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Development of Land Cover and Carbon Storage in Plawangan Hill of Gunung Merapi National Park, Yogyakarta, Using Landsat Data Series 2009, 2013, 2017, and 2023

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Abstract

Globally, habitat loss, deforestation, and climate change are mostly caused by land cover changes (LCC). The amount of land covered by trees has had a major impact on global warming and climate change. Increasing the amount of land cover helps to mitigate climate change and global warming. This study aims to investigate the changes in land cover and carbon storage in Plawangan Hill, Indonesia, over four years (2009, 2013, 2017, and 2023). The study site was defined as a conservation area that has been periodically impacted both directly and indirectly by volcanic eruptions. Images from Landsat 7 and 8 were used to collect data. Additionally, land cover changes were assessed using the forest canopy density (FCD Mapper) model, which was then utilized to quantify the carbon storage of the research site. The findings demonstrated fluctuations in land cover changes between 2009 and 2023. Additionally, changes in land cover have a direct impact on changes in carbon storage. The age of the trees, type of vegetation, succession stage, and history of eruptions were the variables that were apparent to be the main causes of these changes.

Keywords: *forest canopy density, model, climate changes, Indonesia*

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Introduction

The function of the forest and its ability to provide environmental services are greatly influenced by land cover (Coulston et al., 2014; Velastegui-Montoya et al., 2022). Additionally, the amount of forest land cover plays a significant role in global warming and climate change. Increasing forest land cover contributes to reducing climate change and global warming (Griscom et al., 2020; Basuki et al., 2022). However, a number of anthropogenic and natural variables affect the extent to which forest land cover extends. It is crucial to recognize that forest land cover is also increasingly threatened by deforestation, fragmentation, and degradation (Voigt et al., 2021; Shanee et al., 2023). These are all fuelled by factors such as shifting land use, urbanization, climate change, and natural catastrophes such as volcanic eruptions, floods, and natural forest fires. Moreover, international attention has been focused on the high pace of deforestation and forest degradation, which has resulted in forest devastation. This is because the problem not only results in the loss of tropical forest land cover like those in Indonesia, but also in an increase in greenhouse gas (GHGs) emissions, which eventually causes GHGs to build up in the atmosphere (Sadono et al., 2022). Because of these threats and disruptions, many forests in Indonesia need to be sustainably managed and conserved.

Conserving forests helps decrease greenhouse gas emissions (Kremen et al., 2000; Sanquetta et al., 2011). Forest conservation is defined as the ability to establish and preserve forested areas for the sustainability of current and future generations (Pawar & Rothkar, 2015). According to the most recent IPCC assessment published in October 2018, regeneration and forest conservation alone might account for 24–30% of the climate change response. With more than 100 countries incorporating trees in their climate promises for 2025 or 2030, this fact is well acknowledged. Importantly, the state of Indonesia's forests 2022 emphasizes the importance of tropical forests in combating climate change. According to the Ministry of Environment and Forestry (MoEF) Republic of Indonesia (2022), the government has pledged to reduce GHG emissions by 29% by 2030 and up to 41% with sufficient international support. This was done to lessen the hazards associated with climate change.

The protection of ecosystems and diversity of flora and fauna are the primary goals of conservation areas, which contribute to efforts to maintain the quantity of forest land cover. This feature provides conservation areas with the

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capacity to absorb and store forest carbon stocks, especially forested areas. The capacity of vegetation to absorb carbon can reduce carbon emissions into the atmosphere, thereby limiting the rise in the earth's surface temperature. According to previous studies, protected areas globally are thought to absorb 0.5 Gt CO_2e annually, or about 25% of the carbon absorbed by all terrestrial ecosystems (Melillo et al., 2016; Matheus, 2018). Nevertheless, by 2100, carbon absorption is expected to drop to about 0.3 Gt CO_2e, and if a more drastic climate change scenario is applied, it may potentially reach zero. Between 2012 and 2017, 1.62% of Indonesia's 43 land national parks decreased (Dwiyahreni et al., 2021). This reveals that designating a national park does not automatically ensure that there is no risk of loss of forest cover in these areas.

The study site of this research is one of Indonesia's mountainous protected areas in the Special Region of Yogyakarta (DIY). Plawangan Hill is the protected area and the part of Mount Merapi National Park (MMNP). The MMNP area has the potential to be an important phenomenon to be organized in the spatial pattern and the roles of the parties from an ecological, economic, and sociocultural standpoint. Aside from its high potential for biodiversity and the attraction of tourists, the MMNP area itself plays a significant and strategic role as the primary source of water for Central Java and DIY Provinces, providing clean water supplies and irrigation for agricultural land. The MMNP region offers IDR141.3 million in year indirect economic advantages due to its carbon storage (Widodo et al., 2017).

According to the Decree of the Minister of Energy and Mineral Resources Number 13.K/HK.1/MEM.G/2021, Plawangan Hill has been stated as a geo-heritage location because of its stunning views of tropical forests and unusual and diversified geological features that have unique rocks formed by Mount Merapi's 40,000-year-old eruption. Historically, Plawangan Hill was directly and indirectly affected by the Merapi eruption, which could become the major factor affecting land cover changes in this area. Plawangan Hill was formerly a part of Perhutani, which was later designated as a conservation area in 2004 (Wijayati & Rijanta, 2020). In this instance, the area's land cover gradually changed as the status of the Plawangan forest changed from management to conservation. Several studies have been conducted in Plawangan Hill regarding important issues related to anuran diversity and feeding habits (Kuswantoro et al., 2011), conflict resolution, sand mining (Sulaksono & Hadiyan, 2015), vegetation analysis (Muslih, 2019), birdwatching tourism (Pratiwi, 2020), epiphytic orchids (Priambodo et al., 2021), and various types of terrestrial mammals (Sulaksono et al., 2022). Previous studies on Plawangan Hill have generally focused on wildlife, tourist attractions, and vegetation. However, no studies have been conducted on the level of land cover and the amount of carbon storage in Plawangan Hill, which is one of the forests' most important functions in reducing climate change. In addition, the MMNP was designated as a conservation area in 2004, and the massive eruption of 2010 periodically affected the land cover of Plawangan Hill. Therefore, the aim of this study was to determine how Plawangan Hill's land cover and carbon storage changed throughout the four-year period before and after the volcanic eruption.

