Vol. 13(3): 824-848, September 2025

DOI: https://doi.org/10.23960/jsl.v13i3.1217

Jurnal Sylva Lestari

P-ISSN: 2339-0913
E-ISSN: 2549-5747

Journal homepage: https://sylvalestari.fp.unila.ac.id

Full Length Research Article

Land Use Mapping of Areas with Intense Socio-Economic Activities using Integrated Unmanned Aerial Vehicle and Geographic Information System

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ARTICLE HISTORY:

Received: 11 June 2025
Peer review completed: 4 August 2025
Received in revised form: 25 August 2025
Accepted: 9 September 2025

KEYWORDS:

Geographic information systems
Land use
Maximum likelihood classification
Socio-economic
Unmanned Aerial Vehicle

ABSTRACT

Indonesia's national park development faces a challenging task due to human activities that threaten territorial integrity and gradually degrade the ecosystem. In Aketajawe Lolobata National Park, local communities rely heavily on park resources, resulting in observable changes in land use and land cover. However, periodic monitoring is complicated by limitations in satellite imagery availability and processing, as well as associated time and cost, making it difficult to acquire accurate information on land use. To address this, the study utilized unmanned aerial vehicle imagery to identify and map areas with intense socio-economic activities within the conservation area, aiming to understand the socio-cultural dynamics that affect conservation efforts. The land use classification involved four stages: (1) Orthomosaic image processing, (2) Image interpretation, (3) Supervised classification, and (4) Accuracy assessment. This study produced high-resolution imagery of approximately 640.21 ha with a ground sampling distance of up to 2.89 cm/pixel, which improved the accuracy of land surface interpretation. Mapping was performed at a scale of 1 cm to 2 m. The primary land use was classified into five classes: forest (436.65 ha), agriculture (168.76 ha), water body (20.87 ha), bare land (12.84 ha), and built-up (1.09 ha). The corresponding kappa coefficients were 0.78, 0.66, 0.73, 0.7, and 0.79, respectively, indicating generally reliable agreement. The present findings demonstrate the reliability and accuracy of unmanned aerial vehicle technology as a valuable tool for forest managers to map land use in critical and sensitive areas, such as national parks. As these platforms continue to evolve, this study presents a compelling case for their use in Indonesia's national parks. It also highlights the study's limitations and the advantages of this technology, as well as its potential applications in national park management.

1. Introduction

Indonesia protects 54 national parks, encompassing approximately 16,094,804.89 ha, which constitutes 59.84% of the total conservation area of 26,894,122.42 ha. This vast expanse represents 13.35% of Indonesia's overall forest cover, which amounts to 120,471,864.69 ha (KLHK 2023). These parks are primarily established to serve two purposes: first, to preserve Indonesia's biodiversity and protect the traditional ways of life of indigenous peoples, including their resources for livelihoods, and second, to conserve natural resources for various purposes such as education, tourism, scientific research, and spiritual activities (KLHK 2023). The Directorate General of Nature Resources and Forest Conservation, under the Ministry of Forestry, is the responsible entity for preserving biodiversity and the natural resources the community needs, considering the social and economic relationship with the park resources. A socio-economically significant area is defined by Kelter et al. (2023), Moustakas (2023), Othengrafen et al. (2024) and Seyidova et al. (2024) as a geographic region or community whose value is shaped by its economic activities, social structures, population demographics, cultural influences, and community engagement, all of which have an impact on quality of life and social cohesion. Therefore, areas of high economic value are characterized by significant financial activity, abundant natural resources, and a wide range of income-generating opportunities.

In Indonesia, there are 6,381 villages situated near conservation areas, including 134 indigenous communities residing within national park boundaries (Mulyana et al. 2019; Prayitno 2020), including the Togutil people in Aketajawe Lolobata National Park (Agustamanda, 2024), the Anak Dalam in Bukit Tiga Puluh National Park (Isyaturriyadhah 2024), and the Mentawai tribes in Siberut Mentawai National Park (Nugroho et al. 2023). These communities maintain their strong connections with the natural resources of national parks, including tea plantations in Gunung Halimun Salak (Dewi et al. 2023; Sardjo et al. 2022), coffee plantations in Mount Ciremai National Park (Fajrul'Aini and Nawiyanto 2021), and in Gunung Gede National Park (Padmanaba et al. 2017). While the Indonesian government has made significant progress in national park development, the management of these areas faces serious challenges in maintaining their territorial integrity due to human activities within the park area, especially among communities that depend on park resources for their livelihoods (Meilani et al. 2021). This heterogeneous relationship is shaped by diverse cultural and historical backgrounds across regions and ethnic groups in Indonesia, which are influenced by their historical and cultural backgrounds (Ranubaya et al. 2024; Widiaryanto 2020). As a result, this diversity influences how communities and national park management interact with, depend on, and manage forest resources, as well as both constraints and opportunities for the park to implement inclusive and ecologically sound management strategies.

The biodiversity conservation strategy framework has emerged as a critical concern for governmental agencies and national park management amid increasing anthropogenic pressures within national park territory. It is one of the primary focal areas of the Indonesian Biodiversity Strategy and Action Plan (IBSAP) 2025-2045 (BAPPENAS 2024). A study highlighted the insufficient and inaccurate data on the extent of anthropogenic impacts on land-cover change and the remaining habitats (Roy et al. 2022). While these conservation areas are established to preserve biodiversity, natural habitats, and indigenous people's culture, they are increasingly impacted by various human activities that pose threats to their ecological integrity (Kiswanto et al. 2025; Rianawati 2021; Tilman et al. 2017), and the magnitude and rate of change in biodiversity within habitats are typically poorly quantified (Dornelas et al. 2023). As a consequence, effective management efforts are necessary to monitor national park forests effectively, as most parks in Indonesia lack sufficient human resources and suffer from inadequate government funding (PATTIRO 2020; Nugraha et al. 2024). A key challenge, therefore, is achieving reliable, timely, and cost-effective monitoring methods for land use information based on high-accuracy land feature information. This is beneficial for national park resource management, environmental oversight, and informed decision-making in long-term biodiversity preservation strategies for national park development.

