 https://doi.org/10.1051/bioconf/202515601004

The use of drones and Artificial Intelligence for dugong sighting detection in a limited resource scenario

Akbar Ario Digdo[1,2,3*], *Elisabeth* Astari[1], *Bella* Riskyta Arinda[1], and *Topan* Cahyono[1]

[1]YAPEKA, Kota Bogor 16153, Jawa Barat, Indonesia
[2]Center for Transdisciplinary and Sustainability Science (CTSS), IPB University, Indonesia
[3]International Union for Conservation of Nature and Natural Resource (IUCN) SSC Sirenia Specialist Group

Abstract. The use of commercially available drones and artificial intelligence (AI) has grown in popularity in the last decade. Nonetheless, its usage to detect cryptic and high-mobility marine mammals remains constrained by resource-intensive nature, vast coverage areas, hardware limitations, and environmental variables. This study aims to recount our experience conducting a combination of drone and AI-assisted detection (WISDAM) in a scenario with limited resources to detect dugongs. The operation was conducted in September 2023, April 2024, and May 2024 in North Sulawesi, Indonesia. Prior to flight path design, CMS questionnaires and satellite data were utilized in order to comprehend the spatial and temporal context of the dugongs and their preferred habitat. A DJI Air 2s drone was used in 28 flights, covering 12.09 km^2, yielding 8,509 photos. In total, 47 photos comprise dugongs, including seven with multiple individuals. 56 sightings were successfully identified manually by multiple analysts to minimize bias, and seven photos (12.5%) were considered dubious. AI detection is rather limited compared with manual detection's numbers of positively identified dugong photos. Out of 153 AI detections, only 27 (17.6%) were True Positives. Therefore, more flights are needed to enhance the sample size for machine learning.

1 Introduction

Dugong (*Dugong dugon*) is a seagrass specialist listed as vulnerable on the International Union for Conservation of Nature and Natural Resources (IUCN) Red List at a global scale [1]. Still and all is a critical, cryptic animal that is difficult to sight with inexperienced eyes and cannot be easily marked or recaptured [2]. Therefore, its distribution and population number are very limited or even absent in many parts of the world, including Indonesia [3]. Whereas, estimation of dugong abundance and distribution are essential to implementing management and conservation policies on a national and international level. For instance, the IUCN depends heavily on population size to define conservation status [4]. The Indonesian

* Corresponding author: akbar@yapeka.or.id

National Plan of Action of Dugong and its Habitat (Seagrass) Conservation document (hereafter NPOA for Dugong Conservation) indicated that “population data is unknown, certainly due to minimally conducted population surveys. Dugong ecological surveys are resource-intensive surveys, both in terms of funding and human resources.” NPOA for Dugong Conservation as well is an integrated document in which data and information ought to be based on one of them, population and habitat [5]. Whereas, information failure can lead to conservation action program mismanagement. Additionally, the Indonesian government has established derivative regulation for dugong protection in updated Law Number 32 of 2024 32/2024 on Conservation of Natural Resources and Ecosystems and Law Number 31/2004 on Fishery [6].

Indonesia is recognized as a country that has a significant Dugong population, as confirmed by several studies [3]. The dugong presence in Indonesia is supported by the vast area of seagrass beds as its habitat [7, 8]. 17 species of seagrass currently occur in Indonesian waters [9]. Dugongs forage both in near-shore and subtidal seagrass meadows (up to 40 m deep) and prefer to feed on soft tissue seagrasses such as *Halophila* and *Halodule* in mostly intertidal zones [10, 11]. Researchers used various approaches to monitor dugongs' abundance and distribution, including direct–indirect observations (e.g., sighting, stranding, questionnaire) and remote monitoring (e.g., acoustic telemetry and satellite) [2, 12-14]. Despite the invaluable insight provided through such studies, some approaches have inherent biases in location, scale, or sample size that generate uncertainty in the representativeness of data.

Unmanned Aerial Vehicle (UAV, termed drone hereafter) usage has been emerging for the last ten years [13]. The popularity of small UAVs (<2 kg) received a lot of attention from researchers interested in conducting intensive, repeatable wildlife surveys due to their availability, affordability, and operation convenience. In addition, drones bridge the gap from traditional methods of studying marine megafauna in a direct natural environment (e.g., increase detectability, minimize human risk components, and allow researchers to access remote areas) [13-15]. However, some limitations such as short flight endurance, aviation regulations, environmental variability, and big capital at the beginning (e.g., drone purchase, pilot certification), have constrained the use of drones in survey applications. Associated aerial imagery processing technique is used for verification tools and analysis processes that require low cost and a low level of expertise [14]. Aerial survey design and methods are under development to adapt not only the new technology but strict civil aviation regulations as well (e.g., legal horizontal range of UAV operation restricted to within visual line of sight (VLOS), which severely limits the area that can be surveyed.). Although, in Indonesia, drones can be operated Beyond Visual Line of Sight (BVLOS) referring to Ministry of Transportation Decree no. 37/2020, as long as the drone has Detect & Avoid (DAA) system and tracking system capabilities. However, these kinds of drones are not typically marketable and thus significantly reduce drone survey operational range. Scientific best practices for the use of UAVs in wildlife surveys are being developed to maximize the conservation outcomes. One of them, the standardized UAV survey method created spatially explicit models of dugong density across the survey area and abundance estimate [16]. This study used the novelty of standardized grid sampling, flight planning, data collection, and processing procedures approach features subsequent to the Convention on the Conservation of Migratory Species of Wild Animals (CMS) questionnaire surveys conduction [16, 17]. Allen Coral Atlas satellite imagery assisted us in the detection of benthic coverage areas (in this case seagrass) for the estimation of grid sampling and flight planning. The objective of this paper is to present our experience in implementing aerial survey and AI operations to collect dugong sightings in limited resource conditions, by combining multiple methods to pinpoint the most relevant survey area. This paper is part of the ongoing attempt to systematically survey dugong presence and determine its population in North Sulawesi, Indonesia.