Methods

Research site Merapi Volcano is one of the massive quaternary core volcanoes of the Sunda Arc in Indonesia, which is produced by the northward sinking of the Indo-Australian Plate beneath the Eurasian Plate (Hamilton, 1973; Gertisser & Keller, 2003). Moreover, it is an active volcano in the province of Yogyakarta and has the potential to increase natural tourism. Mount Merapi (MMNP) was designated as a national park as part of the government's efforts to promote sustainable natural resource management and ecosystem biodiversity (Suryanto et al., 2010). According to Dwi and Susilowati (2015), Yogyakarta is situated between S7°47′49.445″ and E110°22′13.904″, and has a total area of 3,185.80 km^2. MMNP shares its border with two provinces, the Yogyakarta Special Region and Central Java, as well as four sub-districts: Sleman, Magelang, Boyolali, and Klaten. Mount Merapi has erupted 61 times since the 15th century, but the 2010 eruption was the largest in recorded history (Umaya et al., 2020). The merapi region falls under the category of type B (tropical monsoon area), which is distinguished by high-intensity rainfall from November through March and a dry season that can frequently be extremely dry without any rainfall from April to October. The range of annual precipitation is 2,500–3,500 mm (Sutomo & Fardila, 2013).

Forest land cover and carbon storage ***Data collection and image processing*** Four multi-spectral spatial resolutions with the fewest clouds of Landsat 7 (ETM) for pre-eruption 2009 and Landsat 7 (OLI) 2013, 2017, and Landsat 8 for 2023 years post-eruption were downloaded. To take advantage of the limited availability of cloud-free pictures, data from the United States Geological Survey (USGS) website were used (Emaran et al., 2016; Hossain et al., 2016). The Plawangan Hill vector boundary and Google Earth images from 2023 were used as additional data (Table 1).

All satellite images were geometrically rectified to the World Geodetic System (WGS84) datum and referred to as the USGS L1T findings (Storey et al., 2014; Roy et al., 2016). With the help of the Universal Transverse Mercator framework, the images were projected in the Geo-TIFF format (Zone UTM 49 South). Radiometric and geometric modifications were performed using the unrestricted software quantum GIS. To minimize atmospheric influences that interfere with data processing (Young et al. 2017; Zhou et al. 2019). Before being processed by the FCD Mapper Ver.2 program with support from CEOS, TIFF/GEO TIFF, and BMP or BSQ/BIL formats, each of the seven groups of Landsat images were converted to BIL format. Finally, the coverage of satellite images was restricted to the vector bounds of Plawangan Hill. Landsat TM satellite data were georeferenced to the WGS 1984 UTM 49S. A root square mean error of 0.5, or approximately 15 m of ground accuracy, was produced using 31 control points selected from 1/25,000 scale topographic maps using the nearest-neighbor approach. GPS technology was used to pinpoint the locations of the

Figure 1 Map of research area (A) Indonesia flowed by (B) Special Region of Yogyakarta, (C) Sleman Region and (D) Plawangan Hill.

Table 1 Detail information of research data collection

Data	Acquisition date	Sources
Landsat 7, Path/Row 120/065, spatial resolution 30 m	05/06/2009	USGS[1]
Landsat 8, Path/Row 120/065, spatial resolution 30 m	28/09/2013	USGS[1]
Landsat 8, Path/Row 120/065, spatial resolution 30 m	18/05/2017	USGS[1]
Landsat 8, Path/Row 120/065, spatial resolution 30 m	22/07/2023	USGS[1]
Ground check	13/10/2023	Plawangan hill
Plawangan hill boundary	2009, 2013, 2017, 2023	BPKH

Note: United States Geological Survey (USGS[1]), Balai Pemantapan Kawasan Hutan (BPKH)

samples and test sites. However, the GPS point reduced positional inaccuracies, typically averaging 4 m (Gunlu et al., 2014).

Analysis of land cover and carbon storage changes SNI-Standard Nasional Indonesia Number 7645-2010 is the land cover change order framework used for land cover classification by the National Standardization Agency (BSN, 2010). Based on the QGIS software, the land cover class was split into 5 categories: non-forest, open forest, low-density forest, moderately dense forest, and high-density forest. In this instance, attention was paid to two important aspects, specifically post- and pre-eruption-affected areas. By employing this method, Equation *[1]* was used to calculate the LCC portion.

$$CP = \frac{CLCA^{*} - PLCA}{PLCA} \cdot 100\% \qquad [1]$$

note: CP = change proportion (%), $CLCA*$ = current landcover changes area (ha), $PLCA$ = previous landcover changes area (ha).

Once the land cover class was identified, the carbon storage for each class was calculated based on the carbon storage value (Tosiani, 2015; Malahayati & Masui, 2019). The land cover class definitions and carbon storage values used in this study are listed in Table 2.

To streamline the land cover categorization procedure, FCD Mapper Ver.2 was utilized to examine tree canopy density in the research area. The state of the forest vegetation was evaluated using FCD Mapper (Rikimaru et. al 2002; Joshi et al. 2005). The advanced vegetation index (AVI), bare soil index (BI), shadow index (SI), and thermal index (TI) were estimated using this technique using FCD Mapper Ver.2. The FCD map was produced using FCD Mapper Ver.2 for the years 2009, 2013, 2017, and 2023 and the rate per pixel was determined. The key computations and equations utilized by the FCD model to generate the data are displayed in Table 3.

Land cover was analyzed using the FCD Mapper Ver.2. The training data were compiled from the 4 Landsat images. The training data were used to categorize photos for the years 2009, 2013, 2017, and 2023 using a supervised classification-maximum likelihood classification technique. Post-classification smoothing was performed using a 3 m × 3 m pixel majority filter to lessen the salt-and-pepper effect caused by the unpredictability of spectral effects. To simplify

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Table 2 Explanation of land cover classes

Land cover class	Description	Carbon storage (ton ha^{-1})
Non-forest (NF)	Non-forest areas include open exposure areas, sediments, buildings, and areas that have not yet shown signs of regrowth after volcano eruption (0–27.93%)	2.50
Open forest (OF)	Areas with bushes, grasses and sporadic reeds, spikes, and natural trees (27.93–32.97%)	4.00
Low-density forest (LDF)	Areas with naturally distributed trees or shrubs in which are still undergoing the succession process and have not yet attained a stable forest ecosystem and areas with a canopy of plants at the pole stage (32.97–36.85%).	30.00
Moderately dense forest (MDF)	Areas with trees which have open canopy of various tree stage (36.85–42.67%).	98.38
High-density forest (HDF)	Land comprising mature trees; an area where the healthy trees occupy the land cover (42.67–100%).	98.84

Adapted from land classification system developed by the BSN (2010); Pujiono et al. (2019).