Unmanned aerial vehicles (UAVs), also known as drones, have emerged as a rapidly evolving technology with numerous applications (Robinson et al. 2022). UAV technology offers several benefits over conventional human aerial surveys using piloted flight, including its low cost, flexibility in data acquisition, and ability to collect real-time geographical data for analysis (Iglhaut et al. 2019; Naufal et al. 2024; Utomo 2019). UAVs offer present images and excellent spatial resolution, making them ideal for identifying and mapping vegetation and sensitive areas within the forest (Rees et al. 2018; Giles et al. 2023; Wu 2024), ecologically important geospatial data due to their low cost (Naufal et al. 2022), analyzing forest quality, including tree density, land cover and carbon counting (Messinger et al. 2016; Mlambo et al. 2017; Tang and Shao 2015), improve inventory of forest biodiversity and wildlife composition (Bagaram et al. 2018; Buchelt et al. 2024; Fricker et al. 2015). Image captured using UAV imagery can produce 5 cm resolution photographs, detecting individual plants, vegetation kinds, gaps, human settlements, and patterns in the landscape that were previously impossible to discern with normal remote sensing data (Utomo 2019; Zhang and Zhu 2023). Furthermore, drones can access remote or difficult-to-reach areas that are inaccessible to humans or animals, making them ideal for conducting surveys in challenging environments, such as during wildfires or in dense forest canopies (Hartmann et al. 2021; Tang and Shao 2015). The use of UAVs, integrated with geographic information systems (GIS), enhances the analysis of land cover changes (Tarmizi and Rizwan 2024; Martinez et al. 2021). UAVs have proven effective in urban planning and land use management, as this technology provides detailed insights into human settlements and landscape patterns, which are essential for urban development and environmental planning (Shakhatreh et al. 2019). This technology is an alternative method to detect land use changes overcomes the constraints of common remote sensing methods in forestry by satellite imagery (Natesan et al. 2019), such as due to limitation on flexibility data acquisition (Jumaat et al. 2018), athmorspheric problems such as thin clouds, haze and smoke (Nieto et al. 2024), various images resolution with high-resolution images cover smaller ground areas and tend to be more costly and less frequently available (Mishra et al. 2020) and medium to low-resolution images (e.g. 10 meters or more) lack the spatial detail needed to detect subtle or small-scale changes, affecting applications like land use classification and detail land use features (Guo et al. 2025). Furthermore, the processing of land use data from low-resolution satellite images has some limitations; its results are of lower accuracy than those obtained from high-resolution satellite images and land use information acquired from processing in some areas is not consistent with the actual situation (Puttinaovarat et al. 2023).

Considering the limitations of land use mapping based on satellite imagery, the study mapped land use in Aketajawe Lolobata National Park (ALNP) using UAV imagery and maximum likelihood classification (MLC), specifically identifying and delineating areas of high socio-economic sensitivity. Investigating land use information in this sensitive area is fundamental because it is an essential input for land management and prediction tasks (Puttinaovarat et al. 2023), as well as providing core information to support scientific activities (Hermosilla et al. 2022). Furthermore, accurate land use classification is vital for the sustainable management of natural resources and to learn how the landscape is changing due to climate and human activities (Basheer et al. 2022), resources management and their impacts on humans and their surroundings (Sridhar et al. 2021), and land monitoring (Jamali et al. 2019), all of which require detailed land use maps as an essential input (Basher et al. 2022). UAV technology has been utilized to generate land use data, enabling aerial photography at low elevations and facilitating operations during cloudy days or rainy seasons (Quamar et al. 2023). This is because during the monsoon season, clouds are the main cause of disruptions during the collection of satellite images. Therefore, this technology may be an effective alternative method to be used in Indonesia, as the country experiences significant cloud cover, ranging from 70% to 90% (Cahyono et al. 2015). In the national park, this technology is also relevant due to its ability to access previously inaccessible areas (Noor et al. 2016).

Many socio-economic activities have been identified within ALNP, specifically in the Aketajawe block management, due to the high demand for national park natural resources and territorial conflicts. These activities resulted in the conversion of green areas into agricultural areas and built-up areas (ALNP 2024). For instance, coconut plantations were visible in national park areas, serving as a primary agricultural commodity that contributed to economic growth in North Maluku (Ansari et al. 2023). Therefore, the objective of this study is to assess the capability of UAVs to generate land use data in ALNP. It also aims to identify the impacts of human activities within the national park. This study findings offer significant benefits for effective monitoring of national park resources. Additionally, the results can be integrated as a fundamental input in forest land management planning and provide valuable insights for future studies seeking to adopt improved land survey strategies.

2. Materials and Methods

2.1. Study Area

Aketajawe Lolobata comprises two blocks, with the Aketajawe Block covering a total area of 77,793.95 ha and the Lolobata Block covering 89,525.37 ha. This national park is located in North Maluku, Indonesia (ALNP 2024), and it lies between 0°46′30"–0°25’30" N and 127°36′0"–127°51′0" E. The Aketajawe block served as the study area because it experienced more complex anthropogenic pressure due to several human socio-economic activities, such as resin harvesting, build-up facilities, coconut farming, agricultural land and traditional or cultural activities, compared to the Lolobata block, as Lolobata territory is relatively remote, so it is difficult for villagers to access (ALNP 2024). Five locations (Sidanga, Tayawi I, Tayawi II, Tanalaou, and Akejawi) with intense socio-economic activities were selected within the national park covering 640.21 ha, as shown in **Fig. 1**.

2.2. Methods

The mapping of socio-economic active areas within the study area was conducted using UAVs to capture high-resolution aerial images. These images were subsequently processed using a Geographic Information System (GIS) application to develop thematic land-use maps. Given the expansive area of the National Park, the study focused on identifying and delineating the land use of five selected locations (**Fig. 1**). In general, the methodology was divided into four major stages: (1) Orthomosaic image processing, (2) Image interpretation, (3) Supervised classification performed using the parametric rule, and (4) Accuracy assessment was performed by calculating both the overall accuracy and the kappa coefficient. **Fig. 2** illustrates the methodology flow for this study.

