Spatial distribution and temporal change of vegetation restoration after the eruption of Mount St. Helens: from 1984 to 2019

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Abstract. Approximately ten terrestrial volcanic eruptions occur yearly, significantly impacting the surrounding area. Mount St. Helens has been one of the most popular active volcanoes in recent years. This study analysed the vegetation cover status from 1984 to 2019. Remote Sensing and GIS technology were mainly used in this study to perform detailed research on the rates and trends of vegetation change. The results show that the vegetation in the study area has continued to recover in general, but some areas are consistently devoid of vegetation growth. After analysing the spatial and temporal perspectives, the vegetation recovery rate was relatively slow in the eastern part of the study area. This vegetation recovery status may be related to factors such as volcanic eruption, deep slope, lack of seeds, and massive wildfires. The area in the north-western part of the eruption area gained rapid growth in the first ten years, which may be caused by plant measures.

Keywords: Vegetation Restoration, Remote Sensing, GIS Technology, Mount St. Helens.

1. Introduction

There are about ten terrestrial volcanic eruptions on Earth each year, which impact the surrounding area significantly (Dale et al., 2005a). There are two main types of effects on vegetation following volcanic eruptions. The first is the primary effect, which involves the physical destruction of surface vegetation when lava reaches the surface and flows. The high temperature of lava can form fires around the flowing path and burn plants that survive next to the lava (Dale et al., 2005a, Swanson et al., 2013). At the same time, volcanic ash can be carried farther by the wind and deposited on leaves, preventing photosynthesis in plants and making them sick or die (Cochran et al., 1983). The other one is secondary effects. It includes the impact on vegetation from air components, precipitation and soil changes caused by volcanic eruptions. Besides that, the lava-hardened land is unsuitable for new vegetation (Dale et al., 2005a). However, secondary effects can be more complex. According to Dale et al. (2005b), the fragmented sediments left by volcanic activity may make it easier for plants to take root. Therefore, it is essential to consider more influencing factors to explore the response of vegetation to disturbance. Although the narrow gaps created by volcanic eruptions provide opportunities for small plants to grow, overall, volcano eruptions still significantly disrupt the surrounding ecology (Garrec et al., 1984, Dale et al., 2005a).

Different methods can be used to analyse the vegetation cover status and change for different study situations. For example, an integrated index named Remote Sensing based Ecological Index (RSEI). It consists of four key indexes: greenness, dryness, wetness and land surface temperature. The model was well established as it could be used in any climate condition (Xu et al., 2019). However, the index contained in the model focused more on the urban side and might be caused some uncertainty in a long-term study (Ning et al., 2020). Alternatively, a previous study tent to use the attribution of the vegetation to evaluate the condition of ecology development as it is the basis of a well-developed ecosystem and has unique spectral properties (Huete, 2012). The use of the index could be divided into two classes: ratio-based indices and soil-line-based or orthogonal indices (Lawrence and Ripple, 1998). The ratio-based indexes are based on the high reflectivity of leaves in the Near-infrared band and the high absorption of a red band in the chlorophyll. A classical way is to normalise these two properties to enhance their idiosyncrasy, and this method is usually called normalised difference vegetation index (NDVI) (Rouse, 1974). Another class is based on eliminating the effect of soil brightness beyond the area where vegetation fails to cover (Srinivas et al., 2004). To perform this, the soil line had to be calculated, which is the typical range of the soil signature in red/NIR bands and is the linear regression of NIR against the red band for exposed soil. The drifting from the soil line indicates the increase in vegetation cover. Lawrence and Ripple (1998) compared several methods within these two index groups in their study area. The results showed that ratio-based indexes have higher accuracy than soil-line-based indexes. Among all these indexes, the NDVI has the highest accuracy, whose goodness of fit R^2 is 0.65.

