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Isolation and Detection of Antibiotic-Resistant *Staphylococcus aureus* from Street-Vended Chicken Intestines in a Philippine Urban Setting

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ABSTRACT

Foodborne pathogens, particularly *Staphylococcus aureus*, is commonly associated with the street food, causing a wide array of diseases such as staphylococcal food poisoning (SFP), which leads to diarrhea, nausea, and more. This study aimed to detect and isolate putative antibiotic-resistant *S. aureus* isolates in *isaw* and tomato-based condiment randomly collected from the food stalls around Barangay Ampayon, Butuan City, Philippines. The putative isolates were selectively grown and morphologically characterized using Tryptic Soy Broth and Baird-Parker Agar. Further characterization was conducted through biochemical testing using assays such as Gram staining, Indole test, Catalase test, Methyl-red test, Triple Sugar Iron Test, and Coagulase test. The study revealed that 19 isolates of the presumptive *S. aureus* were detected, with 15 isolates expressing the characteristics of typical *S. aureus* through biochemical tests. All 15, or 100%, of the suspected *S.aureus* isolates expressed resistance to Oxacillin. However, on the other hand, 100% of these isolates were also susceptible to Ciprofloxacin and Cotrimoxazole, with only 14 isolates, or 93%, showing susceptibility to Gentamicin and Tetracycline. One isolate was characterized as multidrug resistant (MDR) due to its resistance to Oxacillin, Gentamicin, and Tetracycline. The presence of MDR *S. aureus* in this study implies significant health risks to both the vendors and consumers of *isaw*, highlighting the importance of proper food preparation and food safety regulations in the Philippines, especially towards commonly sold consumables such as chicken products and sauces.

Keywords: *foodborne pathogens, food stalls, multidrug resistance, condiment, isaw*

1 Introduction

Street food, delicacies prepared and sold by vendors on the streets, has gained significant popularity worldwide due to its affordability, convenience, and diverse flavors (Ceyhun Sezgin and Şanlıer 2016). However, the preparation and consumption of street food carries potential health risks, as these vendors, the ingredients, and even the hygiene practices and food handling techniques they utilize can act as carriers of foodborne pathogens.

One of the most common street foods in the Philippines is *isaw*, or grilled chicken intestines (Harkins 2017). It is revered for its unique taste among locals and tourists alike, especially with the addition of tomato sauce, which plays a crucial role in enhancing the flavors of street food dishes. Behind this success and popularity, however, lies an increased presence of foodborne pathogens, specifically *Staphylococcus aureus*, a Gram-positive, coccus-shaped pathogen (Moloi et al. 2021).

Being frequently found in undercooked poultry, meat, and eggs, *S. aureus* initiates infection using its ability to produce enterotoxins that can cause Staphylococcal foodborne disease (SFD), resulting in symptoms such as vomiting, nausea, stomach cramps, and diarrhea (Hennekinne et al. 2012). Recorded cases of *S. aureus* infections in the Philippines have also been known to cause necrotizing pneumonia and toxic shock syndrome in extreme cases, which is exacerbated by the challenge of detecting the microbe and its toxins due to its lack of odor in street foods (Valle et al. 2016).

Moreover, the emergence of antibiotic resistance and multidrug resistance (MDR) in *S. aureus* poses a significant public health concern due to the extensive use and misuse of antibiotics in human medicine and agriculture (Gatadi et al. 2019). One such variant that has been labeled as the one of the leading causes of both nosocomial and community infections worldwide is the Methicillin-Resistant *Staphylococcus aureus* (MRSA), which has grown to ignore the effects of the staph disease-treating Methicillin since the 1960’s and has cloned, disseminated, and acquired greater resistance against other treatments extensively to the point of being able to cause local outbreaks if left undetected and unresolved (Masim et al. 2021). The nigh-impossible challenge of reversing antimicrobial resistance back towards susceptibility, the decreasing reliability of modern drugs, and the time-gated race against the constantly evolving MDR bacteria leads to the burden of detecting and documenting the presence of S. aureus, especially in countries that have a known scarcity of information, like the Philippines (Medina & Pieper 2016).

Despite numerous studies on *S. aureus* contamination in street food around the world, there is a lack of information on its presence and antibiotic resistance profile in isaw and tomato sauce sold in Barangay Ampayon, Butuan City, Philippines — an area with high student consumption due to its proximity to Caraga State University. Addressing this gap is crucial to understanding local food safety risks and antibiotic resistance patterns. With street food consumption being a popular trend among many Filipinos, *S. aureus* and its unique resistance patterns, as well as its tendency to be found in local delicacies, make this a prime target for study.

This study aims to detect antibiotic-resistant *S. aureus* from isaw and tomato-based condiment samples obtained from food stalls around Barangay Ampayon, Butuan City, by isolating, characterizing the isolates through their morphology and biochemical reactions, and determining the antibiotic susceptibility profiles of the presumptive *S. aureus* isolates.

The findings of this study will raise public awareness of the potential risks associated with consuming street food, such as *isaw*, and provide valuable data for local health officials, policymakers, and food vendors. The opportunity to provide ideas for appropriate interventions and regulations may also be garnered from the results of the study, reducing the prevalence of foodborne diseases in the study area while ensuring the microbiological safety of street food, alongside the promotion of safer street food practices and enhancing public health measures against the threat posed by *S. aureus* and its MRSA and MDR variants for the Philippines and the world.

2 Methodology

Study Area

The study was conducted along the roadside around Caraga State University in Barangay Ampayon, Philippines (Figure 1), specifically at locations where crowded street food stalls are commonly found.

Collection of Samples

The collection of samples was conducted in accordance with the street food collection protocol of Mamun et al. (2013), with some modifications. Fourteen samples of *isaw* and tomato-based condiment were collected in triplicate from seven street food stalls based on crowd density and prevalence of the street food mentioned. The samples were collected using pre-sterilized plastic containers and stored in a sealed ice box to maintain a low temperature before being immediately transported to the Caraga State University Microbiology laboratory for analysis. A permission letter was sent to the barangay captain of the municipality prior to sample collection.

Isolation of Staphylococcus aureus

The collected samples of *isaw* and sauce were homogenized with a 1:10 ratio, following the protocol of Lakhanpal et al. (2019). Specifically, 25 g of *isaw* and 25 mL of condiments were separately mixed with 225 mL of buffered peptone water. Then, it was transferred to the stomacher to homogenize the samples. The homogenized samples were then

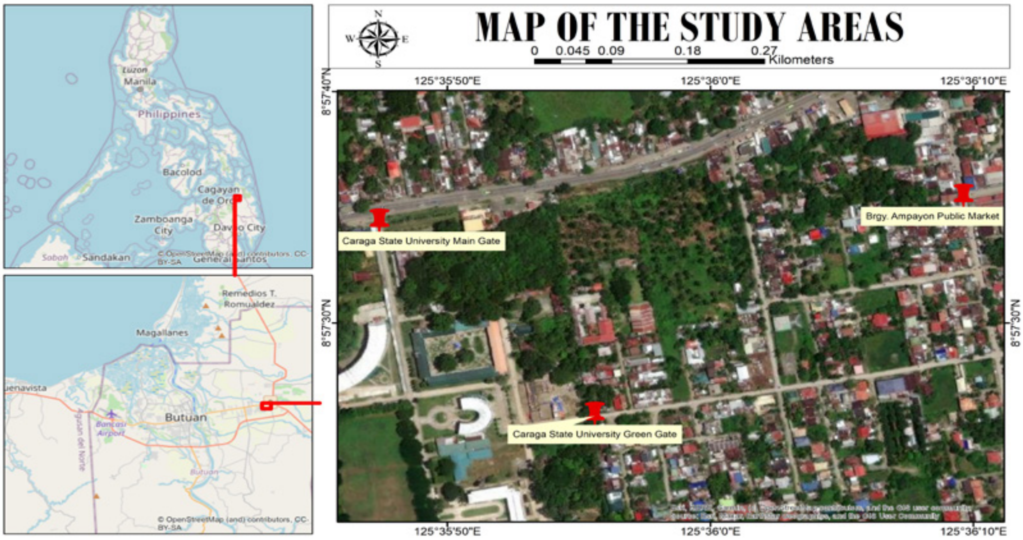

Figure 1. Location of the sampling area. The top left panel displays a map of the Philippines, highlighting the location of Butuan City (red line). The bottom left panel shows Barangay Ampayon (red line) on the Butuan City Map. The right panel shows the map of the sampling areas (three sites) in Barangay Ampayon.

subjected to enrichment to support the growth of *Staphylococcus aureus* using Tryptone Soy Broth (TSB), as it is the most commonly used culture medium (González-Machado et al. 2024). Four replicates of sterile 9 mL TSB were prepared for each isaw and tomato-based condiment sample, and were then inoculated with 1 mL of homogenized sample into the test tubes. The TSB test tubes were then incubated for 24 h at 37°C.

The enriched isolates were inoculated into selective media plates using the freshly prepared Baird-Parker medium with Egg Yolk Tellurite and incubated at 37°C for 48 h (FDA 1998). The isolates were subjected to subculturing for purification and then further characterization through biochemical assays.

Characterization of the Staphylococcus aureus isolates

The putative *Staphylococcus aureus* isolates were characterized by the following biochemical tests: indole test (MacWilliams 2012), methyl red test (McDevitt 2009), coagulase test (Aryal 2022), triple sugar iron test (Lehman 2005), and catalase test (Reiner 2010).

For the indole test, the putative *S. aureus* isolates from the samples were inoculated into sterile Tryptone Soy Broth tubes and incubated at 37°C for 24 h. After incubation, five drops of Kovács reagent were added to the test tube, and color changes in the medium were observed. The expected result of S. aureus isolates is negative (MacWilliams 2012). The methyl red test involved inoculating the assumed *S. aureus* isolates onto freshly prepared Methyl Red and Voges-Proskauer (MR-VP) broth and incubating them at 37°C for 48 h. Five drops of methyl red reagent are then directly dropped into the MR-VP broth test tubes, with a positive result expected for *S. aureus* (McDevitt 2009). The slide or drop technique was employed in the Catalase test, with 3% hydrogen peroxide as the primary agent of this test. A small amount of *S. aureus* was carefully deposited onto the slide. Then, the slide containing the bacterium was treated with a drop of hydrogen peroxide. Bubbles were expected as a result, indicating a catalase-positive result (Reiner 2010).

During the coagulase test, presumptive *S. aureus* isolates were inoculated into sterile TSB for broth culture, then freeze-dried rabbit plasma was diluted with a ratio of 1:10 in physiological saline. The diluted plasma was then pipetted into sterile test tubes, each containing 0.5mL. Afterwards, the broth culture of *S. aureus* isolates was pipetted into the diluted plasma test tubes at 0.1mL. After mixing, the test tubes were incubated at 37°C. Examination for clotting was checked every six hours, but not more than 24 hours of incubation. *S. aureus* isolates were expected to be coagulase-positive (Aryal 2022). The TSI test was conducted using the stab-and-streak method, wherein *S. aureus* isolates were inoculated by vertically inserting a sterile needle into the agar deep to near the base of the tube, followed by streaking of the agar slant. Afterward, TSI slants were incubated for 18 to 24 h at 37°C. In this test, *S. aureus* isolates were expected to be negative (Lehman 2005).

Antimicrobial susceptibility assay

All the putative *S. aureus* isolates that exhibited the expected biochemical test results were subjected to antibiotic susceptibility screening following the Kirby-Bauer Disk Diffusion Susceptibility test protocol by Hudzicki (2009). This CLSI-recommended test utilizes antibiotic discs with a fixed volume, aimed at identifying the resistance of *S. aureus* isolates to these agents (Yang et al. 2019). The *S. aureus* isolates were tested for antibiotic susceptibility to Oxacillin (penicillin), ciprofloxacin (fluoroquinolones), tetracycline (tetracyclines), gentamicin (aminoglycosides), and cotrimoxazole (Table 1). Commercially available antibiotic disks were used with antibiotic concentrations prescribed by the European Committee on Antimicrobial Susceptibility Testing (EUCAST) guidelines. The plate disk diffusion technique was determined to be the primary method of initiating this assay, as there is a greater opportunity to isolate and detect MRSA due to the presence of oxacillin discs in the test, which is known to be stable in the disc diffusion technique and is structurally and pharmacologically related to Methicillin (Drew et al., 1972).

3 Results and Discussion

Isolation of Staphylococcus aureus from isaw and tomato-based condiment

Nineteen suspected *S. aureus* were detected from the samples—ten from the isaw and nine from the tomato sauce. The presence of *S. aureus* in the samples can be attributed to several factors. A study by Wang et al. (2012) attributes the appearance of the bacterium from the production process, be it storage of chicken carcasses with damaged or lacking packaging with other food products, or the sheer demand for the popular street food and sauce causing a lack of attention in checking for cross-contamination and observing proper storage and freezing times compared to withdrawal and transportation times. Chicken intestines, alongside human skin, have also been determined to be a frequent source of *S. aureus* isolates, indicating that human error, particularly concerning local street vendors exposed to crowds and open air, can also be the cause of contamination by simply being unhygienic or improperly cleaning or preparing the *isaw* (Kitai et al. 2005).

Similar to the study by El-Hadedy and El-Nour (2012), the halo formation around the *S. aureus* isolates (Figure 2) indicates lipase activity. The grey-black color of the shiny colonies is formed due to the reduction of potassium tellurite from the egg yolk tellurite emulsion (Silva et al. 2000). Morphological characteristics of the *S. aureus* isolated from the *isaw* and tomato sauce samples are expressed as Gram-positive cocci arranged in clusters similar to the *S. aureus* isolates in the study of Sina et al. (2011).

Characterization of the suspected Staphylococcus aureus isolates

After confirming the morphology of the cell and colony of presumptive *S. aureus* isolates, biochemical tests, including the Indole test, Methyl Red test, Coagulase test, Triple Sugar Iron test, and Catalase test, were used for characterization.

Out of the nineteen presumptive *S. aureus* isolates, fifteen (79%) were positive for the methyl red test, coagulase test, and catalase test, then negative for the indole test and TSI test, which passed the guidelines for characterizing typical *S. aureus* (Bergey 1994, Aryal 2022).

All suspected *S. aureus* colonies exhibited the presence of yellow rings during the Indole test,

Table 1. Antimicrobial agents used for antibiotic resistance screening of *Staphylococcus aureus* and their zone diameter breakpoints (EUCAST, 2024).

Antimicrobial Agent	Disk Content	Zone Diameter Breakpoints to the nearest whole (mm)	
		Susceptible	Resistant
Oxacillin (Penicillin)	1 µg	≥ 13	<10
Ciprofloxacin (Fluoroquinolones)	5 µg	≥ 50	< 17
Tetracyline (Tetracyclines)	30 µg	≥ 22	< 22
Gentamicin (Aminoglycosides)	30 µg	≥ 18	< 18
Cotrimoxazole	25 µg	≥ 17	< 14

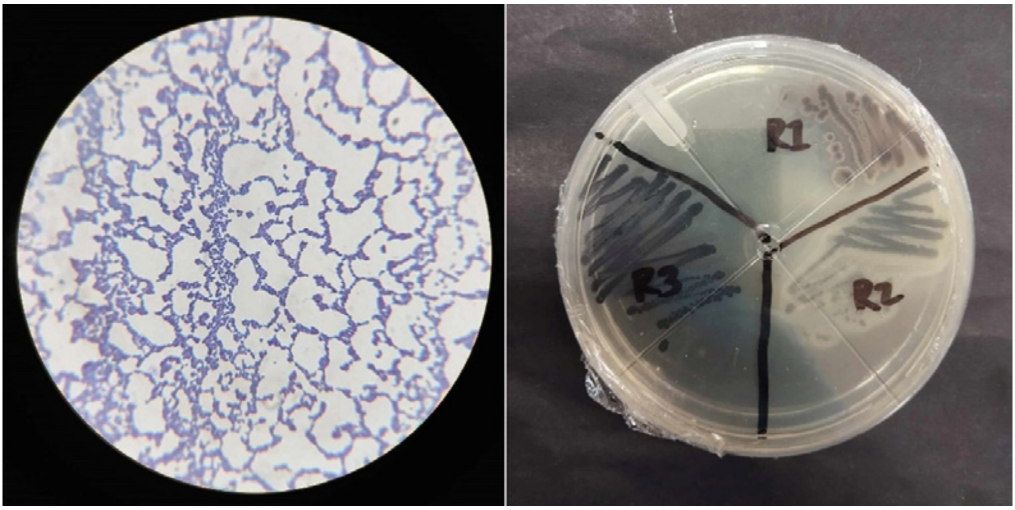

Figure 2. The left photo shows a suspected *Staphylococcus aureus* isolate gram stain under a microscope oil immersion objective lens (1000x). The cells are purple, cocci-shaped, and packed like grapes. The right photo shows colonies from the sample grown on Baird Parker media plates incubated at 37°C for 48 hours. *S. aureus* is black and shiny with a halo.

Table 2. Biochemical characterization of suspected *S. aureus* isolates from the tomato sauce and isaw samples in food stalls. Positive reaction (+), adverse reaction (-), acidic reaction (A).

***S. aureus* isolates**	**Colony Morphology**				**Gram Reaction**	**Cell Morphology**	
	Color	**Forms**	**Texture**	**Elevation**		**Shape**	**Arrangement**
Sauce							
KR1	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
KR2	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
KR3	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
KR4	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
KR5	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
KR6	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
KR7	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
KR8	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
KR9	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
Isaw							
IR1	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
IR2	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
IR3	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
IR4	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
IR5	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
IR6	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
IR7	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
IR8	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
IR9	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered
IR10	Black	Circular	Smooth	Convex	Positive	Cocci	Clustered

indicating a negative result of the biochemical test due to a lack of tryptophanase activity, indicating an inability to break down tryptophan to pyruvate and ammonia, a result typical of *S. aureus* (Hartline 2023). Meanwhile, in the Methyl Red test, all 19 suspected *S. aureus* isolates from the samples expressed a red ring similar to the positive control, indicating that the isolates can ferment one or more organic acids formed during glucose fermentation.

In the coagulase test, all suspected *S. aureus* isolates from both *isaw* and sauce samples exhibited a positive result, forming clumps of the diluted rabbit plasma, in line with results from other studies (Rakotovao-Ravahatra et al. 2019). This test serves as a benchmark for differentiating and characterizing *S. aureus* from other bacteria due to the species' ability to cause blood clots using the enzyme coagulase, which converts fibrinogen to fibrin, as it resembles prothrombin (Lucia et al. 2017).

All presumptive *S. aureus* isolates yielded an acid-positive reaction in the TSI test, characterized by yellow coloration of both the slant and agar deep, indicating glucose and lactose fermentation (Isnan et al. 2017). In the research of Hasan et al. (2016), vancomycin-resistant *S. aureus* and methicillin-resistant *S. aureus* strains isolated from burn wounds expressed similar results.

On the other hand, 15 (79%) out of 19 isolates were catalase-positive, indicating that the isolates were able to produce the enzyme catalase, a characteristic of *S. aureus*, as observed in the bovine-based study by Pumipuntu et al. (2017). Catalase production is a virulence factor of S. aureus, as the presence of this enzyme enables the bacteria to resist both intra- and extracellular killing via hydrogen peroxide (Mandell 1975, Kanafani and Martin 1985). However, four (21%) out of 19 isolates were catalase-negative, which could indicate the presence of a rare strain of the bacteria, such as in the case study by Yilmaz et al. (2005), which reported a catalase-negative methicillin-resistant *S. aureus* (MRSA) isolated from a patient who suffered from sepsis syndrome, which made detection methods complicated due to the nonconformance of the results.

Antibiotic susceptibility test

An antibiotic susceptibility test was conducted to determine the sensitivity of the 15 *S. aureus* isolates to Oxacillin (penicillin), gentamicin (aminoglycosides), ciprofloxacin (fluoroquinolones), cotrimoxazole, and tetracycline (tetracyclines).

The antibiotic resistance pattern of the presumptive *S. aureus* isolates shows that 15 (100%) of the isolates were susceptible to ciprofloxacin and cotrimoxazole, indicating that these drugs were effective against the presumptive S. aureus isolates. Gentamicin and tetracycline susceptibility was also observed in fourteen (93%) of the isolates, contrary to studies that have showcased the complete tetracycline resistance of modern *S. aureus* isolates (Grossman 2016).

On the other hand, all of the presumptive *S. aureus* isolates were resistant to Oxacillin, which belongs to the same antibiotic class as Methicillin. They thus could be labeled as MRSA (Eromo et al. 2016). This resistance can be attributed to the acquisition of staphylococcal cassette chromosome mec (SCCmec), which contains genes encoding proteins that render the bacterium resistant to most β-lactam antibiotics such as Methicillin and Oxacillin (Lee et al. 2018). Even worrying is that this high resistance usually comes at the cost of reduced virulence. However, it is largely unknown how most MRSA clones have achieved the goal of simultaneously expressing sufficiently high methicillin resistance and aggressive virulence characteristics, using different approaches in convergent evolution, which urges hasty intervention from global health organizations (Otto 2013).

The presence of one presumptive *S. aureus* isolate that is resistant to three different classes of antibiotics, namely Oxacillin, gentamicin, and tetracycline, can be characterized as being a multidrug-resistant (MDR) strain (Magiorakos et al. 2012). This result aligns with the study by Eromo et al. (2016), which also found MDR *S. aureus* in ready-to-eat street foods, as it was resistant to ampicillin, cloxacillin, ceftriaxone, and other tested antibiotics. The MDR phenotype in *S. aureus* has become increasingly prevalent over the past few decades, with the *ori*C environment being identified as the so-called storehouse of drug resistance genes, capable of safeguarding even foreign genes that would typically cause cell destruction if overexpressed (Hiramatsu et al. 2014).