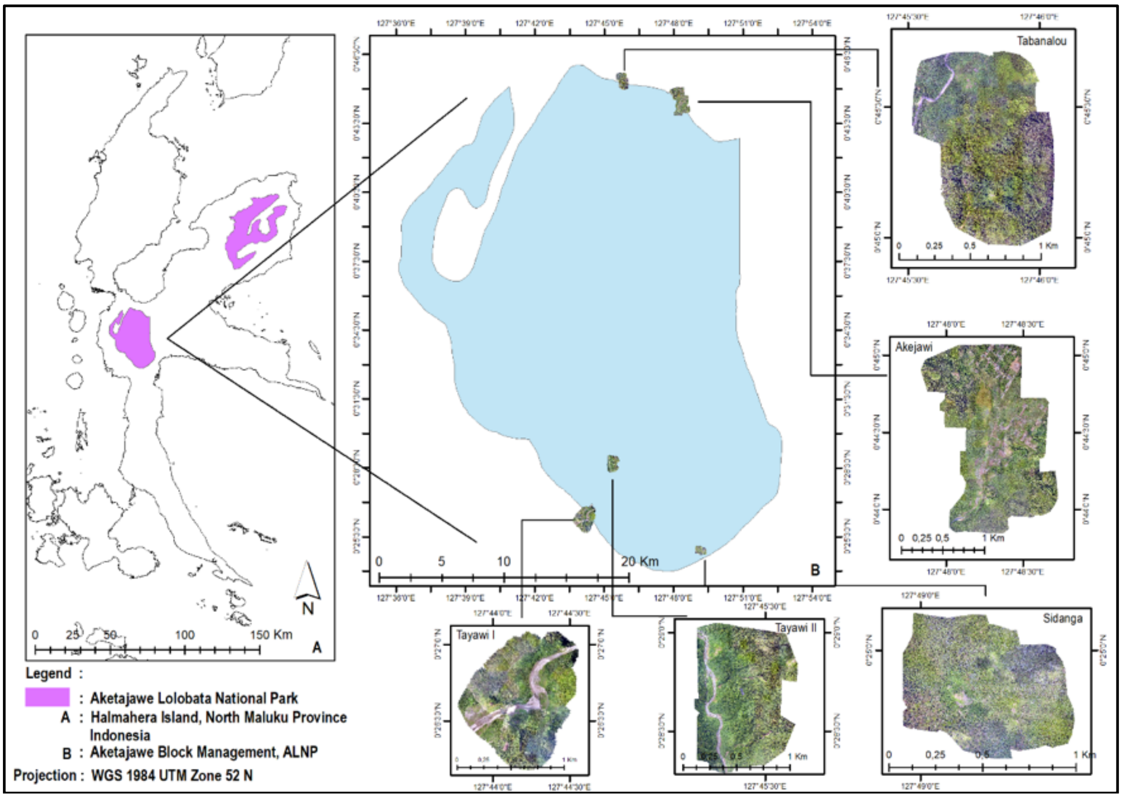


Fig.1. Sampling area for the unmanned aerial survey in Aketajawe Lolobata National Park.

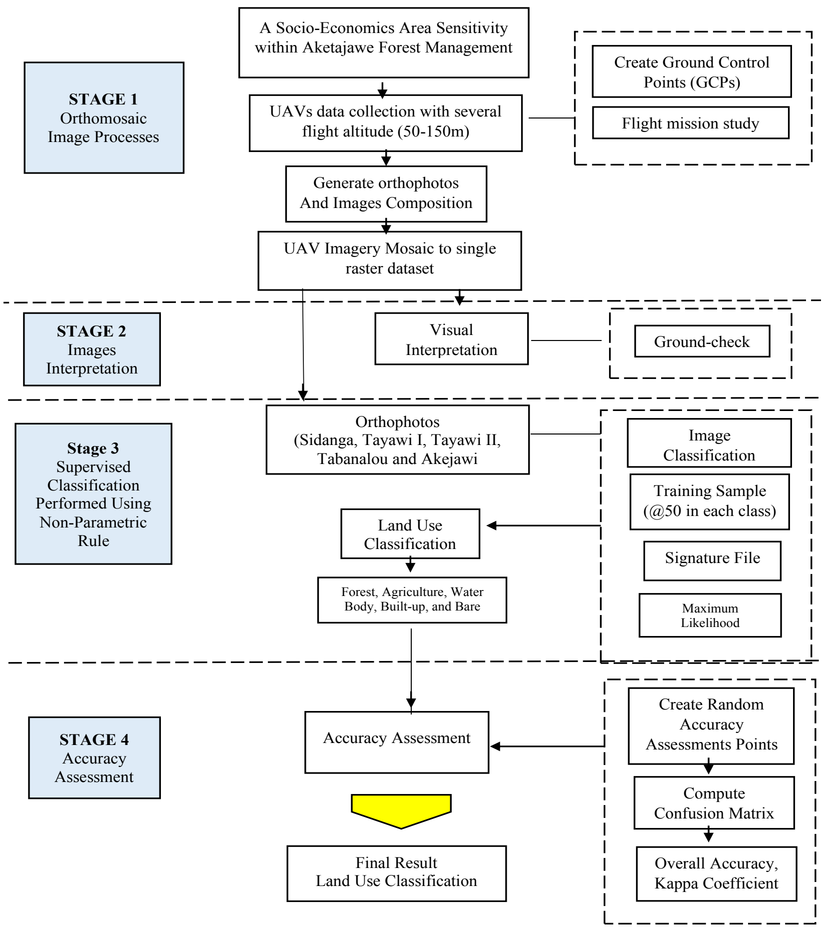


Fig. 2. Flow chart for land-use classification for an area with intense socio-economic activities in Aketajawe Lolobata National Park using UAV imagery and GIS application.

2.2.1. Aerial photographs acquisition

DJI Phantom 4 was used to collect field data. It is a popular, low-cost quadcopter drone type of UAV developed by DJI, and the Phantom 4 (**Fig. 3**) is primarily used for aerial photography and entertainment purposes, while also meeting the mandatory requirements for aerial surveys. It features a mobile mapping system equipped with a global navigation satellite system (GNSS), an inertial measurement unit (IMU), and distance-measuring instruments (DMI), enabling it to perform automated aerial surveys with satisfactory accuracy. This type of drone has been widely used by researchers globally (Clark et al. 2017; Hovhannisyan et al. 2018), including in Indonesia (Arif et al. 2018; Suteris et al. 2018; Utomo 2019), across multiple research disciplines due to its ease of use and the availability of various functional modalities.

Weight		1380 gram
Flight time		28 min
Max. Speed		20 m/s (ATTI mode, no wind)
Max flight altitude		6000 metres
Camera Spec	Sensor	1/2.3" Effective pixels:12.4 M
	Lens	FOV 94° 20 mm (35 mm format equival
	FOV	FOV 94°
	ISO Range	100-3200
	Image size	4000x3000

Obstacle Sensing System Obstacle Sensory Range 2 - 49 feet (0.7 - 15 m) Operating Environment Surface with clear pattern and adequate lighting (lux > 15)

Fig. 3. DJI Phantom 4 specifications.