2 Methods

2.1 Study sites

Drone surveys were conducted in North Minahasa and Manado City, North Sulawesi, in September 2023, April 2024, and May 2024. Manado City is situated to the west of North Minahasa, and both areas are known for their potential to support dugong populations, although the precise population size is still unknown [1, 3]. Five villages were selected for drone survey: Tarabitan (1°44'34.2"N, 124°58'55.8"E), Bahoi (1°43'43"N, 125°01'32.2"E), Kulu (1°41'56.6"N, 124°57'00.3"E), Lantung (1°41'05.9"N, 124°55'58.1"E), and Tongkaina (1°34'05.8"N, 124°48'17.2"E) (Fig.1), considering local reports of dugong sightings and studies on their habitat. These areas have healthy seagrass beds, including *Halophila* and *Halodule*, which are vital food sources for dugongs [18, 19].

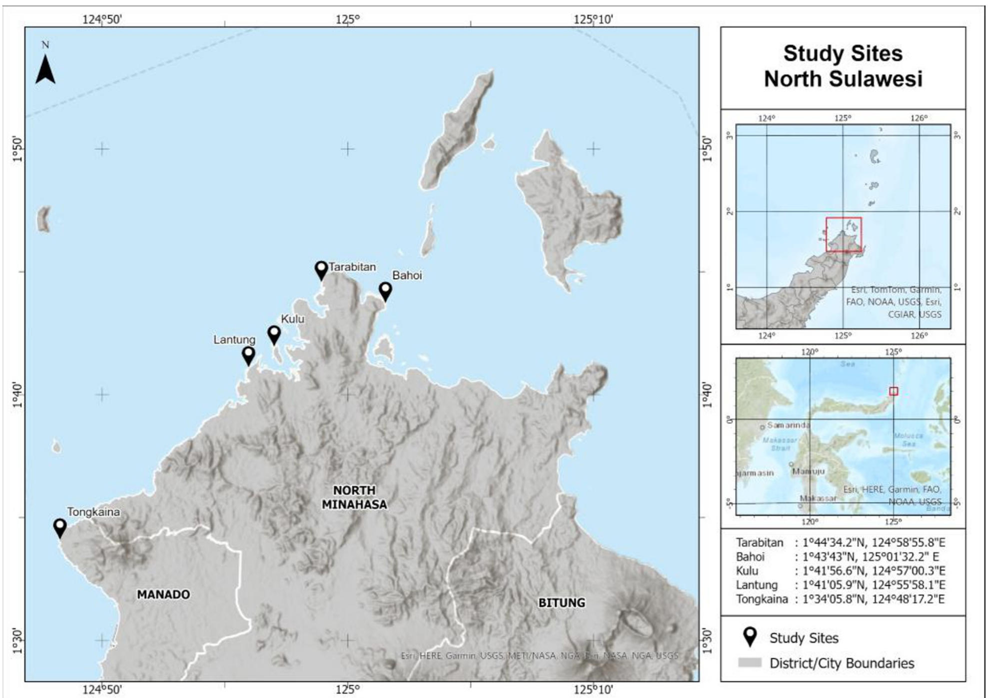

Fig. 1. Study sites.

2.2 Site selection

In this study, layered methods were used to determine the most suitable drone survey area, overlaying seagrass presence and high hotspot-level areas of dugong sightings to select the most appropriate areas for the drone systematic survey, taking into account limited drone performance and flight time available for the research. In the first layer, we utilized the benthic habitat dataset provided by Allen Coral Atlas, which offers an open-access, high-resolution, and wide-ranging representation of seagrass meadows in our study area. Allen Coral Atlas calculates benthic coverage down to 10 meters using a combination of machine learning algorithms with Object-Based Analysis (OBA) and composite satellite imagery. The dataset also provides a consistent and detailed global benthic habitat map with 5 meters of spatial resolution, deriving from a high spatial resolution satellite image mosaic (Planet

Dove; 3.7 meters x 3.7 meters pixel) resolution daily satellite imagery combined with wave models and ecological data [20]. In the second layer, we used the CMS Dugong Questionnaire surveys to collect dugong sighting density per square kilometer and human-dugong interaction (i.e. small-scale fishery, maritime transportation, potential bycatch) in the area [17]. Third, we determine hotspot areas by calculating sighting density per kilometer based on CMS Questionnaire result and overlaying with seagrass extent based on Allen Coral Atlas to design UAV flight plan.