Possible causes for the prevalence of these strains within isaw and its accompanying tomato sauce involves the presence of enzymes like catalase, which aids its survival by protecting it from the chicken and human hosts' immune system;

Table 3. Biochemical characterization of suspected *Staphylococcus aureus* isolates from the sauce and isaw samples in food stalls. Positive reaction (+), negative reaction (-), acidic reaction (A).

Isolate No.	Indole Test	Methyl Red Test	Coagulase Test	Triple Sugar Iron Test		Catalase Test
				Slant	Butt	
KR1	-	+	+	A	A	+
KR2	-	+	+	A	A	+
KR3	-	+	+	A	A	+
KR4	-	+	+	A	A	-
KR5	-	+	+	A	A	-
KR6	-	+	+	A	A	+
KR7	-	+	+	A	A	+
KR8	-	+	+	A	A	+
KR9	-	+	+	A	A	+
IR1	-	+	+	A	A	+
IR2	-	+	+	A	A	+
IR3	-	+	+	A	A	-
IR4	-	+	+	A	A	-
IR5	-	+	+	A	A	+
IR6	-	+	+	A	A	+
IR7	-	+	+	A	A	+
IR8	-	+	+	A	A	+
IR9	-	+	+	A	A	+
IR10	-	+	+	A	A	+

Table 4. Antibiotic susceptibility test results of S. aureus isolated from the isaw and sauce in street food stalls in Barangay Ampayon, Butuan City, Philippines. Susceptible (S) or resistant (R) oxacillin (OXA), gentamicin (GEN), ciprofloxacin (CIP), cotrimoxazole (COT), and tetracycline (TET) are displayed.

Type of Antibiotic	No. resistant	No. sensitive	Sensitive (%)	Resistant (%)
Oxacillin	15	0	00	100
Gentamicin	1	14	93.33	6.67
Ciprofloxacin	0	15	100	00
Cotrimoxazole	0	15	100	00
Tetracycline	1	14	93.33	6.67

and genes like the *Agr* gene, which helps *S. aureus* form biofilms and adhesion factors to remain in the food stalls and the products they serve (Siddique et al. 2024). The crowd density in these stalls, alongside the difficulty in upholding proper hygiene measures, also unwillingly aids the acquisition of MDR genes, as contact with the unseen *S. aureus* in *isaw* and tomato sauce by different people with varied microbiomes can lead to horizontal gene transfer, allowing the pathogen to become even more resistant and virulent (Evans et al. 2020).

4 Conclusion

The presence of multiple MRSA isolates and one MDR *S. aureus* strain in locally served *isaw* and tomato-based condiments highlights a significant risk, not only to the health of consumers and vendors in the community, but also to the current level of food safety in the country and its localities. Not only this, but the threat of a potential *S. aureus* outbreak in Butuan City has now become a possibility, especially considering the resilience and virulence factors of the pathogen in question. These findings prompt immediate action from both the local government unit and the health sector, including seminars by vendors and relevant safety personnel, training, health education, and regular inspections of served street food. These measures are key factors in preventing the spread of the pathogen and instilling knowledge among the people regarding the issue.

With this in mind, this reasearch provides recommendations for further study such as: (1) utilizing methods like 16S rRNA or Whole Genome Sequencing to confirm the identity of the presumptive *S. aureus* isolates as well as the specific genes they utilize to confer multidrug resistance; (2) identify other foodborne pathogens in street food samples aside from *S. aureus*; (3) conduct microbiological analysis of other street food samples and food stalls that were sold in Barangay Ampayon, Butuan City and; (4) utilize other antibiotics for antimicrobial susceptibility testing for further analysis of antibiotic-resistant *S. aureus,* especially concerning MRSAs. To establish a link between street food contamination and vendors, an epidemiological study should be conducted.

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7 Author Contribution

V.D.B. Gaston conducted the study, collected data, performed the analysis, and contributed to the original draft. J.V. Rosen conceptualized the study design, supervised the project, and edited the manuscript. V.D.B. Gaston wrote the manuscript draft for the journal. All authors reviewed and approved the final version of the article.

8 Statement of Conflict of Interest

There is no conflict of interest among authors.

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Air-Drying Time and Moisture Loss Dynamics of Short-Length Commercial Green Falcata (*Falcataria falcata* (L.) Greuter & R. Rankin) Lumber: Implications for Small-Scale Lumber Processing in Caraga Region, Philippines

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ABSTRACT

This study examined the air-drying rate of 2" x 4" x 4' short-length commercial green falcata (*Falcataria falcata*) lumber in Butuan City, Philippines, from September to December 2024. It aimed to determine the drying duration required to achieve moisture contents of 15%, 20%, and 25%, which are critical for preventing fungal decay and improving lumber stability and usability. A total of 24 lumber samples were collected and monitored under ambient conditions, with 2" sample segments taken from lumber ends periodically, including ¼" trim ends. From each lumber specimen, a 2-inch segment was removed from one end, and an additional ¼-inch slice was trimmed off to eliminate surface irregularities and possible drying defects. The 2-inch sample was immediately weighed using a precision balance, then oven-dried at 105 °C for 24 hours or until its mass stabilized to obtain the oven-dry weight needed for moisture content determination. For the drying assessment, the remaining length of each board was gradually reduced by cutting 2-inch sections from alternating ends. This procedure was repeated until the lumber reached a moisture content of less than 15%. The results revealed significant variation in drying times across stacking months, with September showing the fastest drying (20 days to 15% MC) and December the slowest (77 days). The regression analyses showed that the drying process is best described by polynomial and exponential models, indicating that moisture loss does not occur at a constant rate. Instead, drying is typically faster during the early stages when the lumber still contains high free water and gradually slows as the moisture content approaches fiber saturation. These findings provide a localized and practical reference for air-drying estimates, contributing to efficient and sustainable lumber processing practices in the Caraga Region.

Keywords: *drying behavior, seasonal variation, lumber handling practices*

1 Introduction

Falcata (*Falcataria falcata*) is a large, fast-growing tree native to Southeast Asia that can reach heights exceeding 30-40 meters (Hassan and Rahman 2019, Hughes et al. 2024). It is one of the most used raw materials in the wood industry, and plays a significant role in the Philippine timber industry. It is extensively cultivated as a fast-growing industrial plantation species across tropical regions (Krisnawati 2011). It is recommended for harvest at a minimum age of seven years to ensure optimum wood quality (Listyanto 2018). It has become one of the principal raw materials for veneer and plywood production (Jimenez et al. 2015). Research demonstrates that young falcata trees, aged 3-7 years, can be successfully processed into veneer and plywood, with all age groups meeting glue bond requirements, despite some quality variations in lathe checks (Jimenez et al. 2022).

According to the DOST-FPRDI (2020), falcata is the dominant plantation species in the Caraga Region, and of the approximately 733,500 m³ of plantation logs produced in 2017, 67% came from Caraga, with 91 % of these being falcata. Freshly sawn falcata lumber contains high moisture content, making it prone to warping, shrinkage, fungal attack, and dimensional instability if not properly dried. Wood drying is a crucial operation in wood processing that ensures the physical integrity and stability of wood during remanufacturing and use (Elustondo et al. 2023). Proper drying, handling, and storage minimize undesirable changes in moisture content during service, helping to avoid major dimensional change problems (Simpson 2010, Bergman 2021). Although kiln drying offers controlled conditions, air drying remains the most common method in the Philippines due to its low cost and accessibility, particularly for small-scale farmers. In the Philippines, lumber used for construction or indoor applications is typically dried to a moisture content of 12–15%, with 15% widely accepted as the practical target for air-dried lumber under local climatic conditions.

Air drying rates depend on wood species, dimensions, and local climate, making it difficult to establish a single standard drying schedule. Methods such as those developed by Simpson and Hart (2001) have demonstrated that stacking date and geographic location significantly affect drying times, with differences of several weeks observed under varying conditions. However, despite such advances, there is limited information on the air-drying behavior of falcata under Philippine conditions, particularly in the Caraga Region, where the species dominates plantation forestry.

2 Materials and Methods

2.1 Lumber Sampling

Six rough-sawn, 2"×4" nominal (approximately 5 cm × 10 cm in radial and tangential directions, respectively) short-length *F. falcata* lumber specimens were collected monthly from a commercial lumber mill in Butuan City from September to December 2024. A total of 24 lumber samples were obtained over the four-month sampling period. All lumber specimens were sourced from a single commercial batch harvested from *F. falcata* trees belonging to the same plantation age class, which helped maintain consistency in growth characteristics. Each board was visually examined; only boards with comparable color, grain pattern, and no visible defects were included. The selected lumber size (2"×4"× 4') represents the most common commercial dimension in the local industry, as other lengths are typically produced on a made-to-order basis. Local standards in falcata log production are primarily 2' and 4', intended mainly for plywood manufacturing.

The initial moisture content (MC) of the samples was measured using a wood moisture meter (FPRDi-FA507) to confirm that the values exceeded 30%, thereby ensuring the wood was above the fiber saturation point (FSP). This step was necessary to validate that the samples were in a green condition suitable for drying evaluation.

2.2. Sample Preparation

From each lumber specimen, a 2" segment was cut from one end, and a ¼" trimming was discarded to remove surface irregularities and potential drying defects. The 2" sample segment was immediately weighed using a precision balance before being oven-dried (Memmert oven) at 103 ± 2 °C (ASTM standard) for 24 hours or until no further change in mass was observed.

For the drying test, the remaining lumber was progressively shortened by successively cutting 2" segments from alternating ends. This method was first adapted in this study to characterize drying behavior. The process continued until the measured MC of the lumber dropped below 15%. The cutting sequence is shown in Figure 1.

2.3 Oven-drying Method

The gravimetric method for determining the moisture content (MC) of a sample segment was calculated using Equation (1), as also used by Barański et al (2021), where MC is the moisture content (%), W1 is the initial weight (g), and W0 is the oven-dried weight of the wood sample (g). Sampled lumber was air-dried in the screened-sided workshop building of the Forest Products Innovation and Training Center at CarSU-CoFES, protecting the lumber piles from rain and excessive

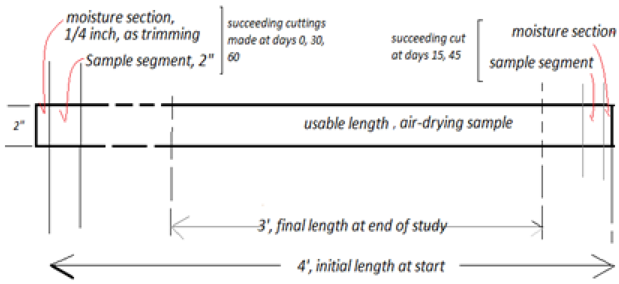

Figure 1. Scheme of preparation of the cut

sun exposure. The lumber was arranged with spacers and dry stickers on top of a dry table.

$$MC = \frac{W_1 - W_0}{W_0} \times 100\% \quad (1)$$

2.4. Data Analysis

2.4.1. Air Drying Time

For each monthly batch, the average moisture content (MC) from the successive measurements was calculated and then plotted against the number of drying days to show how MC changed over time. To better understand this relationship, different trend lines were tested, including linear, exponential, and polynomial (second- to third-order), to determine which one best matched the drying pattern of the samples. The association between air-drying time (in days) and d, the average moisture content of subsequent measurements for each monthly set, was calculated and plotted. To determine fitness, the best-fit correlation was plotted, either linear or nonlinear (exponential or polynomial with two to three orders of magnitude). In a related study, Simpson (2004) estimated the air-drying time of lumber using multiple regression analysis. Following this approach, when the polynomial trend provided the closest fit for the falcata samples, the drying behavior could be expressed using the following Equation:

$$y = a^3 + bx^2 + cx + d$$

or, alternatively,

$$y = a^2 + bx + c$$

$$y = ax + b$$

and,

$$y = e^x$$

where, $y =$ MC(100%)

a,b,c,d = coefficients of the model

x = air-drying time, days

e = mathematical constant, approximately 2.718281

The regression coefficients of the equations were determined using the MS Excel Data Analysis tool pack add-in's regression tool. Using Equation 2, the air-drying time (days) for MC levels of 30%, 25%, 20%, and 15% for each piling month or stacking month was estimated.

2.4.2. Air-drying Estimate

An air-drying time estimate was established, showing corresponding curves of the relationship between stacking time in September, October, November, and December and drying time, which were plotted to provide a visual representation of the relationship. During the drying period from September to December, Butuan City generally experiences warm tropical conditions, with average temperatures ranging from 31°C to 33°C and monthly rainfall between 123 mm and 243 mm (Weather Atlas 2025). These values provide a general context for the drying environment, although the actual weather during the study was not recorded. The estimates were predicted based on the averages of each month. Three curves were plotted representing 15%, 20% and 25%.

3 Results and Discussion

3.1. Air drying time of falcata lumber

The air-drying test of falcata lumber, conducted from September to December 2024 (Figure 2), aimed to determine the drying duration required to achieve moisture contents of 15%, 20%, and 25%. The lumber stacked in September had an initial moisture content of about 32% and showed a rapid decline during the first 15 days, reaching an approximately 16% moisture content. The target of 25% was achieved within the first 7 days, while the 20% level was reached after about 12 days. By the 20th day, the lumber attained the 15% moisture content target, and stabilized between 16-17% up to 45 days of drying (Fig. 2a). Most decay fungi and blue stain fungi cannot develop in wood with a moisture content below 20% (Zabel and Morrell, 2020). Which is why keeping wood dry is critical for long-term durability. The air-drying of six lumber samples stacked in October began with moisture contents ranging from 35.80% to 61.73%, with an average of 50.34% (Fig. 2b). The results of the study show that the October air-drying process lasted only 30 days. However, the multiple regression analysis of the data estimated that falcata lumber would need about 52 days to reach the target moisture content of 15%. At this point, the moisture content was estimated to be between 12.03% and 14.28%, with an average of 12.92%. The projected drying curve, along with the equilibrium moisture content (EMC) values recorded on selected days (Figure 4). In contrast, the September trial reached the same target moisture content in just 20 days, indicating that falcata lumber dried much more slowly in October.

The falcata lumber stacked and air dried in November has an initial MC of 26-45% down to 14-15% within 30 days (Figure 3c). The drying curve shows a fast initial moisture loss in the first 15 days, followed by slower drying as the wood approaches EMC. December air-drying time of six lumber samples showed that the green lumber started with MC ranging from a low of 34.36% to a high of 41.75% (an average of 37.80%). The samples reached 19.57% to 21.70% MC, with an average of 20.81%, after 60 days of air-drying (Fig. 3b). Figure 4 shows the average air-drying time of sample lumbers in December, as well as the equilibrium moisture contents on particular days. Research on favorable moisture conditions for wood-deteriorating organisms reveals that most decay fungi require moisture contents above the fiber saturation point (typically 25-30%) for optimal growth. However, some species can operate at lower levels (Carll and Highley 1999).

Wood contains two forms of moisture: bound water within cell walls and free water in liquid form within cell voids. According to Thybring and Fredriksson (2023), this shift reflects the transition from the loss of free water in the over-hygroscopic range to the slower diffusion of bound water in the hygroscopic range. Species-specific differences are distinct, as Braz et al. (2015) found that Acacia mangium boards dried more slowly than Tectona grandis boards under identical environmental conditions, recommending separate analysis for each species. The broken lines represent the equilibrium moisture content (EMC), which is the point at which wood naturally balances with the surrounding air. The drying curves of falcata lumber approach this line over time, indicating that the wood is gradually adapting to the local climate. The moisture content of the wood, given enough time, reaches equilibrium with its surrounding environment (Mitchell 2018). Jenkins first used the word "equilibrium moisture content" in (1934). This slower drying rate may be related to seasonal weather conditions, as factors such as relative humidity, temperature, and rainfall are known to influence air-drying performance. However, specific weather data were not recorded during the trials. The drying rate is affected by external drying conditions (Walker et al. 1993, Keey et al. 2000). The drying behavior of wood is influenced by anatomical characteristics, such as fiber diameter, lumen diameter, and cell wall thickness, which affect the intensity of drying (Eloy et al. 2021). According to Richter and Dallwitz (2000), falcata wood is diffuse-porous. Diffuse-porous species exhibit high sensitivity to environmental conditions during drying, varying with atmospheric and soil moisture levels (Meinzer et al. 2013). The drying process is further complicated by interactions between temperature, relative humidity, air velocity, and wood species characteristics (Chong et al. 2019).

Research on air-drying lumber has consistently demonstrated the effectiveness of multiple regression models for predicting drying times. Simpson (2004) developed multiple regression equations to estimate air-drying times of red oak, sugar maple, and ponderosa pine lumber using historical weather records of temperature and relative humidity. Simpson and Wang (2004) extended this approach to small-diameter logs, creating both linear and nonlinear regression models that relate daily moisture content loss to initial moisture content, temperature, relative humidity, and log diameter. Cai and Oliveira (2012) developed similar models for dimensional spruce/pine lumber, incorporating temperature, relative humidity, initial moisture content, and wind speed, while finding wind direction to be insignificant.

The regression coefficients and corresponding coefficient determination for each stacking month or pile month are shown (Table 1). The R2 ranges from 0.9 to 1. Analysis that fits well or fitted such that September, October follow a polynomial

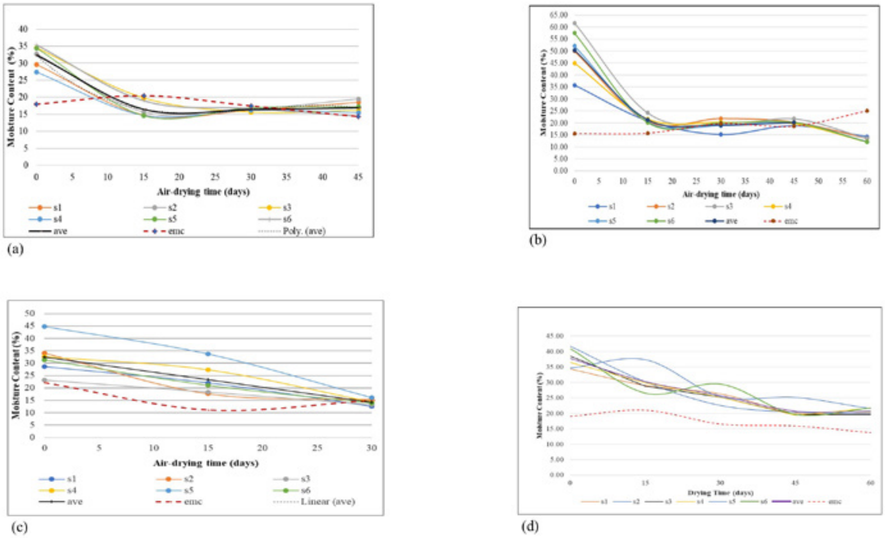

Figure 2. Drying curves of air-drying time of falcata lumber stacked in September 2024 (a). Drying curves of air-drying time of falcata lumber stacked in October 2024 (b). Drying curves of air-drying time of falcata lumber stacked in November 2024 (c). Drying curves of air-drying time of falcata lumber stacked in December 2024 (d). Legend: s1- sample 1; s2- sample 2; S3- sample 3; s4-sample 4; s5- sample; s6- sample

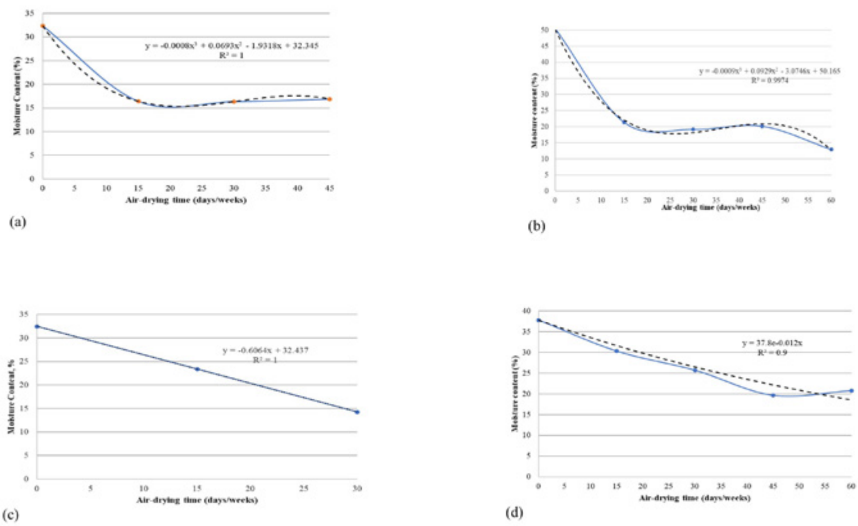

Figure 3. Average drying curves of air-drying time of falcata lumber stacked in September 2024 (a). Average Drying curves of air-drying time of falcata lumber stacked in October 2024 (b). Average Drying curves of air-drying time of falcata lumber stacked in November 2024 (c). Average Drying curves of air-drying time of falcata lumber stacked in December 2024 (d).

Table 1. Regression coefficients, and coefficient determinations for each stacking or pile-months and drying times of short-length falcata lumbers from September-December 2024.

Stacking/ Piling Month	a	b	c	d	R^2
September	-0.0008	0.0693	-1.9318	32.345	1
October	-0.0009	0.0929	-3.0746	50.165	0.9974
November*	-0.064	32.437			1
December**	37.8e				0.9

*Polynomial (3rd order); * Linear; ** Exponential*

(3rd order), November linear, and December, exponential. Simpson (2004) estimated air-drying times of lumber using multiple regression and demonstrated that the relationship between moisture content loss and initial moisture content during drying is nonlinear. Chanpet et al. (2020) described the average drying curves (time and moisture content) of rubberwood lumber at different velocities in Thailand, and the relationships are nonlinear. Bryś et al. (2021) determined model parameters of the drying characteristics of beech and willow sawdust as best described by linear, rational, and logarithmic equations.

