Monitoring of Forest Changes in Mount Kenya National Park Based on Domestic High-Resolution Satellites

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Abstract

With the increase in population and the growing demand for timber, especially fuelwood, Kenya's forests are facing the threat of serious deforestation and illegal logging activities. At present, remote sensing has become an important means of monitoring the dynamic changes of forest resources with its advantages of wide monitoring range, fast speed and low cost. This paper selected Mount Kenya National Forest Park as the study area, employing domestic 2-meter resolution satellite images (Gaofen-1 satellite constellation, Gaofen-6 and the Ziyuan-3 satellites) to conduct dynamic forest change monitoring from 2019 to 2023. The optimized semantic segmentation model DeepLabv3+, which is based on the Pytorch deep learning framework, was used to achieve fine segmentation of forest element boundaries via a spatial pyramid pooling module and an encoder-decoder architecture. The method of manual annotation was used to mark the forest changes and their causes from 2019 to 2023. The newly added forest was mainly restored by artificial planting, covering an area of 3078.71 ha. The total area of forest reduction was 2,425.91 ha. There were 542 patches of forest land occupied by new arable land, covering an area of 1,613.41 ha. It was the most important cause for the forest reduction. 327 patches of forest reduction were due to artificial logging, covering an area of 408.34 ha, which was the secondary cause of forest loss. Human activities were more constrained at higher altitudes, hence, the most of planting and lost forest patches usually occurred below 2,600 meters above sea level. Effective implementation of environmental protection policies was an important reason for the emergence of large areas of new plantation while the occupation of arable land and logging were main factors for the forest reduction in Mount Kenya.

1. INTRODUCTION

Kenya has abundant forest resources, such as tropical rainforests, montane forests, and tropical grassland forests. Kenya's forestry protection policy has been implemented for many years. But with the increase in population and the growing demand for timber, especially fuelwood, Kenya's forests are still facing the threat of serious deforestation and illegal logging activities. Forest resource monitoring is an important part of forest resource management. Understanding the dynamic changes of forest resources is a prerequisite for scientific management of forest resources. At present, remote sensing has become an important means of monitoring the dynamic changes of forest resources with its advantages of wide monitoring range, fast speed and low cost (Lausch et al., 2016). This paper selected Mount Kenya National Forest Park as the study area, and used domestic 2-meter resolution satellite imagery to monitor forest dynamic changes from 2019 to 2023, in order to provide a scientific basis for the refined management of Kenya's forests and enhance the international application and utilization level of China domestic satellites.

2. STUDY AREA

Mount Kenya is the largest extinct volcano in the East African Rift Valley, located in central Kenya (Figure 1). The base of Mount Kenya is about 1,600 meters above sea level. Mount Kenya is rich in vegetation, and the types of vegetation vary with altitude and rainfall. At an altitude of 2,000-2,500 meters, it is mainly cedar. The dominant tree species in the southeast slope with higher altitudes (2,500-3,000 meters, with annual rainfall exceeding 2,000 mm) is bamboo. The middle altitude area (2,600-2,800 meters) is a mixed area of bamboo and Podocarpus. Above 3,000 meters above sea level are *Hypericum* trees. At an altitude of 3,400-3,800 meters, grasses, fescue and mosses dominate. Vegetation disappears above 4,500 meters above sea level. There are many plantations below 2,000 meters above sea level, where coffee, sisal, bananas, etc. are grown on the fertile soil developed from volcanic rocks. Mount Kenya and the surrounding area are called Mount Kenya National Park (Poletti et al. 2019).