2.3 Flight plan

We designed the flight plan using the DJIFlightPlanner app to fly a series of parallel line transects over the area previously identified based on the Allen Coral Atlas data and CMS Survey. The design of the flight plan included areas to represent multiple dugong sighting densities. We set the flight altitude and other parameters such as overlap, vehicle speed, overlap, and frame rate using the DJIFlightPlanner app. Consultation with Airspace Traffic Control was made to ensure compliance with safety and regulation. The drone surveys were conducted using the Mavic Air 2s manufactured by DJI **(**Supp. 1**)**.

2.4 Image processing

All aerial images were manually reviewed post-flight using the WISDAM (Wildlife Imagery Survey – Detection and Mapping) app by trained observers [21]. This process involved systematically scanning the image from left to right and top to bottom using grid navigation to identify dugongs and other marine megafauna while assessing the environmental conditions. The observers drew geometries on the images, tagged each identified animal, and recorded several sighting information using the digitizer page. The Docker App was also utilized to run the machine learning detection using the WISDAM app.

3 Results and discussion

North Sulawesi becomes one of the provinces with the most dugongs log (518/50.14%) based on information compiled via media sources and publications from 2010 to 2022 [22]. The peak was in the interest of a certain number of community-based Marine Protected Area (MPA) existence [23-25]. These MPA establishments are based on dugongs and their habitat presence.

Conservation regulation should be based on the year-round distribution of focal species. However, this is difficult for dugongs for which movement covers a variety of ecosystems in wide-ranging areas, some inaccessible and remote. Although their ‘home’ location while breeding or foraging remains predicted, they only come to the surface to breathe or rest for short periods of time and cannot be sighted when submerged [26]. Additionally, the colour vagueness compounds detection rate. Consequently, our team uses various approaches to monitor abundance and distribution, including direct (e.g., sightings, drone surveys) and indirect observations (e.g., Allen Coral Atlas, questionnaire). Despite the invaluable insight provided through such studies, some approaches have inherent biases in location, scale, or sample size which generate uncertainty in the representativeness of population data.

3.1 Pre-Aerial survey phase

3.1.1 Allen coral atlas

Based on interactive mapping from the Allen Coral Atlas, the North Minahasa coast consists of 39.4% reef/algae, 32.73% seagrass, 18.81% rock, 1.81% rubble, 1.6% sand, and 0.09% microalgae mats. Manado City comprises 38.17% seagrass, 29.03% rock, 24.40% coral/algae, 8.18 rubble, and 0.21% sand. North Minahasa has ± 5,962 hectares of seagrass meadows, while Manado City has ± 1127.4 hectares of seagrass meadows [20].

Allen Coral Atlas was used to estimate seagrass coverage in our Area of Interest (AOI hereafter). These AOIs include Tarabitan (44.99 ha), Bahoi (12.37 ha), Tongkaina (41.68 ha), and Kulu-Lantung (136.17 ha), respectively. The presence of seagrass is critically linked to the potential habitat of dugongs, as seagrass forms both the primary diet and habitat for this marine mammal [27]. Support for this correlation comes from a previous study that reported dense seagrass coverage in our targeted areas, where species from the genus *Halodule, Halophila,* and *Cymodocea* are recognized as the preferred diet for dugongs [18, 19].

3.1.2 CMS questionnaire

Prior to the UAV operation, we deployed the "Standardised Dugong Catch and By-Catch" a structured mixed questionnaire developed by UNEP-CMS to 180 respondents across three villages (Bahoi, Bulutui, and Tarabitan). We did not survey some villages (Kulu, Lantung, and Tongkaina) due to operational limitations (e.g., surveyors, time, and funding). Of 180 respondents, 86 admitted to having seen dugongs.

Described sighting spots were compiled and brought about 42,730 ha of collated sightings. A kernel density analysis was conducted to determine varying hotspot areas. Over the questionnaire, we tabulated 5 hotspot area categories, hotspot areas encompassing ranges of reported dugong sightings: Very Low (1 sighting), Low (2-3 sightings), Medium (4-5), High (6-7), and Very High (>7 sightings), as displayed in Fig. 2.