Mount St Helens is currently more active than most volcanoes in the world, and in 1980 it was the site of the largest and most severe eruption in US history (United States Geological Survey, 2022). Marzen et al. (2011) believed that the 1980 eruption of Mount St. Helens caused over six hundred square kilometres of vegetation destruction. In 1982, the government of the US established a protected area in part of the eruption-affected area to restrict human activity (Marzen, 2001). Then Mount St Helens became an excellent opportunity to investigate plant responses to external disturbances in different situations. Detecting changes in vegetation areas over time following major geological disturbances is an integral part of the study of vegetation recovery. At the same time, such studies can also provide relevant data for interpreting physical processes on Earth (Marzen et al., 2011).

Therefore, it is crucial to explore the long-term vegetation changes at Mount St. Helens after its eruption. Marzen (2001) analysed vegetation recovery in different areas of the Mount St. Helens region from 1984 to 1998. The previous results showed that vegetation recovery in the area around Mount St. Helens varied depending on the resource management strategy. Vegetation recovered faster on some privately owned land with continued fertilisation than in natural conditions. Also, the slope is one of the factors determining the retention of volcanic sediments and thus affects vegetation recovery in St Helens Volcano (Dale et al., 2005a). Compared with the previous study, this study covers a more extended period of vegetation monitoring. This study uses a combination of remote Sensing (NDVI) and GIS technologies to explore the vegetation cover of the St. Helens volcanic region every five years from 1984 to 2019, calculate the rates and trends of vegetation change, and speculate on and explain the causes of the phenomenon. The study could provide other researchers with more data and information on the ecology of Mount St. Helens.

2. background of Study area

Mount St Helens, located in the state of Washington, is near the other two volcanoes: Adams and Rainier. Prior to its violent eruption in 1980, Mount St Helens was a well-known recreational area in the USA, when it was as conical as Mount Fuji (Marzen, 2001). However, according to survey records from the United States Geological Survey (2022), the volcano has been experiencing periods of intermittent eruptions since at early as 1800; at that time, it had continued small steam-driven outbreaks. Moreover, analysis of the current behaviour of Mount St Helens indicates that the volcano is still active. Since 2004, there has been surface swelling and seismic activity in the Mount St Helens area, so researchers believe that the magma reservoir beneath the volcano has been slowly repressurising (United States Geological Survey, 2022).

The 1980 eruption destroyed the upper 400m of the summit of Mount St Helens and caused a massive collapse of the mountain's northern slope (United States Geological Survey, 2022). The main area affected by the eruption concentrated on the volcano's north flank. Therefore, an area of approximately 887.9 km2 was selected as the study area of this research, including the whole peak area of Mount St. Helens and the northern part of it (Figure 1).

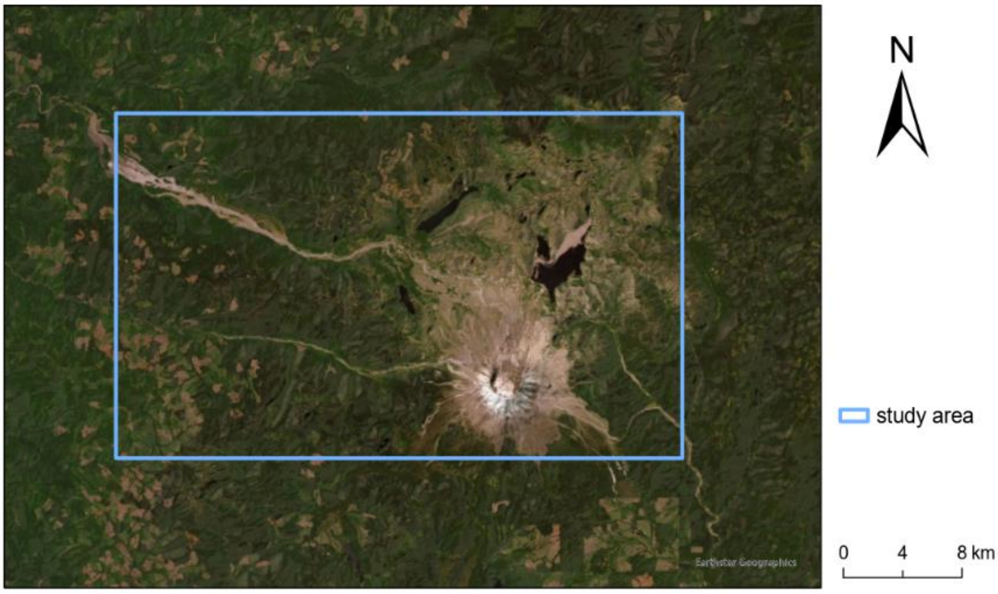

Figure 1. Map of the study area.