3.2 Air drying Estimate

The estimated air-drying time of green 2"×4" ×4' commercial Falcata lumber varied considerably depending on the month of stacking. When stacked in September, lumber samples were predicted to reach a moisture content (MC) of 15% in approximately 20 days. However, this target was achieved in 52 days in October, 29 days in November, and as long as 77 days in December. At a target MC of 20%, the drying period was shortest in September, requiring only 9 days, compared to 18 days in October, 21 days in November, and 53 days in December. For the 25% MC level, the September stacking required only 5 days, while both October and November required 12 days, and December extended to 35 days (Figure 4). A similar trend was observed at 30% MC, where September stacking required just 2 days, in contrast to 9 days in October, 4 days in November, and 19 days in December. These estimates clearly demonstrate that the month of stacking has a strong influence on the air-drying rate of falcata lumber, with September providing the most favorable drying conditions and December the slowest.

3.6. Air-drying rate difference

Table 2 presents the drying rate of the sampled lumber, expressed as percent per day (%/day). The mean drying rate ranged from 0.28% in December to 0.62% in October. Analysis of variance under a Completely Randomized Design (ANOVA-CRD) revealed a statistically significant effect of stacking month on air-drying rate ($p = 0.0001857$) (Table 3). Post hoc comparisons using Tukey's Honestly Significant Difference (HSD) test (Tukey-Kramer) revealed significant differences among the pairs: September–October (x1–x2), September–November (x1–x3), October–December (x2–x4), and November–December (x3–x4). Conversely, no significant difference was observed between the pairs September–December (x1–x4) and October–November (x2–x3).

4 Conclusions

Results demonstrated that drying rates varied considerably across months, with September providing the most favorable conditions (20 days to reach 15% MC) and December the least favorable (77 days to reach 15% MC). Such variation shows the possible influence of seasonal climatic conditions on drying efficiency. Furthermore, the results show that the drying process is best explained by polynomial and exponential models, reflecting the nonlinear nature of moisture loss. The wood moisture is lost rapidly during the initial stage as free water evaporates, and then more slowly in later stages as bound water diffuses out from the wood structure. While these variables may influence drying performance, the present study did not collect data related to tree age or anatomical characteristics. Future studies incorporating these parameters would help strengthen the understanding of moisture-loss behavior and inform air-drying recommendations for falcata lumber.

Beyond these findings, the study shows several opportunities for strengthening future research. Factors such as tree age, the presence of heartwood and sapwood, and other inherent wood characteristics may also influence drying behavior and deserve further examination.

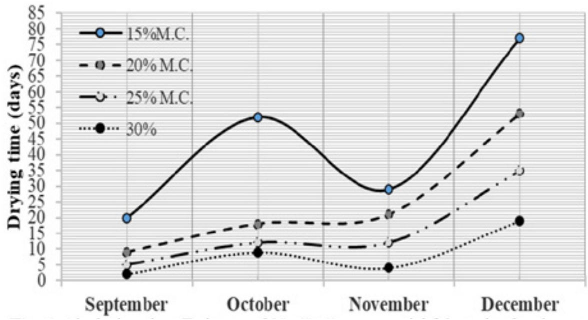

Figure 4. Air-drying time: Estimate of 2 "x 4" x4' commercial falcata lumber in green-rough condition.

Table 2. Drying rate, percent per day (%/day), of lumber based on Stacking Month.

	September	October	November	December
	0.25	0.36	0.53	0.23
	0.29	0.61	0.62	0.36
	0.41	0.80	0.33	0.32
	0.26	0.55	0.61	0.25
	0.38	0.67	0.96	0.22
	0.47	0.76	0.58	0.32
Mean	0.34	0.62	0.61	0.28

Table 3. ANOVA-CRD shows the significant difference in Air-drying rate.

Source	DF	Sum of Square	Mean Square	F Statistic	P-value
Groups (between groups)	3	0.003022	0.001007	10.8983	0.0001857*
Error (within groups)	20	0.001849	0.0000924		
Total	23	0.004871	0.0002118		

*Note: Figure in * indicates a significant difference.*

Table 4. Tukey HSD/Tukey Kramer shows the significant differences between months.

Pair	Difference	SE	Q	Lower Cl	Critical mean	P-value
x1-x2	0.02018	0.004	5.1408	0.004642	0.01554	0.008238*
x1-x3	0.01878	0.004	4.7852	0.003246	0.01554	0.0144*
x1-x4	0.005262	0.004	1.3405	-0.01028	0.01554	0.7797
x2-x3	0.001396	0.004	03556	-0.01414	0.01554	0.9942
x2-x4	0.02544	0.004	6.4813	0.009903	0.01554	0.00096*
x2-x4	0.02404	0.004	6.1257	0.008507	0.01554	0.0017*

*Note: Figure in *, indicates a significant difference.*

Exploring methodological improvements, such as using electric fans to accelerate air-drying and monitoring potential drying defects throughout the process, could provide deeper insights and enhance the practical application of air-drying techniques. Overall, the results of this study provide localized empirical evidence that can help refine drying time estimates and support improved lumber handling practices in the Caraga Region.

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6 Author Contribution

RN Cossid contributed to the supervision of the study, development of the methodology, data curation, and preparation of the original draft. CS Casilac Jr. was responsible for data curation and manuscript editing for publication. RL Palaso contributed to data curation and writing of the original draft. EP Cuenca, MF Almacen, and JC Illustrisimo contributed to the conceptualization of the study, data gathering, and writing of the original draft.

7 Statement of Conflict of Interest

The authors declare no conflict of interest associated with the conduct and publication of this manuscript.

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Willingness to Pay for Smartphone-Based Plant Care Advisory Services: Evidence from Dang Xa Urban Area, Hanoi, Vietnam

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ABSTRACT

In the context of digital transformation and urban agricultural development, smartphone applications providing plant care advice are becoming increasingly popular and are expected to bring many benefits to urban residents. However, the level of acceptance and willingness to pay for these services has not been fully studied. This study aims to analyze the willingness to pay (WTP) of urban residents for smartphone-based plant care advice services in the Dang Xa urban area, Hanoi. Data was collected from 115 households through direct surveys. The analysis methods included descriptive statistics, exploratory factor analysis (EFA) based on the Technology Acceptance Model (TAM), and multiple linear regression. The results indicate that the average WTP is estimated at 37,826 VND (approximately USD 1.46), with substantial variation across respondents. Regression results show that perceptions of the application's usefulness, income, and gender have a positive, statistically significant impact on residents' willingness to pay. Meanwhile, perceptions of ease of use and other demographic characteristics have not yet shown a significant impact. Based on this, the study proposes several policy and management implications to promote the development and expansion of digital plant care advisory services in urban contexts.

Keywords: *Smartphone-based advisory services, Willingness to pay, Plant Care Advisory Services, Digital agricultural services, TAM*

1 Introduction

Urban gardening has expanded rapidly in Vietnam, particularly among middle-income households seeking safer, higher-quality food (Pham et al. 2023). In large cities such as Hanoi, residents increasingly cultivate vegetables and ornamental plants in limited spaces, including balconies, rooftops, and small yards. Despite its potential to enhance household food security and urban sustainability, urban gardening often faces constraints, including limited technical knowledge, inappropriate plant varieties, soil management problems, and pest control issues, which reduce plant productivity and survival (Trung & Loan 2025). At the same time, conventional agricultural extension services in Vietnam have traditionally prioritized rural areas, leaving urban gardeners with insufficient access to professional plant care guidance (Faltmann 2023, Pham & Turner 2020, Trung & Loan 2025).

Advances in digital technology, especially the widespread use of smartphones, create new opportunities to address this gap through smartphone-based plant care advisory services (Bonke et al. 2018, Emeana et al. 2020, Fox et al. 2021, Mangole et al. 2024, Michels et al. 2020). These services typically provide real-time information on planting techniques, weather conditions, pest management, and access to expert consultations, making them particularly suitable for urban residents with limited time and space (Emeana et al. 2020, Fox et al. 2021). In line with Vietnam's national digital transformation and digital agriculture initiatives, such services are increasingly recognized as policy-relevant tools for modernizing agricultural extension and improving service inclusiveness. However, despite their potential benefits, the adoption of smartphone-based advisory services remains limited, partly due to concerns about cost, data security, service reliability, and varying levels of digital literacy among users (Michels et al. 2020).

Existing literature has examined the role of digital advisory services in agriculture, mainly focusing on rural farmers and productivity outcomes, while evidence from urban contexts-especially in developing countries – remains scarce (Bonke et al. 2018, Emeana et al. 2020, Fox et al. 2021, Michels et al. 2020). In particular, there is limited empirical research on urban residents' willingness to pay (WTP) for smartphone-based plant care advisory services in Vietnam. To further explain how urban residents accept and evaluate smartphone-based plant care advisory services, this study incorporates the Technology Acceptance Model (TAM). The TAM posits that an individual's acceptance of a new technology is primarily determined by two main perceptions: perceived usefulness and perceived ease of use (Davis, 1989). In the context of urban gardening, perceived usefulness (PU) reflects the extent to which users believe smartphone-based advisory services can improve plant health, while perceived ease of use (PE) reflects the extent to which the application is perceived as user-friendly and compatible with users' digital skills. These perceptions shape users' attitudes toward the technology, thereby influencing their behavioral intentions to accept and pay for the service. By incorporating TAM into an economic pricing framework, this study links the WTP of urban residents not only to socioeconomic characteristics but also to behavioral and cognitive factors related to technology adoption. This integrated approach allows for a better understanding of service adoption decisions. It helps explain why potential users may or may not be willing to financially support smartphone-based plant care advisory services in the Vietnamese urban context.

Against this backdrop, this study aims to assess residents' WTP for smartphone-based plant care advisory services in Dang Xa Urban Area, Hanoi. By identifying the level of WTP and its key socioeconomic and behavioral determinants, the study contributes empirical evidence to the limited literature on digital agricultural services in urban Vietnam. The findings also provide policy-relevant insights for service providers and policymakers seeking to design effective pricing strategies, enhance service adoption, and promote the sustainable development of digital advisory services for urban agriculture.

2 Theoretical Basis and Research Model

2.1 Technology Acceptance Model (TAM)

The Technology Acceptance Model (TAM), proposed by Davis (1989), suggests that consumers' behavior in accepting and using technology is primarily influenced by two factors: perceived usefulness (PU) and perceived ease of use (PE). Perceived usefulness reflects the extent to which users believe that using technology will improve their work efficiency or quality of life, while perceived ease of use reflects the ease of learning and using that technology. In the context of smartphone-based plant care consulting services, PU can be understood as the extent to which users believe the application helps them care for their plants more effectively, reduce pest and disease risks, and save time and costs. PE reflects the user-friendliness of the interface, ease of operation, and accessibility.

2.2. Willingness to Pay for Digital Services

Willingness to Pay (WTP) is a measure reflecting the economic value that consumers are willing to pay for a particular product or service. In research on digital services, WTP is infuenced not only by perceived benefits and costs, but also by socioeconomic factors such as income, gender, Age, education level, and household characteristics (Bonke et al. 2018). For urban residents, the decision to pay for plant care consulting services may also be influenced by factors such as family care responsibilities, household size, and the presence of children or elderly family members.

2.3. Research Model

Based on theoretical foundations and research overview, this study proposes a model to analyze the relationship between willingness to pay for smartphone-based plant care consultation services and the following groups of factors: (i) perceived usefulness; (ii) perceived ease of use; and (iii) socio-demographic characteristics of urban residents.

3 Methodology

3.1 Data Collection Method

Primary data were collected through face-to-face interviews with 115 residents in Dang Xa Urban Area, Hanoi. This approach was chosen to ensure a high response rate, clarify survey questions, and improve respondents' understanding of the hypothetical market scenario, which is essential to the reliability of contingent valuation studies.

The survey was designed following an open-ended contingent valuation method (CVM). Before eliciting WTP, respondents were provided with a standardized, detailed description of the smartphone-based plant care advisory service. The description outlined a hypothetical market scenario and clearly explained the service's main features and assumed benefits, including improved plant health and quality, time savings in daily plant care, and enhanced quality of life for urban residents. Instead of using dichotomous-choice questions with predetermined bid levels, respondents were directly asked to state the maximum amount they would be willing to pay for the service. This open-ended elicitation approach allowed respondents to freely express their valuation without being constrained by predefined bid amounts, thereby reducing potential starting-point and anchoring biases commonly associated with closed-ended CVM formats.

To support respondents in providing realistic and thoughtful responses, the questionnaire included clarifying statements regarding the payment context, such as the assumed payment vehicle (e.g., monthly subscription fee) and the conditions under which the service would be provided. In addition, respondents were reminded to consider their household budget constraints and alternative expenditures when stating their maximum WTP.

Given the importance of interviewer performance in face-to-face valuation surveys, all interviewers received intensive training prior to data collection. The training focused on ensuring a consistent presentation of the valuation scenario, a clear explanation of the service attributes, and proper administration off the open-ended WTP question. Interviewers were instructed to avoid suggesting any price levels, refrain from prompting respondents toward specific answers, and maintain a neutral and professional tone throughout the interview. Pilot surveys and role-playing exercises were conducted to help interviewers handle respondents' questions, address potential misunderstandings, and appropriately identify protest or zero WTP responses.

To enhance data quality, face-to-face interviews were conducted at times and locations convenient for respondents, such as their homes or common residential areas. Interviewers ensured privacy during the interview process and verified that respondents fully understood the valuation question before recording their responses. Respondents were informed that participation was voluntary and that all responses would be kept confidential. These measures contributed to improved response accuracy, reduced measurement error, and enhanced the overall reliability of the collected data.

3.2 Description of Research Variables

Dependent variable

The dependent variable in this study is the WTP of urban residents for a smartphone-based plant care consultation service. WTP is elicited using an open-ended contingent valuation question, in which respondents are asked to state the maximum amount of money they are WTP per month for access to the service under the specified hypothetical market scenario. The WTP variable is treated as continuous and non-negative. Zero values are allowed and interpreted as either genuine zero WTP or protest responses, which are further examined during data cleaning and robustness checks.

Independent variable

The independent variables are divided into two main groups: technology acceptance factors based on the TAM, and socio-demographic characteristics.

(i) TAM variables

Following the TAM framework, the model includes two latent cognitive constructs: Perceived Usefulness (PU) and Perceived Ease of Use (PE).

Each construct is measured using multiple observed indicators rated on a five-point Likert scale, ranging from 1 ("*strongly disagree*") to 5 ("*strongly agree*"). After validating the measurement scales through exploratory factor analysis, composite scores for PU and PE are computed as factor scores. These factor scores are continuous variables capturing respondents' cognitive evaluation of the service.

(ii) Socio-demographic variables

A set of socio-demographic variables is included to control for individual and household characteristics that may influence WTP. These variables include: Gender: binary variable (*1=male, 0=female*), Age: categorical group of respondent's Age (*1=18-25 years, 2=26-35 years, 3= 36-45 years, 4=46-55 years, 5=above 55 years*); Education level (Edu) is also measured as an ordinal variable, indicating the highest level of education attained by respondents: *1=below high school, 2= high school, 3=vocational college and 4=university degree or postgraduate education*; Occupation status: dummy variable capturing 1= retirement or non-working status; 0= Others; Income (Income per month): ordinal variable measured in income group: 1=<3 millions, 2=3-5 millions, 3= 5-10 millions, 4=10-20 millions, 5=>20 millions; Marital status (Marriage): binary variable (1=married, 0= single); Household size (Hhsize): total number of household members; Number of children (Kid): number of children in the household; Number of elderly members (Elder): number of household members aged 60 years or older.

These variables are included to account for heterogeneity in economic capacity, household responsibilities, and preferences.

3.3 Data Analysis Methods

Descriptive statistics

Descriptive statistical analysis is first conducted to summarize the characteristics of the survey sample and provide an overview of respondents' socio-demographic profiles and WTP distribution. Measures such as means, standard deviations, frequencies, and percentages are reported for key variables.

Reliability analysis of measurement scales

The reliability of the PU and PE scales was assessed using Cronbach's alpha. All constructs exceeded the recommended threshold of 0.7, indicating satisfactory internal consistency.

Exploratory factor analysis (EFA)

Exploratory factor analysis is applied to validate and reduce the observed indicators of PU and PE into underlying latent constructs. Prior to EFA, data suitability is assessed using the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's test of sphericity. The KMO measure was 0.82, and Bartlett's test of sphericity was statistically significant ($p < 0.001$), confirming the suitability of the data for factor analysis (Hair et al., 2010). Factors with eigenvalues greater than one are retained, and items with factor loadings below a predefined threshold are excluded to ensure construct validity and internal consistency. Based on the EFA results, the two latent factors corresponding to PU and PE are clearly grouped, with no substantial cross-loadings, thereby confirming the discriminant validity of the measurement scales (Table 1). After EFA, the PU and PE were retained, and factor scores were computed for use in the regression analysis.

Econometric model

To analyze the determinants of WTP, a multiple linear regression model is employed. Given that WTP is observed as a continuous variable through an open-ended CVM, the baseline econometric specification is expressed as:

$$WTP_i = \beta_0 + \beta_1 PU_i + \beta_2 PE_i + \sum_{k=1}^{K} \gamma_k Z_{ik} + \varepsilon_i$$

Where:

WTP_i is the stated monthly willingness to pay of respondent i;

PU_i and PE_i are the factor scores representing perceived usefulness and perceived ease of use;

Z_{ik} is a vector of socio-demographic control variables;

β_0 is the intercept;

β_1,β_2, and γ_k are parameters to be estimated;

ε_i is the error term, assumed to be independently and identically distributed with zero mean and constant variance.

Ordinary Least Squares (OLS) is the primary estimation method. Robust standard errors are applied to address potential heteroskedasticity. The SPSS 22.0 package was used for this analysis.

4 Results and Discussion

4.1. Descriptive statistics of the sample

The descriptive statistics (Table 2) indicate that the sample is relatively balanced by gender, with 59.1% male and 40.9% female respondents. Regarding age distribution, the majority of respondents fall within the economically active age groups, particularly 46-55 years (28.7%), followed by 26-35 years (24.3%) and 36-45 years (22.6%). Respondents aged 55+ account for 19.1%, while the youngest group (18-25 years) represents only 5.2% of the sample.

In terms of educational attainment, the sample is characterized by a high level of education. More than 60% (61.7%) of respondents hold a university

Table 1. Rotated factor loadings of PU and PE items

Item code	Measurement items	Perceived Usefulness (PU)	Perceived Ease of Use (PE)
PU1	Using a smartphone-based plant care advisory service can improve the effectiveness of my plant cultivation.	0.871	
PU2	The service helps me save time and effort in taking care of my plants.	0.870	
PU3	Receiving plant care guidance through a smartphone is convenient for me.	0.814	
PU4	I am less concerned about the accuracy of the information provided by the service.	0.808	
PU5	I am less concerned about the security and privacy of my persona information when using the service.	0.831	
PE1	I believe that the interface of the plant care advisory application would be user-friendy and easy to use.		0.619
PE2	I think that using the smartphone-based plant care advisory service would be easy and would not require advanced technical skills.		0.923
PE3	I expect that it would be easy for me to learn how to use the smartphone-based plant care advisory service.		0.922

Table 2. Socio-demographic characteristics of respondents

Characteristics	Categories	Percentage
Gender	Male Female	59.1 40.9
Age group	18-25 years 26-35 years 36-45 years 46-55 years Above 55 years	5.2 24.3 22.6 28.7 19.1
Education Level	Below High School High School Vocational College University Degree or Postgraduate Education	3.5 7.0 27.8 61.7
Occupation Status	Retired or non-working Others	21.0 79.0
Income per month	<3 millions 3-5 millions 5-10 millions 10-20 millions >20 millions	7.8 8.7 27.0 51.3 5.2
Marital Status	Married Single/divorce	89.6 10.4
Household Size Number of household members in the family	1 person 2 persons 3 persons 3 persons 4 persons 5 persons 6 persons	4.3 14.8 27.8 40.9 11.3 0.9
Number of children Number of children lesss than 16 years old in the family	0 person 1 person 2 persons	61.7 30.4 7.8
Number of elderly members Number of household members aged 60 years or older	0 person 1 person 2 persons	72.2 22.6 5.2

degree or postgraduate qualification, while 27.8% have completed vocational college education. The proportions of respondents with a high school education (7.0%) or below high school level (3.5%) are relatively small.

Regarding occupational status, 79.0% of respondents are currently employed or engaged in other active occupations, whereas 21.0% are retired or not working at the time of the survey. Regarding monthly income, over half of the respondents (51.3%) report an income level of 10-20 million VND, followed by those earning 5-10 million VND (27.0%). Lower-income groups earning below 5 million VND account for 16.5%, while only 5.2% report a monthly income exceeding 20 million VND.

In terms of marital status, the sample is predominantly married (89.6%), while 10.4% are single or divorced. Household size varies across the sample, with most households consisting of three or four members, accounting for 27.8% and 40.9%, respectively. Smaller households with one or two members account for 19.1%, while larger households of five or more members constitute a relatively small proportion.

Regarding household composition, 61.7% of respondents report having no children under 16 years old, while 30.4% have one child, and 7.8% have two children. In addition, most households (72.2%) do not include elderly members aged 50 years or older, whereas 22.6% report having one elderly member, and only 5.2% have two elderly members.

Overall, the descriptive statistics suggest that the sample consists mainly of middle-aged, well-educated, married individuals with moderate to high incomes, living in medium-sized households, which is consistent with the characteristics of the urban households targeted in this study.

4.2. Willingness to pay for the smartphone-based plant care advisory service

Based on 115 valid responses (Table 3), the estimated mean WTP is 37,826 VND (approximately USD 1.46), with considerable variation across respondents (SD = 17,309 VND, equivalent to USD 0.67). Individual WTP values range between 10,000 VND (USD 0.38) and 95,000 VND (USD 3.65), using an exchange rate of 26,000 VND per USD.

