayan-Tibetan glaciers which received such name due to the amount of snow and ice volumes in the Himalayas that are comparable with those reserves in Polar regions on a global scale (Bolch et al. 2012).

Complex tectonic structure of the region is represented schematically in Fig. 3. The mountain-building processes giving the birth to the Himalayan and the Tibetan Plateau were caused by the collision of Asia and India which began in the Cenozoic with active volcanism, outward expansion and thrusting in central Tibetan Plateau (Taylor and Yin 2009, Xia et al. 2011). Further tectonic development, the Himalayan-Tibetan orogen resulted in additional tectonic strains during Paleozoic and Mesozoic which is spatially correlated with the distributed Triassic flysch complex in the Qiangtang terrains (Ren et al. 2013, Li et al. 2017). The construction of the Tibetan Plateau included regional formations as a result of crustal shortening, which now forms its modern structure. Northern blocks of the Tethyan Himalaya developed during the Eocene with the Kunlun Mts. formed in the west and the Qilian Mts. in its eastern border (Fig. 4).

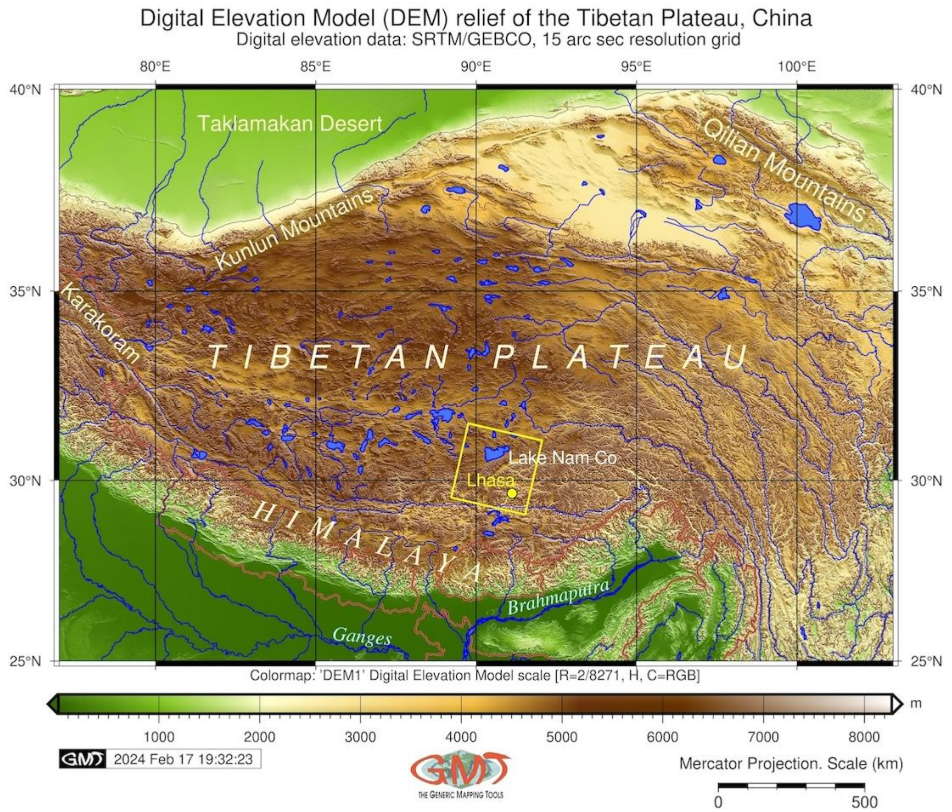

Fig. 4. DEM relief of the Himalaya and Tibetan Plateau, China. The study area is shown as yellow rotated square which displays the position of the satellite images. *Software*: GMT. *Map source*: author.

Mantle dynamics of upper lithosphere and anisotropy of the margins of the Tibetan Plateau resulted in surface deformation, which shaped heterogeneous geomorphic forms (Xiao et al. 2023). Such setting created favourable conditions for environmental evolution that influenced paleoclimate and is now reflected in a rich variety of landscapes over the Tibetan Plateau. As a result, ecosystems over the Tibetan Plateau are notable for variability, rich taxonomic patterns, diversity and regional dynamical development of West China.

The surroundings of Lake Nam Co with Nyenchen Tanglha Mountains located in Lhasa Tehran, Tibetan Plateau, have experienced rapid glacier retreat over the past 10 years (Yao et al. 2007, Ji et al. 2018, Li et al. 2024a, Xue et al. 2024). Snow and ice melting results of the climate warming which includes the rise of air and water temperatures in the region. For instance, Huang et al. (2017) report the raise of water temperatures in the lake over at an approximate rate of 0.5°C during recent four decades since 1979 and high rates of warming for air temperatures over land with 0.2°C. Warming in both mountain glaciers and surface of high-altitude lakes is observed in Tibetan Plateau as a result of climate-environmental changes and affects the surrounding landscapes (Shi et al. 2022).