3. Methods

3.1. Data Resources

The satellite images were obtained from the United States Geological Survey's open-source site for remote sensing data. The satellite images are in the Landsat Collection 2 level 2 dataset. This dataset has undergone an improved atmospheric correction, and different algorithms are used for the various sensors. Therefore, using this data source in this study makes the results more accurate. This study used Landsat 5 and Landsat 8 from the Landsat series of satellites. The skipping of the intermediate Landsat 7 is because its data had stripes of missing data due to its damaged Scan Line Corrector. Specifically, from 1984 to 2009, images from Landsat 5 were used, while the data for 2014 and 2019 were derived from Landsat 8. In addition, satellite images from the summer months of June to August were used to reduce the impact of seasonal changes on vegetation studies.

3.2. NDVI

Numerous studies have demonstrated the significant effect of green vegetation on reflections in the spectrum's near-infrared (NIR) and red bands (El-Gammal et al., 2014). Thus, NDVI can effectively discriminate vegetation cover areas (Pettorelli et al., 2005, Huang et al., 2021). Scattering by healthy leaves within the canopy and absorption by photosynthetic pigments resulted in a decrease in reflected red bands and an increase in reflected NIR energy in vegetation cover areas (El-Gammal et al., 2014).

$$NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}} \tag{1}$$

However, in different studies, depending on the characteristics of the study site, researchers often use various thresholds to define the meaning of NDVI value (El-Gammal et al., 2014, Huang et al., 2021). In the research of Gross (2005), areas with NDVI values less than or equal to 0.1 are thought to correspond to arid areas like snow, rock, or sand, while regions with medium values (from 0.2 to 0.3) are supposed to represent shrubs and grasslands, and areas with high NDVI values (higher than 0.6) are thought to correspond to temperate forests and tropical rainforests. In the research of Badamasi et al. (2010) for Nigeria, the NDVI values were divided into six categories, specifically distinguishing various areas of vegetation with different densities. Whereas, considering that the specific location and climatic conditions of Mount St. Helens are pretty different from the study area of these researchers, the criteria from Sobrino et al. (2001), whose thresholds are 0.2 and 0.5, would ultimately be adopted for this study. Their thresholds are proven reliable under applying to multiple plant species. Therefore, 0.2 and 0.5 were used to distinguish the presence or absence of vegetation and whether there is full vegetation cover, respectively.

3.3. Data processing

Data from satellites was analysed by computer through QGIS to get NDVI results. Furthermore, those NDVI images were reclassified by the thresholds. Then these vegetation coverage classes were transferred from raster data to polygon to calculate their area.

In addition to image processing, a data analysis process is included in this study. To better deduce the annual change of vegetation status, the annual change rate of vegetation area was calculated by the following equation:

$$A_c = A_2 - A_1 \tag{2}$$

Where Ac is vegetation area changed between two studied years. A1 is the vegetation area in the earlier studied year. A2 is the vegetation area in the later studied year.

$$A_p = \frac{A_c}{A} * 100 \tag{3}$$

Where Ap is the percentage of vegetation changed between two studied years. A is the total area of the study area.

$$C = \frac{A_p}{T} \tag{4}$$

Where C is the annual vegetation change rate, and T is the number of years between the two studied years.

4. results

Figure 2 shows that the exposed non-vegetated ground continued to shrink from 1984 to 2019. A general trend for vegetation recovery is inward movement from the eruption-affected outer area to the central volcanic zone (Figure 2, Table 1). Along the river valleys, vegetation gained the fastest recovery rate and tended to form dense vegetation covers. The northern part of the eruption area achieved more recovery than the southern side of the research area.