Table 3 Forest canopy density mapper's formulas and method

Index	Formula or algorithm
NDVI	= (NIR–Red/NIR + Red)
AVI	= [NIR × (256-Red) × (NIR–Red) + 1]1/3, (NIR–Red)>0
	= [NIR ×(65536-Red) × (NIR–Red) + 1]1/3 , (NIR–Red)>0
ANVI	= This index is derived from NDVI and AVI by PCA
BI	= [(SWIR1 + Red) – (Blue + NIR) / (SWIR1 + Red) + (Blue + NIR)] × 100 + 100
	= [(SWIR1 + Red) – (Blue + NIR) / (SWIR1 + Red) + (Blue + NIR)] × 25600 + 25600
SI	= [(256– Blue) × (256 – Green) × (256 – Red)]1/3 (Landsat 7)
	= [(65536–Blue) × (65536 – Green) × (65536 – Red)]1/3
TI	= This index is calibrated from the thermal data band
FD	= This index is calculated from the first principal component of VI and BI
SSI	= This index is calibrated for the forested land
FCD	= $(VD \times SSI + 1)^{1/2}–1$

Note: Landsat bands: Visible bands = blue, green, red; NIR = near infrared; SWIR = shortwave infrared indices: VI = vegetation index; NDVI = normalize difference vegetation index; AVI = advance vegetation index; ANVI = advanced normalize vegetation index; BI = bare soil index; TI = thermal index; VD = vegetation density; SSI = scaled shadow index; FCD = forest canopy density
Source: Rikimaru et al. (2002); Mon et al. (2012); Pujiono et al. (2019).

the measurement of the area for each type of land cover classification, image classification was finally converted into a vector format.

Accuracy assessment The accuracy of each FCD land cover classification result was evaluated by comparing it with boundary surveys, historical geotagged data, and Google satellite images (Disperati et al., 2015; Tsutsumida & Comber, 2015; Negassa et al., 2020). The producer accuracy in Equation *[2]* defines map correctness from the perspective of the map producer. This demonstrates that the actual features on the ground are consistently and precisely displayed on the planned map. Additionally, it is the number of reference sites that are accurately segregated from the overall number of locations used as references for that class.

$$PA = \frac{TPC}{TPCR} \quad [2]$$

note: *PA* = producer accuracy (%), *TPC* = total pixel count for classification; *TPCR* = total pixels in classification from reference data (i.e., total rows).

Equation *[3]* demonstrates that the user accuracy is equivalent to the correctness of the user result. In essence, user accuracy indicates how frequently the class shown on the map is available on the ground. This additional factor reduces commission errors, bringing the total number of commission errors to zero. User accuracy is calculated as the total number of correct classifications divided by the overall number of rows for a specific class.

$$UA = \frac{TPC}{TPCR} \quad [3]$$

note: *UA* = user accuracy (%), *TPC* = total pixel count for classification, *TPCR* = total pixels in classification from the reference data (i.e., total columns).

Equation *[4]* was used to calculate the proportion of precision across all classes in the described image. The overall accuracy of the map or the percentage of accurately ordered pixels can be used to demonstrate the accuracy of all land cover classes.

$$OA = \frac{SDE}{TAP} \quad [4]$$

note: *OA* = overall accuracy, *SDE* = total diagonal elements, *TAP* = total accuracy points or pixels (total column).

The classifications and reference data arrangement are

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represented as percentages using the Kappa statistics (Wang et al., 2012; Babu et al., 2020; Negassa et al., 2020). The 6 categories of Kappa values ranged from 0 to 1; 0 indicates a low probability of accuracy. There was a very small probability of accuracy between 0.10 and 0.20, a good chance between 0.21 and 0.40, a moderate chance between 0.41 and 0.60, a significant chance between 0.61 and 0.80, and a basically perfect chance between 0.81 and 0.99 (Cohen, 1968; Hillmayr et al., 2020). According to the RSPO (2017), Kappa accuracy values between 50% and 90% were considered sufficient. Excellent accuracy was defined as a Kappa coefficient value greater than 0.6. The translation result is sufficiently accurate for remote sensing if the Kappa coefficient is larger than 0.6, meaning that no further examination is required.

Results

Changes of land cover The study's findings showed several changes in land cover from 2009, which were less dense than those from 2013. Plawangan Hill was primarily covered in moderately dense forest areas in 2013. In 56% of these cases, the change from HDF to MDF was noteworthy, followed by a 49% change in MDF to LDF. Nevertheless, 37% of the NF areas were LDF (Table 4a). Similarly, the majority of land cover changed from 2013 to 2017 and became denser. Consequently, there was an 80% increase in high-density forest areas. Table 4b presents the 54% change in land cover from the MDF to the HDF. This shift included an increase of 67% from OF to MDF, 66% from LDF to MDF, and 28% from LDF to HDF. The remaining alterations were evident in the land cover, including a 28% change from both the OF and NF areas to the LDF.

Between 2017 and 2023, there were numerous changes in land cover from dense to less dense. Following changes from MDF to NF, OF, and LDF, with percentages of 31%, 19%, and 13%, respectively, there was a 17% change from HDF areas to MDF. In addition, Table 4c indicates that in some OF areas in 2017, 59% of the land cover had changed to NF areas by 2023. Therefore, from 2009 to 2023, the land cover of Plawangan Hill predominantly changed within two classes:

Table 4 Land cover changes in four years in Plawangan Hill: a) 2009–2013, b) 2013–2017, c) 2017–2023, d) 2009–2023

a) 2009–2013

LCC 2009	LCC 2013					Total 2009
	NF	OF	LDF	MDF	HDF	
NF	1.03	8.47	10.19	7.91	0.09	27.70
OF	0.33	3.87	6.91	6.12	0.68	17.92
LDF	0.18	1.16	4.18	7.11	1.79	14.42
MDF	0.09	1.10	5.00	11.79	2.87	20.84
HDF	1.49	1.67	6.46	31.41	15.01	56.03
Total 2013	3.12	16.27	32.74	64.35	20.44	136.91

b) 2013–2017

LCC 2013	LCC 2017					Total 2013
	NF	OF	LDF	MDF	HDF	
NF	0.83	0.10	0.95	0.93	0.56	3.36
OF	0.51	0.54	3.44	10.81	0.93	16.24
LDF	0	0.36	1.86	21.51	9.03	32.75
MDF	0	0	0.66	28.80	35.13	64.59
HDF	0.09	0	0.26	3.76	16.40	20.51
Total 2017	1.44	0.99	7.17	65.80	62.05	137.45