Glacier retreat and snow melt are a common occurrence in recent decades due to several unique regional meteorological and characteristics of Nyenchen Tanglha Mountains and other Tibetan highlands (Wu and Zhu 2008). For instance, changes include the downward trend of snow depth in the high altitude-mountains and, in contrast, upward trend of snow depth in the plains of Tibetan Plateaus. The retreat of glaciers and the melting of snowmelt in the surroundings set off environmental and geological processes. As a result, the surface area of Lake Nam Co is expanding. Now it occupies 10,680 km^2 of catchment area and a total area of 2017 km^2. Recent studies report variations in surface area of lake in response to climate change over the Tibetan Plateau. According to the reported data, since the past 40 years (from 1970 to 2008), the surface area of Lake Nam Co expanded in 27.98 km^2 with relative variation rate of 1.45%, which specifically means the increase from 1935.88 km^2 in 1970 to 2025.53 in 2008 (Liao et al. 2012). Such expansion in lake's surface results from the hydrological inflow from local rivers and melting glaciers situated in the nearby areas. Nyainqen Tanglha Mountain Range, located to the south of the Lake Nam Co has a large number of glaciers which meltwater runs into the lake basin through rivers and streams (Zhou et al. 2013).

Recently, water mass in lakes increased in the Inner Tibetan Plateau which is related to the increase in lake's level and rate due to global warming. Recent studies report that glacier meltwater affects the hydrological cycle through redistributed components of water recharge and discharge on the plateau (He et al. 2024) which accelerates these processes through geologic settings. Thus, glacier meltwater recharge takes up to 10% of the total groundwater recharge over Lhasa River Basin and this percentage increases (Chen et al. 2021). Further effects of climate change resulted in extensive permafrost degradation over the Tibetan Plateau as a result of the rise in air temperature and notable warming (Wan et al. 2018, Pepin et al. 2019, Yang et al. 2023, Zhao et al. 2024). For instance, the rise in temperatures results in changes in lake evaporation which is a key component of the lake water balance (Lazhu et al. 2016). Yang et al. (2010) report the increase in the lower altitudinal occurrences of permafrost over the last three decades along with the increase of mean annual ground temperatures. Prominent increase is recorded over the past two decades in the southern part of the region where Lake Nam Co and Nyenchen Tanglha Mountains are situated.

The degradation of the permafrost and related processes of soil freezing and thawing cause environmental deterioration. One of the main environmental problems in Tibetan Plateau is soil erosion. Through snowmelt and glacier runoff, erosion accelerates the rate of soil losses and destroys upper vegetation layer since the underlying ground surface is abraded of the rock materials, leaving debris on the bedrock surface (Li et al. 2024b). Furthermore, snowmelt and glacier runoff result in a deficit of surface water which becomes less available for plants and direct irrigation for agricultural purposes which leads to vegetation decline.

Nam Co Lake significantly affects local climate and weather conditions through lower albedos, large heat capacities, and reduced surface roughness. Such effects on processes of lake-air interactions largely impact the distributions of heat fluxes, cumulus clouds, and precipitation which creates local setting for moisture conditions and distribution of lacustrine types of vegetation (Dai et al. 2018). Moreover, the hydrology of Lake Nam Co and complex topography of the surrounding terrain have important impacts on the local weather and climate (Zhao et al. 2022). The variations in hydrological balance become more essential since the lake belongs to the endorheic basin of Qinghai-Tibet Plateau (Zhu et al. 2010). In turn, glacier is highly sensitive to changes in air temperature when positive accumulated air temperature and precipitation level trigger changes in glacier surface albedo (Zhou et al. 2010). Such interconnected and complex processes lead to gradual changes of glacier extent, hydrological regime that affect external surface processes in soil and vegetation in Lhasa.

Data handling

The data covers the area of Lake Nam Co, SW region of the Tibetan Plateau (*see* Fig. 4). The United States Geological Survey (USGS) provided the necessary satellite imagery to perform, visualise and map land cover analysis with 30-m resolution multispectral Landsat 8-9 Operational Land Imager (OLI) and Thermal Infrared (TIRS) satellite images. The images cover study area of Nyenchen Tanglha Mountains and Lake Nam Co for six dates in cold period with high level of snow/glacier extent:

- 31 December 2013,
- 21 December 2015,
- 10 December 2017,
- 16 December 2019,
- 21 December 2021,
- 03 December 2023.

High-quality images were selected in December, which is the period with the high snow and glacier extent. These time periods reflected a significant variation in glacier and snow coverage over the ranges of Nyenchen Tanglha Mountains which shows the development of land cover types after snow and glacier melt, and hydrological-environmental setting of Nyenchen Tanglha Mountains and Lake Nam Co, Tibetan Plateau (Fig. 5).

The images were selected with minimal cloudiness to analyse landscape dynamics (all the used available scenes had low cloudiness and low distortion of visibility). The Landsat OLI/TIRS image for 31. December 2013 was used as a training polygon for retrieving the seed for machine learning. The requirement for cloudiness level was set up on lesser than 10% of all the Landsat images. Additional thematic data include Digital Elevation Model (DEM) used for analysis of relief, the Shuttle Radar Topography Mission (SRTM), the General Bathymetric Chart of the Oceans (GEBCO) for topographic mapping and geological dataset mapped using vector layers.