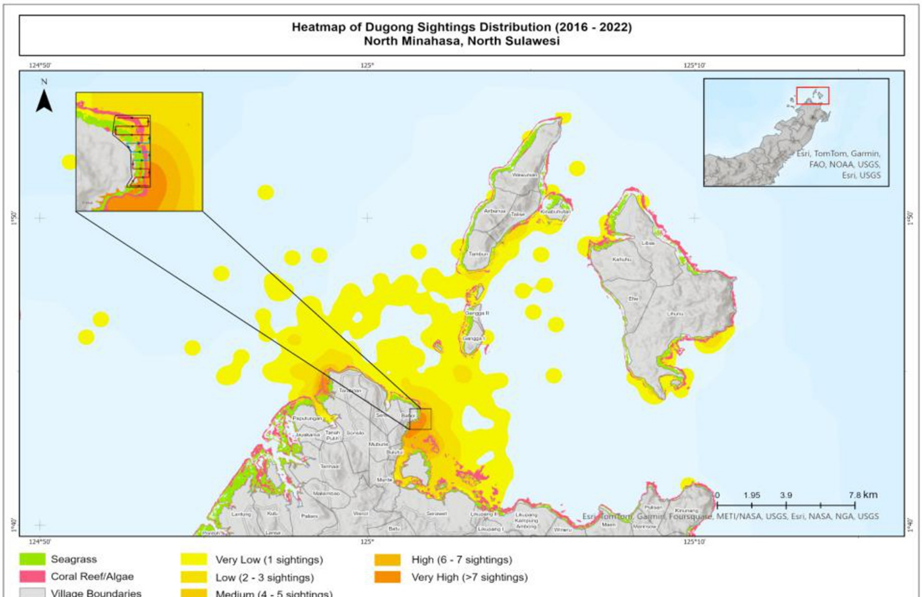

Fig. 2. Heatmap of dugong distribution (2016-2020), North Sulawesi.

We deployed CMS Questionnaires to collect data on dugong sighting abundance and distribution based on local community perspectives. This tool aids us in determining the rough number of the dugong population and mapping important habitats for dugong. Additionally, the questionnaire captured sighting information on sea turtles and other cetaceans and revealed threats to these populations by gathering information on fishery activity, fishing effort, and by-catch. We chose this protocol considering it enables quick and cost-effective implementation, ensures scientific rigor for quantifiable results, integrates spatial and demographic data, and offers a flexible reporting approach [17]. It is important to note that the collected data was derived from indirect observation methods, such as interviews rather than direct sightings, and involved a cohort of individuals who were reflecting on their memories of such sightings. Consequently, the representation of the described scenarios, including temporal and spatial details, may not be entirely accurate.

The questionnaire comprises over 100 questions that must be asked to respondents, alongside additional instruments, including table and map which are required to be completed by the surveyor during the interview session. To enable a more thorough understanding of the various components and the sorts of information that can be retrieved by executing in the manual, it is essential to conduct dedicated training for all enumerators. In multiple instances of administering this questionnaire across different locations, we observed that certain enumerators completed the questionnaire but did not submit the associated spatial data table. Additionally, there were cases where enumerators failed to utilize the provided maps, and in some instances, the maps were used, but the corresponding spatial data was not reported

3.1.3 Flight plan

Subsequent to hotspot consideration, the flight plan was determined by the seagrass cover area detected by Allen Coral Atlas on the defined hotspot space. Flight plans were selected with high seagrass cover area (%) within hotspots with the greatest dugong number. Aside from that, accessibility to the mainland. The 1,209.21 ha (19.4%) surveyed area consisted of 235.22 ha (19.4%) of seagrass and 152.88 ha (12.6%) of coral reef (Fig.3) [20].

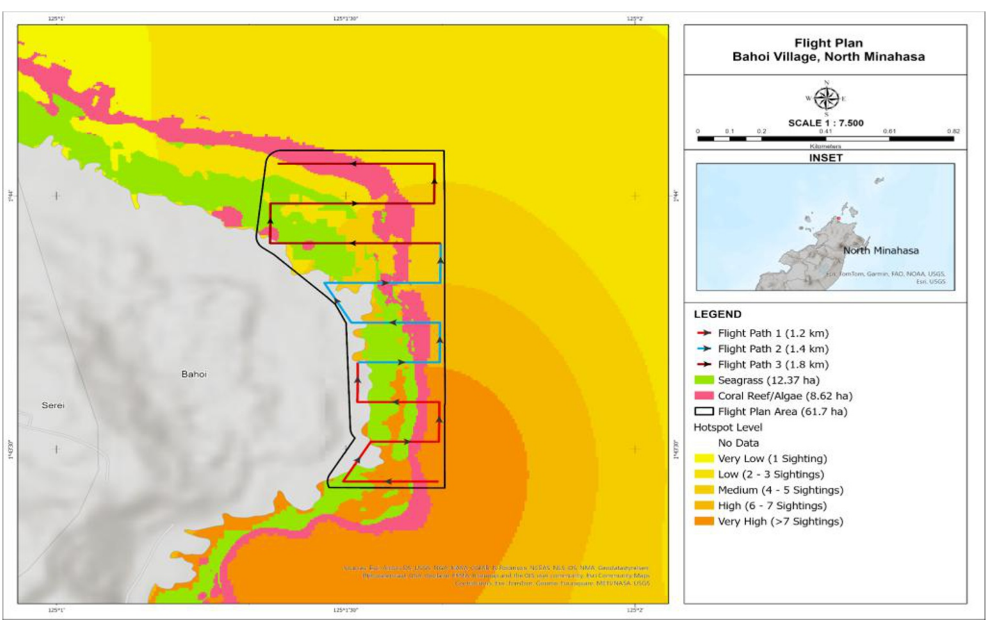

Fig. 3. Flight plan Bahoi Village, North Minahasa.

3.2 UAV aerial survey phase

We conducted 28 flights across five villages and collected a total of 8,507 images with a total of 511 minutes of cumulative flight time. We conducted at least two to three repetitions of flights for the same flight plan on subsequent survey days to enrich the encounter data, providing a more comprehensive dataset for analysis. Each image was captured in a 3-second interval between frames as it flew over the survey area with an in-flight speed of 31.2 km/hr (16.85 knots). In the first survey in Tarabitan, we initially used a 5-second interval per frame, but we reduced this interval in subsequent surveys to three seconds. This adjustment was made to enhance the data collection efficiency. The details of all flights and images collected are provided in Supp. 2.