c) 2017–2023

LCC 2017	LCC 2023					Total 2017
	NF	OF	LDF	MDF	HDF	
NF	0.45	0.09	0.00	0.18	0.60	1.32
OF	0.55	0.15	0.00	0.00	0.23	0.92
LDF	3.00	1.31	0.84	1.04	0.88	7.06
MDF	20.16	12.31	8.45	9.18	15.51	65.60
HDF	3.56	4.03	5.15	10.36	38.76	61.85
Total 2023	27.72	17.88	14.43	20.75	55.98	136.77

d) 2009–2023

LCC 2009	LCC 2023					Total 2009
	NF	OF	LDF	MDF	HDF	
NF	2.61	15.74	7.45	1.75	0.09	27.65
OF	0.67	7.34	7.03	2.85	0.05	17.95
LDF	0.34	4.00	5.86	3.57	0.66	14.43
MDF	0.21	3.46	7.67	8.27	1.17	20.79
HDF	0.77	5.40	17.22	26.19	6.46	56.04
Total 2023	4.61	35.95	45.23	42.62	8.44	136.85

Note: LCC = land cover changes; NF = non-forest; OF = open forest; LDF = low-density forest; MDF = moderately dense forest; HDF = high-density forest

HDF and NF. Table 4d shows that there was a 31% shift to LDF and 47% change from HDF to MDF. However, there was a 57% shift in land cover from non-forested to open forests in those areas. In 2023, the HDF remained at 12% from the past, whereas the NF remained at 9% of the overall area. It was evident from the land cover changes between 2009 and 2023 that over half of the area remained at 41% for both OF and LDF and 40% for the MDF class.

Changes of carbon storage Plawangan Hill's carbon storage increased and decreased throughout a range of time periods from 2009 to 2023 owing to various factors, since the land cover and carbon storage were interdependent. Table 5 presents the values of both the land cover and carbon storage at the study site. The Plawangan Hill's carbon storage in tons per hectare. In 2009, HDF had the largest amount of carbon storage (68%) followed by MDF (25%). Only 1% of the carbon was stored in both the OF and NF, whereas 5% was stored in the LDF. In addition, carbon storage increased by 26% in 2013, with increases of 67% in MDF, 21% in HDF, and 10% in LDF. In contrast, NF and OF did not change from the previous year.

Furthermore, there was a significant 35% increase in carbon storage in 2017, with the largest increase occurring in MDF (51%), HDF (48%), and LDF (2%), whereas little to no carbon was stored in the NF and OF. Furthermore, carbon storage will decline by 18% in 2023. MDF had a 64% increase in carbon storage, followed by LDF's 21% rise and HDF's 13% increase in HDF. Ultimately, there is a 4% reduction in carbon storage in Plawangan Hill from 2009 to 2023.

Accuracy and land cover map Table 6 demonstrates that the image classification for 2023 had an overall accuracy of 90.32% and a Kappa score of 86.23%. Moreover, the accuracy of each forest type category was assessed using producer and user accuracies. In 2023, the non-forest accuracy matrix was 100%, indicating the accuracy of both producers and users in that sequence. According to the ground-checking activities in the field, the producer accuracy predicted that the non-forest class in this instance was accurate. Accordingly, HDF received 100% accuracy ratings from both producers and users. In the process of verifying the producer's accuracy, the HDF was precisely discovered during the ground checking. Furthermore, the MDF was 82% accurately defined by the producer, but was 100% precise in the field. In the field, the accuracy value of LDF was 92%, despite the producer accuracy being 100%. Accordingly, although the user accuracy value decreased to 60%, the OF producer value was 75%. The shrubs and sparse vegetation in this instance caused a misinterpretation between the OF and LDF.

There were non-forested areas on the north, middle, and south sides of Plawangan Hill. Additionally, the east side of the hill includes most of the open forest areas. Areas of low- and moderate-density forests were observed on all sides. However, most of the high-density forest area was located on the south side of Plawangan Hill, with lesser amounts scattered toward the west and east.

Discussion

Land cover changes of Plawangan Hill According to the study's findings, there was a decrease in land cover between 2009 and 2013. Several variables could certainly contribute to these changes. The 2010 eruption history indicated that

Table 5 Detail data of land cover and carbon storage of Plawangan Hill

Years	Land cover class	Area (ha)	CS (ton ha^{-1})
2009	NF	28.26	70.66
	OF	18.09	72.34
	LDF	14.66	439.79
	MDF	20.82	2,048.39
	HDF	56.38	5,580.17
2013	NF	33.92	84.81
	OF	16.44	65.76
	LDF	33.05	991.41
	MDF	64.72	6,367.55
	HDF	20.55	2,034.43
2017	NF	1.44	3.60
	OF	0.99	3.96
	LDF	7.25	217.35
	MDF	66.35	6,527.51
	HDF	62.27	6,162.99
2023	NF	4.85	12.13
	OF	36.36	145.44
	LDF	45.57	1,367.04
	MDF	42.85	4,215.19
	HDF	8.54	844.99

Note: NF = non-forest; OF = open forest; LDF = low-density forest; MDF = moderately dense forest; HDF = high-density forest; CS = carbon storage

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the explosion of the volcano harmed Perhutani-planted healthy vegetation in the HDF area. Consequently, the area was still in the succession stage in 2013 before becoming MDF. Meanwhile, with the aid of volcanic materials, the NF began to flourish with vegetation-like shrubs in 2009. In this instance, some species of vegetation could grow during the recovery process because the needles and stem branches of the vegetation that fall on the sediment surface act as mulch and aid in supplying the nutrients needed for seedling growth (Sutomo & Wahab, 2019; Prach et al., 2021).

Furthermore, there were noticeable significant changes in the land cover on Plawangan Hill between 2013 and 2017. Volcanic components are presumably the main cause of the rapid recovery of vegetation (Moran et al., 2000; Jakovac et al., 2021). In areas where they have erupted, materials from volcanoes are advantageous for the long-term regeneration of vegetation but not in the short term (Saputra et al., 2022; Torres et al., 2023). Vegetation requires at least four years to recover. As a result, Table 4b emphasizes that in 2017, the land cover of the study area was substantially better than it had been in the previous period.