Paramount to data acquisition is the proper setup, flight planning, and suitable weather conditions (Asnawi et al. 2019; Pepe et al. 2018). To prepare flight missions in the study area, an updated shapefile of Aketajawe Lolobata National Park, acquired from the database, was converted into a KML or KMZ file, which is a prerequisite for Pix4D Capture. It is an important stage to establish a clear boundary, thereby differentiating the study areas from the surrounding regions. Accordingly, a topographic map was used to set up the aircraft's altitude and flight path, another important step in anticipating possible drone obstacles during flight missions and minimizing the probability of aircraft crashes during the survey. Thus, the drone altitude was established between 50 and 150 meters above ground level, with 80% overlap and 70% sidelap, to obtain data at its best resolution. **Table 1** shows the village name, acquisition time, and total number of images taken. A total of 4,163 overlapping aerial photographs were collected. The images of the identified area were obtained from various data acquisitions between 2019 and 2023 to examine patterns in land use classification within the national park, particularly at the five locations.

Table 1. Details of field data acquisition

No.	Location	Flight time	Area Coverage (ha)	Flight Altitude (m)	Total Images	Ground Sampling Distance (GSD, cm/pixel)
1	Sidanga	23’20”	63.9	154	298	5.65
2	Tayawi I	2.03’13’’	136	75	1246	2.89
3	Tayawi II	25’20”	118	150	375	5.75
4	Tabanalou	33’54”	111.02	150	330	5.78
5	Akejawi	1.16’43”	264.45	100	1914	3.86
	Total				4163	

2.2.2. Image processing

This study utilized photogrammetric software to generate orthophotos for each area. The generation of orthophotos comprises several crucial stages. The workflow generally commences with acquiring images obtained through UAV surveys. These images must exhibit substantial overlap to enable the structure-from-motion (SFM) algorithms used by the software (Blanco-Sacristán et al., 2021; Gonçalves, 2023).

Once the images are imported into photogrammetric software, the first step is to align the photos. The software then estimates camera positions and orientations, refining these estimates through a bundle adjustment process that optimizes the spatial arrangement of the images (Piermattei et al. 2015). It is important to verify the estimated camera positions for misalignments, as these can significantly affect the quality of the final orthophoto (Smith and Vericat 2015; Turner et al. 2015). Following the alignment, the next stage involves generating a dense point cloud. This is achieved through dense stereo-matching techniques, which create a three-dimensional scene representation based on the aligned images (Alidoost and Arefi 2017). The quality of the point cloud can be influenced by the settings chosen during processing, such as the number of key points and tie points per image (Mohren and Schulze 2024). Once the dense point cloud is generated, it creates an orthomosaic and a digital surface model (DSM) (Nagendran et al. 2019).

The final steps in the orthophoto generation process include exporting the orthophoto and DSM. Photogrammetric software enables the export of these products in various formats, ensuring they are georeferenced and suitable for further analysis or integration into geographic information systems (GIS) (Svane et al. 2022). To ensure the accuracy of the final orthophoto, three to six ground control points (GCPs) are incorporated by using a printed X sign banner that is spread uniformly in a relatively open area (Garcia et al., 2020; Seo et al., 2024).

GCP has been performed during the initial stages of the process using coordinate measurements from a Garmin 62s GPS device, which helps correct any discrepancies in the spatial data (Abdulrahman et al. 2020; Nagendran et al. 2019; Turner et al. 2015). Furthermore, these images already incorporated a coordinate system; thus, the final product would be geotagged with (x, y, z) coordinates and in TIFF file format. The orthophoto product was subsequently analysed using ArcGIS software for further spatial analysis.

2.2.3. Data analysis

A digital orthophoto from each sampling area exported with the WGS 1984 UTM Zone 52N projected coordinate system was examined in ArcGIS software for image interpretation and supervised classification. Image interpretation refers to extracting meaningful information from raster images, such as satellite imagery and aerial photographs (Šetka et al. 2021). Here, image interpretation helped evaluate and identify existing features, as well as any other valuable land information or geographical features present in the study area. The aim is to produce actual land use information, especially with regard to socio-economic activities, and to visualize the extent of community activities within the national park. Both visual literacy and geospatial thinking are crucial elements for practical image interpretation as they enhance the ability to identify patterns and assign meanings to observed data (Bourdouxhe et al. 2020). Therefore, to ensure the accuracy of the interpretation, a ground study was conducted on the key features.

Although land use information can be derived from the visual interpretation of UAV imagery, the method is flawed because it is subjective and lacks the quantitative depth required for comprehensive analysis (Ivošević et al., 2025). Maximum likelihood classification is a spatial technique that facilitates quantitative examination for which visual interpretation is lacking. Therefore, its application in this study can enhance the reliability of land use data, which will be valuable in producing insights for areas characterized by intense human socio-economic activities, especially in national park settings. This was previously limited by data acquisition through satellite imagery.

Furthermore, an unsupervised classification has been tested before supervised classification by MLC to explore the underlying structures of UAV images and identify potential issues before building a supervised model. Spectral signatures have been developed for each identified class in MLC, including forest, agricultural land, water bodies, built-up areas, and bare land. The geospatial analysis then examines each pixel in the image to the class type to which its signature is most comparable (Rwanga and Ndambuki 2017). The supervised classification method is a widely used and frequently applied technique for quantitative analysis in remote sensing image processing (Richards 2022). This method also generated training samples representing specific classes in each study area, including forest, agricultural land, water bodies, bare land, and built-up areas. These training samples were selected in agreement with UAV orthomosaic images (**Fig. 2**).