We had originally set the altitude at 130 meters above ground level to capture a broader area, but the aerial imagery lacked sufficient resolution to depict marine animals clearly. While a higher altitude provided wider coverage, it compromised detail, reducing clarity for animal identification, so it was changed to 100 meters for accurate documentation. Since the sun's glare obscures some parts of the photos, an 80% forward overlap (end lap) was set to allow for multiple images of the sighted animals to ease identification. Additionally, 1% side overlap (side lap) was set to reduce the number of images taken, which can lead to shorter flight times and less data to process.

A UAV was used at a time, and two flights a day were conducted per UAV, representing surface area coverage varying between 0.4 km^2 to 0.9 km^2 per flight and between 0.61 km^2 to 3.16 km^2 per day. A total of 12.09 km^2 was surveyed, with each flight being repeated three times on different survey days, averaging 3.03 km^2 of area coverage per flight. A healthy battery was limited to a 20 to 25-minute optimal flight (one flight); due to these battery limitations and the lack of access to the charging station for the drone, we carried three backup batteries, so we used them alternately. We could only take four flights each day before returning to the office to recharge batteries and survey in subsequent field trips. A boat was needed, and the take-off was either done on the front deck of the boat or in the hands of one of the survey teams. One of the survey teams manually landed and retrieve the drone.

In our operation, drone surveys quenched our visual yearning of marine megafauna. However, technical expertise must be prioritized as we experienced some lessons learned from the method application. Battery consumption might be one of the important factors in running the drone. In the first place, we used 5-s intervals per frame and decided to mark it down to 3-s intervals. Minimizing the intervals decreases the overall flight time, allowing the drone to capture more images during each survey. This strategy aims to optimize battery usage per flight with/without affecting captured image quality.

Our team suffered an unfortunate experience during the surveys in Tarabitan Village (first site), a drone fell down into the waters due to the flight control connection disruption. The reason for the crash is uncertain. This incident occurred once; however, due to concerns regarding the drone's conditions, specifically, damage to both the drone and the battery caused by saltwater inundation, it was deemed necessary to discontinue its use and the flights at other sites continued with a different drone with similar specifications. Thus, it is essential to implement a strict and comprehensive pre-flight checklist protocol to ensure that batteries and the controller are fully charged with a proper wireless control connection and that firmware is up to date. A detailed pre-departure checklist needs to be established and followed to verify that all safety precautions are in place and the flight settings are correctly programmed. These protocols help mitigate potential issues, enhance the reliability of drone operations, and ensure the safety and success of each survey mission.

We started the drone mission in the morning and afternoon to maximize the probability of detecting dugongs and to optimize the efficiency of battery consumption and adjust to the high tidal cycle. Dugongs, being strictly marine mammals, forage primarily over shallow, intertidal seagrass meadows [28]. Their foraging behavior is influenced by tidal periodicity, which restricts access to these intertidal feeding grounds to approximately two periods within a 24-hour cycle. Similar to how terrestrial grazers are constrained by topography, dugong habitat use is restricted by water bathymetry, which limits their access to specific foraging areas. This behavior may be driven by the higher nutrient content of seagrass found in these zones [27]. Additionally, inshore boating disturbances might encourage dugongs to move closer to the shore during quieter periods. Considering the importance of sufficient light for drone operation and the need to minimize interference with natural behaviors, drone flights were scheduled for morning or late afternoon when conditions were optimal for observation while taking into account the tidal cycle. Night flights were avoided due to the lack of adequate lighting for effective monitoring.

This also aligns with the battery consumption, as warmer air decreases density and increases density altitude. This reduction in air density can negatively affect the drone's aerodynamic performance, motor efficiency, and overall control, making cooler times of day (early morning or late afternoon) more suitable for flight operations [29].

UAV battery consumption ranged from 65 to 75% (mean = 74%, SD = 0.03). During the survey, we experienced an issue where the controller and drone disconnected. While the exact cause remains unclear, we suspect it may have been due to battery health or firmware error.

3.2.1 Environmental Conditions

All dugong surveys were conducted in weather conditions characterized by low wind speed, minimal swell, and the absence of rain. Overall, during the surveys, the sky was cloudy to clear, the winds were calm, or there were no winds. However, on our flights in April 2024, the sky was affected by the massive amount of ash from the eruption of Ruang Mountain a week before [30]. All the flights were conducted in the morning and afternoon (8 am - 10 am and 4 pm - 5.30 pm) to avoid high air temperatures, during the high tide, and when the water started to recede. The team used the Tides application to monitor the tide. This app offers a simple way to view tidal conditions on nearby tide stations, the last and next tide through fully automated tide tables, charts, and predictions.