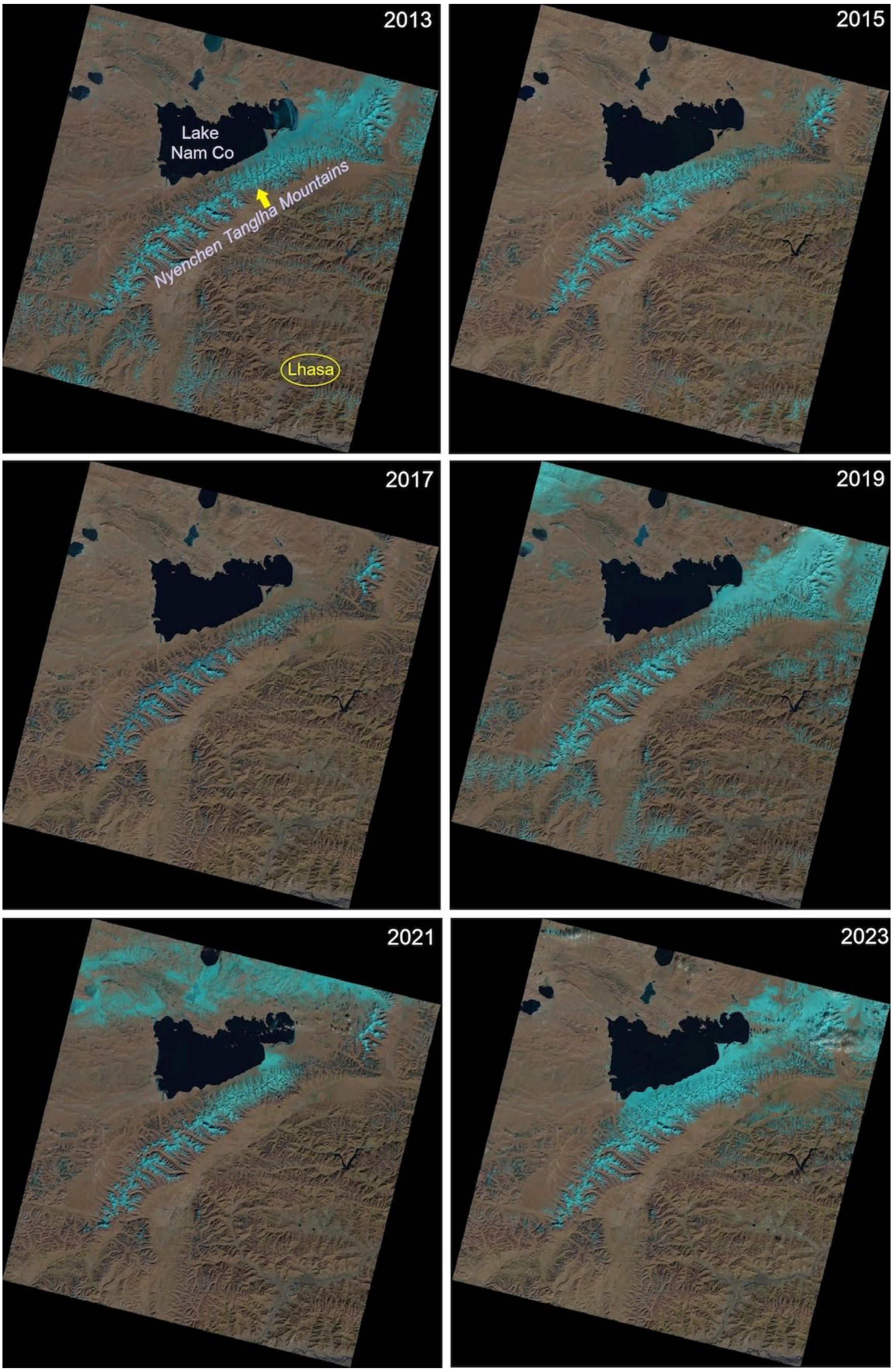

Fig. 5. Original dataset: Landsat scenes covering Lake Nam Co and Nyenchen Tanglha Mountains, Tibetan Plateau, China. The annotations of key geographic features are added on the first image (2013). *Data credit*: USGS. *Compilation*: author.

Along with the similarity in seasonal timing (winter period of December and November) necessary for comparing the differences in land cover types, the Landsat OLI/TIRS images had also already been ortho-rectified and corrected using Landsat Collection Level 1 corrections for terrain to allow for direct comparison of the imagery. All the data are predefined and projected using Universal Transverse Mercator (UTM), Zone 46 for western part of the People's Republic of China (P.R.C.).

Basin-wide topographic raster data in digital format were available from GEBCO, NetCDF format, and the GEBCO website, which provided the necessary terrain reference data for the evaluation of relief of the surroundings. The topographic map was plotted using GMT using scripting methods for cartographic data visualization described earlier (Lemenkova 2021b, 2022b). Data import was performed using GDAL libraries embedded in GRASS GIS.