This study identifies at least 50 training samples in each land use class, referring to the UAV image band 4. Generally, the number of training samples should ideally be at least 10 to 30 times the number of spectral bands used in the classification process (Maurya et al. 2021; Rashidiyan et al. 2020). The signature has been created to statistically characterize each land use class. The signature (SIG) files contain various information about the land use classes described, and then continue to maximum likelihood classification. This stage was applied to classify the images into five classes: forest, agricultural land, water body, built-up, and bare land, adhering to Indonesia's detailed and nationally standardized land use classification system under the Indonesian National Standard SNI 7645-1:2014, which is a comprehensive Land-Cover/Land-Use (LCLU) classification scheme, as listed in **Table 2**. To generate reliable and valid final land use classification data, accuracy assessment has been performed using two key metrics: overall accuracy and the Kappa coefficient (Foody, 2020; Rwanga and Ndambuki, 2017). This study utilized a minimum of 76 accuracy assessment points in each study area, which were automatically and randomly generated using ArcGIS 10.8, to reduce bias, errors, and miscalculations. These points were then used to calculate confusion matrices within ArcGIS, allowing a comprehensive accuracy assessment in each study area.

Table 2. Land use classification scheme (adopted from Indonesian National Standard SNI 7645-1: 2014)

No.	Land-use Class	Description
1.	Forest	Natural forests that have grown and developed naturally are stable and show no evidence of exploitation or logging.
2.	Water body	Open waters, including rivers, lakes, and reservoirs.
3.	Agricultural land	Land use for dry agricultural activities such as coconut plantations and rice fields (characterized by a bunding pattern).
4.	Bare land	Open land without vegetation (rock, beach sand, or other open areas).
5.	Built-up	Land used for settlements, including rural areas, public facilities and infrastructure, showing clear evidence of human habitation or structures.

3. Results and Discussion

3.1. Unmanned Aerial Vehicle Imagery

A total of 4,163 images were collected, covering an estimated 640.21 ha mapped from 34 flights across five sampling areas. The most extensive flight occurred in the Tobelo Dalam resin harvesting region in Tayawi, which covered 118 ha in one flight. The maximum distance between the aircraft and the remote controller during this flight was approximately 950 meters, powered by a single Phantom battery. The cumulative flight duration for the 34 flights, from take-off to landing, was 4 hours, 42 minutes, and 30 seconds. As data collection was conducted without internet or mobile network connectivity, the base map of the study area was pre-downloaded during flight planning and integrated with topographic data to ascertain the appropriate altitude of the aircraft for each mission.

The ground sample distance (GSD) was determined using the technical specifications of Phantom 4, specifically focal length, camera elevation, image resolution, and sensor dimensions. As expected, images captured at higher altitudes typically exhibited lower resolutions than those taken at lower altitudes, as shown in **Table 1**, where the aircraft altitude was set at 75, 100, or 150 meters, depending on the topographical conditions. A 75 or 100 meter height was employed in relatively flat regions, while a 150 meter height was utilized in hilly areas. The GSD values for three distinct aircraft altitude settings (75, 100, and 150 meters), used to ensure over 80% overlap, are presented in **Table 1**. Orthomosaic processing and analysis were performed using Agisoft Metashape, resulting in several orthophotos, as presented in **Fig. 4**.

Fig. 4. Several important land information spots were spotted from UAV aerial survey in Sidanga, Tayawi, Tabanalou, and Akejawi.

3.2. Image Interpretation

Image interpretation using GIS software reveals that UAV-based orthophotos can effectively capture areas of intense socio-economic activity within the national park, producing high-resolution images at a scale ranging from 1 cm to 2 m, and providing a level of detail that not only enhances image clarity but also significantly aids in interpretation. The lower the scale, the finer the resolution, and the easier the interpretation. The UAV imagery can easily detect agricultural land managed by local communities. For instance, coconut plantations were visible in Sidanga, Tayawi, and Tabanalou, while more diverse agricultural practices were observed in Akejawi, including paddy fields, vegetable gardens, and fruit orchards. Coconut is recognized as the primary agricultural commodity in the North Maluku region, and therefore, it is the key driver of economic growth, with potential for increased production and value-added products such as copra and coconut oil (Ansari et al., 2023). Additionally, with high-resolution images, this study identifies the *Pigafetta* species and the rattan canopy in Tayawi. These plants have economic value to the Togutil people, such as rattan for various handicrafts and furniture (Risnawati et al., 2022), and *Pigafetta* sp. provides essential resources, including food, materials, and medicinal products (Dennehy et al., 2019).

From a social perspective, the Togutil people maintain their traditional practice of resin harvesting as a primary source of income; this practice is deeply embedded in their cultural identity and local knowledge systems, which emphasize the sustainable use of forest resources (Nurrani 2015; Putri et al. 2019). The Togutil people's approach to forest management reflects a balance between economic needs and conservation goals, showcasing how indigenous practices can contribute to the sustainable management of national parks (Al Muhdhar et al. 2019). Furthermore, some shelter Togutil people were also captured along the Tayawi River and in the central point of Tayawi, where *Agathis* resin is harvested. These shelters serve as resting places for community members who are involved in hunting animals, gathering resin, and transporting this material back to their settlements. Interestingly, the UAV-based surveys of Togutil settlement in Tayawi revealed a clear view of the villages' pattern and spatial arrangement, characterized by the presence of residences, agricultural fields, shelters, roads, and public infrastructure (**Fig. 4**). **Table 3** summarizes the land characteristics of these areas. The imagery reveals that the Togutil villages are encircled by forests with abundant green spaces, while another detailed high-resolution land information produced from Akejawi shows agricultural spatial patterns and community settlements around the national park (**Fig. 4**).

Table 3. UAV-based land information and description for the Togutil settlement in Tayawi

Land Use Information	Description
Housing	Typically consists of houses occupied by one Togutil household
Church	Community religious facility serving various purposes, including worship services, community meetings, and other social gatherings
Agricultural field	Household garden plots in the backyard are used to grow vegetables and cassava, while larger agricultural plots are used for coconut plantations
River	The Tayawi River is closest to the Togutil settlement and serves as the community's primary source of water
National Park Site-Office	Resort Tayawi is a site office operated by Aketajawe Lolobata National Park for education, tourism management, and forest monitoring activities
Togutil school	A jungle school established by an international NGO to support local education
Public infrastructure	Government-built infrastructure around the Togutil settlement, including roads, river dams, and an irrigation system
Shelter	A resting place for the Togutil people to use during hunting and rattan harvesting activities

The distinctiveness of Togutil culture, lifestyle, and traditions has been recognized as one of the cultural uniqueness of North Maluku Province (Hasan et al. 2021). The indigenous community has contributed to regional tourism development, emerging as an attractive destination (Putri et al. 2019), with an additional avenue to generate economic revenue for the Togutil people. The integration of Togutil cultural values into forest resource management, tourism activities, and agricultural practices fosters a sense of ownership among community members, which, in turn, enriches the overall tourist experience (Putri et al. 2019). This approach not only helps to preserve cultural heritage but also ensures that tourism development delivers economic and social benefits to both the local community and national park management.