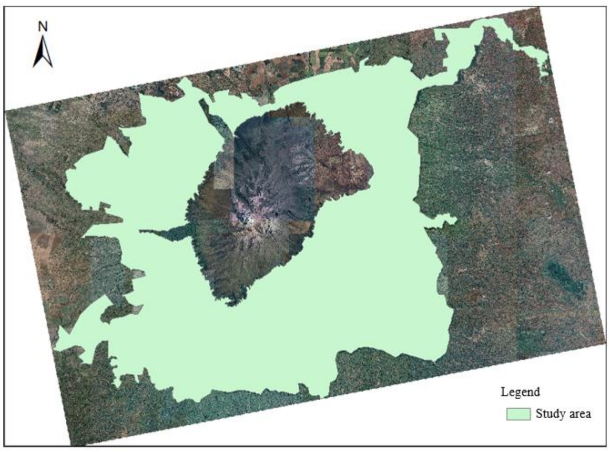

Figure 1. The geographic location of the study area - Mount Kenya National Forest Park

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3. DATA SOURCE

The data sources used were the Gaofen-1 satellite constellation (GF1 B, C, and D), Gaofen-6 (GF6), and Ziyuan-3 satellites (ZY3-01, ZY3-02 and ZY3-03). The imaging data for the study area is chosen based on characteristics such as temporal phase and cloud cover. A total of 24 imaging scenarios (both panchromatic and multispectral) were selected in 2019 and 2023.

The 2m/8m optical satellite constellation (GF-1 B, C and D) was successfully launched on March 31, 2018. The leading user is the Ministry of Natural Resources. This satellite constellation consists of three operational satellites with the same configuration and the same performance state. The satellite designed life is 6 years. Its spatial resolution is 2 meters panchromatic, with multi-spectral better than 8 meters, and the imaging swath of a single satellite is more than 60 kilometers. After the three satellites networked, they have the ability of global coverage with 15 days and 2 days site re-visits, and can achieve 11 days global coverage and 1 day site re-visits by cooperating with GF-1. The 2m/8m optical satellites are the first high-resolution constellation for civil use in China. It represents the highest development level of civilian satellite constellation remote sensing in China at present. It greatly improves the real-time investigation and monitoring capability of the Ministry of Natural Resources for natural resources overall elements including mountains, waters, forests, farming fields, lakes and grasses etc with full data coverage under all weather conditions (Natural Resources Satellites Remote Sensing Cloud Service Platform, 2025).

GF-6 satellite was successfully launched on June 2, 2018. It is mainly used in fine agricultural observation, forestry resource survey and other industries. The Ministry of Natural Resources is its main user. The satellite has realized the domestic manufacture of 8-band CMOS detector. For the first time in China, "red-edge" band which can effectively reflect the spectral characteristics of crops has been added, which greatly improves the monitoring ability of agriculture, forestry and grassland resources.

GF-6 satellite is equipped with 2-meter panchromatic/8-meter multi-spectral camera, 16-meter multi-spectral medium resolution wide-swath camera, 2-meter panchromatic/8-meter multi-spectral camera with 90 km swath width and 16-meter multi-spectral camera with 800 km swath width. After the networking operation of the GF-6 and GF-1 satellites, the time frequency of remote sensing data acquisition will be improved from 4 days to 2 days, which will provide data support for agricultural and rural development, ecological civilization and other major needs (Wang et al., 2016).

ZY3-01 is the first civilian high-resolution optical stereo mapping satellite of China. It was successfully launched on January 9, 2012. It integrates mapping and resource investigation functions into one. The main leading user is the Ministry of Natural Resources of P.R. China. Other users include Ministry of Emergency Management, Ministry of Ecology and Environment, Ministry of Housing and Urban-Rural Development, Ministry of Transport, Ministry of Water Resources, and Ministry of Agriculture and Rural Affairs, etc. The satellite adopts three-linear array mapping method. The stereo images are derived from the observation with different angles of view at the same ground point through the forward, nadir and backward-looking cameras with certain intersection angles. At the same time, the three-dimensional ground coordinates are obtained accurately with precise internal and external orientation parameters, which can be used to produce 1:50,000 mapping products and to carry out the updating of 1:25,000 and larger scale topographic maps. The multi-spectral data together with the high-resolution nadir panchromatic data can be used for interpretation of terrain elements, natural resources investigation and monitoring and other related applications.