Data processing

Satellite images were processed and classified using the Geographic Resources Analysis Support System (GRASS) Geographic Information System (GIS) which presents a powerful tool for cartographic data analysis and remote sensing data processing. The software version used in this study is 8.3.1.

Creating color composites. Colour composites of the satellite image Landsat 8-9 OLI/TIRS were performed using a combination of various multispectral bands for identification of land features performed in the GRASS GIS. Technically, the command employed for creating composites is based on the 'r.composite' module of GRASS GIS. The representation of selected colour composites is shown in Fig. 6 with the selected bands 3-4-5, 7-5-4 and 5-4-3. The correspondence of the bands in Landsat 8-9 OLI/TIRS to the spectral bands is as follows: Band 3 – Green; Band 4 – Red; Band 5 – Near Infrared (NIR); Band 7 – Shortwave Infrared (SWIR) 2.

Clustering. First, the computational region has been set to match the scene extent which has the following coordinates of the central point: 90.64° N; 30.31° W. This was performed using the 'i.group' module. Afterwards, the clustering has been performed using 'i.cluster' module which generates the signature file using data on spectral reflectance in the bands of the Landsat images and reports it using k-means clustering algorithm. Following that, the next step included the classification process which was implemented using the maximum likelihood discriminant analysis by "i.maxlik" module of GRASS GIS. The visualization of the results of the classification was technically done using the set of cartographic modules in GRASS GIS.

Image classification. The information regarding the land cover classes was derived, simplified and adopted from the existing studies with defined 10 land cover types which were chosen for the region of Nyenchen Tanglha Mountains and Lake Nam Co as follows: 1) glacier and perennial snow; 2) water; 3) mountain rocks; 4) bare soil and gravel lands; 5) built-up areas, cities and rural settlements; 6) forest areas and mixed vegetation; 7) mountain grasslands and shrubland; 8) alpine steppe and meadows; 9) irrigated and agricultural lands; 10) sandy land and deserts.

The reclassification of the images with identified classes was performed using the 'r.reclass' module of GRASS GIS. Built-up areas cover all non-vegetated surfaces covered with impervious infrastructure: Lhasa and other settlements. Bare soil class accounted for any other vegetation clearing or losses, either for as a result of glacier retreat or land degradation.