4.3. Econometric Results

Table 4 presents the results of the multiple linear regression model examining the determinants of urban residents' WTP for the smartphone-based plant care advisory service. The dependent variable is the stated monthly WTP, while the independent variables include socio-demographic characteristics and factor scores derived from the exploratory factor analysis. The regression model explains 41.9% of the variation in WTP, with an adjusted R2 of 0.357, and the F-statistic of 6.747 is statistically significant at the 1% level ($p<0.001$), indicating that the model has good overall explanatory power and is statistically reliable.

Socio-demographic factors

Among the socio-demographic variables, gender and income are statistically significant predictors of WTP. The coefficient for gender is positive and significant at the 1% level, indicating that male respondents are WTP, on average, approximately 9,053 monetary units (9,053 VND) per month than female respondents, holding other factors constant.

Income also has a positive, statistically significant effect on WTP, suggesting that respondents with higher incomes are more willing to pay for the service. This result is consistent with economic theory, as individuals with greater purchasing power tend to exhibit higher WTP for value-added digital services.

Other socio-demographic variables, including Age, education level, occupation status, marital status, household size, number of elderly household members, and number of children, do not show statistically significant effects at conventional levels. However, the coefficient for the number of children in the household is negative and marginally significant at the 10% level, implying that households with more children may face tighter budget constraints, which could reduce discretionary spending on digital advisory services.

Technology Acceptance Model (TAM) factors

The regression results highlight the dominant role of technology acceptance factors in explaining WTP. Perceived Usefulness (PU) has a strong positive and highly significant effect on WTP. Specifically, a one-unit increase in perceived usefulness is associated with an increase of approximately 7,451 monetary units in monthly WTP (7,451 VND).

In contrast, Perceived Ease of Use (PE) has a positive but statistically insignificant effect on

Table 3. Estimated mean willingness to pay for the smartphone-based plant care advisory service

Statistic	**Value (VND) ***
Mean WTP	37,826
Standard deviation	17,309
Minimum	10,000
Maximum	95,000
Observations	115

*Note: * 1 USD = 26,000 VND (June 2025)*

Table 4. Determinants of willingness to pay for the smartphone-based plant care advisory service

Variables	Coefficient (B)	Std. Error	Standardized β	t-statistic	VIF
Constant	17,106.147	10,741.205	-	1.593	
Gender	9,053.312***	2,733.319	0.258	3.312	1.077
Age	1,013.283	1,545.098	0.070	0.656	1.995
Education	-2,580.965	2,182.214	-0.116	-1.183	1.697
Occupation	5,588.182	4,041.118	0.132	1.383	1.609
Income	4,849.436***	1,721.753	0.279	2.817	1.737
Marriage	8,013.294	5,429.024	0.142	1.476	1.644
Household size	-694.553	1,529.595	-0.042	-0.455	1.501
Number of children	-4,147.950*	2,383.738	-0.153	-1.740	1.373
Number of elderly	1,708.119	2,864.325	0.057	0.596	1.594
Perceived Usefulness (PU)	7,451.279***	1,374.954	0.430	5.419	1.118
Perceived Eese of Use (PE)	1,961.442	1,360.920	0.113	1.441	1.095
Number of observations (N)	115				
R^2	0.419				
Adjusted R^2	0.357				
F static	6.747				
Sig.	0.000				

*Notes: The dependent variable is monthly WTP. PU and PE are factor scores derived from EFA. Robust standard errors are reported. *** p<0.01, denotes significance at the 1% level** p<0.05, at the 5% level* p<0.10, at the 10% level. All variance inflation factor (VIF) values are below 2, indicating no multicollinearity concerns.*

WTP, which suggests that while ease of use may contribute to favorable perceptions of the service, it does not directly translate into higher WTP once perceived usefulness and socio-demographic factors are controlled for.

4.4. Discussion

The findings provide several important insights into how urban residents value smartphone-based plant care advisory services. First, the substantial effect of perceived usefulness confirms the central proposition of the TAM: users' valuation of a digital service is primarily driven by the extent to which they believe the service delivers tangible benefits, such as improved plant care efficiency, time savings, convenience, and reliable information. This finding aligns with previous literature, including that of Bonke et al. (2018).

The insignificant effect of perceived ease of use suggests that, in the context of a hypothetical digital service, ease of use may be viewed as a basic or expected feature rather than a differentiating factor that warrants a higher price. This result is consistent with previous studies on digital and mobile services, which often find that ease of use influences adoption intention indirectly through perceived usefulness rather than directly affecting WTP (Bonke et al. 2018, Emeana et al. 2020, Fox et al. 2021, Mangole et al. 2024, Michels et al. 2020, Widianto 2022).

From a socio-demographic perspective, the positive effects of gender and income indicate heterogeneity in valuation across population groups. The higher WTP among male respondents may reflect differences in technology engagement or spending preferences, while the income effect underscores the importance of affordability considerations in pricing digital advisory services. The negative (through marginal) effect of having children highlights potential budget trade-offs within households, suggesting that family-related financial obligations may limit discretionary spending on non-essential services.

Overall, the results imply that policy makers and service providers aiming to promote smartphone-based plant care advisory services should prioritize enhancing and clearly communicating the practical benefits of the service rather than focusing solely on interface simplicity. Emphasizing measurable outcomes – such as improved plant health, reduced time commitment, and reliable guidance – may be more effective at increasing users' WTP, particularly among higher–income and technology–oriented user segments.

5 CONCLUSIONS

The study examines urban residents' WTP for smartphone-based plant care advisory services using a framework that integrates socio-demographic characteristics and the TAM. Based on survey data from 115 households in the Dang Xa urban area of Hanoi, the findings provide empirical evidence on the key determinants shaping users ' valuation of digital plant care services in an urban context.

The results indicate that technology acceptance factors, particularly perceived usefulness, play a more decisive role in explaining WTP than most socio-demographic characteristics. The substantial and statistically significant effect of perceived usefulness confirms that users' valuation of the service is primarily driven by the extent to which they expect tangible and practical benefits, such as improved plant care outcomes, time saving, and access to reliable guidance. In contrast, perceived ease of use may be regarded as a basic requirement rather than a value-enhancing attribute in the context of digital advisory services.

Among socio-demographic factors, income and gender are found to influence WTP, highlighting heterogeneity in users' valuation significantly. Higher-income respondents demonstrate a greater WTP, reflecting affordability constraints and differences in purchasing power. The higher WTP observed among male respondents may be associated with variations in technology engagement or spending preferences. Additionally, the marginally negative effect of having children suggests that household budget constraints may limit discretionary spending on non-essential digital services.

From a policy and managerial perspective, these findings imply that efforts to promote smartphone-based plant care advisory services should prioritize enhancing and clearly communicating the service's functional benefits, rather than focusing exclusively on interface simplicity. Service providers should emphasize measurable, outcome-oriented benefits, such as improved plant health, reduced maintenance time, and reliable, expert-backed recommendations, to increase perceived usefulness and, consequently, users' WTP.

In terms of pricing and market segmentation, differentiated pricing strategies may be considered to improve accessibility across income groups, for example, through tiered service packages or introductory pricing for lower-income households. Policymakers and urban agricultural planners may also support the adoption of such digital services by integrating them into broader urban greening or smart-city initiatives, thereby enhancing their perceived value and social relevance.

Despite its contributions, this study is subject to certain limitations. The analysis is based on a relatively small sample and a single urban area, which may limit the generalizability of the findings. Future research could expand the sample size and incorporate multiple urban contexts. Additionally, future studies may investigate the role of trust, information quality, and long-term usage experience in shaping users' WTP for digital plant care advisory services.

6 Statement of Conflict of Interest

Le Thi Thanh Loan, who serves on the JESEG Editorial Board, had no involvement in the review of this manuscript to preserve objectivity in the evaluation process. Furthermore, the authors affirm that there are no financial or personal relationships that could be perceived as potential conflicts of interest in relation to this work

7 Author Contribution

Le Thi Thanh Loan was involved in the conception and design of the study, data analysis and interpretation, drafting and revision of the manuscript for significant intellectual content, served as the lead and corresponding author, and gave final approval for the version to be published. Bui Phuong Nhung contributed to the study conception, data collection, and approved the final version for publication.

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A Spatial Analysis of Agricultural Land Loss Across the Urban–Rural Gradient: Applying DEGURBA in Butuan City, Philippines (2010–2020)

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ABSTRACT

Urban expansion is a major driver of agricultural land loss in rapidly developing cities. In the Philippines, urbanization is accelerating not only in metropolitan centers but also in secondary and intermediate cities, contributing to the conversion of productive agricultural land. Traditional urban–rural classifications based on administrative boundaries are often inadequate for capturing the complex, fragmented, and transitional nature of urban growth. This study addresses this limitation through a decadal (2010–2020) spatial analysis of agricultural land cover change, using Butuan City, Philippines, as an illustrative case within the Degree of Urbanisation (DEGURBA) framework. Leveraging government-produced land cover maps derived from satellite remote sensing and implementing a dasymetric DEGURBA approach based on Google Open Buildings and barangay-level census data, agricultural land change across urban centers, urban clusters, and rural areas was quantified and analyzed. Results show a total loss of approximately 49.8 km^2 (9.6%) of agricultural land over the decade, with the most pronounced losses occurring in urban clusters—transitional zones where high shares of remaining cropland coincide with rapid outward urban expansion. These findings highlight the relevance of urban clusters as priority areas for land-use monitoring and informed planning. While rural areas retained most of the agricultural land, they also showed signs of encroachment along expanding urban fringes. The case of Butuan City illustrates how combining standardized urban–rural typologies with fine-resolution geospatial data enables more consistent assessments of land-use transitions. This integrative framework can be applied globally to enhance monitoring of agricultural land dynamics and to support evidence-based strategies for sustainable urban and regional planning.

Keywords: *Agricultural Land Cover Change, Barangay Census Data, Dasymetric Mapping, Degree of Urbanisation (DEGURBA), Google Open Buildings, Urban-Rural Gradient, Urbanization.*

1 Introduction

Urban expansion is widely recognized as a key driver of land-use change, particularly in developing countries, where rapid urban growth often leads to the conversion of high-value agricultural land (Huang et al. 2020, Seto et al. 2012). In Southeast Asia, urbanization and population concentration in peri-urban areas have significantly disrupted traditional land-use systems (Tacoli 2003, Webster, 2002). These transitional zones, located between urban and rural areas, are particularly susceptible to agricultural land conversion, as elevated land values and development incentives lead to shifts toward residential and commercial uses (Custodio & Sombilla 2025).

In the Philippines, urbanization is intensifying not only in major metropolitan areas but also in secondary and intermediate cities (Ortega et al. 2015, Santillan & Heipke 2024). This accelerating urban expansion, often manifesting as urban sprawl, has led to the progressive loss of agricultural lands, the fragmentation of contiguous farmland, and the widespread conversion of these areas for residential, commercial, and other urban uses (Bravo 2017, Malaque & Yokohari 2007, Murakami & Palijon 2005). Recent national-scale analysis using satellite remote sensing data confirms that such agricultural land conversions to built-up areas have been widespread across the Philippines from 2000 to 2020, including within legally protected prime agricultural zones, highlighting persistent spatial and governance challenges (Araza et al., 2026). Recent evidence suggests that these challenges are further complicated by the uneven progress of institutional reforms and land-use policies, which have failed to stabilize agricultural productivity in many regions (Custodio & Sombilla, 2025). Butuan City, in northeastern Mindanao, exemplified this trend, undergoing land transformation amid national trends in decentralization and spatial expansion. Earlier studies have documented a significant increase in the spatial extent of built-up areas and other land cover changes in this city through the combined use of satellite remote sensing and geospatial analysis (Asube et al. 2021, Bentozal et al. 2024, Cacayan et al. 2022, Cloma & Asube 2020). One such study (Bentozal et al. 2024) documented the ongoing conversion of rice croplands and identified areas highly susceptible to future urban encroachment. While offering valuable insights into the characteristics and spatial distribution of vulnerable croplands, the study did not employ a standardized framework to classify and compare agricultural land transitions across the city's urban, peri-urban, and rural zones.

Urban–rural classification in the Philippines is traditionally based on barangay-level designations, where each barangay (the smallest administrative unit) is officially categorized as either urban or rural. This classification is based on criteria such as population size, the predominance of non-agricultural employment, and the presence of infrastructure and basic services (PSA, 2013). While this binary system serves administrative and statistical functions, it may fail to accurately reflect the complex, gradual transitions occurring in areas undergoing urban expansion. For instance, some barangays officially classified as rural may already exhibit urban characteristics, such as dense housing or commercial activity. In contrast, others categorized as urban may still include significant agricultural or undeveloped land. Moreover, because barangays vary widely in size and spatial configuration, treating them as the basic unit for urban–rural classification introduces inconsistencies into spatial analysis. Some barangays encompass large, heterogeneous areas that include both densely built-up and predominantly agricultural zones, while others may be small but highly urbanized. This spatial variability, combined with the binary urban–rural designation, limits the ability to map and analyze land-use/land-cover changes with sufficient geometric detail. As with other classification systems based solely on administrative boundaries, this approach fails to capture the full range of differences between areas, particularly those undergoing transition (van Eupen et al. 2012). As a result, such an approach is often inadequate for capturing the complex, fragmented, and transitional nature of urban growth, particularly in peri-urban areas where land use patterns shift rapidly and irregularly.

To better reflect these dynamics, a shift in perspective is necessary, one that moves beyond dichotomous labels and acknowledges the fluidity of land use patterns along the urban–rural continuum. Treating urban and rural areas as strictly separate entities does not reflect the complexity of real-world landscapes. Instead, these areas should be viewed as part of a continuum, with land characterized along a gradient from rural to urban, where mixed land uses often coexist (van Vliet et al. 2020). Recognizing this, several studies have highlighted the value of finer-resolution urban–rural typologies, particularly gridded approaches, for supporting spatial planning and land change assessments in the urban-rural continuum. For example, Franconi et al. (2024) used population density and land cover data to characterize communities along the urban-rural gradient, thereby capturing the relationships among human communities, their activities, and the environment.

Meanwhile, Eupen et al. (2012) introduced a rural typology in Europe that leveraged high-resolution raster data on geography, population density, and accessibility to capture regional diversity in rurality. This approach enabled the consistent identification of comparable rural areas and their transitions with urban zones, providing a spatially explicit framework for both scientific analysis and policy communication. In a similar effort to represent the urban–rural continuum, Dijkstra et al. (2021) introduced the Degree of Urbanisation (DEGURBA), a harmonized classification method developed by international organizations and endorsed by the UN Statistical Commission to support global comparisons. DEGURBA categorizes areas into urban centres (cities), urban clusters (towns), and rural areas by grouping contiguous grid cells that meet specific thresholds for population density and total population size (European Commission & Statistical Office of the European Union 2021, Van Migerode et al. 2024). The DEGURBA method has been utilized as a primary method for urban-rural delineations to support the analysis of land use change (Gibas & Majorek 2020), land use efficiency (Melchiorri et al. 2019, Schiavina et al. 2022), and population ageing (Klimanek & Filas-Przybył 2019), among others. These works emphasize the importance of moving beyond administrative boundaries tto understand better the complex dynamics of urban transformation and its effects on land resources, particularly agriculture.

Within the Philippine context, however, such approaches remain limited. Most urban growth and land conversion studies still rely on administrative boundaries as the unit of analysis (Araza et al. 2026, Bravo 2017, Murakami & Palijon 2005, Olfato-Parojinog et al. 2023, Santillan & Heipke 2024). Although satellite remote sensing data and techniques have been employed for land cover mapping and change detection, particularly to assess impacts on agriculture (Araza et al. 2026, Fargas Jr. et al. 2021, Malaque & Yokohari, 2007), these are rarely combined with urban–rural classifications to provide comparative analyses across different zones. Moreover, the integration of frameworks such as DEGURBA remains scarce in the national literature, despite its growing adoption in international urban studies. There is thus a critical gap in applying harmonized, globally recognized methods to contextualize and analyze agricultural land change in the Philippines' dynamic urban and peri-urban environments.

Global gridded datasets have emerged to provide more spatially detailed representations of the urban–rural continuum. For example, the Global Human Settlement Layer (GHSL) includes products such as the GHS Settlement Model Grid (GHS-SMOD) (Schiavina et al., 2023) and the GHS Urban Center Database (GHS-UCDB) (European Commission et al. 2024), which offer globally standardized urban–rural typologies using the DEGURBA methodology. These datasets enable spatial comparisons and analyses across different regions; however, their applicability at local scales is often limited. This limitation is primarily due to discrepancies between modeled and actual population distributions, generalization of built-up extents, and the lack of alignment with official administrative boundaries. Consequently, these global products may not fully reflect ground realities in cities like Butuan. Moreover, aside from GHSL, few efforts in the Philippines have combined barangay-level population data with detailed building footprints to classify urban and rural areas and map human presence. This gap limits our ability to analyze urbanization processes and land-use transitions at the spatial detail necessary for effective local planning and land management.

This study addresses these limitations by examining the relationship between the degree of urbanization and agricultural land cover change through a spatial typology grounded in the DEGURBA classification. Using Butuan City, Philippines, as a case study area, the analysis applies this framework in combination with official land cover maps produced by the National Mapping and Resource Information Authority (NAMRIA) for 2010 and 2020 to provide a structured assessment of where and how agricultural land conversion has occurred, as well as its implications. In doing so, the study represents one of the first applications of the DEGURBA framework in the Philippine context to systematically analyze agricultural land cover change along the urban–rural gradient, introducing a standardized, grid-based approach that complements existing administrative-boundary-based analyses.

To guide the analysis, this study aims to answer the following research questions:

- How does the distribution of agricultural land vary across DEGURBA-defined urban centers, urban clusters, and rural zones in Butuan City?
- What are the patterns and magnitudes of agricultural land cover change from 2010 to 2020 in these zones?
- How can the DEGURBA be used to anticipate areas of potential agricultural land loss?
- What are the implications of these spatially differentiated agricultural land conversion

patterns for land-use planning, agricultural land management, and food security in an urbanizing city such as Butuan?

The remainder of the paper is structured as follows. Section 2 describes the study area, data sources, and methodological framework, including the dasymetric population mapping and the implementation of the DEGURBA classification. Section 3 presents the results of the agricultural land cover analysis across urban centers, urban clusters, and rural areas, with emphasis on spatial patterns and land cover transitions between 2010 and 2020. Section 4 discusses these findings in relation to urban expansion and agricultural land conversion, their implications for land-use planning and food security, and outlines key limitations and directions for future research. Finally, Section 5 summarizes the main conclusions and highlights the broader relevance of the proposed framework for analyzing agricultural land dynamics in urbanizing cities.

2 Materials and Methods

2.1 Study Area

Butuan City (Figure 1) is a highly urbanized city located in the northeastern part of Mindanao, Philippines. Serving as the regional center of Caraga Region (Region XIII), it occupies a total land area of approximately 817 square kilometers and comprises 86 barangays (CGB 2022). The city lies within the lower Agusan River Basin and is traversed by the Agusan River, the third longest river in the Philippines. Its terrain includes riverine plains, lowland agricultural zones, and upland forested areas. Strategically situated at the intersection of several major road networks, Butuan functions as a commercial and administrative hub in northeastern Mindanao. It plays a significant role in trade, education, and government services in the region. According to the 2020 Census by the Philippine Statistics Authority (PSA), the city had a population of 372,910, up by about 20% from 309,709 in 2010 (PSA, 2022). Of the city's population in 2020, about 68.5% live in 41 barangays classified as urban (PSA, 2025).

2.2 Methodology Overview

The methodology of this study consists of four major steps. First, a gridded population map of Butuan City for the year 2020 is produced at a 1-km spatial resolution using a dasymetric mapping approach, with barangay-level population data and detailed building footprints as primary inputs. Second, the DEGURBA classification method is applied to the gridded population map to delineate urban centers, urban clusters, and rural areas. Third, a spatial overlay analysis is conducted between the DEGURBA classification and land cover maps to quantify the extent of agricultural and other land cover classes. Finally, the distribution and temporal trends of agricultural land cover are analyzed across the three DEGURBA-defined zones to assess spatial patterns and the magnitude of change.

2.3 Datasets Used

This study uses four primary datasets covering Butuan City (Figure 2): (1) a vector file of barangay boundaries, (2) population data for the year 2020, (3) building footprints that are temporally closest to the year 2020, and (4) land cover maps for the years 2010 and 2020.

2.3.1 Barangay Boundaries and Population Data

The barangay boundaries were extracted from the "Philippines–Subnational Administrative Boundaries" shapefile, available from the Humanitarian Data Exchange (UNOCHA-Philippines, 2022). The NAMRIA produced this shapefile in collaboration with the PSA. Barangay-level population data were obtained from PSA (2022, 2025) and joined as attributes of the barangay boundary shapefile.

2.3.2 Building Footprints

Building footprints were extracted from Google Open Buildings v2 (Google Research 2025, Sirko et al. 2021), a large-scale, open-access geospatial dataset derived from high-resolution satellite imagery using deep learning-based building detection. Google's Research team developed the dataset to provide precise global building footprint data, particularly for regions where such information is limited or unavailable. Each building polygon in the dataset is accompanied by a confidence score ranging from 0 to 1, representing the model's estimated likelihood that the detected footprint corresponds to an actual building. These confidence scores were used as quality indicators in subsequent analyses, with lower-confidence detections filtered out to minimize potential false positives.