ZY3-02 is a follow-up business satellite of ZY3-01, which was successfully launched on May 30, 2016. ZY3-02 satellite is optimized on the basis of ZY3-01. It carries payloads of three-linear array mapping camera and multi-spectral camera. The image resolution of forward and backward view is improved from 3.5 meters to better than 2.5 meters. It also carries a set of experimental laser altimetry payload. The satellite has better image fusion ability, higher image elevation measurement accuracy than 01 satellite. After ZY3-02 is put into operation, it networks with ZY3-01, which can shorten the re-visit period from 5 days to 3 days at the same place, and greatly improve the acquisition ability of 1:50,000 stereo mapping for graphic information resources in China (You et al., 2020).

ZY3-03 is the third one of the ZY-3 satellite series, which was successfully launched on July 25, 2020 in Taiyuan satellite launch center, China. It has the capability of stereo imaging with three-linear array camera and multi-spectral camera with the same configuration of ZY-02, and elevation measurement with laser altimeter. The elevation measurement accuracy of single laser point is better than 1m with point spacing of 3.6km. The satellite designed lifetime is 8 years longer than 5 years of 02 satellite. ZY3-03 can network with ZY3-01/02 to establish China's optical stereo mapping satellite constellation, which will shorten the re-visit period from 3 days to 1 days at the same place, and ensure the long-term, stable high resolution stereo images acquisition for national surveying and mapping. It has developed the globally advanced capability of stereo mapping and greatly improve the ability of natural resources survey for social and economic development in China.

4. RESEARCH METHODS

4.1 Forest Status Information Extraction

Steps of forest information extraction in 2019 and 2023 was demonstrated in Figure 1.

4.1.1 Basemap construction: To produce 2-meter DOM data, the sensor correction images were processed through panchromatic image ortho-rectification, multispectral image ortho-rectification, fusion, and other stages. The monitoring image base map data was created after statistical computing, stretching, mosaicing, cached slicing, slicing conversion data package, service release, and other processing steps.

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4.1.2 Remote sensing image interpretation sample generation: The samples were prepared using DOM data from 2-meter domestic satellites and forest data which was from the "Global Ecological Environment Remote Sensing Monitoring 2019 Annual Report - Global Forest Cover Status and Changes" by the National Remote Sensing Center of the Ministry of Science and Technology of the People's Republic of China. The steps of vectorization, automatic cropping, manual elimination, and correction were carried out to form a forest sample dataset, with a sample size of 512×512 pixels (Table 1).

Data	Satellites	Bands	Ground resolution
Satellites images	GF1 B/C/D	Pan/multispectral bands	2m/8m
	GF6	Pan/multispectral bands	2m/8m
	ZY3-01/02/03	Pan/multispectral bands	2.1m/5.8m
Auxiliary data	2018 forest results data (from the "Global Ecological Environment Remote Sensing Monitoring 2019 Annual Report - Global Forest Cover Status and Changes")		

Table 1. Data source of sample dataset

4.1.3 Forest information extraction: 10078 samples were generated, and the training and prediction sets were allocated in a ratio of 8:2. The optimized semantic segmentation model DeepLabv3+, which is based on the Pytorch deep learning framework, is used to achieve fine segmentation of element boundaries via a spatial pyramid pooling module and an encoder-decoder architecture (Liu et al. 2021). MIoU (Mean Intersection over Union) is a commonly used semantic segmentation model evaluation metric that measures model performance by calculating the ratio between the intersection and union of the predicted results and the true labels. The calculation formula for MIoU is: MIoU = TP / (TP + FP + FN), where TP represents true positives, FP represents false positives, and FN represents false negatives. MIoU can comprehensively consider the pixel-level prediction accuracy of the model and fairly evaluate the model when dealing with objects of different categories and sizes. MIoU accuracy in this study was 90.5%。