There has been a decline in land cover changes between 2017 and 2023. The majority of the area that experienced a decline was found in the wilderness zone of MMNP. Plawangan Hill's status and seasonal factors were potentially the primary drivers of this reduction. Most of the delicate plants that flourished on the elevated Plawangan Hill were *Schima wallichii*, *Cyrtostachys renda*, *Calamus rotang*, *Gigantochloa apus*, and *Bambusa vulgaris*. Nonetheless, due to intense winds and their advanced age, these vegetation types have either fallen or shattered. Moreover, Plawangan Hill has been a conservation area since 2004, which means that it has not undergone any planting activities to enhance land cover or interfere with plant growth or demise (Pawar & Rothkar, 2015). A few trees in the wilderness zone were damaged and uprooted during the ground checking operation. Thus, these aspects could have contributed an essential part of the 2023 changes in land cover, particularly in the OF and LDF classes.

Carbon storage changes of Plawangan Hill Land cover could enhance the capacity of forest carbon storage or cause carbon depletion, which has a major effect on global climate change (Sadono et al., 2022). In line with this, land-cover succession enhances the relationship between land cover and carbon storage (Bhan et al., 2021). The results of this study revealed that Plawangan Hill's carbon storage in four years experienced both increases and decreases since it was affected by the land cover of the area. The findings of the study showed that due to the effects of forest land cover, Plawangan Hill's carbon storage fluctuated over the course of four years. Rapid regrowth of bamboo, bushes, and other vegetation on Plawangan Hill from 2009 to 2013 revealed a 26% increase in carbon storage in this area. The results of the present study are consistent with those of previous studies, which show that the duration of succession has a substantial impact on carbon storage in disturbed ecosystems such as active volcano mountains (Utami et al., 2023).

It was also demonstrated that the carbon storage in the research region increased by 35% between 2013 and 2017. Before 2017, Plawangan Hill made significant progress seven years after the 2010 merapi eruption. These results are consistent with those of other studies on the positive effects of volcanic material on forest recovery and succession (Ishaq et al., 2020; Saputra et al., 2022). Nevertheless, owing to the age and type of vegetation, 18% of the carbon storage in this area decreased from 2017 to 2023. The vegetation identified in the OF and LDF during the ground-checking operations had a low potential to sequester carbon. Species found in the upper region were *S. wallichii*, *C. renda*, *C. rotang*, *G. apus,* and *B. vulgaris*. The ability of a forest to store carbon depends on the age of the tree and the type of vegetation. The amount of carbon stored depends on the growth stage of the plant and the environment in which it grows (Ariyanti et al., 2018; Nuranisa et al., 2020).

Accuracy assessment The FCD Mapper method was selected for this study over the other three methods because of several factors, including its 61% overall accuracy (OA) in identifying four stand density groups. It also had a maximum likelihood (ML) of 57%, fuzzy probability of 49%, and belief dempster shafer of only 45% (Nugroho et al., 2012). The accuracy of the FCD SAVI model was 83.67%, while the accuracy of the original FCD model was 84%, according to the results of another study (Nugraha & Citra, 2020). Hence, the overall accuracy of the current study was 90.32%, indicating that the computations used to determine the changes in land cover were reliable. However, the presence of

Table 6 Accuracy estimation for classified image in 2023

LC class	Ground checking Landsat 2023							
	NF	OF	LDF	MDF	HDF	TU	PA (%)	UA (%)
NF	1	0	0	0	0	1	100	100
OF	0	3	0	2	0	5	75	60
LDF	0	1	12	0	0	13	100	92
MDF	0	0	0	9	0	9	82	100
HDF	0	0	0	0	3	3	100	100
TP	1	4	12	11	3	31	-	-
OA							90.32	
OKV							86.24	

Note: LC class = land cover class; NF = non-forest; OF = open forest; LDF = low-density forest; MDF = moderately dense forest; HDF = high-density forest; TU = total user; PA = producers accuracy; UA = user accuracy; TP = total producer; OA = overall accuracy; OKV = overall Kappa value

B. vulgaris, *G. apus*, *C. rotang,* and other similar species in some areas made it difficult to distinguish between the OF and LDF classes. Given the same height and structure of various vegetation types, the error matrix in this instance could have occurred in the land-cover class demarcation (Olofsson et al., 2014; Souza et al., 2020). Consequently, ground checking was necessary to confirm the accuracy of the data analysis.

Conclusion

In four distinct years (2009, 2013, 2017, and 2023), there have been increases and decreases in the land cover classes of Plawangan Hill. The overall changes in Plawangan Hill's land cover between 2009 and 2023 appear to be less dense. The fluctuations in carbon storage in the research area were greatly affected by this variability. Several variables, including the age of trees, types of vegetation, succession stage, and history of eruptions, have emerged as the primary causes of these changes. Therefore, one of the negative trends resulting from these changes might be the early warning system for MMNP to closely monitor the land cover and carbon storage of Plawangan Hill. Moreover, future conservation efforts can be determined by positive trends in the changes.

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References

Ariyanti, D., Wijayanto, N., & Hilwan, I. (2018). Keanekaragaman jenis tumbuhan dan simpanan karbon pada berbagai tipe penggunaan lahan di Kabupaten Pesisir Barat Provinsi Lampung. *Jurnal Silvikultur Tropika*, *9*(3), 167–174. https://doi.org/10.29244/J-SILTROP.9.3.167-174

Babu, R. G., Maheswari, K. U., Zarro, C., Parameshachari, B. D., & Ullo, S. L. (2020). Land-use and land-cover classification using a human group-based particle swarm optimization algorithm with an LSTM classifier on hybrid pre-processing remote-sensing images. *Remote Sensing*, *12*(24), 4135. https://doi.org/10.3390/RS12244135

[BSN] Badan Standard Naional. (2010). *Klasifikasi penutup lahan* (SNI 7645:2010). BSN.