In the absence of building footprints explicitly dated to 2020, the 2021 version of the dataset was used, under the assumption that changes in building stock between 2020 and 2021 are limited relative

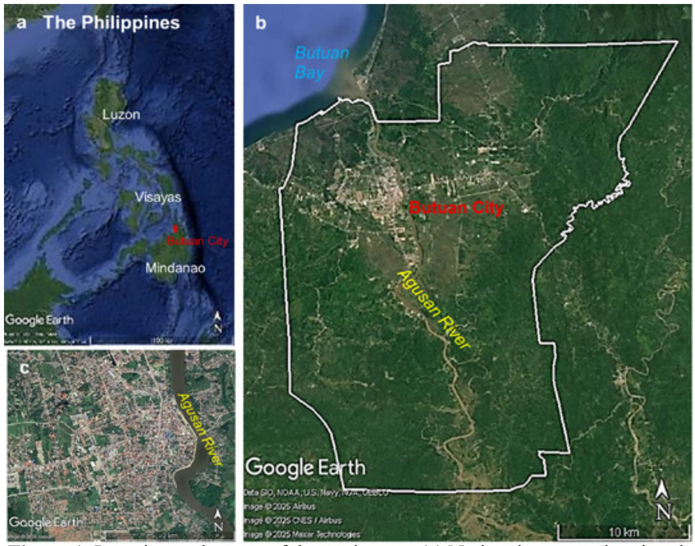

Figure 1. Location and extent of the study area. (a) National context showing the location of Butuan City in Mindanao, Philippines. (b) Administrative boundary of Butuan City, highlighting urban and surrounding rural landscapes. (c) Close-up view of the city center, with the Agusan River flowing through the city.

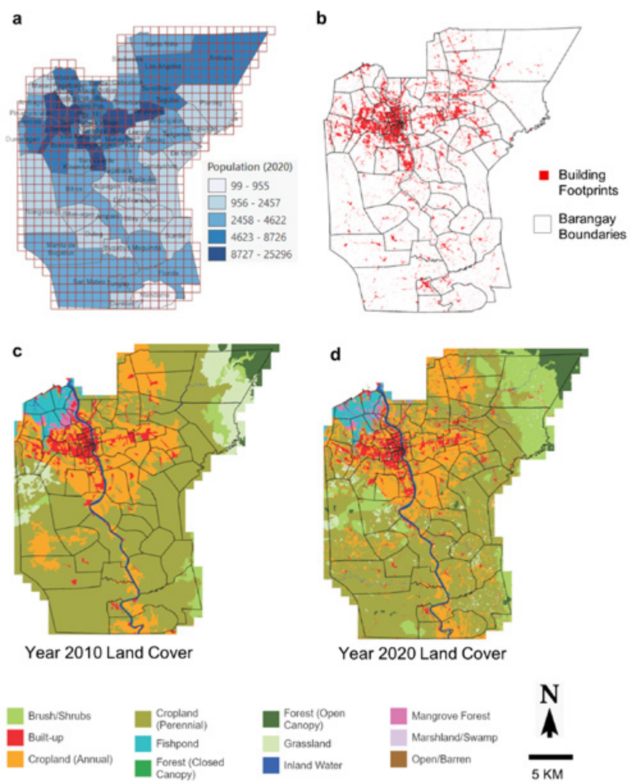

Figure 2. Overview of datasets used in the study: (a) Barangay boundaries and 2020 population data for Butuan City overlaid with 1 × 1 km grid cells used for DEGURBA classification; (b) Google Open Buildings footprint data for the year 2021; (c) 2010 land cover map; and (d) 2020 land cover map.

to the spatial scale of the 1 km DEGURBA grid. The dataset was accessed at https://sites.research.google/gr/open-buildings/, which provides building polygons in vector format along with their associated metadata (e.g., area, perimeter, and confidence). Validation studies have reported that Google Open Buildings in Southeast Asia achieves precision values above 0.80 in low-, medium-, and high-density built-up zones (Google 2025). Independent validation further indicated that approximately 79% of sampled building footprints were correctly identified at confidence thresholds of 0.65 or higher (Estrada et al. 2025), confirming the dataset's reliability.

Before analysis, building polygons with confidence scores below 0.65 and areas smaller than 6 m² were removed. The minimum area constraint followed the minimum habitable room size defined in the National Building Code of the Philippines (Republic of the Philippines 2005). After applying these criteria, a total of 145,403 building footprints were retained for analysis, with an average surface area of 76.44 m2. All retained building footprints were treated as potential residential structures for population allocation, an assumption that is later revisited in the discussion of limitations.

2.3.3 Land Cover Maps

Land cover maps of Butuan City for the years 2010 and 2020 were extracted from national land cover datasets in shapefile format, produced by NAMRIA. The 2010 land cover map was obtained from the Caraga Center for Geo-Informatics (CCGeo) at Caraga State University, based on data previously provided by NAMRIA during CCGeo's implementation of the GeoSAFER Mindanao Program (CSU 2019). The 2020 land cover map was downloaded directly from the Geoportal Philippines (https://www.geoportal.gov.ph/). The land cover maps have 12 classes, namely Annual Crop, Brush/Shrubs, Built-up, Closed Forest, Open Forest, Fishpond, Grassland, Water, Mangrove Forest, Marshland/Swamp, Open/Barren, and Perennial Crop. Both the Annual Crop and Perennial Crop are agricultural land cover classes of interest in this study. Annual crops (e.g., rice, corn) are planted and harvested within a single year, while perennial crops (e.g., coconut, banana, oil palm) live for more than two years, often requiring less frequent planting and harvesting.

According to the accompanying metadata, the 2010 land cover map was created through the visual interpretation of ALOS AVNIR-2 imagery (10-m resolution, acquired from 2007 to 2010), SPOT imagery (2.5–10 m resolution, acquired from 2006 to 2009), and Landsat imagery (30-m resolution, acquired in 2010). The 2020 land cover map was generated primarily through digital interpretation of Sentinel-2 imagery (10 m resolution) acquired from 2018 to 2019, supplemented by other high-resolution satellite imagery.

All land cover maps were rasterized at 30-meter resolution using a majority rule. Doing so ensures consistency across years, as this resolution aligns with the native resolution of the 2010 dataset and supports reliable temporal comparisons. Also, the original name of some classes was slightly modified for easier categorization and to improve clarity, e.g., Closed Forest and Open Forest were renamed as Forest (Closed Canopy) and Forest (Open Canopy), respectively; Annual Crop and Perennial Crop were renamed as Cropland (Annual) and Cropland (Perennial), respectively. The rasterized maps were converted back to vector format (polygons) to allow spatial overlay analysis with the DEGURBA classification layer.

All datasets were projected into the Universal Transverse Mercator (UTM) Zone 51, using the World Geodetic System (WGS) 1984 coordinate reference system (CRS).

2.4 Gridded Population Mapping and DEGURBA Classification

Barangay-level population counts for the year 2020 were disaggregated into a regular grid using a dasymetric population mapping approach, following the methodological guidance of the DEGURBA framework (European Commission & Statistical Office of the European Union 2021). The objective was to derive a gridded population surface that reflects the spatial distribution of inhabitants within administrative units and serves as the basis for DEGURBA classification.

The analysis employed a 1 km × 1 km grid for two reasons. First, DEGURBA explicitly defines urban centers, urban clusters, and rural areas based on population density and contiguity of 1 km² grid cells, making this resolution a methodological requirement and ensuring comparability with international applications. Second, a 1 km grid represents a practical compromise between spatial detail and data reliability when disaggregating population from heterogeneous barangays that vary widely in size, shape, and internal land-use composition. Finer grids would increase sensitivity to modeling assumptions, whereas coarser grids would obscure peri-urban gradients central to this study.

Population disaggregation was performed in two stages. First, barangay-level population totals were allocated to individual building footprints, which were used as ancillary information under the assumption that population presence is spatially associated with buildings. All retained building footprints were treated as potential residential structures. Within each barangay, the total population was proportionally distributed across its building footprints, such that each building received a share of the barangay population based on its relative presence within the barangay. This step produced a building-level population representation consistent with the PSA's total population counts.

Second, the building-level population estimates were aggregated to the 1 km × 1 km grid. For each grid cell, the populations of all buildings whose centroids fell within the cell were summed to produce an estimated population count for that cell. The resulting gridded population surface represents the spatial distribution of population across Butuan City in 2020 and serves as input for the DEGURBA classification.

Following the generation of the gridded population surface, the DEGURBA classification was applied to categorize each grid cell as part of an urban center, urban cluster, or rural area, in accordance with the DEGURBA methodological manual (European Commission & Statistical Office of the European Union 2021). The classification was based on population density thresholds, minimum cluster population requirements, and contiguity rules, as summarized in Table 1. Grid cells that did not meet the criteria for urban centers or urban clusters were classified as rural.

In this study, the term peri-urban is used descriptively to refer to areas classified as urban clusters under the DEGURBA framework, reflecting their transitional role between urban centers and rural areas.

2.5 Spatial Overlay Analysis and Temporal Trend Assessment of Agricultural Land Cover Change

Following the DEGURBA classification, a spatial overlay analysis was conducted to quantify the extent of agricultural and other land cover classes across the defined urban centre, urban cluster, and rural zones. The analysis involved intersecting the DEGURBA-classified grid with land cover maps for the years 2010 and 2020. The overlay enabled the extraction of land cover statistics for each DEGURBA category, allowing a disaggregated analysis of land cover distribution by degree of urbanization. By comparing results across the two reference years (2010 and 2020), the study quantified patterns of land conversion or persistence, highlighting the magnitude and direction of change (e.g., agricultural loss or retention) within urban, peri-urban, and rural contexts.

The 2020 DEGURBA classification was used as a static reference layer in this study to ensure consistency in spatial delineation across the analysis period. Although land cover and population distribution may change over time, using a fixed DEGURBA layer allows direct comparison of agricultural land cover dynamics across stable urban, peri-urban (urban clusters), and rural zones.

All processing and spatial analysis were conducted using Geographic Information System (GIS) software (ArcGIS Pro 3.5). It is essential to note that, while the reported area of Butuan City is approximately 817 km² (CGB 2022), the GIS-computed area of the city, based on the barangay boundaries using the UTM Zone 51N, WGS 1984 CRS, is only 649.96 km². This difference reflects variation between reported administrative-area statistics and the GIS-derived area based on the best available barangay boundary data. Moreover, the DEGURBA classification's unit of analysis is 1 × 1 km, and Butuan City is represented by 720 grid cells, some of which extend beyond the city's administrative boundaries. Additionally, the land cover maps did not fully cover the entire city, particularly areas near Butuan Bay (see Figure 1b). For this study, we retain the 1 × 1 km grid cells as the unit of analysis for DEGURBA classification. However, for reporting land cover change analysis results, we limited the analysis to the spatial extent where the required datasets (i.e., barangay boundaries, DEGURBA classification, and land cover maps) intersected. In this case, the total area coverage is 649.88 km².

3 Results

3.1 Butuan City's Degree of Urbanization

Figure 3a illustrates the DEGURBA classification of Butuan City for 2020, delineating urban centers, urban clusters, and rural areas. Approximately 6% (42 km²) of the city is classified

Table 1. Degree of Urbanisation (DEGURBA) classification criteria applied to 1 km × 1 km grid cells following the official DEGURBA methodology (European Commission & Statistical Office of the European Union, 2021).

DEGURBA Class	Population density threshold	Cluster population	Contiguity rule
Urban center	≥ 1,500 persons/km²	≥ 50,000	4-neighbor (no diagonals)
Urban cluster	≥ 300 persons/km²	≥ 5,000	4-neighbor (including diagonals)
Rural	< 300 persons/km²	Not applicable	Not applicable

as an urban center, primarily encompassing the densely populated central barangays, which have population densities exceeding 1,500 inhabitants per square kilometer. Approximately 19% (124 km²) falls under the urban cluster category, representing areas with at least 300 inhabitants per square kilometer. The remaining 75% (484 km²) is considered rural.

Urban clusters are primarily distributed around the urban center, with notable concentrations extending toward the city's eastern and southern parts. A distinct urban cluster is also visible in the southern portion of the study area. In contrast, no urban clusters are identified north of the urban center.

In comparison, Figure 3b presents the PSA urban–rural classification at the barangay level, which applies a binary scheme. Unlike DEGURBA's population-density-based grid approach, the PSA classification tends to overgeneralize by assigning entire barangays to either urban or rural categories. This results in several areas identified by DEGURBA as urban clusters, particularly in the eastern and southern parts of the city, being classified as rural under the PSA scheme.

3.2 Changes in Agricultural and Other Land Cover Types in Butuan City (2010–2020)

The land cover composition of Butuan City in 2010 (Figure 4) was predominantly agricultural, with cropland (perennial) occupying the most significant share at 376.17 km² or 58% of the total land area (649.88 km²), followed by cropland (annual) at 142.87 km² (22%). Combined, these two types of cropland accounted for 80% (519.04 km²) of the city's total area. Other significant land cover types included grasslands (6%), built-up areas (5%), and brush/shrubs (3%).

By 2020 (Figure 4), agricultural areas remained dominant but showed overall decline, with perennial cropland decreasing to 344.91 km² (53%) and annual cropland to 124.33 km² (19%). This decline represents a combined loss of 49.8 km² of agricultural land over the decade, equivalent to a 9.60% reduction in total agricultural area. There was a significant increase in brush/shrubs, expanding from 19.01 km² (3%) to 80.35 km² (12%).

Built-up areas increased from 32.75 km² (5%) to 42.78 km² (7%), accounting for only a relatively small portion (10 km²) of the total change. Grassland decreased significantly—from 38.95 km² (6%) in 2010 to just 14.68 km² (2%) in 2020. Forest (open canopy) increased slightly, while inland water and mangrove forest remained relatively stable. While the total mapped area of mangrove forest and fishponds did not show a pronounced net decline between 2010 and 2020, visual inspection of the land cover maps indicates substantial changes in their spatial configuration, including fragmentation and localized losses, particularly along coastal and riverine zones (Figure 2c & d).

3.3 Urban-Rural Gradient Land Cover Composition and Changes

Figure 5 highlights how land cover composition varies across Butuan City's urban center, urban clusters, and rural areas, and how these distributions changed between 2010 and 2020.

In the urban center, built-up areas constituted the largest single land cover class, covering 18.21 km² in 2010 and increasing slightly to 19.04 km² in 2020. Built-up land accounted for approximately 43–45% of the total urban center area (42 km²). Other land cover types remained limited in extent. Within the remaining agricultural land, a clear shift in cropland composition was observed: annual cropland declined from 14.99 km² to 10.02 km², while perennial cropland increased from 2.86 km² to 7.57 km². Grassland, brush/shrubs, and open/barren land appeared only in 2020, but each occupied relatively small areas.

In the urban clusters, land cover was more diverse but still predominantly agricultural. In 2010, annual and perennial croplands together covered approximately 108.31 km², or nearly 87% of the total urban cluster area (123.90 km²). By 2020, the area had declined slightly to 99.37 km², as the built-up area increased from 12.14 km² to 16.46 km². There

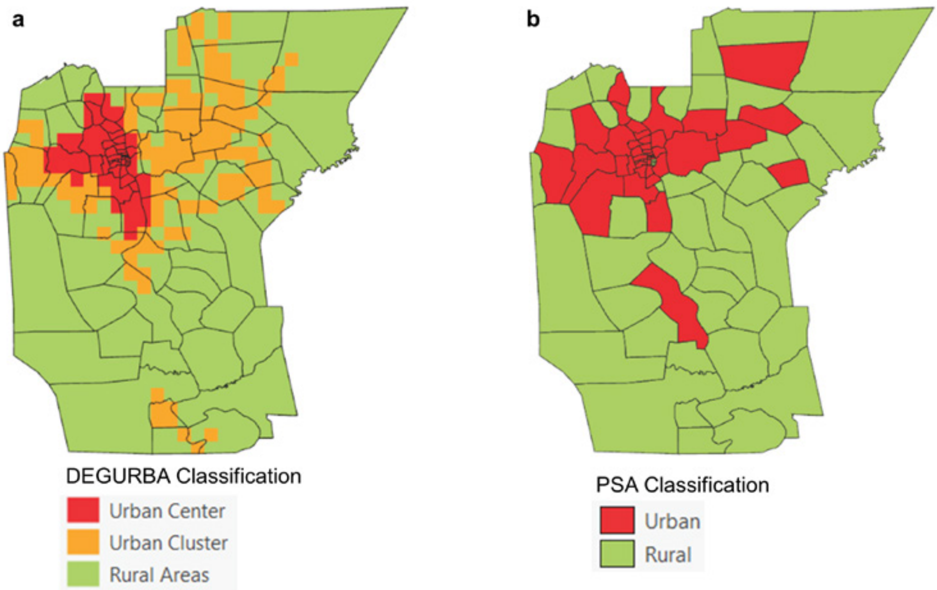

Figure 3. Comparison of urban–rural classifications in Butuan City for the year 2020: (a) Degree of Urbanisation (DEGURBA) classification based on a 1 km population grid; and (b) Philippine Statistics Authority (PSA) classification applying a binary urban–rural designation at the barangay level.

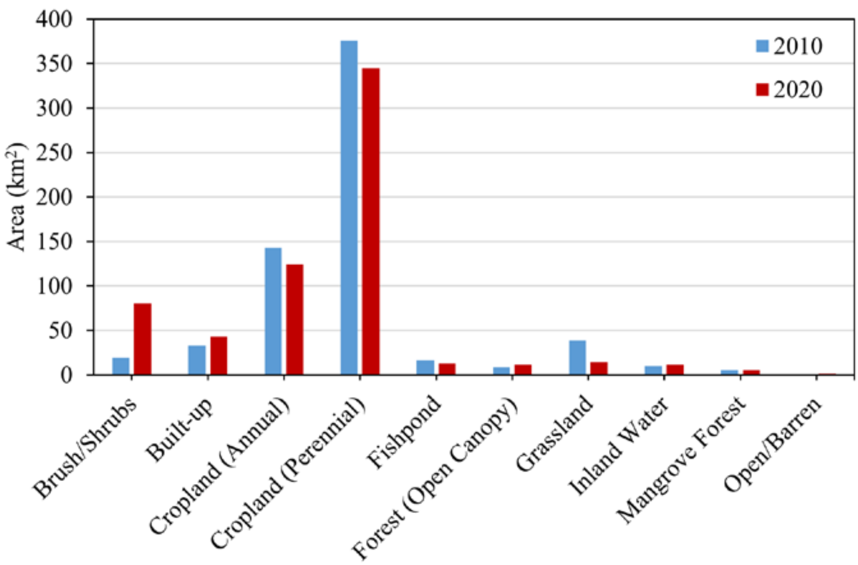

Figure 4. Land cover distribution in Butuan City for the years 2010 and 2020.

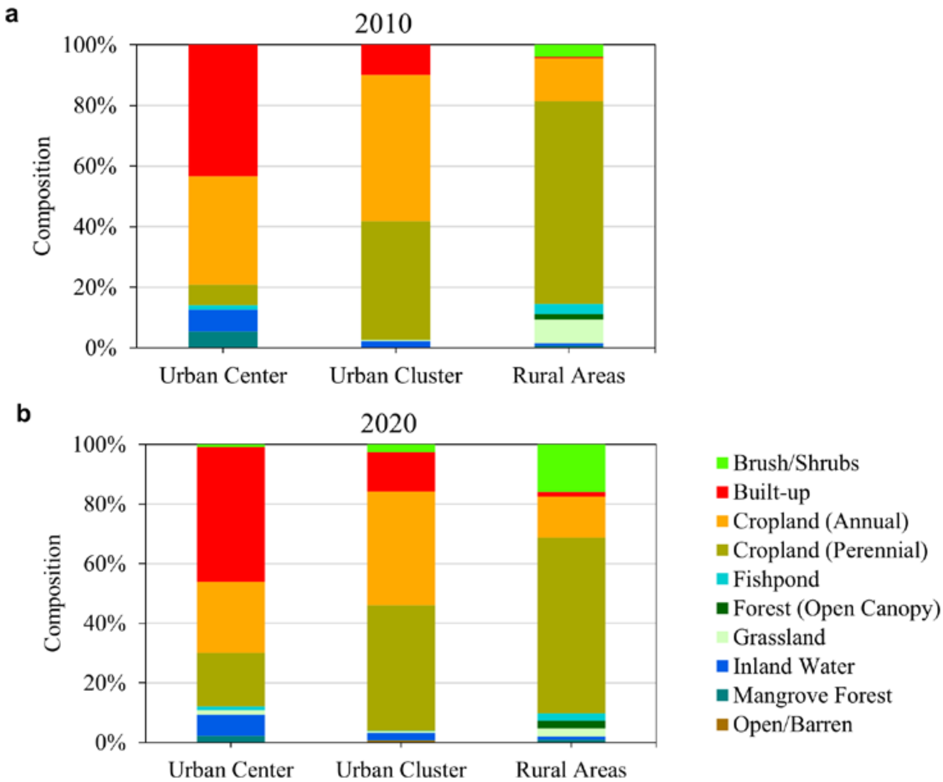

Figure 5. Land cover composition within the urban center, urban cluster, and rural areas of Butuan City for 2010 (a) and 2020 (b).

were also increases in brush/shrubs (from 0 to 3.03 km²), grassland (from 0.56 km² to 0.82 km²), and open/barren land (from 0 to 0.86 km²), indicating a trend toward land fragmentation and conversion. A small amount of forest (open canopy) also emerged in urban clusters by 2020, covering 0.06 km².

In rural areas, agriculture remained the dominant land use, though with notable changes. Perennial cropland decreased from 324.92 km² in 2010 to 285.19 km² in 2020, while annual cropland remained stable, with a slight decrease from 67.97 km² to 67.02 km². These losses were accompanied by a substantial increase in brush/shrubs, which expanded from 19.01 km² in 2010 to 77.01 km² in 2020. Built-up area in rural zones also increased significantly, from 2.40 km² to 7.27 km². Other natural land covers, including grassland, forest (open canopy), and inland water, persisted in rural areas with moderate variability over time, while mangrove forests and fishponds exhibited relatively stable aggregate extents but pronounced spatial reorganization, reflecting fragmentation and localized change as documented earlier (Section 3.2).