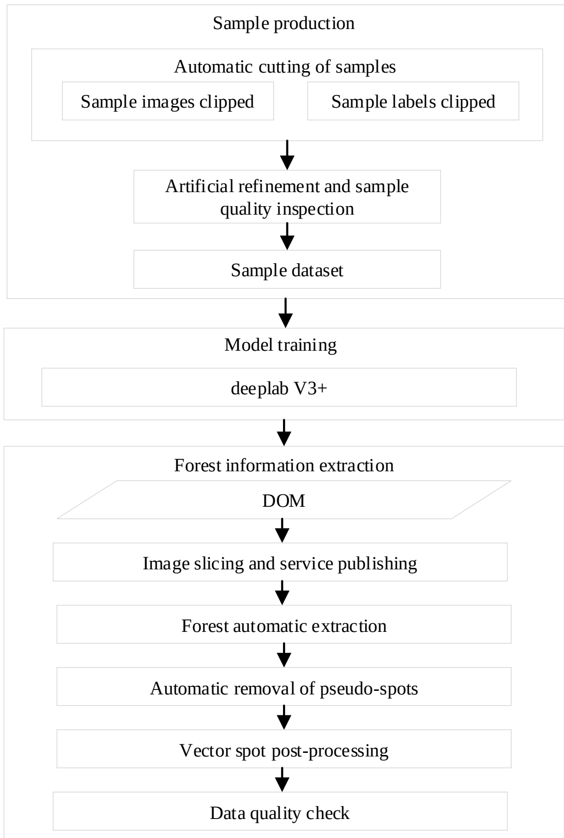

Figure 2. Flow chart of forest information extraction.

4.2 Forest change information extraction

The method of manual annotation was used to mark the forest changes and their causes in Mount Kenya National Forest Park from 2019 to 2023. The types of changes were categorized as: unchanged, increased, and decreased (Table 2). The reasons for increase include artificial planting and natural recovery. The reasons for decrease include occupied by arable land, aquaculture water surfaces, buildings, roads, logging, fire, water conservancy development. Meanwhile natural reduction and coverage by other vegetation were other reasons of forest decrease.

The minimum area of the change information was 1,600 square meters. The mathematical foundation used the

GCS_WGS_1984 geographic coordinate system, with units in degrees.

Change types		Reasons for change		Description
Code	Name	Code	Name	
1	No change			
2	Increased forest	21	Mainly artificial planting	There is obvious human activity around (roads, buildings, farmland, etc.)
		22	Natural recovery	There is no obvious human activity around (roads, buildings, farmland, etc.)
3	Decreased forest	31	Occupation of cultivated land	
		32	Occupation of Shrimp and crab pond	
		33	Occupation of buildings	
		34	Occupation of roads	
		35	Logging	
		36	Burnt area	
		37	Natural reduction	There is no obvious human activity around (roads, buildings, farmland, etc.)
		38	covered by other vegetation	
		39	Water conservancy development	Reservoirs (with obvious dam bodies) and their water surface occupation

Table 2. Classification table of forest change types.

5. RESULTS AND CONCLUSIONS

5.1 Forest change monitoring and analysis

Forest status information in 2019 and 2023 was illustrated in Figure 3 and Figure 4. 1,683 change patches covering 5,558.99 ha were retrieved. The extent of forest land in 2019 decreased by 2,425.91 ha in 2023. At the same time, the forest area in 2019 rose by 3,133.08 ha in 2023. Overall, the forest area rose by 707.17 ha from 2019 to 2023.