According to Figure 3 and Table 2, rapid recovery of vegetation occurred right after the eruption. Bare-vegetated land expanded in the first decade, especially from 1989 to 1994. This increasing trend slowed down since 1994, and the recovery area for bare-vegetated land has gained almost no increase since 2009. A particular trend was identified in 2014: an unexpected peak occurred for fully vegetated land. The change of the fully-vegetated land was not distinct from the eruption to 2009, but it significant fluctuated from 2009 to 2019. The non-vegetated land kept decreasing from 1984 to 2014, but a rebound appeared in 2014.

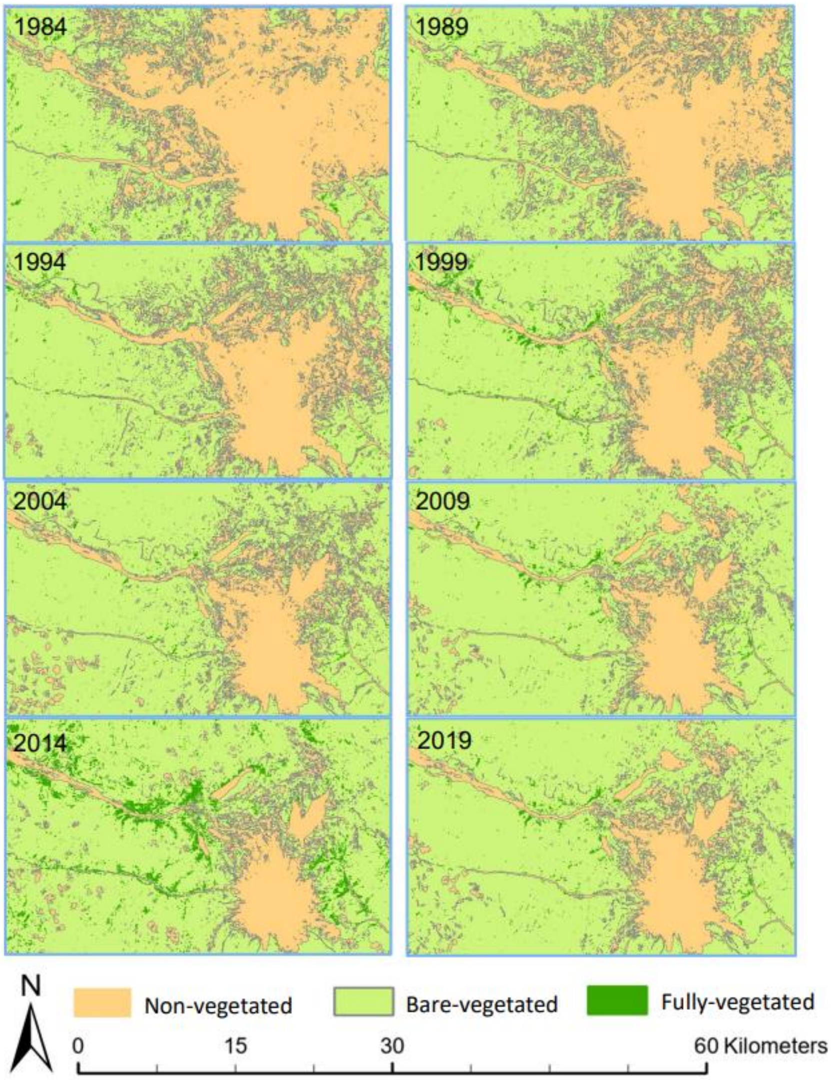

Figure 2. Vegetation coverage status from 1984 to 2019

Table 1. Area of different land status from1984 to 2019 (unit: km^2)

	1984	1989	1994	1999	2004	2009	2014	2019
Non-vegetated	470.34	396.15	272.46	243.35	211.70	176.58	151.64	176.58
Bare-vegetated	415.88	490.92	613.94	638.89	674.67	707.95	710.39	707.95
Fully-vegetated	1.70	0.85	1.52	5.59	1.55	3.39	25.89	3.39