3.4 Land Cover Transitions Driving Agricultural Land Change

Between 2010 and 2020, agricultural land in Butuan City underwent notable transitions (Figure 6). Most of the cropland stayed the same, but there were signs of both development and land abandonment. About two-thirds (66.7%) of annual cropland remained unchanged, while nearly one-fourth (24.3%) shifted to perennial crops. However, 6.8% of annual cropland was converted to built-up areas, and a smaller portion was converted to brush or shrubs. Perennial cropland was more stable, with 78.1% remaining the same, but about 10% turned into brush/shrubs, and 2.2% became built-up.

The disaggregated results (Figure 7) reveal significant spatial variations in the transition of cropland across the urban center, urban cluster, and rural areas between 2010 and 2020.

For areas classified as Cropland (Annual) in

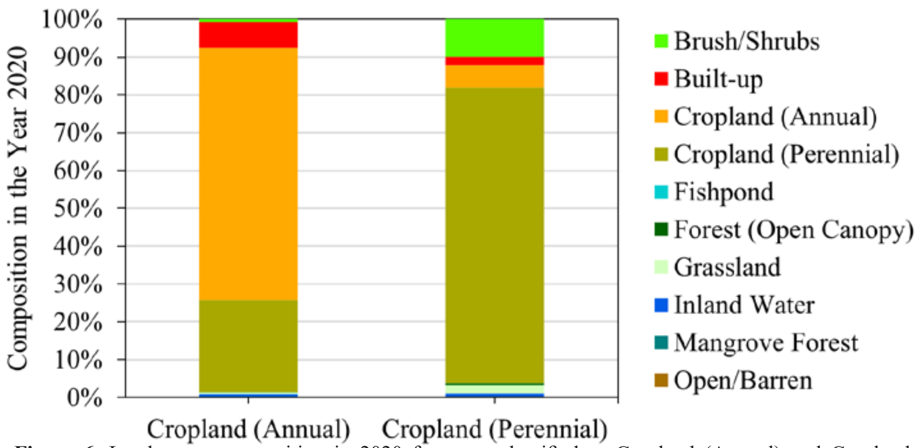

Figure 6. Land cover composition in 2020 for areas classified as Cropland (Annual) and Cropland (Perennial) in 2010, showing the types and proportions of land cover these areas transitioned into over the decade.

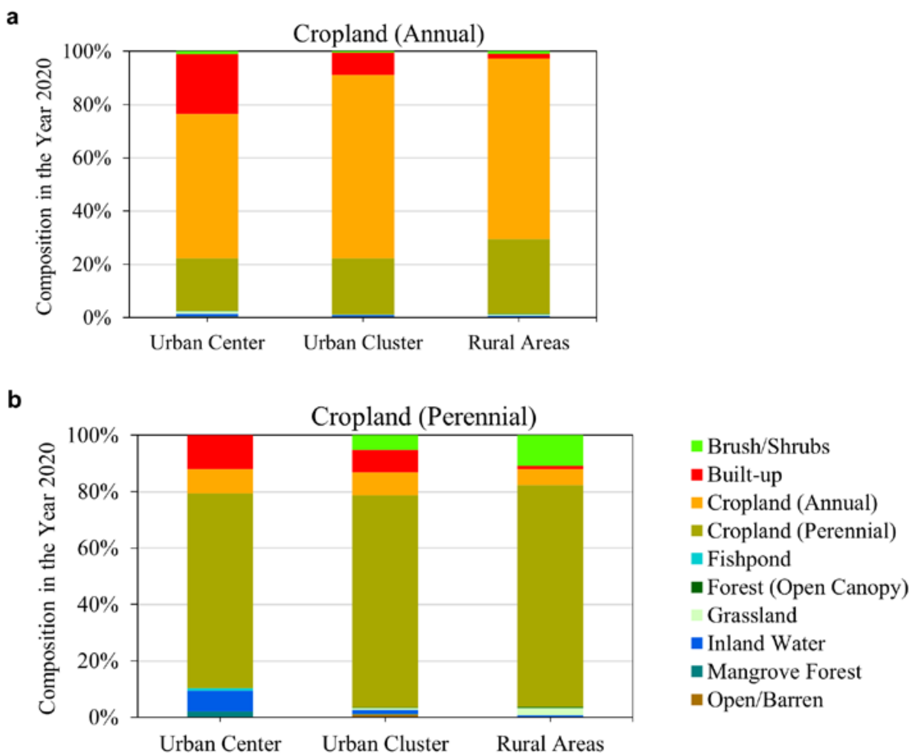

Figure 7. Land cover composition in 2020 of areas that were classified in 2010 as (a) Cropland (Annual) and (b) Cropland (Perennial), showing the types and proportions of land cover these areas transitioned into by 2020, disaggregated by urban center, urban cluster, and rural zones.

2010 (Figure 7a), the majority remained agricultural in 2020, particularly in urban clusters (68.74%) and rural areas (67.69%). A considerable portion also transitioned into Cropland (Perennial), especially in rural areas (28.11%) and urban clusters (21.11%). In the urban center, the largest share (54.24%) also remained as annual cropland, though 19.92% became perennial. It is notable that the conversion of annual cropland to built-up land is largest in the urban center (22.37%), compared to 8.37% in urban clusters and just 1.90% in rural areas. Transitions to brush/shrubs, inland water, and grassland were relatively minor but were present across all zones.

For areas classified as Cropland (Perennial) in 2010 (Figure 7b), the majority also retained their original land cover, with very high proportions retained across all zones—78.64% in rural areas, 75.33% in urban clusters, and 69.22% in the urban center. However, conversion to brush/shrubs was more pronounced in rural areas (10.70%) and urban clusters (5.23%). Conversion to built-up areas was highest in the urban center (12.00%), followed by urban clusters (8.05%) and rural areas (1.21%). A small portion of perennial cropland also shifted to annual cropland, grassland, and inland water, with rural areas showing the broadest range of transitions.

4 Discussion

This study applied the DEGURBA classification to examine the distribution and changes in land cover—particularly agricultural land—across different parts of Butuan City between 2010 and 2020. By delineating the city into urban centers, urban clusters, and rural areas based on population density and built-up presence, the analysis provides a spatially explicit perspective on agricultural land dynamics along the urban–rural gradient.

4.1 Butuan City's Urbanization Pattern

The DEGURBA classification results reveal a non-uniform spatial distribution of urbanization across Butuan City, with urban clusters forming preferentially around, but not evenly surrounding, the urban center. The concentration of urban clusters to the east and south of the city center suggests that urban expansion is occurring in a spatially selective manner rather than through radial growth.

The limited presence of urban clusters north of the urban center reflects the influence of local physical and land-use constraints on urban spatial development (Zhang et al. 2024). Coastal features, such as Butuan Bay, along with the prevalence of fishponds and other water-related land uses, appear to restrict population concentration and urban expansion in these areas. As a result, urban clustering is more pronounced in directions where larger contiguous tracts of developable land remain available.

The comparison with the PSA barangay-level urban-rural classification highlights the added spatial detail provided by DEGURBA. By relying on population density thresholds applied to a regular grid, DEGURBA identifies transitional areas of population concentration that remain masked under a binary administrative classification. This distinction is particularly evident in peri-urban areas, where population density exceeds rural thresholds but falls short of levels characteristic of the urban core. These findings illustrate how the DEGURBA framework captures the spatial structure of urban–rural transitions more explicitly than administrative classifications, providing a clearer basis for identifying zones where urbanization processes are actively unfolding.

4.2 Agricultural Land Distribution across the Urban–Rural Gradient

The results show that agricultural land is predominantly located in urban clusters and rural areas, while the urban center is predominantly built-up land. In 2020, more than 80% of both urban cluster and rural zones remained covered by cropland, including both annual and perennial types. In contrast, cropland occupied only a small fraction of the city core, reflecting the city's advanced stage of urban development. These findings confirm that agriculture continues to play a significant role in the outer parts of the city, particularly in rural areas, underscoring its continued importance for local land-based production.

4.3 Spatial Patterns and Pathways of Agricultural Land Conversion

A comparison between 2010 and 2020 reveals an apparent decline in agricultural land across all DEGURBA zones, with distinct conversion pathways that vary by degree of urbanization. At the national scale, recent satellite-based analyses have shown that agricultural land conversion to built-up areas has been widespread across the Philippines since 2000 (Araza et al. 2026). The patterns observed in Butuan City reflect broader national trends while also revealing how these processes manifest differently along the urban–rural gradient. In the urban center, the dominant transition involved converting annual cropland to built-up land, indicating that urban development has increasingly encroached on the remaining agricultural areas. Similar patterns of cropland loss near existing built-up areas have been documented in earlier studies of Butuan City, which identified rice croplands as particularly vulnerable to urban encroachment over longer time horizons (Bentozal et al. 2024). The DEGURBA-based analysis presented here refines these findings by situating such conversions explicitly within zones of high population density and built-up concentration, highlighting the heightened vulnerability of remaining cropland in already densely developed environments. This pattern mirrors broader global evidence linking urban expansion to cropland loss (Huang et al. 2020, Potapov et al. 2021).

In contrast, substantial losses of perennial cropland were observed in urban clusters and rural areas. These losses were accompanied by a pronounced expansion of brush and shrubland, particularly in rural zones. Land-cover transitions could indicate abandonment, reduced cultivation intensity, or changes in land management, potentially linked to declining agricultural profitability, limited labor availability, or land held for future development. This interpretation is consistent with broader evidence showing that the Caraga region—where Butuan City is located—exhibits the lowest agricultural labor productivity in the Philippines, making rural areas especially susceptible to labor reallocation and shifts away from active agricultural land use (Custodio & Sombilla 2025). Similar patterns of agricultural land contraction associated with labor constraints and declining production incentives have been documented at the national scale (Taer 2025).

Changes in cropland composition may also indicate shifts in farming practices. The conversion of annual cropland to perennial crops across several zones may reflect a preference for production systems that require less frequent planting and lower labor inputs. At the same time, the conversion of cropland—exceptionally annual cropland—to built-up land in the urban center and cluster zones underscores the growing pressure exerted by outward urban expansion. The conversion of perennial cropland into brush or shrubland further suggests a reduction in active land management. All these patterns are consistent with the influence of changing agricultural strategies, labor constraints, and urban development pressures on agricultural land cover change in the Philippines (Adamopoulos & Restuccia 2020, Araza et al. 2026, Huang et al. 2020, Taer 2025).

4.4 Outward Urban Expansion and Pressure on Peri-Urban and Rural Land

Built-up areas increased across all DEGURBA zones during the study period, but the most pronounced growth occurred outside the urban center. While built-up land in the urban center expanded by less than 1 km² between 2010 and 2020, it increased by more than 4 km² in urban clusters and nearly 5 km² in rural areas. This pattern indicates that urban expansion in Butuan City is primarily outward-oriented, extending into peri-urban and rural landscapes.

Such spatial dynamics underscore the heightened vulnerability of urban clusters and rural areas, where agricultural land remains widespread but is increasingly exposed to development pressures. They also illustrate how the DEGURBA framework helps capture the gradual and dispersed nature of urban expansion, patterns that could be missed when analyses rely solely on administrative boundaries.

Beyond retrospective assessment, the results suggest that the DEGURBA classification can also be used as a heuristic tool to anticipate areas of potential agricultural land loss, and in Butuan City, urban clusters and adjacent rural zones consistently exhibited both high shares of remaining cropland and the most pronounced increases in built-up land, indicating that these transitional areas represent priority zones of future conversion risk, by explicitly delineating functionally peri-urban areas rather than relying on static administrative labels. In these DEGURBA highlights, agricultural land is most at risk from encroaching urban development. In this sense, the degree of urbanization serves not only as a descriptive indicator of current land-use patterns but also as a spatial proxy for identifying agricultural areas likely to experience heightened development pressure in subsequent periods.

4.5 Implications for Land-Use Planning and Food Security

The spatially differentiated cropland conversion pathways identified using the DEGURBA framework have essential implications for land-use planning in Butuan City. Compared to the traditional PSA-based classification, which applies a binary urban–rural designation at the barangay level, DEGURBA provides a spatially explicit representation of transitional zones where agricultural and urban land uses coexist. This representation allows more precise differentiation between consolidated urban areas, predominantly agricultural rural areas, and urban clusters that function as transitional spaces under increasing development pressure.

As demonstrated by the results, urban clusters concentrate both substantial remaining cropland and the most pronounced recent land conversion, indicating that these areas represent critical zones where agricultural land is most exposed to urban encroachment. From a planning perspective, urban clusters are particularly well-suited for enhanced land-use monitoring, early identification of conversion hotspots, and more targeted development control measures compared to areas that are either entirely urban or predominantly rural. Incorporating DEGURBA-based spatial typologies into local land-use planning processes could therefore support more informed zoning decisions, help prioritize areas for agricultural land protection, and guide the management of urban expansion to reduce unplanned or fragmented land conversion.

Beyond land-use governance, the observed patterns also carry potential implications for food security. Research on rural–urban transitions in the Global South emphasizes that the loss and fragmentation of agricultural land at the urban periphery can weaken local food provisioning systems and increase reliance on market-based food access, often without commensurate gains in stable non-farm livelihoods (Choithani et al. 2024). Evidence from rapidly urbanizing regions in Asia similarly suggests that outward urban expansion can displace productive cropland and introduce longer-term pressures on food security by reducing local food production capacity and increasing spatial disconnects between cities and their traditional food sources (Sheng et al. 2025). In Butuan City, the conversion of cropland—exceptionally annual cropland—to built-up land in urban centers and clusters, together with land-cover patterns indicative of reduced land management in rural areas, reflects these broader rural–urban transition dynamics. These findings underscore the importance of considering potential food-system risks alongside land-use change when designing urban and regional development strategies.

4.6 Limitations and Future Research Directions

While this study demonstrates the value of applying the DEGURBA framework to analyze agricultural land cover change along the urban–rural gradient in Butuan City, several limitations should be acknowledged and point to important directions for future research.

First, the analysis was based on two temporal reference years (2010 and 2020). Although this allowed for a consistent comparison of land cover change across DEGURBA-defined urban centers, urban clusters, and rural areas, using only two time points limits the ability to capture longer-term trends and transitional dynamics. Incorporating an additional temporal reference year, such as around 2000, would enable a more comprehensive assessment of land cover trajectories, including changes in the composition of the urban–rural gradient, longer-term shifts in agricultural and non-agricultural land cover types, and more precise identification of land cover transitions driving agricultural land loss. Including a third time period would therefore strengthen the temporal robustness of the analysis and provide deeper insight into the evolution of agricultural and other land cover change in Butuan City.

The inclusion of an earlier reference year was limited by data availability. At the time of this study, no NAMRIA land cover map for 2000 was available, and the nearest available product from the agency was the 2003 land cover map. To avoid inconsistencies in decadal temporal analysis, the study therefore focused on the 2010–2020 period. Future research could address this limitation in several ways. One option is to extend the temporal coverage by incorporating earlier NAMRIA land cover maps, albeit at a non-decadal temporal scale. Alternatively, existing global or regional land cover products, such as the Global Land Analysis & Discovery (GLAD) cropland dataset used by Araza et al.(2026), could be explored, provided their accuracy is independently assessed, given their non-authoritative nature. Another promising direction is the generation of multi-temporal agricultural land cover maps using machine learning or deep learning methods (Oliphant et al. 2019, Pelletier et al. 2019, Talukdar et al. 2020) applied to freely available satellite imagery, such as Landsat and Sentinel-2, enabling the construction of consistent long-term land cover time series.

Second, the DEGURBA classification used in this study was based on population and built-up patterns derived from 2020/2021 data and remained constant throughout the analysis period. While this approach supports consistent spatial comparison, it does not explicitly capture temporal shifts in settlement structure and population distribution. Incorporating time-varying DEGURBA classifications, updated at multiple reference years, would allow future studies to examine how transitions between urban, peri-urban, and rural categories evolve and how these changes interact with agricultural land conversion processes.

Third, the analysis employed the standard DEGURBA grid resolution of 1 km × 1 km, as required by the official methodology, ensuring comparability with international applications. However, grid resolution can influence the delineation of urban clusters and the representation of peri-urban gradients, particularly in heterogeneous landscapes. Future studies could explore the sensitivity of agricultural land change patterns to alternative grid sizes (e.g., 500 m), especially for localized or intra-urban analyses. Such comparisons would help clarify the scale at which urban–rural transitions and agricultural land conversion processes are most effectively captured, while balancing spatial detail and data reliability.

Fourth, limitations of dasymetric population mapping should be considered. The analysis assumed that all mapped building footprints contributed equally to residential population distribution. Although this assumption is reasonable in the context of Butuan City, where residential structures dominate, it may introduce uncertainty in areas with mixed land use or higher concentrations of non-residential buildings. Future research would benefit from building footprint datasets that explicitly distinguish between residential and non-residential structures, allowing the population to be allocated only to residential buildings.

In addition, integrating three-dimensional (3D) building information, such as building height or floor-area data, represents a promising avenue for improving dasymetric population mapping (Maroko et al., 2019). Allocating population based on building volume or usable floor space, rather than footprint area alone, would enable a more realistic representation of population distribution, particularly in denser urban and peri-urban zones where vertical development is present.

Finally, while this study focused on the administrative boundaries of Butuan City, urbanization processes and land-use transitions often extend beyond them. Expanding future analyses to include adjacent municipalities would better reflect continuous urban development and mitigate potential edge effects in the DEGURBA classification.

5 Conclusion

This study presented a spatial analysis of agricultural land loss across the urban–rural gradient in Butuan City, Philippines, demonstrating the value of applying the DEGURBA framework in a national context where standardized urban–rural typologies remain rarely used. By integrating population density, building footprints, and authoritative satellite-derived land cover maps, the study provides one of the first applications of DEGURBA for systematically examining agricultural land distribution and conversion across urban centers, urban clusters, and rural areas in a Philippine city. This approach provides a spatially consistent alternative to traditional barangay-based classifications, enabling more precise differentiation of land-use dynamics along the urban–rural continuum.

The analysis estimated a loss of approximately 49.8 km² (9.6%) of agricultural land between 2010 and 2020, with the most pronounced reductions occurring in urban clusters—transitional zones experiencing increasing development pressure. These findings underscore the importance of urban clusters as priority areas for land-use monitoring and informed planning, particularly in cities where agricultural land and urban expansion are increasingly intersecting. By explicitly distinguishing these zones, the DEGURBA framework helps clarify where agricultural land conversion is most concentrated and where planning attention may be most effectively directed.

A key strength of the DEGURBA framework lies in its ability to transcend administrative boundaries and represent settlement patterns using a regular, grid-based system. This ability enables the identification of gradual, spatially dispersed land-use transitions, particularly in peri-urban areas, more clearly than is possible with binary urban–rural classifications at the barangay level. In this sense, DEGURBA serves not only as a descriptive tool for analyzing current land-use patterns, but also as a practical framework for anticipating areas at heightened risk of future agricultural land loss.

Overall, this study demonstrates that the

DEGURBA framework provides a scalable, standardized, and policy-relevant approach for analyzing agricultural land cover change along the urban–rural gradient in the Philippine context. By revealing how agricultural land loss varies with degrees of urbanization, the approach offers a practical tool for supporting evidence-based urban planning and sustainable land management, particularly in urbanizing cities such as Butuan.

6 Acknowledgement

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7 Statement of Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

8 Author Contribution

Jojene R. Santillan: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Meriam Makinano-Santillan: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. All authors have read and agreed to the published version of the manuscript.

9 Data availability statement

Barangay boundary data were obtained from the Humanitarian Data Exchange (https://data.humdata.org/dataset/cod-ab-phl). Population data were sourced from the Philippine Statistics Authority's Urban Population of Caraga (2020 Census) release (https://rssocaraga.psa.gov.ph/content/urban-population-caraga-based-2020-census-population-and-housing). Building footprint data were accessed from the Google Open Buildings dataset (https://sites.research.google/gr/open-buildings/). The 2010 and 2020 land cover maps were obtained from the Philippines' National Mapping and Resource Information Authority (NAMRIA), with the 2020 dataset accessible via Geoportal Philippines (https://www.geoportal.gov.ph/) and the 2010 dataset provided directly to the authors through a collaboration with NAMRIA. Additional supporting data are available from the corresponding author upon reasonable request.

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11 Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this manuscript, the authors utilized ChatGPT 5 to enhance the clarity and quality of the language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Protected Area Management Effectiveness of the Agusan Marsh Wildlife Sanctuary, Philippines: An Assessment Using the Management Effectiveness Tracking Tool (METT)-4

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ABSTRACT

The Agusan Marsh Wildlife Sanctuary (AMWS) is a critical wetland whose long-term sustainability depends on the effectiveness of protected area governance and management. This study assessed the management effectiveness of AMWS using the Management Effectiveness Tracking Tool version 4 (METT-4), focusing on how management inputs, processes, and institutional arrangements address threats and deliver conservation outcomes. Data were collected through Key Informant Interviews (KII) with 44 members of the AMWS Protected Area Management Board (PAMB), complemented by secondary data from management plans, spatial datasets, and institutional records. Threat analysis indicated that overall pressures were perceived as low but emerging, particularly human intrusion and disturbance ($\bar{x}$ = 0.523), agriculture and aquaculture expansion ($\bar{x}$ = 0.432), and energy production and mining activities in adjacent areas ($\bar{x}$ = 0.386), based on normalized scores ranging from 0 (no threat) to 1 (maximum threat). These pressures are concentrated mainly in Multiple Use Zones (MUZs) and are driven by population growth, land-use conversion, and external extractive activities. The overall METT score for AMWS was 75.52%, indicating excellent management effectiveness. Context scored highest (100%), reflecting a strong legal and institutional foundation and clear recognition of tenure and governance arrangements. Planning, outputs, and outcomes received good ratings (76.63%, 72.73%, and 70.19%), supported by structured management planning, co-management mechanisms, biodiversity monitoring, and livelihood interventions. Inputs (65.32%) and processes (68.23%) scored lowest, highlighting constraints related to financing, logistics, monitoring coverage, and the absence of a formal buffer zone. Overall, AMWS demonstrates strong participatory governance but requires adaptive management, strengthened enforcement, and sustainable financing to maintain long-term effectiveness.