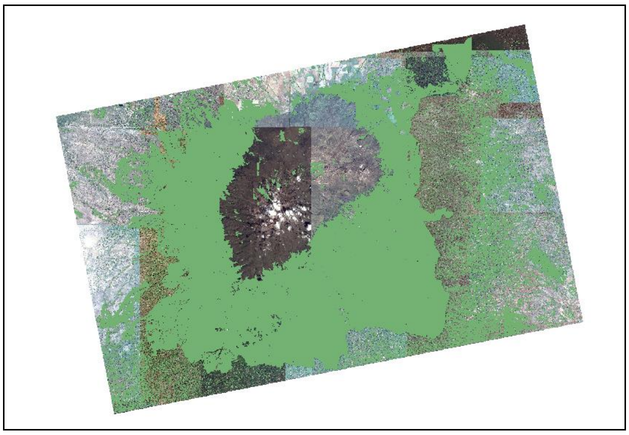

Figure 3. Forest spatial distribution map in 2019.

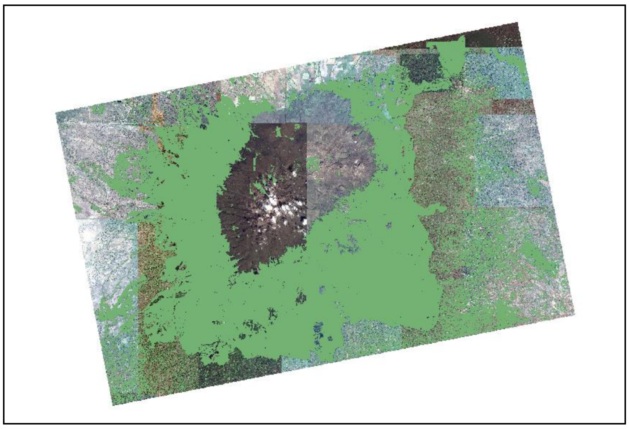

Figure 4. Forest spatial distribution map in 2023.

5.1.1 Newly added forest: The total area of newly added forest was 3133.08 ha. There were 618 patches of newly added forest mainly recovered through artificial planting, covering an area of 3078.71 ha (Figure 5). And 14 patches of newly added forest mainly restored through natural restoration, covering an area of 54.37 ha (Table 3).

Change types	Number of patches	Area (ha)
21	618	3078.71
22	14	54.37
Total	632	3133.08

Table 3. New forest land classification statistics table.

The newly added patches were predominantly distributed on the northwest of Mount Kenya National Park, while only a few patches scattered in other regions (Figure 6).

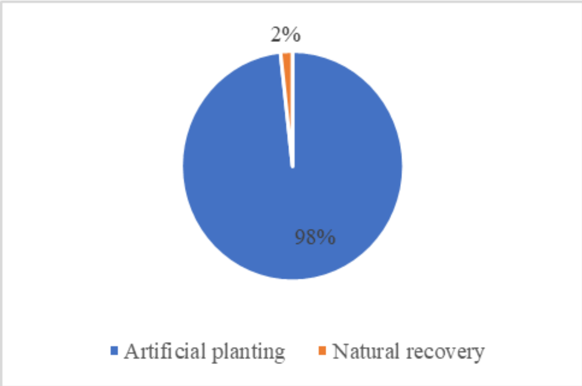

Figure 5. Proportion chart of newly added forests categorized by different causes.

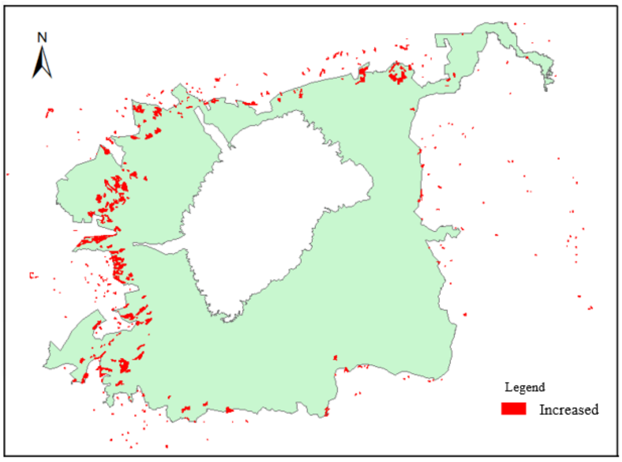

Figure 6. New added forest spatial distribution map.