Basuki, I., Adinugroho, W. C., Utomo, N. A., Syaugi, A., Tryanto, D. H., Krisnawati, H., Cook-patton, S. C., & Novita, N. (2022). Reforestation opportunities in Indonesia: Mitigating climate change and achieving sustainable development goals. *Forests*, *13*(3), 447. https://doi.org/10.3390/F13030447

Bhan, M., Gingrich, S., Matej, S., Fritz, S., & Erb, K. H. (2021). Land use increases the correlation between tree cover and biomass carbon stocks in the global tropics. *Land*, *10*(11), 1217. https://doi.org/10.3390/LAND10111217

Cohen, J. (1968). Weighted Kappa: Nominal scale agreement provision for scaled disagreement or partial credit. *Psychological Bulletin*, *70*(4), 213–220. https://doi.org/10.1037/h0026256

Coulston, J. W., Reams, G. A., Wear, D. N., & Brewer, C. K. (2014). An analysis of forest land use, forest land cover and change at policy-relevant scales. *Forestry*, *87*(2), 267–276. https://doi.org/10.1093/FORESTRY/CPT056

Disperati, L., Gonario, S., & Virdis, P. (2015). Assessment of land-use and land-cover changes from 1965 to 2014 in Tam Giang-Cau Hai Lagoon, Central Vietnam. *Applied Geography*, *58*, 48–64. https://doi.org/10.1016/j.apgeog.2014.12.012

Dwi, S., & Susilowati, A. (2015). Keanekaragaman jenis dan sebaran Selaginella di Provinsi Daerah Istimewa Yogyakarta. *Prosiding Seminar Nasional Masyarakat Biodiversitas Indonesia*, *1*(5), 987–992. https://doi.org/10.13057/psnmbi/m010505

Dwiyahreni, A. A., Fuad, H. A. H., Sunaryo, Soesilo, T. E. B., Margules, C., & Supriatna, J. (2021). Forest cover changes in Indonesia's terrestrial national parks between 2012 and 2017. *Biodiversitas Journal of Biological Diversity*, *22*(3), 1235–1242. https://doi.org/10.13057/BIODIV/D220320

Emaran, A., Rob, M. A., Kabir, M. H., & Islam, M. N. (2016). Modeling spatio-temporal shoreline and areal dynamics of coastal island using geospatial technique. *Modeling Earth Systems and Environment*, *2*(1), 1–11. https://doi.org/10.1007/s40808-015-0060-z

Gertisser, R., & Keller, J. (2003). Trace element and Sr, Nd, Pb and O isotope variations in medium-K and high-K volcanic rocks from Merapi Volcano, Central Java, Indonesia: Evidence for the involvement of subducted sediments in Sunda Arc magma genesis. *Journal of Petrology*, *44*(3), 457–489. https://doi.org/10.1093/PETROLOGY/44.3.457

Griscom, B. W., Busch, J., Cook-Patton, S. C., Ellis, P. W., Funk, J., Leavitt, S. M., Lomax, G., Turner, W. R., Chapman, M., Engelmann, J., Gurwick, N. P., Landis, E., Lawrence, D., Malhi, Y., Murray, L. S., Navarrete, D., Roe, S., Scull, S., Smith, P., Streck, C., Walker, W. S., & Worthington, T. (2020). National mitigation potential from natural climate solutions in the tropics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*(1794). https://doi.org/10.1098/RSTB.2019.0126

Gunlu, A., Ercanli, I., Baskent, E. Z., & Cakır, G. (2014).

Estimating aboveground biomass using Landsat TM imagery: A case study of Anatolian Crimean pine forests in Turkey. *Annals of Forest Research*, *57*(2), 289–298. https://doi.org/10.15287/afr.2014.278

Hamilton, W. (1973). Tectonics of the Indonesian region. *Bulletin of the Geological Society of Malaysia*, *6*, 3–10. https://doi.org/10.7186/bgsm06197301

Hillmayr, D., Ziernwald, L., Reinhold, F., Hofer, S. I., & Reiss, K. M. (2020). The potential of digital tools to enhance mathematics and science learning in secondary schools: A context-specific meta-analysis. *Computers & Education*, *153*, 103897. https://doi.org/10.1016/J.COMPEDU.2020.103897

Hossain, K., Salauddin, M., & Tanim, I. (2016). Assessment of the dynamics of coastal island in Bangladesh using geospatial techniques: Domar Char. *Journal of the Asiatic Society of Bangladesh*, *42*(2), 219–228.

Ishaq, R. M., Hairiah, K., Alfian, I., & van Noordwijk, M. (2020). Natural regeneration after volcanic eruptions: Resilience of the non-legume nitrogen-fixing tree *Parasponia rigida*. *Frontiers in Forests and Global Change*, *3*, 562303. https://doi.org/10.3389/ffgc.2020.562303

Jakovac, C. C., Junqueira, A. B., Crouzeilles, R., Peña-Claros, M., Mesquita, R. C. G., & Bongers, F. (2021). The role of land-use history in driving successional pathways and its implications for the restoration of tropical forests. *Biological Reviews*, *96*(4), 1114–1134. https://doi.org/10.1111/BRV.12694

Joshi, C., De Leeuw, J., Skidmore, A. K., Van Duren, I. C., & Van Oosten, H. (2005). Remotely sensed estimation of forest canopy density: A comparison of the performance of four methods. *International Journal of Applied Earth Observation*, *8*, 84–95. https://doi.org/10.1016/j.jag.2005.08.004

Kremen, C., Niles, J. O., Dalton, M. G., Daily, G. C., Ehrlich, P. R., Fay, J. P., Grewal, D., & Guillery, R. P. (2000). Economic incentives for rain forest conservation across scales. *Science*, *288*(5472), 1828–1832. https://doi.org/10.1126/SCIENCE.288.5472.1828/SUPPL_FILE/1047676.XHTML

Kuswantoro, F., Atmaja, M. B., Permana, W. R., & Trijoko. (2011). Diversity and feeding habit of anura in Plawangan Hill, Yogyakarta after mount Merapi eruption 2010. *International Conference on Biological Science, Faculty of Biology Universitas Gadjah Mada 2011* (pp. 543–546).

Malahayati, M., & Masui, T. (2019). The impact of green house gas mitigation policy for land use and the forestry sector in Indonesia: Applying the computable general equilibrium model. *Forest Policy and Economics*, *109*, 102003. https://doi.org/10.1016/j.forpol.2019.102003

Matheus, F. S. (2018). The role of forests and protected areas in climate change mitigation: A review and critique of the ecosystem services and REDD+ approaches. *Desenvolvimento e Meio Ambiente*, *46*, 23–36. https://doi.org/10.5380/DMA.V46I0.54187

Melillo, J. M., Lu, X., Kicklighter, D. W., Reilly, J. M., Cai, Y., & Sokolov, A. P. (2016). Protected areas' role in climate-change mitigation. *Ambio*, *45*(2), 133–145. https://doi.org/10.1007/S13280-015-0693-1/FIGURES/5

[MoEF] Ministry of Environment and Forestry. (2022). *The state of Indonesia's forests 2022 towards FOLU net sink 2030*. Jakarta: Ministry of Environment and Forestry.