3.3 Image processing phase

Images collected during a thirteen-day survey (8 hours and 31 minutes flight time) were manually reviewed post-flight by one or two trained observers using an image review program featured in WISDAM which standardized the manual processing method [21]. Each image was split into six parts of the scanning area using consistent zooming. Each identified individual dugong was tagged by drawing manual geometry and some information about the sighting was inputted, including classification of mother or calf, certainty level, dugong's position in the water column, and resight information. Calves and mothers were distinguished to monitor the calf-to-mother ratio within the population, aiding future population assessments. Resights of the same individual dugong within the overlap of multiple images, a similar individual is visible across several consecutive images with short time laps between images can be grouped into a resight group labeled with a similar number. Based on our experience, the same individual typically appeared in two to four consecutive images. To validate dugong identifications, we required that sightings be confirmed by at least two observers and categorized as 'certain'. Any sightings not meeting this criterion were eliminated.

The environmental conditions such as turbidity, sea state, and glare were also assessed for each image and each sighting geometry. Each observer reviewed all images and all reviewed images were compared and verified by a lead observer to determine the sighting certainty and environmental condition score.

The total estimated time to review all the collected images in this study was approximately 425 hours (estimated 180 seconds review of an image). The time spent to identify an image varied, depending on multiple factors, such as the observer's identification skill, and the complexity of the image which was affected by image distortion such as glare/sun glitter, water turbidity, sea state, and water depth. When we were reviewing our datasets, environmental factors such as water turbidity and sun glitter often obscure dugongs in drone images, making it challenging to reliably detect dugongs. Despite these challenges, manual detection played a crucial role in the overall workflow, minimizing bias and verifying machine learning outputs.

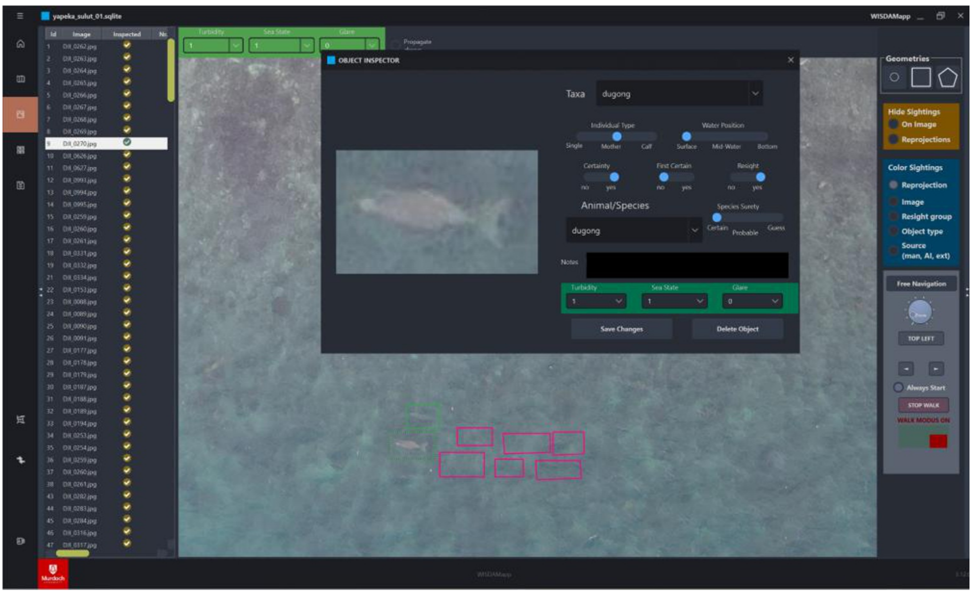

Fig. 4. WISDAM screen interface display in Microsoft Operating System, showing identification process to provide input for the machine learning process. Green boxes indicated dugong in the current image, while red boxes indicated the same dugong in the previous images.

3.4 Dugong counts

3.4.1 Dugong counts

Across all sites surveyed, the number of dugong sightings ranged from 2 to 30 sightings for each site (2-10 adults and 0-10 calves). Of 8,507 images, 56 were capturing Dugongs (43 adults and 13 calves). The maximum number of dugongs happened in Bahoi on April 23rd 2024, whilst the minimum number of dugongs were presented in Tongkaina on 23rd May 2024. No dugongs were detected in Tarabitan across all repetitions. These image capture numbers do not constitute the number of population and further analysis will be needed.

3.4.2 Machine learning detection

Detection of Dugongs from a machine learning system developed by WISDAM built-in tools was using 47 training images provided by 8 surveys to 337 images. Out of 153 machine learning detections, 27 are True Positive, correctly identifying dugongs, while 126 are False Positive, misclassifying non-dugong objects or marine features as dugongs. Additionally, the system failed to detect dugongs in 20 instances, categorized as False Negative. The recall of the system (i.e., the proportion of known dugongs detected in a set of test images) is 57.44%. The precision of the system (proportion of detections that were true dugongs as opposed to false detections) is 17.6%, reflecting that only 17.6% of the machine learning's detections were actual dugongs, with the rest being false detections [31].

At this stage, there is a pressing need for a larger and more diverse set of training data to enhance the machine learning model performance for dugong detection. The limited number of our training data and geographic coverage of our surveys restrict the model's ability to generalize across varying environmental conditions and dugong behavior. It is essential to conduct more flights in various locations. Thus, enriching the training dataset can ultimately lead to enhanced accuracy and reliability in dugong detection through machine learning methodologies.