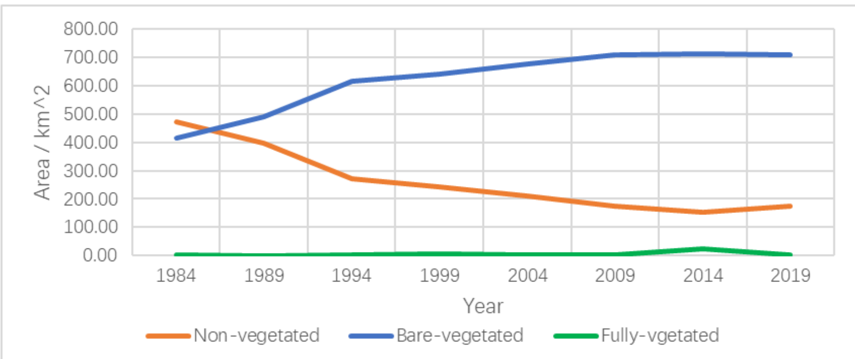

Figure 3. Line chart of Area Change for different land statuses from 1984 to 2019

Table 2. Average Annual Vegetation Change Rate

	1984 - 1989	1989 - 1994	1994 - 1999	1999 - 2004	2004 - 2009	2009 - 2014	2014 - 2019
Bare-vegetated	1.69%	2.77%	0.56%	0.81%	0.75%	0.05%	-0.05%
Fully-vgetated	-0.02%	0.02%	0.09%	-0.09%	0.04%	0.51%	-0.51%

5. Discussion

5.1. Spatial distribution and temporal change of the vegetation recovery

The vegetation recovery rate was relatively slow in the eastern part of the study area. Several possible reasons are causing this phenomenon. One is that these regions can be seen as the eruption mainly-affected areas. For no vegetation in some areas, magma solidified and formed a hard surface to impede the growth of vegetation (Dale et al., 2005b). The main areas where lava flowed during the 1980 eruption are shown in Figure 4, and these areas are entirely devoid of vegetation cover to date.

Another reason is that the lack of vegetation could be caused by the distribution of deep slopes (Figures 5, 6). More complex terrain can further enhance the soil erosion problem (Owens et al., 2010). Although the southern side is the sunward slope, under the circumstances of severe soil erosion problems, the water and nutrient failed to be stored in the soil, further leading to the failure of vegetation recovery. The nutrient and the sallow weathering sediment were strongly eroded in the central part of the eruption area due to the sharp slope, sufficient precipitation, and the massive exposure of bare rock (Cook and Halpern, 2018). The lack of plants prevents this situation from improving, ultimately creating a positive feedback mechanism.

The third hypothesis of the unvegetated area is the lack of seeds, especially for those that could only be trans-carried by insects and birds. The bare rock in those areas cannot supply habitats for creatures. The minor affected area could be recovered faster as the seeds could be buried shallowly. The phenomenon could prove that the margin area was recovered firstly after the volcanic eruption (Figure 2).

Fourth, the slowdown of vegetation density increase in some periods could be caused by shifting the dominant vegetation types from grass to tall shrubs or forests (Cook and Halpern, 2018). The canopy area increases significantly impact the signal of vegetation detected from a remote sensing perspective (Del Moral and Chang, 2015). This secondary succession can be pretty slow and even harder to start in non-vegetation areas. Thus since 1999, vegetation recovery took into a slower phase and slowed down the general recovery rate for vegetation.

Last but not least, the wildfire increase could be the main reason for decreasing vegetation coverage since 2014. A massive wildfire in 2015 ruined one million acres of forests around Washington state and brunt from June to September (Engel et al., 2017). The wildfire problem is expected to be more severe due to climate change as less precipitation and more windy weather. It could make vegetation recovery more difficult in the future (Engel et al., 2017).

The area in the north-western part of the eruption area gained rapid growth in the first ten years. It may be caused by the plant measures managed by Weyerhaeuser Corporation. They removed volcanic ash, sowed grass from the air, and reforested less damaged areas to produce timbers (Teltscher and Fassnacht, 2018). A rapid increase along the river valley could be caused by adequate water resources and nutrients from the river sediment. The recovery of the vegetation in this area could be necessary for the recovery of the whole region's ecological system. It could protect the soil from erosion and stabilise the hydrological system, which is highly broken due to the landscape change by the eruption (Major, 2003).