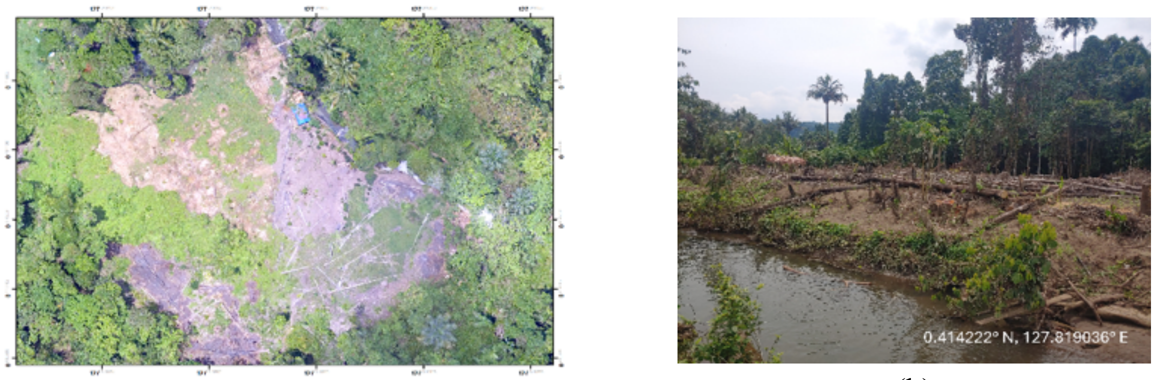
Additional important geographical information can be derived from Akejawi, as presented in **Table 4**, where about 15.17 ha of forested areas have been converted to intensive agricultural practices. These agricultural zones exhibit various cropping patterns and scales. Upon completion of data collection, the agricultural products identified include tomatoes, watermelons, chilies, and mustard greens, all of which provide economic benefits to the Akejawi villagers. These villagers are historically Javanese individuals who migrated to Halmahera Island as part of a transmigration program, and they are recognized for their intensive agricultural practices (Bazzi et al. 2016). In contrast, the island's indigenous population tends to engage in traditional practices with minimal maintenance activities (Faroh et al. 2020). In addition to the intensive agricultural practices in Akejawi, UAV imagery revealed various public infrastructure features, including a river dam, agricultural irrigation systems, human settlements, and roads. Ground verification confirmed the presence of one residential structure within the national park, which Mr. Roji owns (**Fig. 5**).

Table 4. UAV-based land information and description in Akejawi

Land Use Information	Description
Housing	The majority of residents are Javanese transmigrants. Mr. Roji's house, located within the park, also serves as a guesthouse for tourism purposes.
Church	A church in Tayawi that the Togutil community uses for religious purposes, community meetings, and social gatherings.
Agricultural field	The Togutil people mainly use their housing yards to cultivate vegetables and cassava. They also have coconut plantations in larger agricultural areas.
River	The Tayawi River is closest to the Togutil settlement and serves as the primary source of water.
National Park Site-Office	The Aketajawe Lolobata National Park has a site office known as Resort Tayawi, which supports activities such as education, tourism, and forest monitoring.
Togutil school	A jungle school was established by an international NGO to provide education for the Togutil community.
Public infrastructure	Government-built infrastructure around the Togutil settlement, including roads, river dams, and agricultural irrigation.
Shelter	A resting place for the Togutil people to use during hunting and harvesting *Agathis* resin.

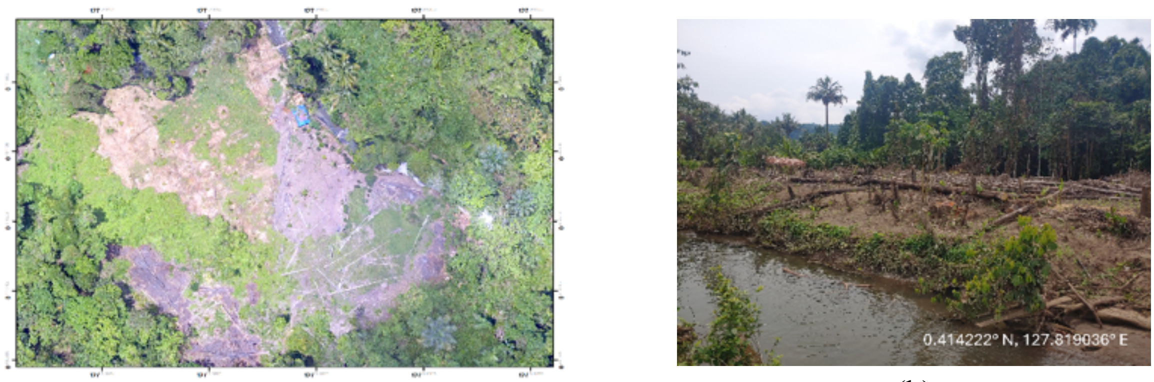
Although areas with high levels of human activities within a national park benefit the nearby communities, they also carry implications for ecological systems and forest integrity. As captured in Sidanga and Tabanalou, illegal logging and land clearing activities were spotted, presumably for agricultural area expansion and to meet the increasing demand for wood for construction (**Fig. 6**). Moreover, more human settlements have been found in Sidanga, with six houses identified within the national park territory (**Fig. 7**). Such existence within the national park zones, particularly those designated for conservation, is a serious concern, one that also violates Indonesian Forestry Law, specifically Act No. 41 of 1999.

Fig. 5. Villager's house (Roji) identified and coconut farm documented based on ground check.



(a) (b)

Fig. 6. Land clearing for agricultural land spotted in Sidanga (a) UAV aerial image (b) ground truthing image.



(a) (b)

Fig. 7. Human settlements spotted in Sidanga (a) UAV aerial image (b) ground truthing image.

3.3. Land Use Maps and Classification

Maximum likelihood classification successfully classified the five primary land use types across all study sites. These include forests, agricultural land (such as paddy fields and coconut plantations), built-up areas (including human settlements and infrastructure facilities), water bodies, and bare land. **Fig. 8** illustrates the land use classification maps for each study site, based on UAV imagery, with a detailed breakdown of land use proportions in **Table 5**.