3.4.3 Advantages of composite method and comparison

We believed that combining different methods (drones, CMS Questionnaire, and Allen Coral Atlas) would bring in thorough information on both scientific and traditional ecological knowledge on dugongs in the area. The CMS Questionnaire is a powerful tool for studying the distribution and relative abundance of marine species and fishery pressure and determining potential conservation hotspot areas [32]. The use of single drones and limited availability of certified drone pilots pose challenges to our drone survey, necessitating substantial investment to expand resources and increase capacity. In this way, additional methods like the CMS Questionnaire give us a bigger and more accurate picture of the number of dugongs in our study areas. Allen Coral Atlas provided us with spatial intelligence on in-water seagrass coverage. This composite method also concluded that the villagers' traditional ecological knowledge taken from the interview stage regarding dugong was comparable to the scientific evidence from drone surveys. The flights that were carried out in the "villagers' interest area" overlapped with seagrass considering remote sensing, ensuing a precious glimpse of dugongs. Hence, community wisdom is an extremely valuable source of knowledge. This study implied that a community-positive perspective regarding dugongs should empower coastal villagers to actively participate in local dugong conservation action, from planning to co-management.

4 Conclusion

This study showed the potential of using drones and AI for dugong detection in a resource-limited scenario, particularly in North Sulawesi. Despite challenges, the drone approach produced promising results, with a total of 56 dugong sightings, covering substantial areas for dugongs. The combination of Allen Coral Atlas data and CMS Dugong Questionnaire data was a key factor. This allowed for strategic, efficient, and affordable site selection by putting dugong hotspot areas on top of the seagrass area based on data from the community. Further improvements, such as increasing AI accuracy through expanded training data by increasing flights and conducting more surveys in varied locations.

Acknowledgment

This research was supported through the IKI-funded project: Conservation of biodiversity, seagrass ecosystems and their services – safeguarding food security and resilience in vulnerable coastal communities in a changing climate (project ID:

18_IV_094_Asia_M_Seagrass Ecosystems). The project is led by the UNEP Convention on Migratory Species, Dugong MoU. The writers would like to thank Amanda Hodgson from Edith Cowan University and Christopher Cleguer from James Cook University for their scientific advice; YAPEKA staff: Faishal Umar, Bonnke P. Sagai, Joandi Arendege, and Satriani for being part of the field data collection and analysis for this article.

References

1. H. Marsh, S. Sobtzick, *Dugong dugon (amended version of 2015 assessment),* in IUCN Red List Threatened Species, e. T6909A160756767 (2019)
2. T. A. Marques, L. Thomas, S. W. Martin, D. K. Mellinger, J.A. Ward, D. J. Moretti, D Harris, P.L. Tyack, Biol. Rev. **88**, 287-309 (2012)
3. T. Quimpo, T. Aquino, L. Aragones, D. Blair, H. de Iongh, A. Digdo, A. Hodgson, S. Jaaman, L. McKenzie, N. Pilcher, L. Ponnampalam, L. Rajamani, H. Marsh, *Maritime Southeast Asia,* in A Global Assessment of Dugong Status and Conservation Needs, United Nations Environment Programme, Bonn (2024)
4. IUCN, *Guidelines for Application of IUCN Red List Criteria at Regional Levels: Version 3.0*, (IUCN Species Survival Commission, IUCN, Gland, Switzerland and Cambridge, UK, 2003)
5. KKP-DJPRL, *National plan of action conservation of Dugong and its habitat (seagrass) in Indonesia (Period 1: 2018-2022)*, (KKP-DJPRL, Jakarta, 2018)
6. *Law Number 32 of 2024 concerning Amendments to Law Number 5 of 1990 concerning Conservation of Biological Natural Resources and their Ecosystems*, (Jakarta, 2024)
7. P.N. Nienhuis, *Structure and functioning of Indonesian seagrass ecosystems*, in Proceedings of International Seminar Coastal Zone Management of Small Island Ecosystems, (Universitas Patimura, CML-Leiden University, AIDEnvironment, 1993)
8. N.D. M. Sjafrie, U. Eko Hernawan, B. Prayudha, I.H. Supriyadi, M.Y. Iswari, Rahmat, K. Anggraini, S. Rahmawati, Suyarso, *Status of Seagrass Meadows in Indonesia* (Pusat Penelitian Oseaongrafi-LIPI, Jakarta, 2018)
9. F. Kurniawan, A.A. Digdo, R.F. Darus, N.P. Anggraini, M.S. Ismet, P. Wicaksono, W. Kiswara, Aquat. Bot. **195**, (2024)
10. A.A. Budiarsa, H.H. De Iongh, W. Kustiawan, P.M. van Bodegom, Environ. Sci. **848**, 4153-4166 (2021)
11. L. McKenzie, R.L Yoshida, H. Marsh, R. Unsworth, *are dugongs fussy eaters?*, in Seagrass-Watch News June 2012, Seagrass-Watch HQ **45**, 3-6 (2012)
12. N.J. Pilcher, J. Williams, G. Hopkins, D. Hess, L. Jaouen, *CMS Dugong MOU Standardised Dugong Catch and Bycatch Questionnaire Final Report*, (CMS Office-Abu Dhabi, United Arab Emirates, 2017)
13. L. Fiori, A. Doshi, E. Martinez, M.B. Orams, B. Bollard-Breen, Remote. Sens. **9(6)**, 543 (2017)
14. C. Cleguer, *Informing dugong conservation at several spatial and temporal scales in New Caledonia,* (James Cook University, Australia, 2015)
15. J. Barreto, L. Cajaíba, J.B. Teixeira, L. Nascimento, A. Giacomo, N. Barcelos, T. Fettermann, A. Martins, Drones **5(1)**, 14 (2021)
16. C. Cleguer, N. Kelly, J. Tyne, M. Wieser, D. Peel, A. Hodgson, Front. Mar. Sci. **8** (2021)
17. N.J. Pilcher, D. Kwan, *Dugong questionnaire survey project manual*, (CMS-UNEP Abu Dhabi Office, United Arab Emirates, 2012)
18. T.S.A. Meidina, M.M. Kamal, F. Kurniawan, H. Darusman, A.A. Digdo, IOP Conf. Ser.: Earth Environ. Sci. **1137**, 012054 (2023)
19. G.E. Heinsohn, W.R. Birch. Mammalia **36(3)**, 414-422 (1972)