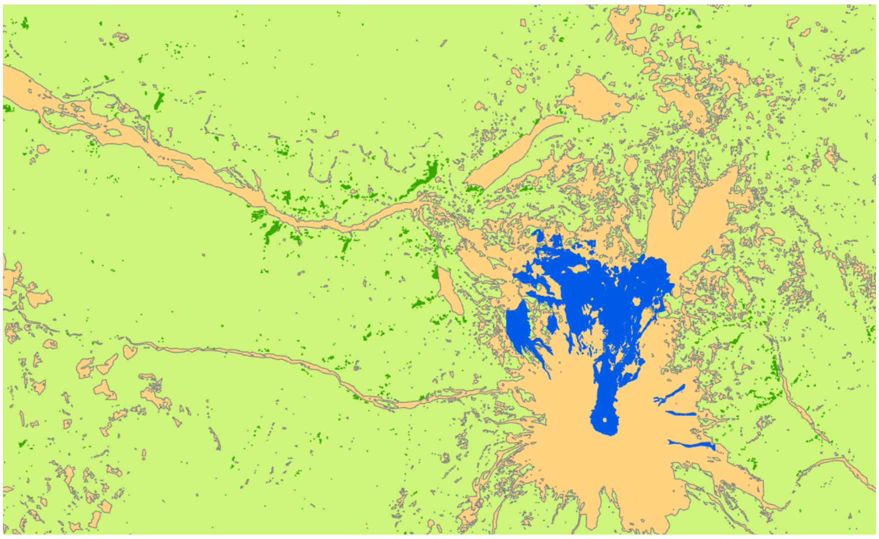

Figure 4. Lava trail map with 2019 vegetation map as base map.

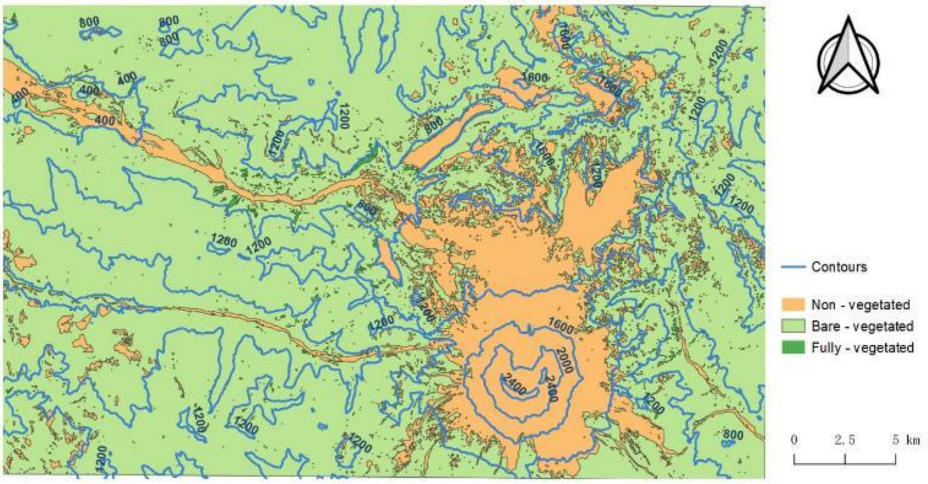

Figure 5. Contour map with 2019 vegetation map as base map.

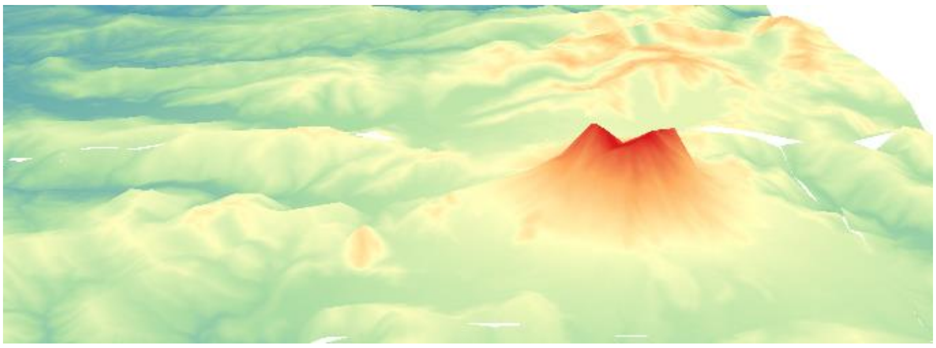

Figure 6. Three-dimensional topography of the study area rendered from DEM image.