5.1.2 Forest reduction status: The total area of forest reduction was 2,425.91 ha. There were 542 patches of land occupied by new arable land, covering an area of 1,613.41 ha. 60 patches of land occupied by new buildings, covering an area of 31.26 ha. 327 patches of forest reduction due to artificial logging, covering an area of 408.34 ha. 104 patches of land that were now covered by other vegetation, covering an area of 352.83 ha (Table 4).

Change types	Number of patches	Area (ha)
31	542	1613.41
33	60	31.26
34	6	3.12
35	327	408.34
36	1	1.46
37	8	7.21
38	104	352.83
39	3	8.28
Total	1051	2425.91

Table 4. Decreased forest land classification statistics table.

The primary type of forest reduction was due to agricultural encroachment (Type 31), accounting for 66.51% of the total area, followed by deforestation (Type 35) and other vegetation cover (Type 38), which accounted for 16.83% and 14.54% respectively (Figure 7).
The reduction patches were mainly distributed in the northwestern part of Mount Kenya National Park, while changes in other regions are minimal, with only sporadic distribution (Figure 8).

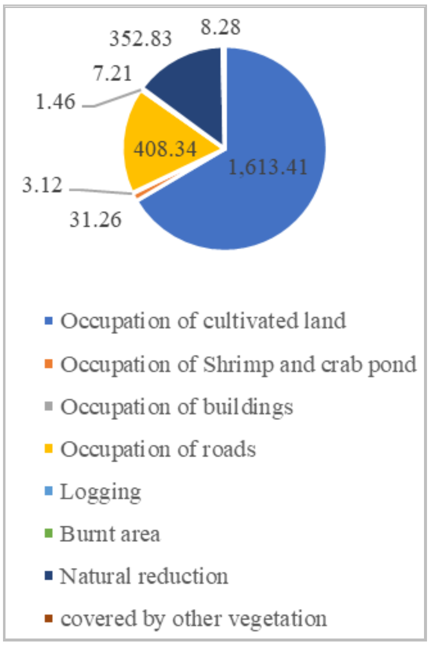

Figure 7. Pie chart of descreased forests categorized by different causes

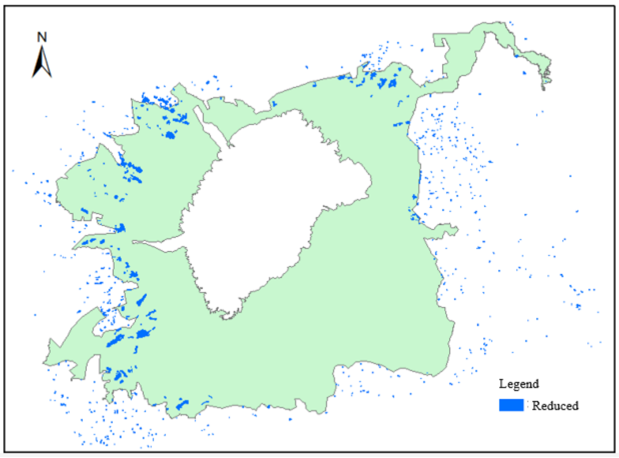

Figure 8. Decreased forest spatial distribution map.

5.2 Analysis of Driving Forces of Change

5.2.1 Influence of geographical location and natural environment: Mount Kenya exhibited a significant elevation range, with human activities increasingly restricted at higher altitudes. Consequently, the majority of forest patches, both newly added and reduced, occurred below 2,600 meters (Figure 9 and Figure 10).