Table 5. Land use classification in the Aketajawe block of Aketajawe Lolobata National Park, North Maluku, Indonesia

No	Study Area	Forest		Agriculture		Built-up		Water Body		Bare Land		Total (ha)
		Area (ha)	%	Area (ha)	%	Area (ha)	,%	Area (ha)	%	Area (ha)	%	
1	Sidanga	44.45	81.73	8.10	14.89	-	-	0.54	0.99	1.30	2.40	54.39
2	Tayawi I	70.38	52.22	45.65	33.87	-	-	13.23	9.82	5.52	4.09	134.79
3	Tayawi II	99.78	91.43	3.73	3.41	-	-	5.63	5.16	-	-	109.14
4	Tabanalou	82.83	77.58	21.17	19.83	-	-	1.37	1.28	1.40	1.31	106.78
5	Akejawi	139.19	59.20	90.11	38.32	1.09	0.46	0.10	0.04	4.62	1.97	235.12
		436.65	68.2	168.76	26.36	1.09	0.17	20.87	3.26	12.84	2	640.21

Table 5 shows that the study area has a predominant forest cover, accounting for 436.65 ha, or 68% of the total area, followed by agriculture and water bodies, with aerial sizes of 168.76 ha (26.35%) and 20.87 ha (3.25%), respectively. The aerial coverage of bare land and built-up areas is 12.84 ha and 1.09 ha, respectively, of the total study area. Akejawi, in particular, has the largest agricultural area of 90.11 ha. This area has undergone substantial human intervention, as evident in its coconut plantations, paddy fields, and a variety of other crops. The MLC technique successfully identified agricultural land within the national park, with coconut being the dominant crop across all study areas. The unique canopy structure of coconut trees, as revealed by UAV-based high-resolution imagery, exhibits distinct spatial, spectral, and textural features that enhance the separability of coconut plantations from other land covers in classification algorithms. This enables the production of effective classifications using supervised machine learning algorithms, thereby improving classification accuracy (Singh et al. 2019). This result aligned with the orthophoto image interpretation conducted in the study.

3.4. Accuracy Classification Assessment

Accuracy assessments are a fundamental component of land use classification validation and reporting, which investigates the reliability and validity of the quality of information gathered to determine whether the image pixels are well-enough classified or misclassified from remotely sensed data. This quantitative method mainly identifies and quantifies by comparing the classified map data with reference data. The present study uses UAV imagery as reference data due to its greater spatial resolution and ability to provide ground-truth information about the land surface. An error matrix was constructed following the classification of UAV images. A total of 76 random points were generated for each study area, and a confusion matrix analysis was used to calculate the producer, user, and overall accuracy of each land cover classification. The results are presented in **Table 6**.

Table 6. Kappa and overall accuracy for MLC result accuracy assessment

Accuracy Assessment	Tabanalou	Sidanga	Akejawi	Tayawi I	Tayawi II
Kappa	0.78	0.66	0.73	0.7	0.79
Overall Accuracy	87%	90%	94%	82%	98%

The overall accuracy for Tabanalou, Sidanga, Akejawi, Tayawi I, and Tayawi II was 87%, 90%, 94%, 82%, and 98%, respectively. Tayawi II notably achieved the highest overall accuracy at 98%, while Tayawi I recorded the lowest at 82%. Generally, achieving the 80% threshold is considered a satisfactory outcome, indicating a high level of reliability in the classification process, and that a significant majority of the classified pixels correspond correctly to their actual land cover types (Hashim et al. 2022; Hejmanowska and Kramarczyk 2024; Li et al. 2023). However, consider the UAV images' resolution imagery, which has cm-level and GCP-based mapping. The accuracy result of this study is indeed lower than what is typically expected and achievable with such data. This happens because of blurred images detected with poor focus in Tabanalou, Sidanga Akejawi and Tayawi I. The blurred images occurred due to the fast movement of the drone or strong wind during data collection. This blur issue causes errors and can degrade the accuracy of automatic photogrammetric processing algorithms (Sieberth et al. 2016).

Table 7 presents the producer accuracy (PA) and user accuracy (UA) assessment. Overall, it was found that only Akejawi detected has perfect PA and UA percentages (100%), which indicates a strong classification result. Forest classification shows high accuracies, with PA ranging from 79.31% (Tayawi I) to 100% (Akejawi), and UA ranging from 88% (Tayawi I) to a perfect 100% in Tabanalau, Akejawi, and Tayawi II. These percentages indicate reliable forest classification in most areas with some minor variation. The water body has an overall strong result, with PA ranging from 66.575 (Sidanga) to 100% (Tabanalou and Tayawi I), and consistently high UA percentages at 80% (Tabanalou), reaching 100% in most areas, which reflects good detection of the water body across study sites.

Table 7. Producer accuracy and user accuracy

No	Land Use	Tabanalou		Sidanga		Akejawi		Tayawi I		Tayawi II	
	Classification	PA	UA	PA	UA	PA	UA	PA	UA	PA	UA
1	Forest	88.64	100.00	87.80	96.74	100.00	95.00	79.31	88.00	100.00	98.00
2	Agriculture	63.64	70.00	50.00	33.33	100.00	66.67	78.57	65.00	66.67	100.00
3	Water Body	100.00	80.00	66.57	100.00	66.66	100.00	100.00	100.00	97.89	100.00
4	Bare Land	100.00	60.00	100.00	62.50	33.33	100.00	100.00	100.00	-	-
5	Built-up	-	-	-	-	100.00	100.00	-	-	-	-

Notes: PA: producer accuracy, UA: user accuracy.

However, the agriculture and bare land classes show a challenge to classification due to varying variable accuracy results. In agriculture, PA ranges from 50% in Sidanga to 100% in Akejawi, while UA varies from 33.33% in Sidanga to 100% in Tayawi II. This inconsistent classification performance indicates that Sidanga shows notably poorer results. Bare land classification has a very high PA at 100% in Tabanalou, Sidanga, and Tayawi I, but a very low PA at 33.33% in Akejawi. UA varies widely, from 60% in Tabanalou to 100% in Akejawi and Tayawi I. Overall, the dataset reveals that forest, water body and built-up classes are classified with high accuracy. Agriculture and bare land show notable variability and possible areas for improving classification methods or data quality.