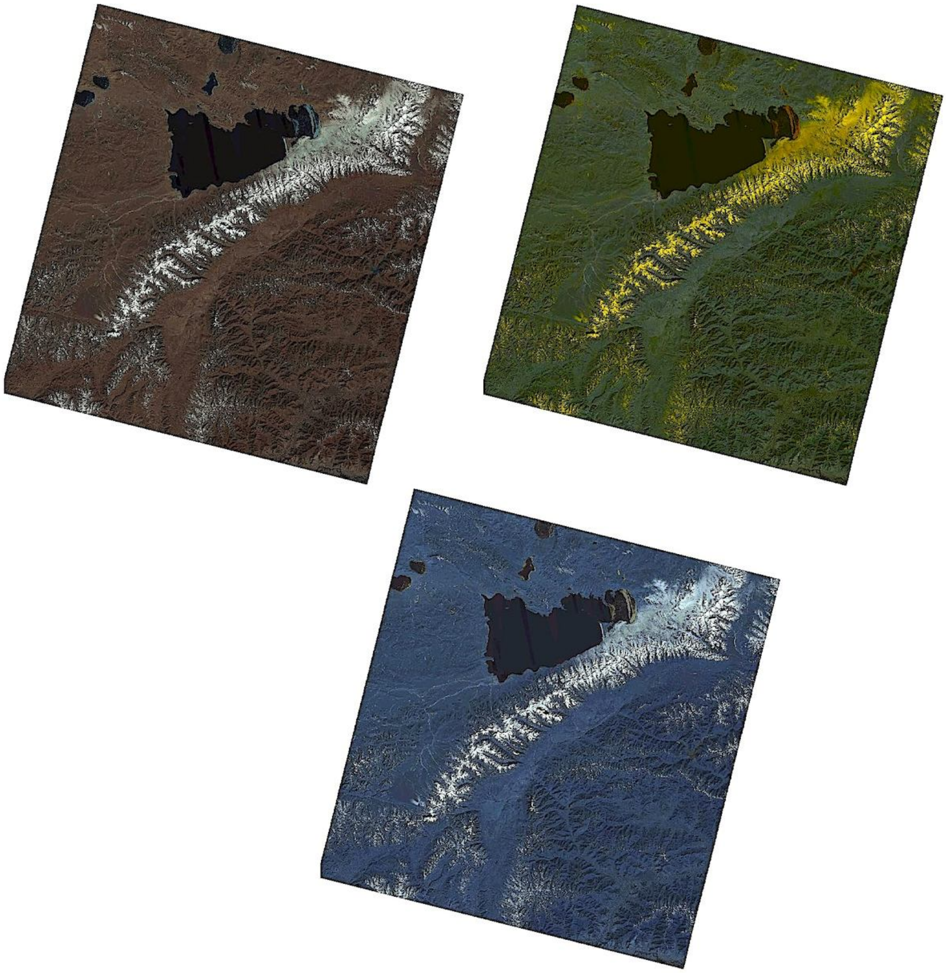

Fig. 6. Colour composites of the satellite image Landsat (example of 2013): combination of various multispectral bands for identification of land features performed in the GRASS GIS where Band 3 correspond to Green; Band 4 – to Red; Band 5 – to Near Infrared (NIR); Band 7 – to Shortwave Infrared (SWIR) 2. (a): Colour composite bands 3-4-5. (b): Colour composite of bands 7-5-4. (c): Colour composite of bands 5-4-3. *Landsat data*: USGS: *Compilation and processing*: author.

Machine Learning. Following land cover class identification using the previous steps of clustering and classification and re-classification, all the six images had been reclassified using ML methods with a special approach of Random Forest (RF). This approach employs the Scikit-Learn ML library of Python programming language along with its Pandas package for complimentary data processing. The essential idea of Random Forest algorithm lies in integrating the data to average noisy yet unbiased models of random data. In this way, RF reduces the variance in dataset. Since trees can capture complex interaction with cells, they are used in RF algorithm as a key approach to data modelling and analysis.

Technical implementation of the RF classification using GRASS GIS scripts consists in the following steps as described in previous work (Lemenkova 2024d). First, the training pixels have been generated from an older land cover classification in 2013 using the 'r.random' module. Afterwards, these training pixels were used to perform a classification on the Landsat images for 2015, 2017, 2019, 2021 and 2023. The training of supervised approach was performed using the 'RandomForestClassifier' function in the 'r.learn.train' model of GRASS GIS and then evaluated the probability of each pixel to be assigned into the specific land cover class using the 'r.learn.predict' module of GRASS GIS. The raster categories are automatically applied to the classification output which was inspected using the 'r.category' module.

Accuracy assessment of the classification was performed by using "i. maxlik" module evaluates the correctness of the classification the cell spectral reflectances in imagery data which is based on the spectral signature information. The accuracy assessment evaluates the probability of correctly classified pixels and visualizes the results on a map holding reject threshold results in percentage of the correctly classified pixels. The logic underlying this method is based on the chi square test which evaluates each discriminant resulted at various threshold levels of confidence in order to determine at what agreement is each cell categorized correctly. Hence, it is the rejection threshold map which contains the computed index to the calculated confidence level for each classified pixel in the classified raster scene of the satellite image.

Results and Discussion

The results of the visualised maps of clusters are shown in Fig. 7 and performed accuracy assessment is presented in Fig. 8.

In the northern range of Nyenchen Tanglha Mountains, glacier retreat is revealed from 2013 to 2017 followed by the advance in 2019 and 2021 and stabilization in 2023, which may drive the changes in vegetation cover due to the fluctuations in water balance masses.

In the southern part of the imagery close to Lhasa, the highest glacier coverage is detected for year 2019 which is caused by higher precipitation and lower temperatures in this period. The change detection analysis in land cover types from 2013 to 2023 demonstrated shifts in ice and snow coverage within both the basin of the Lake Nam Co and the ranges of the Nyenchen Tanglha Mountains (Fig. 9).

The land cover classes computer for each category are summarised in Table 1.

Currently glacier retreat and snow melt in the mountainous regions of Nyenchen Tanglha Mountains and Lake Nam Co across Tibetan Plateau have demonstrated increased fluctuations in the extent as climate warming continues to persist over the past ten years (2013 to 2023). If current trends continue, then the increase in bare soil and degraded lands areas will also continue as a result of glacier retreat, placing more natural land cover types at risk of degrading.