Mon, M. S., Mizoue, N., Htun, N. Z., Kajisa, T., & Yoshida, S. (2012). Estimating forest canopy density of tropical mixed deciduous vegetation using Landsat data: A comparison of three classification approaches. *International Journal of Remote Sensing*, *33*(4), 1042–1057. https://doi.org/10.1080/01431161.2010.549851

Moran, E. F., Brondizio, E. S., Tucker, J. M., da Silva-Forsberg, M. C., McCracken, S., & Falesi, I. (2000). Effects of soil fertility and land-use on forest succession in Amazônia. *Forest Ecology and Management*, *139*(1–3), 93–108. https://doi.org/10.1016/S0378-1127(99)00337-0

Muslih, M. M. (2019). *Analisis vegetasi penyusun hutan alam Bukit Plawangan pada tingkatan tiang dan pohon*. Yogyakarta: Universitas Gadjah Mada.

Negassa, M. D., Mallie, D. T., & Gemeda, D. O. (2020). Forest cover change detection using geographic information systems and remote sensing techniques: A spatio-temporal study on Komto Protected forest priority area, East Wollega Zone, Ethiopia. *Environmental Systems Research*, *9*, 1. https://doi.org/10.1186/S40068-020-0163-Z

Nugraha, A. S. A., & Citra, I. P. A. (2020). Modifikasi model forest canopy density (FCD) pada citra Landsat 8 multi-temporal untuk monitoring perubahan tutupan vegetasi di Kecamatan Sukasada-Bali. *Jurnal Penginderaan Jauh dan Pengolahan Data Citra Digital*, *17*(2), 149–159. https://doi.org/10.30536/j.pjpdcd.2020.v17.a3380

Nugroho, S., Jaya, I. N. S., Saleh, M. B., & Wijanarto, A. B. (2012). Kajian metode deteksi degradasi hutan menggunakan citra satelit Landsat di hutan lahan kering Taman Nasional Halimun Salak. *Jurnal Teknosains*, *1*(1), 2634. https://doi.org/10.22146/teknosains.3988

Nuranisa, S., Sudiana, E., & Yani, E. (2020). Hubungan umur dengan stok karbon pohon duku (*Lansium parasiticum*) di Desa Kalikajar Kecamatan Kaligondang Kabupaten Purbalingga. *BioEksakta: Jurnal Ilmiah Biologi Unsoed*, *2*(1), 146–151. https://doi.org/10.20884/1.BIOE.2020.

2.1.1866

Olofsson, P., Foody, G. M., Herold, M., Stehman, S. V., Woodcock, C. E., & Wulder, M. A. (2014). Good practices for estimating area and assessing accuracy of land change. *Remote Sensing of Environment*, *148*, 42–57. https://doi.org/10.1016/J.RSE.2014.02.015

Pawar, K. V., & Rothkar, R. V. (2015). Forest conservation & environmental awareness. *Procedia Earth and Planetary Science*, *11*, 212–215. https://doi.org/10.1016/J.PROEPS.2015.06.027

Prach, K., Ujházy, K., Knopp, V., & Fanta, J. (2021). Two centuries of forest succession, and 30 years of vegetation changes in permanent plots in an inland sand dune area, The Netherlands. *PLOS ONE*, *16*(4), e0250003. https://doi.org/10.1371/JOURNAL.PONE.0250003

Pratiwi, K. S. (2020). *Pengembangan wisata birdwatching sebagai wisata minat khusus di Bukit Plawangan, Gunungapi Merapi*. Yogyakarta: Universitas Gadjah Mada.

Priambodo, R., Arman, Z., Dewi, M., Cari, R. B., Subhi, F. N., Asharo, R. K., Pasaribu, P. O., & Rizkawati, V. (2021). Inventarisasi dan studi asosiasi anggrek epifit dengan pohon inang di kawasan Bukit Plawangan, Taman Nasional Gunung Merapi. *Bioma*, *17*(1), 19–27. https://doi.org/10.21009/Bioma17(1).3

Pujiono, E., Sadono, R., Hartono, & Imron, M. A. (2019). A three decades assessment of forest cover changes in the mountainous tropical forest of Timor Island, Indonesia. *Jurnal Manajemen Hutan Tropika*, *25*(1), 51–64. https://doi.org/10.7226/jtfm.25.1.51

Rikimaru, A., Roy, P. S., & Miyatake, S. (2002). Tropical forest cover density mapping. *Tropical Ecology*, *43*(1), 39–47.

Roy, D. P., Kovalskyy, V., Zhang, H. K., Vermote, E. F., Yan, L., Kumar, S. S., & Egorov, A. (2016). Characterization of Landsat-7 to Landsat-8 reflective wavelength and normalized difference vegetation index continuity. *Remote Sensing of Environment*, *185*, 57–70. https://doi.org/10.1016/J.RSE.2015.12.024

[RSPO] Roundtable on Sustainable Palm Oil. (2017). *RSPO guidance for land use change analysis*. Retrieved from https://rspo.org/wp-content/uploads/annex-3-luca-guidance-document-english.pdf

Sadono, R., Khan, K., Kusuma, A. F., Siregar, D. I., Yuwono, T., Peday, H. F. Z., & Ruhimat, I. S. (2022). Land cover and carbon storage in a certified sustainable community forest in Sumberejo Village, Wonogiri, Central Java, Using Landsat Data Series 2000, 2015 and 2020. *Agriculture and Forestry*, *68*(3), 183–198. https://doi.org/10.17707/AGRICULTFOREST.68.3.15

Sanquetta, C. R., Corte, D. A. P., & Maas, B. G. C. (2011). The role of forests in climate change. *Quebracho*, *19*(1–2), 84–96.

Saputra, D. D., Sari, R. R., Hairiah, K., Widianto, Suprayogo, D., & van Noordwijk, M. (2022). Recovery after volcanic ash deposition: vegetation effects on soil organic carbon, soil structure and infiltration rates. *Plant and Soil*, *474*(1–2), 163–179. https://doi.org/10.1007/S11104-022-05322-7

Shanee, S., Fernández-Hidalgo, L., Allgas, N., Vero, V., Bello-Santa Cruz, R., Bowler, M., Erkenswick Watsa, M., García Mendoza, G., García-Olaechea, A., Hurtado, C., Vega, Z., Marsh, L., Boonratana, R., & Mendoza, A. P. (2023). Threat analysis of forest fragmentation and degradation for Peruvian primates. *Diversity*, *15*(2), 276. https://doi.org/10.3390/D15020276/S1