Keywords: *Management Effectiveness Tracking Tool, Protected Area*

1 Introduction

The Agusan Marsh Wildlife Sanctuary (AMWS) is an extensive inland wetland system of freshwater marshes, lakes, and interconnected waterways that function as natural catch basins for floodwaters in the Agusan Valley, moderating river flows during the monsoon season and reducing downstream flooding. Proclaimed a protected area under Presidential Proclamation No. 913 on October 31, 1996, AMWS spans 38 barangays across six municipalities in Agusan del Sur, Caraga Region (Sumilhig et al. 2024). Beyond its biodiversity significance, the sanctuary contains the largest intact peatland in the Philippines, serving as a significant carbon sink while supporting wetland-dependent livelihoods and fisheries, and providing habitat for endemic, migratory, and threatened species. AMWS is the largest protected area in Agusan del Sur, the second-largest wetland protected area in the Caraga Region. It ranks second nationally among marshlands in the Philippines, behind LiguasanMarsh (Guerrero 2021). It is legally protected under the NIPAS Act (RA 7586, as amended by RA 11038). Despite its legal status, AMWS faces persistent and emerging threats, such as habitat degradation, land-use conversion, and unsustainable resource use, which remain inadequately regulated, posing ongoing risks to ecosystem integrity and long-term conservation outcomes.

AMWS has gained substantial recognition at the local, national, and international levels for its outstanding ecological value its conservation status. Internationally, AMWS was first designated as a Wetland of International Importance under the Ramsar Convention (Ramsar Site No. 1009) on November 12, 1999, establishing its global significance as a wetland ecosystem; this was followed by its declaration as ASEAN Heritage Park (AHP) No. 42 on November 8, 2018, reflecting its regional importance within the Southeast Asia, and its more recent recognition as a Flyway Network Site (EAAF159) under the East Asian–Australasian Flyway Partnership (EAAFP) on November 10, 2025, underscoring its critical roles in supporting migratory waterbirds along the flyway (Orella et al. 2022, EAAFP 2025). At the national level, the Philippine Government has further recognized the importance of AMWS biodiversity through its classification as an Important Bird Area (IBA PH085), followed by its designation as a Key Biodiversity Area (KBA No. 180) and a Conservation Priority Area (CPA No. 126).

The sustainable management of AMWS, is both crucial and imperative, as effective management enables the identification of degraded areas requiring rehabilitation and the protection of ecologically significant zones. However, persistent degradation of protected areas is frequently rooted in governance failures that are directly reflected in key dimensions of management effectiveness. In the context of the Management Effectiveness Tracking Tool (METT) framework, these failures primarily manifest as weaknesses in management inputs and processes, including inadequate financial and human resources, insufficient logistical support, and limited technical capacity to implement management interventions. Governance challenges are further reflected in weak planning and decision-making processes, poorly coordinated land-use and management plans, overlapping and fragmented institutional mandates among multiple government agencies, and ineffective policy implementation and enforcement mechanisms. Additional constraints include limited monitoring and evaluation systems, unreliable or insufficient data to support evidence-based management, and the absence of capable, empowered, and actively engaged stakeholders. Collectively, these deficiencies undermine adaptive management, reduce management responsiveness to emerging threats, and contribute to the continued undervaluation of protected area and watershed resources (Cruz 2014, Kagaya & Wada 2021, Sulistyaningsih et al. 2021).

The Management Effectiveness Assessment (MEA) is widely recognized as a critical tool for improving conservation outcomes in protected areas (Geldmann et al. 2015, Hockings et al. 2015, Munguía and Heinen 2021). In the context of AMWS, systematically evaluating management strategies using the METT allows identification of gaps in governance, resource allocation, and operational processes, providing evidence to strengthen adaptive management and long-term conservation measures. Key Informant Interviews (KII) with AMWS Protected Area Management Board (PAMB) members are appropriate for this multi-stakeholder protected area, as they capture diverse perspectives and locally grounded knowledge, which are essential for an accurate assessment of management effectiveness and threat mitigation. This study, therefore, aimed to identify the prevailing threats to AMWS and to evaluate the effectiveness of its management strategies using METT-4, thereby supporting more informed, participatory, and evidence-based decision-making.

2 Materials and Methods

Location of the Study

The study focused on the Agusan Marsh Wildlife Sanctuary (AMWS), located in the middle of the Agusan River Basin, the third-longest in the Philippines. AMWS is located in the municipalities of San Francisco, Bunawan, Rosario, Talacogon, Loreto, and La Paz, all in Agusan del Sur. It lies between 8° 07' and 8° 27' East and 125° 47' and 125° 59' North, covering a total area of 40,490.96 hectares. The AMWS also encompasses 11,446.525 hectares designated as a Strict Protection Zone (SPZ), where activities are limited exclusively to research and monitoring. In addition, it includes 29,494.435 hectares classified as Multiple Use Zone (MUZ), where regulated human interventions and sustainable livelihood activities are permitted, subject to the issuance of appropriate clearances and permits and compliance with the Environmental Impact Assessment (EIA) requirements under Presidential Decree No. 1586. Furthermore, AMWS is a sacred ancestral homeland of the Agusan Manobo, encompassing four (4) major Certificates of Ancestral Domain Title (CADT) areas, including CADT 077, CADT 142, CADT 136, and CADT 090 in the municipalities of Talacogon, Rosario, Bunawan, and Loreto, respectively (Figure 1).

Management Effectiveness Tracking Tool (METT)

The Management Effectiveness Tracking Tool (METT) is an assessment instrument designed to monitor progress in improving the management effectiveness of protected areas. It is one of the most widely used, globally applicable, and generic evaluation systems for assessing protected area management effectiveness (WWF International 2007, Apdohan et al. 2019). METT was first introduced in 2002 and is designed to align with the IUCN World Commission on Protected Areas (IUCN WCPA) framework for Protected Area Management Effectiveness (PAME). It was initially developed by the World Bank-WWF Alliance for Forest Conservation and Sustainable Use to provide a standardized and practical method for evaluating the performance of protected area management (IUCN WCPA 2002, World Bank and WWF 2002, Campos et al. 2021). In 2020, METT version 4 was developed and presented as an Excel-based tool to facilitate the implementation and compilation of assessment results, accompanied by a new edition of the METT Handbook. The updated version was officially launched in November 2021 and provides comprehensive guidance on management effectiveness, best practices for applying the METT, illustrative case studies, and resources for enhancing the quality of METT assessments using SMART indicators. It also integrates complementary assessments through the Site-level Assessment of Governance and Equity (SAGE) tool to evaluate governance and equity aspects at the protected area level (IUCN 2021).

Since 2010, the Department of Environment and Natural Resources – Biodiversity Management Bureau (DENR-BMB) has been employing the Management Effectiveness Tracking Tool (METT) to evaluate the strengths and weaknesses of Philippine legislated and proclaimed protected areas, including Local Conservation Areas (LCAs) and other protected areas managed by LGUs (DENR-BMB, 2014). Dizon et al. (2013) highlighted the application of METT in assessing seven (7) Marine Protected Areas (MPAs), demonstrating the tool's flexibility and effectiveness across both terrestrial and marine conservation contexts. At the local level, Campos et al. (2021) applied the METT to evaluate the LGU-managed Mt. Magdiwata Watershed Forest Reserve (MMWFR), while Longaquit (2025) assessed the legislated Tinuy-an Falls Protected Landscape (TFPL), both located in Agusan del Sur.

Furthermore, the METT framework is organized around six (6) core elements of management effectiveness: Context, Planning, Inputs, Processes, Outputs, and Outcomes (Stolton et al. 2020). It employs a rapid assessment approach using a scorecard questionnaire that covers all six elements of the IUCN/WCPA framework. It also comprises two primary components. The first is a set of datasheets that collect key information on the protected area, including its characteristics, management objectives, identified threats, and the personnel responsible for conducting the assessment. The second component consists of assessment forms, which provide a composite evaluation of management effectiveness across thirty-eight (38) parameters corresponding to the six (6) WCPA elements. Each question in the assessment form has four (4) possible responses, scored from 0 (poor) to 3 (excellent), and includes sections for notes, score justification, recommended management improvements, and sources of information (IUCN WCPA, 2002; World Bank & WWF, 2002). The datasheets also feature a threat-ranking system to assess the impact of pressures on protected area values. Threats are classified as high (causing severe degradation, affecting >10% of values), medium (moderate impact, affecting >5–10%), or low (minimal impact, affecting <5%) (Apdohan et al., 2019; Stolton et al., 2020).

Data Gathering, Analysis, and Interpretation

Key Informant Interviews (KII) using the

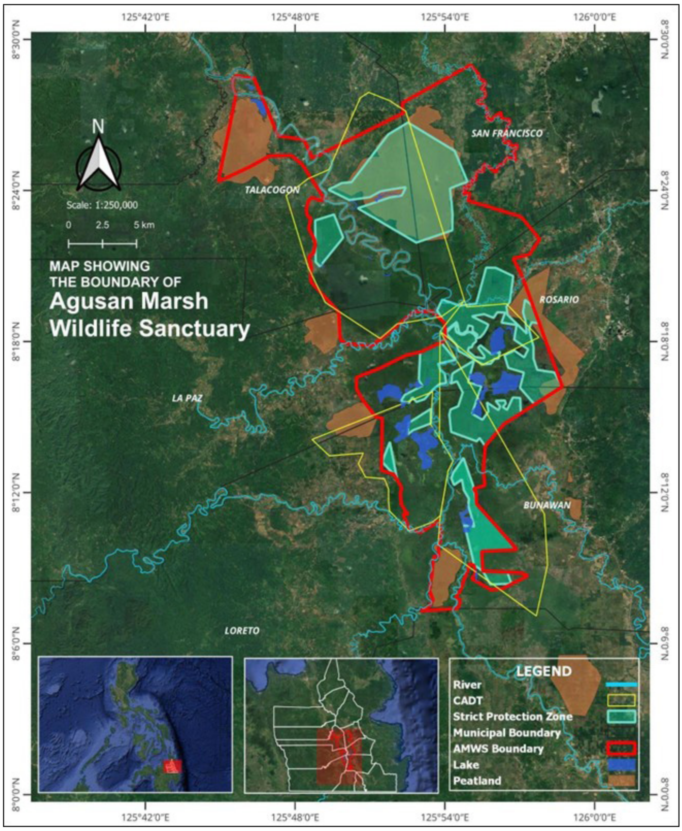

Figure 1. Map showing the boundary and management zones of Agusan Marsh Wildlife Sanctuary (AMWS), Agusan del Sur, Caraga Region, Philippines.

METT 4 survey questionnaire were conducted from February to August 2024 to collect primary data in accordance with DENR Technical Bulletin 2018 05. A total of forty-four (44) respondents, comprising thirty-two (32) males and twelve (12) females, participated in the KIIs. Respondents were selected based on their active membership in the Protected Area Management Board (PAMB), which includes representatives from the Provincial Government of Agusan del Sur, the municipalities of San Francisco, Rosario, Bunawan, Talacogon, Loreto, and La Paz, as well as Barangay LGUs, National Government Agencies (NGAs), Non-Government Organizations (NGOs), Certificates of Ancestral Domain Title (CADTs), and People's Organizations (POs).

In addition, secondary data, including the Protected Area Management Plan, Ancestral Domains Sustainable Development and Protection Plans, and management zones shapefiles, were obtained from the Department of Environment and Natural Resources (DENR), specifically from the Protected Area Management Office of Agusan Marsh Wildlife Sanctuary (PAMO AMWS). The collected data were analyzed using descriptive statistical methods to summarize and interpret the findings. Table 1 presents the interpretation of management effectiveness scores.

3 Results and Discussion

Following the METT 4 methodology, a datasheet for the AMWS was developed to document its key characteristics, identified threats, and management objectives. The corresponding assessment form was completed using a questionnaire comprising four alternative responses, each assigned a score ranging from 0 (poor) to 3 (excellent).

A. Datasheet of AMWS

AMWS Baseline Conditions (based on secondary data)

Table 1. Management Effectiveness Rating Interpretation based on DENR Technical Bulletin 2018-05.

Management Effectiveness Rating	Interpretation
75-100%	Excellent
51-74%	Good
26-50%	Fair
<25%	Poor

i. Biophysical

The Agusan Marsh Wildlife Sanctuary (AMWS) is a complex inland wetland ecosystem characterized by extensive freshwater wetlands, peatlands, rivers, and interconnected water bodies, which together underpin its ecological integrity and biodiversity. Wetland vegetation dominates, providing critical habitat for wetland-dependent species. At the same time, human-modified areas, including agricultural lands and limited built-up zones, occupy a minor fraction of the area, indicating that anthropogenic pressures are currently concentrated in peripheral zones (AMWS Protected Area Management Plan 2021–2031). Management relevance lies in prioritizing core wetland areas for strict protection and focusing enforcement on areas susceptible to human disturbance.

Hydrologically, AMWS functions as the floodplain of the Agusan River, receiving inflows from nine (9) major river systems across a 661,696-hectare catchment (Santillan et al. 2019). Its intricate network of lakes, creeks, and peatlands sustains hydrological connectivity, sediment deposition, and nutrient cycling, but also complicates enforcement and spatial management. High connectivity allows upstream disturbances, such as mining, drainage, or pollution, to propagate through the marsh, underscoring the need for coordinated basin-wide management. Peatland extent further increases vulnerability to fire, drainage, and unsustainable resource use, highlighting the importance of fire mitigation, hydrological regulation, and mining impact assessments. The low to moderately elevated topography (30–200 m above sea level) facilitates seasonal inundation, which supports natural flood regulation but also necessitates adaptive zoning to balance human activities with ecosystem protection. Soils are predominantly alluvial, with localized clay loam, volcanic, and sandy deposits along rivers, influencing habitat stability and restoration potential. Geological variation among municipalities, for example, San Francisco, dominated by alluvium (~60%) versus Rosario with Neogene to recent deposits, affects erosion risk, drainage behavior, and suitable management interventions (Penida et al., 2021). Climatically, AMWS experiences high and evenly distributed rainfall, with peaks from November to January, a long-term average of ~3,600 mm, and a mean annual temperature of 25.6°C (Manlosa and Valera, 2016; Mora-Garcia et al., 2020). These conditions sustain wetland productivity but require flood preparedness, climate-adaptive management, and careful placement of infrastructure.

The AMWS also overlaps four (4) major Certificates of Ancestral Domain Title (CADT) areas, collectively representing the Agusan Manobo ancestral homeland. Indigenous stewardship is central to co-management, enabling the integration of traditional knowledge into sustainable resource use, fire mitigation, and enforcement strategies, particularly in sensitive peatland and hydrologically connected areas (AMWS Protected Area Management Plan 2021–2031). AMWS's baseline characteristics, including wetland dominance, peatland extent, hydrological connectivity, soil variability, and climatic regime, directly shape management priorities. These features inform zoning effectiveness, enforcement strategies, fire and flood risk mitigation, sustainable livelihood planning, and long-term ecosystem resilience.

Furthermore, the AMWS supports exceptionally high biodiversity across multiple taxonomic groups. Faunal assessments have recorded 150 bird species (Sumilhig et al. 2024), 36 amphibians (Almeria and Nuñeza 2013, Sularte et al. 2015, Relox and Camino 2018), 59 fish species (Cuadrado et al. 2019, Baclayo et al. 2020), 11 mollusks (Travis et al. 2007), 32 mammals, 66 butterfly species, and 66 reptile species (Sanguila et al. 2016) within the sanctuary. In addition, 27 species of aquatic beetles have been documented, further highlighting the ecological richness of the wetland ecosystem (Varela and Degamo 2016). Floral diversity in AMWS is equally remarkable, with a total of 721 plant species recorded (Aribal and Fernando 2014, 2018, Sarmiento and Varela 2023). Of these, 205 species are endemic, while 75 species are classified as threatened, including 9 Critically Endangered (CR), 18 Endangered (EN), 33 Vulnerable (VU), 12 Near Threatened (NT), and 3 Other Threatened Species (OTS) (AMWS Protected Area Management Plan 2021–2031).

Biodiversity data in AMWS are used both diagnostically and as contextual background in METT scoring. High species richness and endemism indicate areas of high conservation value, generally correlating with higher METT context and planning scores. Conversely, threatened species are often concentrated in zones experiencing higher perceived threats, such as human settlement, resource extraction, or hydrological disturbance, highlighting critical areas for enforcement, habitat restoration, and targeted monitoring. The exceptional richness, endemism, and threatened status of AMWS taxa underscore the area's ecological importance and inform priority management actions. These include spatially explicit zoning to protect critical habitats, targeted enforcement and patrolling in high-risk zones, integration of sustainable resource use in community-managed areas, and restoration of degraded wetlands to maintain ecosystem integrity and resilience.

ii. Socioeconomic

The Agusan Marsh Wildlife Sanctuary (AMWS) supports a resident population whose daily activities directly influence conservation outcomes, thereby shaping both the threat profile and the METT assessment results. Within the protected area, an estimated 2,686 households reside, including 123 tenured migrants, reflecting sustained settlement within wetland zones. Infrastructure is predominantly residential, with limited commercial and industrial facilities, indicating low levels of large-scale urbanization consistent with the area's protected status (AMWS Protected Area Management Plan 2021–2031). However, the spatial distribution of households within and adjacent to Multiple-Use Zones (MUZs) increases localized pressure on aquatic habitats, peatlands, and forest margins. These settlement patterns help explain the moderate to high perceived threats related to human intrusion, resource use, and habitat disturbance reflected in the KII-based METT scoring, particularly under context, planning, and process components.

Indigenous Peoples (IPs) constitute a significant proportion of the population in the direct impact communities of AMWS. The total Indigenous population in these communities is estimated at 72,842 individuals, distributed across six municipalities, while at the provincial scale, Indigenous Peoples number 152,884 individuals across several ethnic groups, with the Manobo as the dominant group (CADT 090 ADSDPP 2024-2034) (Figure 2). This demographic composition has direct management implications. On one hand, Indigenous governance systems and customary resource-use practices can strengthen participatory planning, legitimacy of zoning regulations, and community-based enforcement, factors that may positively influence METT scores related to stakeholder engagement and management processes. On the other hand, population growth and continued reliance on wetland resources increase aggregate demand for fisheries, agricultural land, and forest products, thereby contributing to the pressures identified in threat assessments.

Additionally, livelihood activities within AMWS are largely natural resource–dependent, reinforcing the linkage between socioeconomic conditions and conservation pressures. Primary income sources include freshwater fishing, corn and rice cultivation, and ecotourism-related services (Campos et al. 2023). Fishing intensity and small-scale agriculture, particularly within MUZs, align with perceived threats to aquatic biodiversity, peatland edges, and riparian habitats recorded during the METT evaluation. Community-based enterprises using wetland-derived materials and adaptive strategies such as floating vegetable gardens (Sitcharon and Malaque 2023) demonstrate resilience and potential compatibility with conservation goals; however, they also underscore continued dependence on ecosystem services. During the KII-based METT assessment, respondents frequently contextualized management effectiveness in relation to livelihood pressures, tenure arrangements, and community participation, indicating that socioeconomic variables influenced perceptions of enforcement adequacy, zoning effectiveness, and overall management performance.

The socioeconomic structure of AMWS, characterized by resident households, tenured migrants, Indigenous stewardship, and resource-dependent livelihoods, serves as both a driver of conservation pressure and a foundation for participatory management. Integrating these socioeconomic dynamics into threat analysis provides a clearer basis for interpreting METT results and identifying priority interventions in enforcement, zoning, and sustainable livelihood support.

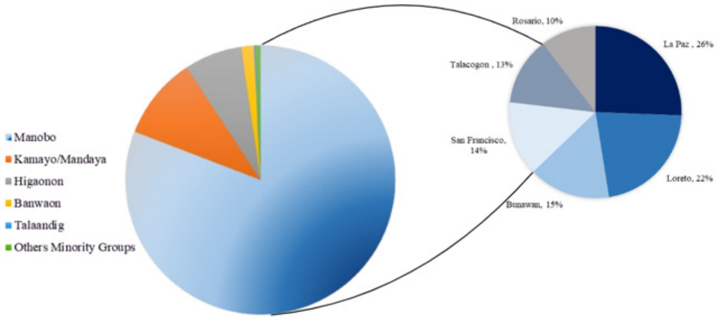

Figure 2. (a) Provincial-scale distribution of Indigenous populations in Agusan Marsh Wildlife Sanctuary (AMWS), with Manobo as the dominant group. (b) Distribution of Agusanon Manobo population across six municipalities in AMWS.

Key Issues and Threats (based on the KIIs)

Despite its designation as a legislated protected area, the Agusan Marsh Wildlife Sanctuary (AMWS) continues to face several management concerns identified through the Key Informant Interviews (KII) (Table 2). The maximum possible threat score was forty-four (44), equivalent to the total number of respondents. However, actual scores per threat category may be lower, as some respondents indicated "no data" or "not applicable," which were excluded from the analysis. Thus, the results should be interpreted as indicative rather than absolute measures of threat intensity.

As shown in Table 2, human intrusion and disturbance recorded the highest mean threat value ($\bar{x} = 0.523$), followed by agriculture and aquaculture activities ($\bar{x} = 0.432$). These categories reflect human activities that alter, degrade, or disrupt habitats and wildlife, including land-use conversion, agricultural expansion, recreational and tourism-related activities, construction, and increased vehicular access within and around the protected area. While many of these activities occur within regulated zones such as the Multiple Use Zone (MUZ), their persistence and spatial expansion suggest mounting pressure on protected area resources.

Although overall threat levels were generally perceived as low by respondents, the concentration of higher mean values in anthropogenic categories indicates that human-driven pressures remain the most significant management concern. Population growth and increasing economic activities within and adjacent to the protected area may further amplify these pressures over time. Consequently, even moderate but sustained disturbances could accumulate and lead to more pronounced ecological impacts if not effectively managed.