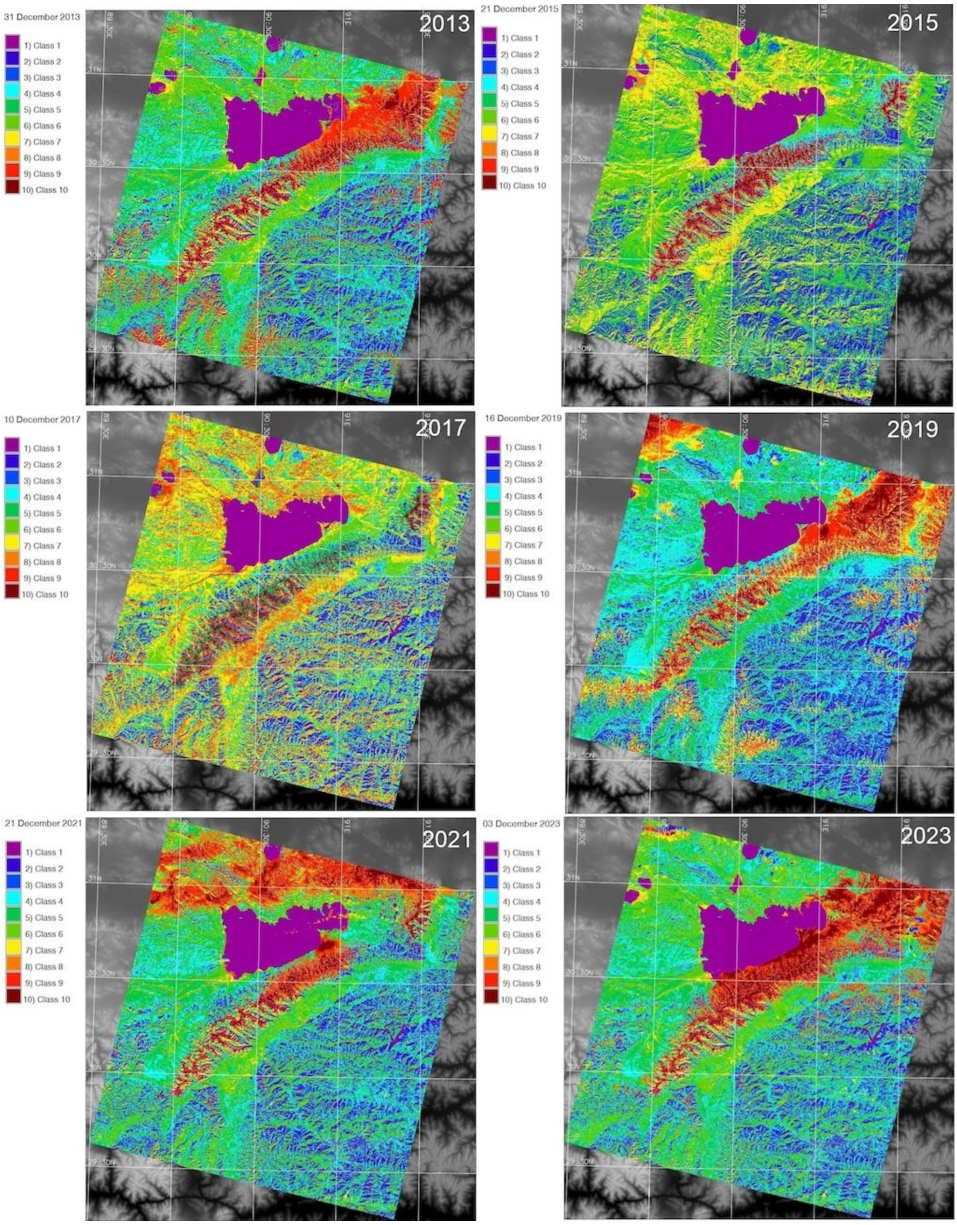

Fig. 7. Clustering of the satellite images Landsat 8-9 OLI/TIRS using k-means. *Source*: author.