Souza, C. M., Shimbo, J. Z., Rosa, M. R., Parente, L. L., Alencar, A. A., Rudorff, B. F. T., Hasenack, H., Matsumoto, M., Ferreira, L. G., Souza-Filho, P. W. M., de Oliveira, S. W., Rocha, W. F., Fonseca, A. V., Marques, C. B., Diniz, C. G., Costa, D., Monteiro, D., Rosa, E. R., Vélez-Martin, E., Weber, E. J., Lenti, F. E. B., Paternost, F. F., Pareyn, F. G. C., Siqueira, J. V., Viera, J. L., Neto, L. C. F., Saraiva, M. M., Sales, M. H., Salgado, M. P. G., Vasconcelos, R., Galano, S., Mesquita, V. V., & Azevedo, T. (2020). Reconstructing three decades of land use and land cover changes in Brazilian biomes with Landsat archive and Earth Engine. *Remote Sensing*, *12*(17), 2735. https://doi.org/10.3390/RS12172735

Storey, J., Choate, M., Lee, K., Markham, B., Morfitt, R., Müller, R., & Thenkabail, P. S. (2014). Landsat 8 operational land imager on-orbit geometric calibration and performance. *Remote Sensing*, *6*(11), 11127–11152. https://doi.org/10.3390/RS61111127

Sulaksono, N., & Hadiyan, Y. (2015). Conflict resolution strategy for ecosystem problems of Mount Merapi National Park: Some lesson from Jurang Jero. *Seminar Nasional Masyarakat Biodiversitas Indonesia*, *1*(6), 1370–1374. https://doi.org/10.13057/PSNMBI/M010618

Sulaksono, N., Pudyatmoko, S., Soemardi, Wardhana, W., Hadiyan, Y., & Nurvianto, S. (2022). Response of terrestrial mammals to various types of disturbance in the Gunung Merapi National Park, Indonesia. *Biodiversitas*, *23*(3), 1635–1647. https://doi.org/10.13057/BIODIV/D230355

Suryanto, P., Hamzah, M., Alias, M., & Mohamed, A. (2010). Post-eruption species dynamic of Gunung Merapi National Park, Java, Indonesia. *Journal of Topical Biology and Conservation*, *7*, 49–57. https://doi.org/10.51200/jtbc.v7i.213

Sutomo, & Fardila, D. (2013). Floristic composition of groundcover vegetation after the 2010 pyroclastic fire on mount merapi. *Jurnal Manajemen Hutan Tropika*, *19*(2), 85–93. https://doi.org/10.7226/jtfm.19.2.85

Sutomo, & Wahab, L. (2019). Changes in vegetation on Mount Agung volcano Bali Indonesia. *Journal of Tropical Biodiversity and Biotechnology*, *4*(2), 54–61. https://doi.org/10.22146/JTBB.41008

Torres, C. M. M. E., Medina-Vega, J. A., Rocha, S. J. S. S. da, Costa, W. da S., Soares, C. P. B., Souza, A. L. de, Jacovine, L. A. G., Lana, J. M. de, & Peña-Claros, M. (2023). Drivers of tree demographic processes in forest fragments of the Brazilian Atlantic forest. *Forest Ecology and Management*, *534*, 120893. https://doi.org/10.1016/ J.FORECO.2023.120893

Tosiani, A. (2015). *Kegiatan serapan dan emisi karbon.* Jakarta: Kementerian Lingkungan Hidup dan Kehutanan.

Tsutsumida, N., & Comber, A. J. (2015). Measures of spatio-temporal accuracy for time series land cover data. *International Journal of Applied Earth Observation and Geoinformation*, *41*, 46–55. https://doi.org/10.1016/ j.jag.2015.04.018

Umaya, R., Hardjanto, Soekmadi, R., & Sunito, S. (2020). Livelihood adaptation patterns of sub villages community in the slope of Merapi Volcano. *IOP Conference Series: Earth and Environmental Science*, *528*(1), 1–13. https://doi.org/10.1088/1755-1315/528/1/ 012020

Utami, I., Sakti, A. D., Yusuf, F. I., Husna, F., & Susanto, D. (2023). Development of secondary forest succession based on estimation of forest carbon stocks ten years post-Merapi Volcano eruption. *HAYATI Journal of Biosciences*, *30*(5), 834–842. https://doi.org/10.4308/ HJB.30.5.834-842

Velastegui-Montoya, A., Montalván-Burbano, N., Peña-Villacreses, G., de Lima, A., & Herrera-Franco, G. (2022). Land use and land cover in tropical forest: Global research. *Forests*, *13*(10), 1709. https://doi.org/10.3390/ F13101709

Voigt, M., Supriatna, J., Deere, N. J., Kastanya, A., Mitchell, S. L., Rosa, I. M. D., Santika, T., Siregar, R., Tasirin, J. S., Widyanto, A., Winarni, N. L., Zakaria, Z., Mumbunan, S., Davies, Z. G., & Struebig, M. J. (2021). Emerging threats from deforestation and forest fragmentation in the Wallacea centre of endemism. *Environmental Research Letters*, *16*(9), 094048. https://doi.org/10.1088/1748-9326/AC15CD

Wang, S. Q., Zheng, X. Q., & Zang, X. B. (2012). Accuracy assessments of land use change simulation based on Markov-cellular automata model. *Procedia Environmental Sciences*, *13*, 1238–1245. https://doi.org/ 10.1016/J.PROENV.2012.01.117

Widodo, S., Sriwidodo, Irham, & Handoyomulyo, J. (2017). Dampak erupsi Gunung Merapi terhadap kawasan Taman Nasional Gunung Merapi (TNGM) di DIY dan Jawa Tengah. *SEPA: Jurnal Sosial Ekonomi Pertanian dan Agribisnis*, *11*(1), 130–141. https://doi.org/ 10.20961/ sepa.v11i1.14164

Wijayati, D., & Rijanta, R. (2020). Evaluasi zonasi Taman Nasional Gunung Merapi. *Jurnal Litbang Sukowati*, *3*(2), 92–106. https://doi.org/10.32630/SUKOWATI. V3I2.93

Young, N. E., Anderson, R. S., Chignell, S. M., Vorster, A. G., Lawrence, R., & Evangelista, P. H. (2017). A survival guide to Landsat preprocessing. *Ecology*, *98*(4), 920–932. https://doi.org/10.1002/ecy.1730

Zhou, D., Xiao, J., Bonafoni, S., Berger, C., Deilami, K., Zhou, Y., Frolking, S., Yao, R., Qiao, Z., & Sobrino, J. A. (2019). Satellite remote sensing of surface urban heat islands: Progress, challenges, and perspectives. *Remote Sensing*, *11*(1), 74. https://doi.org/10.3390/RS11010048