5.2. Limitation of data processing

The Landsat 5 carries a thematic mapper (TM), with band three as the red band, spanning 0.63 to 0.69, and band four for the NIR band, travelling from 0.76 to 0.9. The images for the last two years are from Landsat 8, which has an Operational Land Imager (ORI). For Landsat 8, band four is the red band, capturing from 0.63 to 0.68, while the NIR (band five) range is 0.845-0.885, significantly different from the NIR band wavelength range of Landsat 5. However, the objective differences between the two images are not considered when using the thresholds, which is one possible source of error in the results.

Moreover, an objective problem with NDVI is that it tends to become insensitive to environmental changes when biomass and vegetation density reaches a certain level (Van Der Meer et al., 2001). Studies by Farrar et al. (1994) and Van Der Meer et al. (2001) point out that the response of NDVI to changes in low biomass is almost linear. Still, when biomass reaches high levels, the values of NDVI under changes in biomass do not change significantly (Van Der Meer et al., 2001).

6. Conclusion

In this study, the vegetation recovery after the eruption of Mt Sent Helens in 1980 was identified in a thirty-five-year period. Remote Sensing and GIS technology were mainly used in this study to perform detailed research on the rates and trends of vegetation change.

In the data processing and analysing part, NDVI was used to extract the vegetated area. And DEM data also be used to produce a contour map and a 3D simulation model to further study the geological impact on vegetation recovery.

The results showed that the majority trend for vegetation was increasing. However, the change has some variations spatially and temporary. The vegetation tended to grow from the study area's border and into the central volcanic area, which was seriously damaged. On a small scale, the river valley area gained faster recovery due to the supply of sufficient water and nutrients. The northern-western region has more vegetation than the southern side due to the flatter terrain. Temporary, the vegetation grew rapidly in the first ten years, and the growth rate has slowed since the 1990s. The change in growth rate followed the principle of succession.

REFERENCES

[1] Badamasi, M., Yelwa, S., Abdulrahim, M. & Noma, S. 2010. NDVI threshold classification and change detection of vegetation cover at the Falgore Game Reserve in Kano State, Nigeria. Sokoto Journal of the social sciences, 2, 174-194.

[2] Cochran, V., Bezdicek, D., Elliott, L. & Papendick, R. 1983. The effect of Mount St. Helens' volcanic ash on plant growth and mineral uptake. Wiley Online Library.

[3] Cook, J. E. & Halpern, C. B. 2018. Vegetation changes in blown-down and scorched forests 10–26 years after the eruption of Mount St. Helens, Washington, USA. Plant Ecology, 219, 957-972.

[4] Dale, V. H., Delgado-Acevedo, J., Macmahon, J. & Ernst, G. 2005a. Effects of modern volcanic eruptions on vegetation. Volcanoes and the Environment, 227-249.

[5] Dale, V. H., Swanson, F. J. & Crisafulli, C. M. 2005b. Disturbance, survival, and succession: understanding ecological responses to the 1980 eruption of Mount St. Helens. Ecological responses to the 1980 eruption of Mount St. Helens. Springer.

[6] Del Moral, R. & Chang, C. C. 2015. Multiple assessments of succession rates on Mount St. Helens. Plant Ecology, 216, 165-176.

[7] El-Gammal, M., Ali, R. & Samra, R. 2014. NDVI threshold classification for detecting vegetation cover in Damietta governorate, Egypt. Journal of American Science, 10, 108-113.

[8] Engel, R., Marlier, M. E. & Lettenmaier, D. P. Quantifying the Causes and Propogation of the 2015 Washington Wildfires. AGU Fall Meeting Abstracts, 2017. NH42B-02.