These localized observations are consistent with broader land-use trends within the Agusan River Basin (ARB). Land cover classification analyses revealed that forest cover declined from 67.7% in 1995 to 62.8% in 2017, while agricultural areas expanded from 12.2% to 15.5% during the same period (Santillan et al. 2019). More recent studies have further documented notable land cover changes, including increases in built-up areas and rangelands, alongside reductions in barren lands, indicating ongoing landscape transformation driven by human activities (Makinano-Santillan & Santillan 2023). While overall threat levels in AMWS were generally perceived as low in intensity, the relatively higher mean scores for human intrusion and disturbance, as well as climate-related threats, indicate that specific pressure categories are already significant and potentially escalating. Thus, the perception of low overall intensity should not obscure the fact that anthropogenic and climate-driven stressors are emerging as dominant risks. When viewed alongside documented land-use changes in the broader ARB, these patterns suggest that cumulative and interacting pressures may increasingly challenge the long-term ecological integrity of AMWS.

Complementarily, respondents also identified energy production and mining activities within or outside the protected area ($\bar{x} = 0.386$) as a high-impact threat, particularly given the nearby operational Philsaga Mining Corporation (PMC) site in Rosario, Agusan del Sur. Mining activities are known to contribute to habitat degradation, sedimentation, and water pollution, affecting both terrestrial and aquatic ecosystems (Burdzieva et al., 2018; Wolkersdorfer and Mugova, 2022).

Table 2. Issues and Threats in AMWS based on the answers of the 44 KII respondents.

Agusan Marsh Wildlife Sanctuary (AMWS) Threats	Threat Values							
	High		Medium		Low		Overall	
	Total	Mean	Total	Mean	Total	Mean	Total	Mean
Residential and commercial development within a protected area	17	0.386	11	0.250	15	0.341	43	0.326
Agriculture and aquaculture within a protected area	19	0.432	11	0.250	6	0.136	36	0.273
Energy production and mining within or outside a protected area.	17	0.386	6	0.136	21	0.477	44	0.333
Transportation and service corridors within a protected area	12	0.273	6	0.136	4	0.091	22	0.167
Biological resource use and harm within a protected area.	12	0.273	7	0.159	22	0.500	41	0.311
Human intrusions and disturbance within a protected area.	23	0.523	8	0.182	7	0.159	38	0.288
Natural system modifications	11	0.250	7	0.159	21	0.477	39	0.295
Invasive and other problematic species and genes	6	0.136	4	0.091	13	0.295	23	0.174
Pollution entering or generated within protected area	5	0.114	7	0.159	20	0.455	32	0.242
Geological events	6	0.136	5	0.114	11	0.250	22	0.167
Climate change and severe weather	7	0.159	10	0.227	27	0.614	44	0.333
Specific cultural and social threats	13	0.295	12	0.273	18	0.409	43	0.326
TOTAL	**148**	**3.364**	**94**	**2.136**	**185**	**4.205**	**427.00**	**3.235**

Note: Threats were classified as high (causing severe degradation and affecting >10% of conservation values), medium (moderate impact affecting >5–10%), or low (minimal impact affecting <5%), following the framework of Apdohan et al. (2019) and Stolton et al. (2020). Mean values represent the proportion of respondents who assigned each threat level to each category.

Moreover, the current METT scores reveal both strengths and limitations in AMWS's capacity to respond to such external extractive pressures. While the METT inputs indicate basic legal recognition, staff awareness, and some enforcement procedures, the process scores reflect limited operational mechanisms for addressing threats originating outside the protected area. In particular, the absence of a formal buffer zone reduces the regulatory leverage over adjacent mining and energy operations, constraining its ability to prevent indirect impacts such as pollution, hydrological alteration, and habitat fragmentation. Strengthening governance through formalized buffer management, improved inter-agency coordination, and proactive monitoring could enable AMWS to mitigate external pressures better and safeguard its ecological integrity.

B. Management Effectiveness Assessment (MEA)

Management Effectiveness Score

The METT score results indicate an overall management effectiveness of 75.52%, corresponding to an "excellent" rating under DENR Technical Bulletin 2018-05. Among the METT components, the context obtained the highest score of 100%, reflecting an excellent rating due to the formal gazettement of AMWS through Presidential Proclamation No. 913 and Republic Act No. 7586 (NIPAS Act), as amended by Republic Act No. 11038 (Expanded NIPAS Act of 2018). The planning, outputs, and outcomes components received good ratings of 76.63%, 72.73%, and 70.19%, respectively, mainly attributable to the presence of key management instruments, including the Protected Area Management Plan (2021–2031), Manual of Operations (2018), Ecotourism Management Plan (2023–2028), and three site-specific Wetland Management Plans. Meanwhile, the process and inputs components also obtained good ratings of 68.23% and 65.32%, reflecting improvements such as the revitalization of 200 Park Rangers and the establishment of regular patrolling routes within the protected area. Table 3 presents the summary of METT scores across all management components.

Additionally, the overall METT Score (75.52%) indicates that AMWS has strong enforcement capacity, including routine monitoring, patrolling, and staff awareness of regulations, which collectively support day-to-day management operations. The rating also reflects a relatively high level of adaptive management readiness, suggesting that the sanctuary is capable of adjusting strategies and interventions in response to emerging threats or ecological changes. However, while overall management effectiveness is robust, limitations remain in responding to external pressures such as adjacent mining, agricultural expansion, or other land-use changes, highlighting areas where governance and operational interventions, such as formalized buffer zones and strengthened inter-agency coordination, could further enhance the long-term ecological integrity of AMWS.

i. Context

All key informants assigned a score of 3 (excellent) to the context component, reflecting their clear understanding of the legal status of the Agusan Marsh Wildlife Sanctuary (AMWS). This high score indicates strong legal design and formal recognition of the protected area, but does not necessarily reflect the effectiveness of the on-the-ground management or implementation. AMWS is one of the 249 protected areas in the Philippines, legally established through Presidential Proclamation No. 913 on October 31, 1996, under Republic Act No. 7586, otherwise known as the National Integrated Protected Areas System (NIPAS) Act of 1992. The proclamation initially covered 19,196 hectares of inland wetland habitats and timberlands, encompassing areas within the municipalities of San Francisco, Rosario, Bunawan, Veruela, Loreto, and La Paz in Agusan del Sur, while designating surrounding peripheral areas as buffer zones (Republic of the Philippines, 1996). The excellent context score, therefore, primarily reflects formal recognition and legal basis, rather than the current operational or enforcement capacity within the protected area.

The legal protection of AMWS was further strengthened through the enactment of Republic Act No. 11038, or the Expanded NIPAS Act of 2018, which amended RA 7586 during the administration of President Rodrigo Duterte, on June 22, 2018. This legislation not only reinforced the institutional and management framework of the protected area but also significantly expanded its coverage to 40,490.96 hectares, nearly doubling its initial proclaimed area. The expansion incorporated ecologically sensitive and globally significant ecosystems, particularly peatlands, which play a crucial role in biodiversity conservation, carbon storage, and hydrological regulation. Additionally, AMWS is under the administrative jurisdiction, supervision, and control of the Department of Environment and Natural Resources (DENR), through the Biodiversity Management Bureau (BMB), in coordination with other relevant government agencies. The protected area is mandated to conserve ecologically rich and unique landscapes, including critical habitats of rare, endemic, and threatened species, thereby underscoring its national and international conservation significance (Republic of the Philippines, 2018).

While the eNIPAS expansion strengthened legal recognition and institutional mandate, it has not automatically translated into commensurate increases in funding, staffing, or enforcement capacity. Operational improvements, such as revitalizing park ranger teams and establishing regular patrol routes, have been implemented. However, resource allocation and human capacity have not fully scaled to match the nearly doubled area. As a result, practical management effectiveness—including enforcement, monitoring, and adaptive management—remains constrained, particularly in newly added peripheral and ecologically sensitive zones. This highlights the gap between legal design and recognition, on the one hand, and on-the-ground implementation capacity, on the other, underscoring the need for enhanced governance, targeted resource allocation, and strengthened operational mechanisms to ensure the long-term ecological integrity of AMWS.

Furthermore, in terms of ancestral domain classification, approximately 29,782 hectares of the protected area are covered by four (4) Certificates of Ancestral Domain Title (CADT), namely CADT 077, CADT 136, CADT 090, and CADT 142. These ancestral domains are recognized and protected under Republic Act No. 8371, otherwise known as the Indigenous Peoples' Rights Act (IPRA) of 1997. The presence of these CADTs within the protected area underscores the significant role of Indigenous Peoples in the stewardship, conservation, and sustainable management of the AMWS. It also highlights the importance of integrating customary laws, traditional knowledge systems, and Indigenous governance structures into protected area planning and management, in accordance with the principles of Free, Prior, and Informed Consent (FPIC) and collaborative governance mandated by IPRA (Republic of the Philippines 1997).

ii. Planning

Most key informants rated the planning and management component as 3 (excellent), indicating that regulations controlling human interventions, such as land-use conversion, agricultural expansion, and timber and wildlife harvesting, are actively enforced. The management interventions and strategies are aligned with the sanctuary's agreed objectives and supported by a concrete design for protected area activities. Key planning instruments, including the Protected Area Management Plan (2021–2031), Manual of Operations (2018), Ecotourism Management Plan (2023–2028), and three site-specific Wetland Management Plans, are reviewed annually, actively used in operational decision-making, and regularly updated to address emerging threats identified in the KIIs, such as human intrusion, agricultural expansion, and climate-related pressures. This iterative use of management instruments ensures that planning is not merely procedural but functionally integrated into adaptive management, guiding on-the-ground interventions, prioritizing enforcement, and informing resource allocation to maintain the ecological integrity of AMWS.

Unlike AMWS, which actively uses and periodically reviews its operational plans, Central Cebu Protected Landscape has formal planning instruments but struggles to turn them into effective management responses to pressures such as population growth and land use change, illustrating common limitations in Philippine protected areas where management plans are underutilized or weakly implemented (Quijano et al. 2021). Additionally, national assessments of Philippine protected areas more broadly have highlighted that many areas lack appropriate management infrastructure, funding, and capacity to implement or update their management plans, limiting their ability to respond effectively to evolving threats; in fact, over 40% of protected areas were reported to lack even basic management plans or sufficient capacity to implement them, despite legal status under NIPAS (Mallari et al. 2016).

Institutional support of AMWS is further reinforced through the Protected Area Management Board (PAMB), which operates through Executive and En Banc Committees supported by seven Technical Working Committees covering planning, biodiversity monitoring, law enforcement, education, partnerships, and Indigenous Peoples' relations. It ensures that planning instruments are actively applied in decision-making and operational management. The PAMB composition, comprising national and local government representatives, Indigenous Peoples, civil society, academic institutions, and the private sector, facilitates multi-level governance, adaptive management, and policy development by integrating research findings, annual Work and Financial Plans, and periodic policy reviews into routine management activities. This functional use ensures that planning instruments are practical tools that guide enforcement, biodiversity monitoring, resource allocation, and the implementation of management interventions, rather than remaining as formal documents. By directly linking plans to emerging threats and operational priorities, the PAMB enhances the effectiveness and responsiveness of AMWS management.

iii. Input

Most key informants rated the inputs component as fair (score = 2), reflecting the presence of established policy instruments, financial mechanisms, and institutional arrangements that support protected area management, while also acknowledging existing limitations. This rating is anchored on the adoption of AMWS PAMB Resolution No. 2017-008 and the implementation of DENR Administrative Order (DAO) 2016-24, which prescribes standardized rates for entrance fees, use of facilities, and resource utilization within protected areas. The Special Use Agreement in Protected Areas (SAPA) under DAO 2007-17 further provides a regulated mechanism for allowable resource use, ensuring safeguards for conservation objectives. Financial sustainability is supported by the Integrated Protected Area Fund

(IPAF) under Section 16 of Republic Act No. 11038 (Expanded NIPAS Act of 2018), with 75% of revenues retained through the Protected Area–Retained Income Account (PA-RIA) to finance operations, enforcement, and priority programs.

Despite these mechanisms, input limitations persist. These include absolute funding constraints, delays in fund release, and restrictions on the use of IPAF revenues, which can limit operational flexibility, especially in newly expanded or peripheral zones. Human resource capacity, although strengthened by the Protected Area Management Office (PAMO-AMWS) staff and the revitalization of 200 Bantay Danao (community-based Park Rangers) with logistical support from municipal and provincial governments, remains insufficient to fully cover the expanded 40,490-hectare area and all priority management tasks. Consequently, while policy, financial, and institutional inputs provide a strong foundation, these limitations constrain the full effectiveness of enforcement, monitoring, and adaptive management within AMWS.

iv. Process

The process component reflects the extent to which management actions and procedures are effectively implemented to achieve protected area objectives. In the case of the Agusan Marsh Wildlife Sanctuary (AMWS), this component received a generally good rating, supported by the establishment and operationalization of key management processes, including routine patrolling, biodiversity monitoring, enforcement protocols, and adaptive planning. However, gaps in these processes, such as limited coverage of patrol routes in peripheral zones, inconsistent monitoring of emerging threats, and delays in translating research findings into operational actions, can directly reduce the effectiveness of threat mitigation. For instance, human intrusion, agricultural expansion, and illegal resource extraction may persist in areas with insufficient monitoring. At the same time, climate-related impacts or habitat degradation may go unaddressed if early-warning or adaptive response mechanisms are not fully operational. Thus, while established processes provide a strong framework, their practical limitations constrain the protected area's capacity to entirely prevent or respond to emerging threats, highlighting areas for targeted improvement in AMWS management.

Notably, AMWS PAMB Resolution No. 2021-018 formally approved the protected area's management zoning scheme, designating 11,446.525 hectares as a Strict Protection Zone (SPZ) and the remaining area as a Multiple Use Zone (MUZ). SPZ includes the Crocodile Sanctuary, Flying Fox Sanctuary, Hornbill Sanctuary, and the peatlands. This zoning framework provides clear spatial guidance for protecting and sustainably using resources and supporting development activities, consistent with conservation priorities. The designation and regulation of areas for allowable resource use are implemented in accordance with existing national environmental laws and policies, including Republic Act No. 9147, Republic Act No. 8550, as amended by Republic Act No. 10654, and Republic Act No. 11038. These processes were carried out in compliance with protected area demarcation and delineation requirements under Section 9 of Republic Act No. 7586, as amended by RA 11038, and Rule 9.5 of DENR Administrative Order No. 2018-05. While the zoning provides a strong legal and spatial framework, enforcement effectiveness varies across zones. Patrolling and monitoring in SPZs are generally robust, supported by Park Rangers and community Bantay Danao. However, coverage in peripheral MUZs is limited, which can reduce compliance with resource use regulations. This highlights that, although zoning guides management actions, its conservation impact ultimately depends on the consistent implementation and capacity of enforcement mechanisms, particularly in areas exposed to human pressures such as agricultural expansion, fishing, and intrusion.

Management processes are further strengthened through monthly Communication, Education, and Public Awareness (CEPA) activities conducted by the PAMO-AMWS, aimed at enhancing stakeholder awareness, compliance, and support for conservation initiatives. Indigenous Peoples (IPs) within the CADT areas actively serve as co-managers of the protected area. They are directly involved as site implementers of ecotourism activities, reflecting inclusive and participatory governance. Additionally, IP communities have been key beneficiaries of rehabilitation and reforestation projects within the protected area, reinforcing livelihood support alongside ecosystem restoration.

Scientific monitoring processes are in place within AMWS, as evidenced by the establishment of nine Biodiversity Monitoring Sites (BMS), fifteen Asian Waterbird Census (AWC) sites, and a 2-kilometer Biodiversity Assessment and

Monitoring System (BAMS) transect in the Caimpugan Peat Swamp Forest. These mechanisms provide critical data to guide adaptive management and policy decisions. However, analysis of the METT process component indicates that specific indicators scored lowest, particularly "protection system", which evaluates whether systems are in place to control access and resource use within the protected area, and "resource management", which assesses whether active management of habitats and species is being undertaken. These low scores reflect limitations in the AMWS's ability to regulate human activities in peripheral zones and implement active interventions in resource management, partly due to the absence of a formally established buffer zone. This gap constrains the protected area's overall process effectiveness and highlights areas where enforcement, monitoring coverage, and active management need strengthening to maintain the ecological integrity of AMWS.

v. Output

The outputs component of the AMWS management effectiveness assessment received a fair score, reflecting not only the quantity of outputs produced but also their current level of effectiveness in addressing conservation objectives. In terms of physical infrastructure, AMWS has established key facilities that support conservation and visitor engagement, including the AMWS Visitor Center, a two-story floating building at Lake Panlabuhan co-managed with CADT 090, a designated rest area within the Caimpugan Peat Swamp Forest, bird hides at Lake Mambagongon, and a Park Ranger Station overseeing the Talacogon Peatland. These facilities demonstrate measurable progress in promoting environmental education, biodiversity appreciation, community-based ecotourism, and on-site protection.

Beyond physical infrastructure, outputs also include non-physical results, such as the implementation of zoning policies, enforcement regulations, strengthened partnerships with Indigenous Peoples and local government units, and community-based initiatives linked to ecotourism and conservation. These outputs contribute to institutional strengthening and stakeholder engagement, which are critical components of protected area governance.

However, the fair rating reflects that while outputs are present, their scale, distribution, and effectiveness relative to identified threats remain moderate. For example, although visitor facilities and ranger stations support awareness and protection, they may not yet be sufficient to fully mitigate pressing threats such as agricultural expansion, illegal resource extraction, and human intrusion in peripheral zones. Similarly, while partnerships and livelihood-related initiatives exist, their coverage and impact on reducing dependency on protected area resources require further strengthening. Thus, the assessment suggests that the challenge lies not merely in increasing the number of outputs but in enhancing their strategic alignment, reach, and measurable impact in addressing the most critical socio-ecological pressures affecting AMWS.

iv. Outcome

The outcome component reflects the broader ecological, social, and economic effects of AMWS management, as captured by METT indicators such as biodiversity conservation, sustainable resource use, and community benefits. In this assessment, outcomes are derived from a combination of measured indicators (e.g., biodiversity monitoring data and waterbird census counts), observed trends reported in management records, and perceived improvements reported by key informants. Economically, the AMWS supports local livelihoods by sustaining fish populations that feed into the local fishery market. Agricultural initiatives, including rice production and floating vegetable gardens, provide additional food security and income for Indigenous Peoples and other residents.

In terms of ecological outcomes, AMWS has been a pilot site for peatland research, supporting studies on hydrology, soil carbon sequestration, and biodiversity in peat swamp forests. The establishment of BMS and AWC sites has provided measurable indicators of species abundance and habitat quality, informing adaptive management and contributing to the protection of threatened species. Despite these positive indicators, the fair outcome score suggests that measurable ecological and socioeconomic impacts have not yet fully caught up with recent improvements in planning, zoning, and management processes. Conservation outcomes typically lag behind institutional and procedural reforms, particularly in large and recently expanded protected areas. Thus, while monitoring systems and governance frameworks have strengthened, sustained long-term data collection and impact evaluation are needed to conclusively demonstrate ecosystem recovery, increased biodiversity resilience, and measurable livelihood gains across the entire AMWS.

4 Conclusions

The management effectiveness assessment of Agusan Marsh Wildlife Sanctuary (AMWS) using METT-4 indicates that the protected area possesses a strong legal and institutional foundation, supported by formalized governance structures, approved management plans, and recognized co-management arrangements with Indigenous Peoples. However, the assessment demonstrates that institutional design does not automatically translate into full governance performance on the ground. While policies, zoning frameworks, and planning instruments are in place, implementation capacity, particularly in enforcement coverage, ecological monitoring expansion, and logistical support, remains uneven across the 40,490-hectare protected area.

Anthropogenic pressures such as human intrusion, agricultural expansion, and nearby mining activities interact directly with these implementation gaps. Limited personnel, constrained financial resources, and incomplete monitoring coverage reduce the ability to regulate peripheral zones consistently, detect early signs of habitat degradation, and respond proactively to emerging threats. The absence of a formally established buffer zone further weakens the protected area's capacity to manage external pressures originating outside strict protection areas but affecting ecological integrity within them. Thus, while governance structures are robust in design, enforcement reach, monitoring intensity, and operational responsiveness require strengthening to mitigate socio-ecological pressures effectively.

To address weaknesses identified in the METT assessment, particularly in the inputs and process components, AMWS should strengthen governance and zoning by formally establishing a buffer zone and enhancing enforcement systems in Multiple Use Zones to regulate better peripheral pressures, such as agricultural expansion, human intrusion, and nearby extractive activities. Monitoring and science-based management should be expanded through broader assessments of biodiversity, water quality, fisheries, and peatlands, with standardized long-term datasets integrated into planning and budgeting to improve adaptive management and resource management indicators. To respond to funding, logistical, and personnel constraints reflected in moderate input scores, the sanctuary should improve IPAF utilization efficiency, explore sustainable financing mechanisms such as Payment for Ecosystem Services and strengthened ecotourism models, and invest in field equipment and capacity-building for PAMO staff to enhance enforcement reach. Strengthening community and Indigenous co-management through participatory monitoring, livelihood diversification, and expanded community-based enforcement will further improve governance performance and compliance with zoning regulations. Finally, periodic METT reassessments should be institutionalized to systematically track improvements in protection systems, resource management, and overall implementation capacity over time.

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6 Author Contribution

HJ Sumilhig contributed to the conceptualization and design of the study, including data collection, formal analysis, and manuscript writing. SJ Mulig handled data curation, assisted in formal analysis, and contributed to the writing and revision of the manuscript. GJ Deniega assisted in data collection, documentation, and materials preparation and contributed to manuscript review. S Vasquez led the planning, implementation, and supervision of the study, as well as provided technical guidance and critical revision of the manuscript.

7 Statement of Conflict of Interest

The authors declare no conflict of interest.

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