The peak rainfall on Mount Kenya was observed around 2,200 meters. Due to moisture availability, agricultural practices differed markedly between the northwestern and southeastern foothills. The southeastern foothills were predominantly agricultural, focusing on crop cultivation, whereas the northwestern foothills were more pastoral. To preserve the existing agricultural structure and avoid encroachment on croplands and pastures, newly established plantations were primarily concentrated between 1,600 and 2,500 meters.

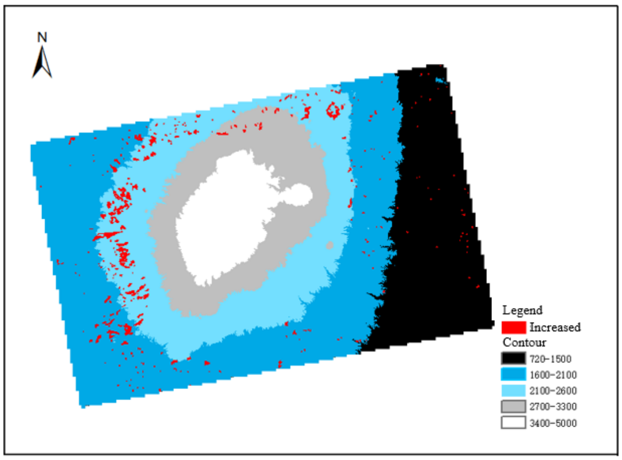

Figure 9. Distribution map of newly added forests across different elevation zones.

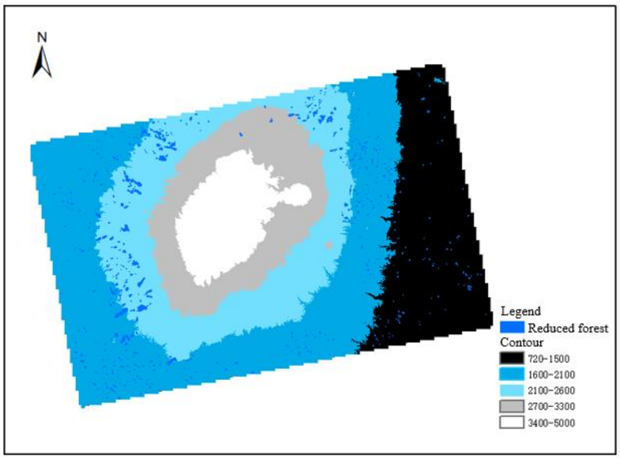

Figure 10. Distribution map of forest reduction across different elevation zones.

The southeastern slope of Mount Kenya was the windward side, receiving substantial rainfall but experiencing lower temperatures. In contrast, the northwestern slope was the leeward side, with less rainfall but higher temperatures, which were conducive to vegetation growth. The northwestern slope supported better forest vegetation, hence the concentration of new plantations there. However, this area also suffered more from human-induced disturbances such as deforestation for agriculture and paper production, predominantly between 1,600 and 2,500 meters.

5.2.2 Effective implementation of environmental protection policies: The government prioritized ecological and environmental conservation. For example, in vegetation protection, it mandated that paper mills must first engage in afforestation. Trees may only be harvested for paper production once a forested area had matured, establishing a sustainable cycle of "plant first, use later" that integrated afforestation with resource utilization. Consequently, the emergence of large-scale new artificial plantations was inextricably linked to these local environmental policies (Ngome et al., 2024).

5.2.3 Impact of agricultural activities and illegal human activities on forests: Kenya was a country that mainly developed agriculture. Its economic development was relatively backward. Agricultural development mainly focused on the cultivation of cash crops such as coffee and bananas. In order to obtain higher economic value, local residents cut down forest land in exchange for more arable land for planting. The occupation of arable land was a major factor in the reduction of forest land. At the same time, the threats to forests were the same as those in neighboring areas, including illegal logging, firewood cutting, illegal logging, charcoal burning, destructive honey collection, settlement and agricultural activities that eroded forests, all of which were the reasons for the reduction of forest area.

6. ACKNOWLEDGEMENTS

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