In addition to overall accuracy, the kappa coefficient is used to assess the validity and reliability of land use classification results. According to studies, combining these approaches provides a more comprehensive assessment of classification performance (Foody 2020; Gunathilaka and Fernando 2022; Hidayah et al. 2022). The kappa coefficient scores obtained in this study indicate substantial levels of agreement, thereby supporting the reliability of the classification outputs. **Table 6** shows the Kappa coefficient results for Tabanalou, Sidanga, Akejawi, Tayawi I, and Tayawi II at 0.78, 0.66, 0.73, 0.7, and 0.79, respectively. Tayawi II had the highest kappa coefficient score at 0.79, whereas Sidanga scored the lowest with 0.66. The variability observed in the kappa coefficients is likely due to the complexity of the land cover characteristics and the classification methods applied in this study. There were issues with integrating various mixed pixels in land use classification, where both supervised and unsupervised methods produced low user and producer accuracy values (Gunathilaka et al. 2022). Furthermore, some misclassifications have been identified that require attention and correction (Foody 2020; Yilmaz et al. 2023). For instance, bare land and agriculture have overlapping spectral signatures in this study of UAV imagery, which confuses probabilistic classification using MLC (Ali 2015). Furthermore, blurred image problems in Sidanga and Tayawi affect the reliability of pixel-based classification. This resulted in a lower kappa score, despite achieving a high overall accuracy. More specific land use classifications will relate to the impact of kappa coefficient scores, indicating that some particular land use types could be more easily distinguishable than others, thus affecting overall classification performance (Shi et al. 2022). This variability underscored the importance of understanding the context of the classification and the specific land-use types involved. Regarding this study limitation in blurred images, UAV image blur correction using blur kernels, overlapping image information, and filtering blurred images out of sequences might be performed to prevent photogrammetric analysis errors (Sieberth et al. 2016), or increasing UAV camera shutter speed relative to ground point motion time (Hann, 2021). Improved training data quality is achieved by collecting more comprehensive and balanced training samples that accurately represent the variability within each class, thereby enhancing the statistical estimates required by MLC (Guizani et al., 2025).

The study aimed to delineate land use in the national park using UAV imagery, showing that Akejawi had the highest classification accuracy score. This outcome is likely due to the spectral distinctiveness of certain land cover types, such as paddy fields and coconut plantations, which contributed to the high accuracy of the classification. For instance, the spectral properties of paddy fields are associated with chlorophyll (Chl) content, and this variation depends on the species, functional groups, and plant communities, which have different effects on spectral properties (Li et al. 2018). As this study has shown, the altered texture of coconut pixels results in distinct spectral signatures that enhance classification performance. Meanwhile, paddy fields are usually found within larger areas that share visually homogeneous characteristics, which improves the accuracy of sample collection during the classification process, making them easier to identify and classify. In contrast, Rosle et al. (2022) demonstrate that although UAVs can detect grass-dominated vegetation, its low structural complexity and lack of clear canopy differentiation result in lower spectral separability, making accurate classification difficult.

The research results suggest that park management should adopt UAV-based forest monitoring regularly to effectively identify and track land-use and land-cover changes in areas that experience more anthropogenic pressures due to intense human activities or natural disasters. Implementing periodic monitoring is a crucial responsibility for preserving ecosystem integrity, maintaining forest intact, and simultaneously accommodating community livelihoods. UAV surveillance provides timely landscape detection, enabling proactive management to anticipate detrimental impacts before they escalate. This approach might support the park management objectives of keeping the forest intact and optimal ecosystem function.

Furthermore, this study findings underscore the effectiveness of geospatial analysis as an effective and powerful method to help park management produce reliable land use classification. Geospatial techniques offer advanced applications in land management. For instance, detailed land use can facilitate optimized zoning management, create designated specific areas for wildlife conservation, tourism development, or support indigenous community activities as an effort to maximize sustainable resource and ecological preservation (Bruggeman et al. 2018).

4. Conclusions

This study presents an alternative and practical method for detecting land use efficiently and safely by demonstrating the effectiveness of UAV-based forest monitoring applications of land use, particularly in areas with significant anthropogenic pressure, with an overall accuracy level above 80%, indicating a high level of reliability. The maximum likelihood classification successfully categorized land use into five classes: forest (436.65 ha), agriculture (168.76 ha), water bodies (20.87 ha), bare land (12.84 ha), and built-up (1.09 ha). Forest was the predominant land use, covering approximately 68.0% of the total study area, followed by agriculture, which accounted for 26.35%. This study's accuracy assessment shows forest, water body, and built-up classes are classified with high accuracy (PA and UA above 79%), agriculture and bare land show notable variability (between 33.33% and 100%). Remote sensing-based UAV surveys have proven to be a robust and reliable approach for generating reliable land surface information in regions subjected to significant human pressure from intense socio-economic activities. Therefore, this study recommends that park management consider routine UAV surveys for timely management interventions that are otherwise challenging to accomplish using satellite imagery alone. Furthermore, to gain a deeper understanding of the socio-economic activities associated with the detected land uses, future research should conduct surveys among residents to identify the specific activities they engage in within the national park for their livelihood. These proposed future directions are designed to capitalize on the successes of this study and further solidify the critical role of UAV technology in sustainable land management and conservation efforts.

Acknowledgments

The authors gratefully acknowledge the support of the German Academic Exchange Service (DAAD), the Southeast Asian Regional Center for Graduate Study and Research in Agriculture (SEARCA), and the Universiti Driven Research Programme (UDRP), Universiti Putra Malaysia, under the theme Sustainable Management and Utilization of Tropical Plant Resources. Sincere thanks are also extended to the village headmen, villagers, and officers of Aketajawe Lolobata National Park for their valuable information, as well as to colleagues and collaborators within the programme for their constructive input and technical assistance throughout the study.

Author Contributions

A.W.U.: Conceptualization, Methodology, Software, Formal Analysis, Writing – Original Draft Preparation, Validation; N.K.: Formal Analysis, Validation, Resources, Data Curation, Writing – Review and Editing, Supervision; Z.S.: Writing – Review and Editing, Administration, Funding Acquisition, Supervision; S.M.R.: Writing – Review and Editing, Supervision; R.S.: Writing – Review and Editing, Supervision.

Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI And AI-Assisted Technologies in the Manuscript Preparation

During the preparation of this work, the authors used Grammarly, a paraphrasing tool, to smartly blend other research into this article and avoid plagiarism. After using this tool, the authors reviewed and edited the content as needed, taking full responsibility for the publication's content.

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