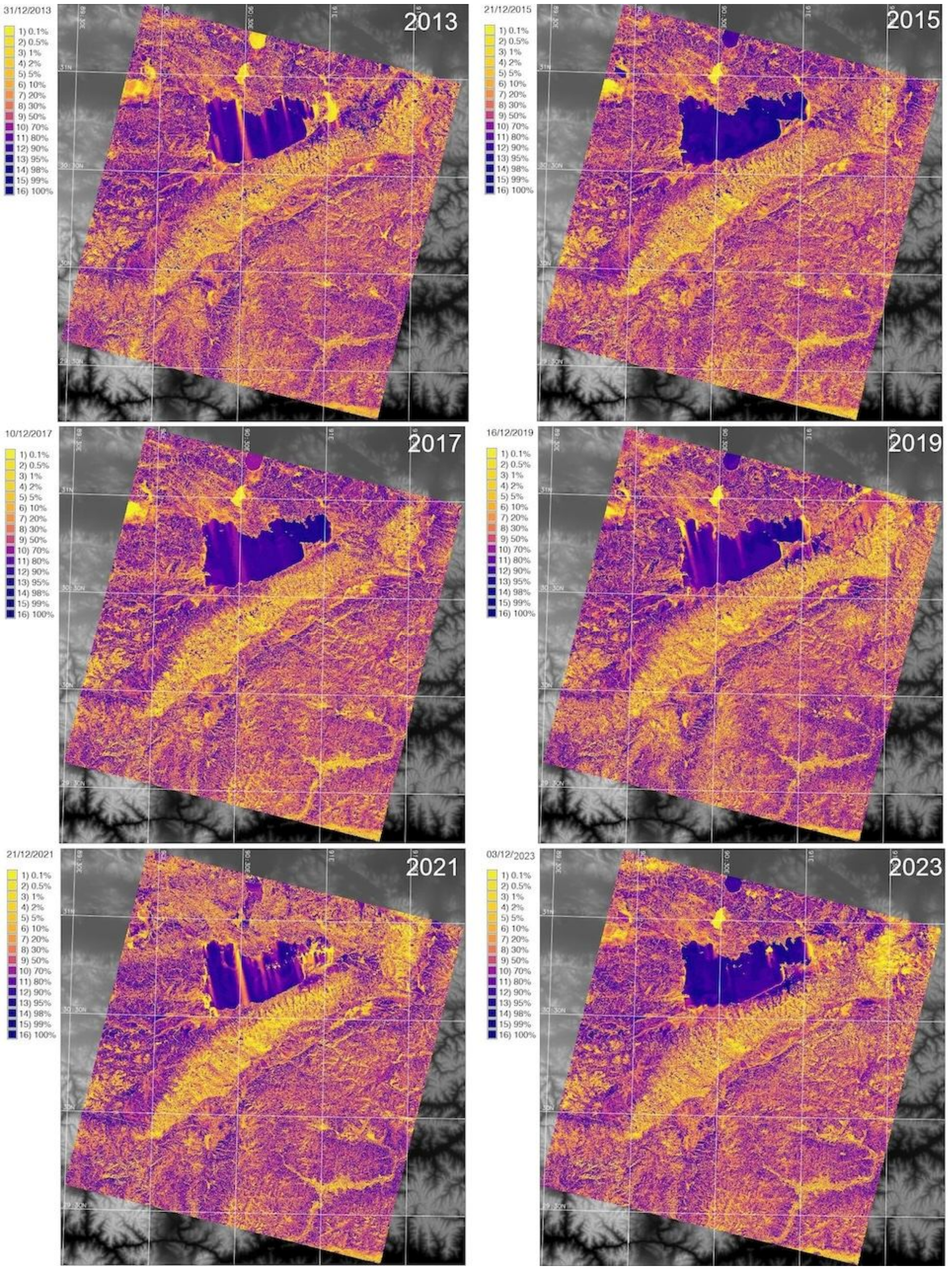

Fig. 8. Accuracy assessment of the satellite images Landsat 8-9 OLI/TIRS images: mapping rejection probability values that indicate pixel classification confidence levels performed using a chi square test. *Source*: author.