20. Allen Coral Atlas, *Imagery, maps and monitoring of the world's tropical coral reefs*, (Zenodo, 2020)
21. A. Hodgson, M. Wieser, C. Cleguer, N. Kelly, F. Maire, *WISDAM User-Manual,* (WISDAM, Australia, 2024)
22. A.A. Digdo, A.O. Debrot, E. Astari, B.R. Arinda, R.J. Henkens, *Using citizen science data to identify population hotspots and conservation priorities for the vulnerable dugong, Dugong dugon (Müller, 1776) in Indonesia* (to be published)
23. C. Septiani, *Socio-ecological modelling on seagrass ecosystems in Sangihe Islands, Indonesia,* (New Castle University, UK, 2022)
24. A. Bonnet, *Status of Dugongs in relation to intertidal and shallow subtidal seagrass beds and human induced threats in North Sulawesi, Indonesia*, (Wageningen University, Wageningen, 2016)
25. A. R. Putriraya, *CEPF Final Project Completion Report,* (CEPF, 2015)
26. M. Waycott, C.M. Duarte, T.J.B. Carruthers, R.J. Orth, W.C. Dennison, S. Olyarnik, A. Calladine, J.W. Fourqurean, K.L. Heck, A.R. Hughes, G.A. Kendrick, W.J. Kenworthy, F.T. Short, S.L. Williams, Proc. Natl. Acad. Sci. U.S.A. **106(30)**, 12377-12381 (2009)
27. G.E. Heinsohn, J. Wake, H. Marsh, A.V. Spain, Aquaculture **12(3)**, 235-248 (1977)
28. J.K. Sheppard, R.E. Jones, H. Marsh, I.R. Lawler, J. Wildl. Manage. **73(1)**, 45-49 (2009)
29. FAA, *Density Altitude*, (Federal Aviation Administration, Idaho, 2020)
30. K. Magramo, *Indonesia issues tsunami alert after volcano erupts on remote island*, (CNN World, 2024)
31. K.M. Ting, *Confusion Matrix*, in Encyclopedia of Machine Learning, Springer, Boston (2011)
32. N.J. Pilcher, K. Adulyanukosol, H. Das, P. Davis, E. Hines, D. Kwan, H. Marsh, L. Ponnampalam, J. Reynolds, *A low-cost solution for documenting distribution and abundance of endangered marine fauna and impacts from fisheries*, PLoS ONE **12(12),** e0190021 (2017)

Supplementary

Supp. 1. Drone specifications

Drone specifications	
Make	DJI ©
Model name and version	DJI Mavic Air 2s
Weight (battery & propellers included)	595 g
Number of rotors	4
Diagonal size (propellers excluded)	302 mm
Battery type	LiPo 3S (only one battery required to fly)
Max flight time	Approx. 30 minutes
Camera name and effective pixel	1" CMOS; 20 Megapixels
Lens field of view	FOV: 88° 35 mm Format Equivalent: 22 mm Aperture: f/2.8 Shooting Range: 0.6 m to ∞
Image aspect ratio used in this study	3:2; 5472 × 3648 pixels

Supp. 2. Flight details of all flights and images collected

Date	Number of flights (cells)	Cumulative flight time (minutes)	Number of images collected	Number of images with dugongs
15th September 2023	4	57	684	0
29th September 2023	4	79	947	0
30th September 2023	4	79	942	0
23rd April 2024	2	22	445	22
24th April 2024	2	24	474	2
25th April 2024	2	27	524	6

Date	Number of flights (cells)	Cumulative flight time (minutes)	Number of images collected	Number of images with dugongs
23rd May 2024	2	56	1114	0
24th May 2024	2	26	526	0
25th May 2024	2	36	721	0
26th May 2024	1	21	426	0
27th May 2024	1	27	539	13
28th May 2024	1	16	325	6
29th May 2024	1	42	843	5
Total	**28**	**511**	**8507**	**56**