[9] Farrar, T., Nicholson, S. & Lare, A. 1994. The influence of soil type on the relationships between NDVI, rainfall, and soil moisture in semiarid Botswana. II. NDVI response to soil oisture. Remote Sensing of Environment, 50, 121-133.

[10] Garrec, J., Plebin, R. & Faivre-Pierret, R. 1984. Impact of volcanic fluoride and SO2 emissions from moderated activity volcanoes on the surrounding vegetation. Bulletin Volcanologique, 47, 491-496.

[11] Gross, D. 2005. Monitoring Agricultural biomass using NDVI time series. Food and Agriculture Organization of the United Nations (FAO), Rome.

[12] Huang, S., Tang, L., Hupy, J. P., Wang, Y. & Shao, G. 2021. A commentary review on the use of normalised difference vegetation index (NDVI) in the era of popular remote Sensing. Journal of Forestry Research, 32, 1-6.

[13] Huete, A. R. 2012. Vegetation indices, remote Sensing and forest monitoring. Geography Compass, 6, 513-532.

[14] Lawrence, R. L. & Ripple, W. J. 1998. Comparisons among vegetation indices and bandwise regression in a highly disturbed, heterogeneous landscape: Mount St. Helens, Washington. Remote Sensing of environment, 64, 91-102.

[15] Major, J. J. 2003. Post-eruption hydrology and sediment transport in volcanic river systems. Water Resources Impact, 5, 10-15.

[16] Marzen, L. J. 2001. Remote Sensing of change in the Mount St. Helens blast zone, Kansas State University.

[17] Marzen, L. J., Szantoi, Z., Harrington, L. M. & Harrington Jr, J. A. 2011. Implications of management strategies and vegetation change in the Mount St. Helens blast zone. Geocarto International, 26, 359-376.

[18] Ning, L., Jiayao, W. & Fen, Q. 2020. The improvement of ecological environment index model RSEI. Arabian Journal of Geosciences, 13, 1-14.

[19] Owens, P. N., Petticrew, E. L. & Van Der Perk, M. 2010. Sediment response to catchment disturbances. Journal of Soils and Sediments, 10, 591-596.

[20] Pettorelli, N., Vik, J. O., Mysterud, A., Gaillard, J.-M., Tucker, C. J. & Stenseth, N. C. 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. Trends in ecology & evolution, 20, 503-510.

[21] Rouse, J. 1974. Monitoring the vernal advancement of retrogradation of natural vegetation. NASA/GSFC, type III, final report, greenbelt, MD, 371.

[22] Sobrino, J., Raissouni, N. & Li, Z.L. 2001. A comparative study of land surface emissivity retrieval from NOAA data. Remote Sensing of Environment, 75, 256-266.

[23] Srinivas, P., Das, B., Saibaba, J. & Krishnan, R. 2004. Application of distance based vegetation index for agricultural crops discrimination. XXth ISPRS Congress, Commission.

[24] SWANSON, F. J., JONES, J. A., CRISAFULLI, C. M. & LARA, A. 2013. Effects of volcanic and hydrologic processes on forest vegetation: Chaitén Volcano, Chile. Andean Geology, 40, 359-391.

[25] Teltscher, K. & Fassnacht, F. E. 2018. Using multispectral Landsat and Sentinel-2 satellite data to investigate vegetation change at Mount St. Helens since the great volcanic eruption in 1980. Journal of Mountain Science, 15, 1851-1867.

[26] United States Geological Survey. 2022. Mount St. Helens [Online]. Available: https://www.usgs.gov/volcanoes/mount-st.-helens/additional-resources-information-about-mount-st-hele [Accessed 25th July 2022].

[27] Van Der Meer, F., Bakker, W., Scholte, K., Skidmore, A., De Jong, S., Clevers, J., Addink, E. & Epema, G. 2001. Spatial scale variations in vegetation indices and above-ground biomass estimates: implications for MERIS. International journal of remote Sensing, 22, 3381-3396.

[28] Xu, H., Wang, Y., Guan, H., Shi, T. & Hu, X. 2019. Detecting ecological changes with a remote sensing based ecological index (RSEI) produced time series and change vector analysis. Remote Sensing, 11, 2345.