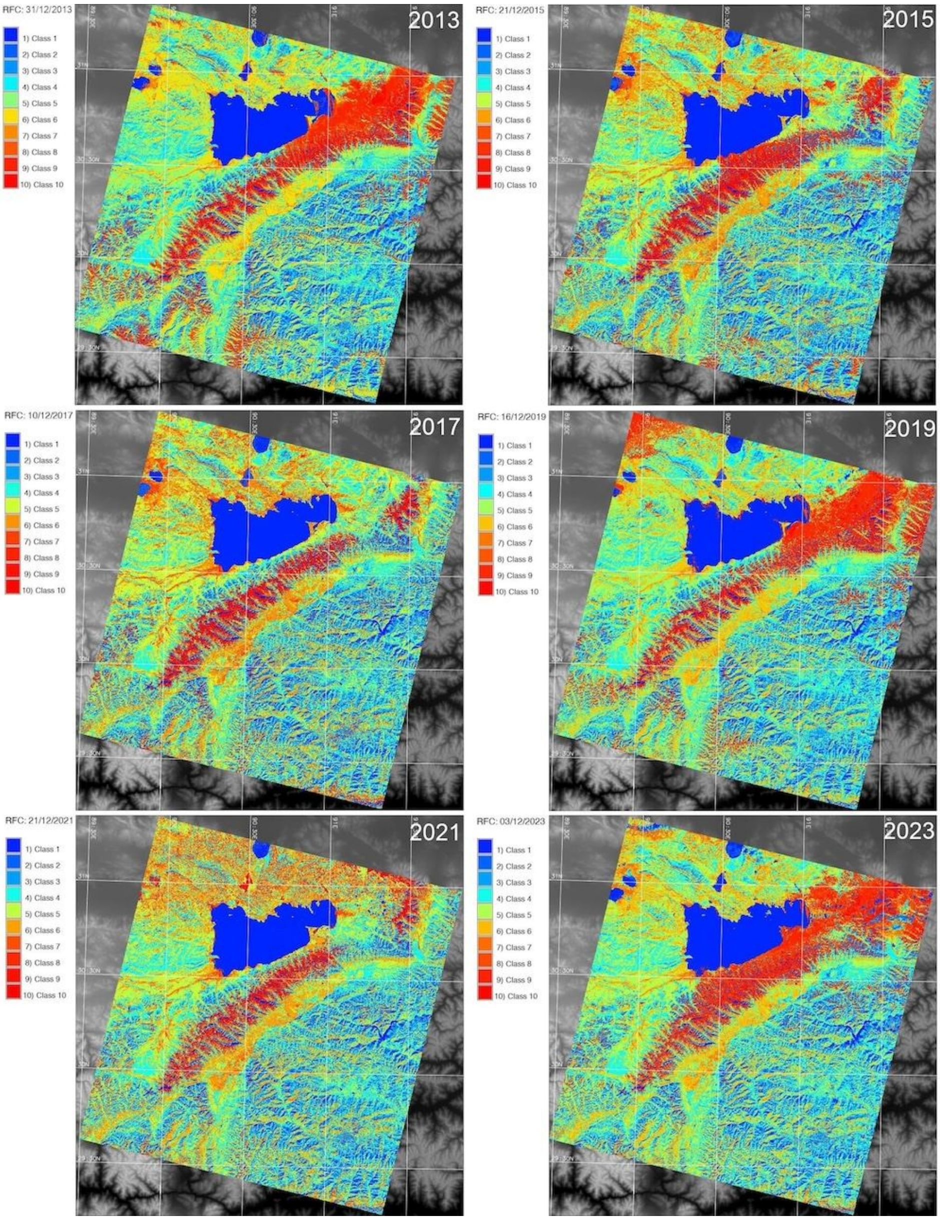

Fig. 9. ML-based classification of the Landsat satellite images: mapping land cover types using Random Forest algorithms by training dataset performed in the GRASS GIS. *Source*: author.

Class	Year					
	2013	2015	2017	2019	2021	2023
1	690	612	719	766	693	653
2	399	467	456	501	456	380
3	541	803	562	863	689	632
4	1105	208	823	1601	1190	1172
5	1578	1336	122	1458	1544	1696
6	1222	1723	1386	304	1004	1158
7	232	1179	1483	442	194	213
8	375	226	896	305	380	248
9	323	135	205	284	339	303
10	153	103	55	170	207	355

Table 1. Statistical results on the estimated classes of land cover types for the decade period (2013–2023) in Lake Nam Co and Nyenchen Tanglha Mountains, southern Tibetan Plateau.

Remote sensing data processing using ML techniques implemented in GRASS GIS has proven to be a useful tool in assessing the possible glacial-hydrological impacts these land cover types may have on a regional scale in Lhasa terrain, especially for basin of Lake Nam Co and the surrounding areas. Using scripting techniques and advanced cartographic solutions of GRASS GIS that employ machine learning approach, we identified the periods of glacier retreat and advances detected in a series of the multispectral satellite images. The obtained results help to better understand biennial fluctuations of glacier extent in Nyenchen Tanglha Mountains and Lake Nam Co. Such knowledge can be used for landscape analysis explaining the effects of global warming processes that lead to either a favourable greening of land cover types around the Lake Nam Co or, in contrast, landscape degradation due to the desiccation and aridification of alpine ecosystems of the Tibetan Plateau.

Conclusion

This study was motivated by the lack of current similar studies that apply machine learning to remote sensing data processing for environmental monitoring of the Qinghai-Tibetan Plateau region. It contributes to the evaluation of global change effects on the western Chinese ecosystems through mapping land cover types in the study area for comparative analysis of changes resulting from glacier retreat and snow melt in Nyenchen Tanglha Mountains. The combination of remote sensing data analysis and approaches of machine learning methods to data modelling essentially provides environmental estimates and cartographic visualization in the form of analyse satellite imagery. These data could then be incorporated into future modelling of Tibetan Plateau at the enlarged scale for prediction of environmental changes and hydrological modelling aimed at sustainable development and conservation of alpine high-altitude ecosystems of western China.

This study demonstrated applications of ML for image analysis for geological and environmental investigation of the study area provides sound tools for a better understanding of the ecosystems's evolution over the selected regions of Tibetan Plateau, China. Glacier dynamics affects hydrological balance, soil structure, permafrost extent and phenology cycles of vegetation. In the northern range of Nyenchen Tanglha Mountains, fluctuations in glacier retreat drive changes in vegetation coverage through water balance. Near Lhasa, the highest glacier coverage was detected for 2019 due to higher precipitation and lower temperatures.

Future research needs to be carried out as to how changes in specific land cover types might alter the glaciological-hydrological cycle of other basin of the alpine lake in Tibetan Plateau in order to compare the behaviour of small-sized lakes that may be facing similar effects from global warming resulted in glacier retreat, analyse and compare those outcomes with regard to the Lake Nam Co. Additional and more extended analyses are required in order to increase both the extent of the land cover classification using a mosaic of images, and to ascertain which specific areas and landscapes of the Qinghai-Tibet Plateau would be at most risk of land degradation from global warming that is reflected in the increased snow melt and rates of glacier retreat. This is possible with a greater availability of higher-resolution remote sensing data on both spatial and temporal scales (*e.g.*, SPOT images) along with larger territorial extent of the analysed dataset as a reference database. Both approaches – increased resolution of datasets and enlarged study extent – are plausible and reasonable suggestions to future studies. The access to the available open datasets with high-resolution imagery ensures the extended analysis of the target areas of Tibetan Plateau and neighboring regions.

To conclude, we contend that the methodological approaches to which software and data future studies use lies in what extent of the Tibetan Plateau region is selected as a target area. We conclude with suggested strategies of landscape analysis that integrate scripting techniques, machine learning algorithms and satellite image processing can be implemented with geological and topographic data to facilitate a further and more detailed analysis on the complex interrelations between topographic, hydrological and environmental processes as key factors in landscape dynamics of the Tibetan Plateau, China.

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