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Site Suitability Analysis for Dairy Buffalo Production in Magdalena, Laguna, Philippines Using Geographic Information System

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ABSTRACT

Site suitability assessment is a crucial step in determining the environmental limits of sustainable dairy buffalo production. This study aimed to assess the suitability of sites for locating potential agricultural lands for smallholder dairy buffalo production in Magdalena, Laguna, Philippines. Physical, agrometeorological, animal health and environmental, and economic factors were selected and the weights of their contributions for site suitability were assessed using the Analytic Hierarchy Process (AHP). Subsequently, all the factors were integrated to generate the site suitability map using geographic information system (GIS). More than 79% (2,701 ha) of the total land area of Magdalena is highly suitable for dairy buffalo production. These areas are mainly influenced by proximity to roads, markets, and water sources, which are the highest-weighted suitability factors. About 0.6 ha (0.02%) of the municipality is considered moderately suitable because of the aggregated factors, including distance to market, distance to livestock and poultry farms, distance to built-up areas, and temperature-humidity index. Validation showed that all the 25 surveyed dairy buffalo farms are in highly suitable areas. GIS and AHP can be effectively used to enhance land-use efficiency and improve the management of dairy buffalo production..

Keywords: *Site suitability, Geographic Information System, Analytic Hierarchy Process, dairy buffalo*

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INTRODUCTION

The Philippine native water buffalo, known locally as Carabao (*Bubalus bubalis*), is primarily characterized by its brownish, swamp-type variety. It is used in agricultural operations and dairy production.(*Gundran and More 1999*). It plays a significant role in draft operations and has the potential to yield 1 to 2 L of milk per day (*del Barrio 2016*). Recognizing its importance, the Philippine government established the Philippine Carabao Center (PCC) under Republic Act 7307, also known as the Philippine Carabao Act of 1992. The PCC's mandate focuses on enhancing the buffalo population and productivity through advancements in reproduction, breeding, nutrition, and animal health. To augment dairy production, the PCC has introduced superior breeds, such as the Indian Murrah, Bulgarian Murrah, Brazilian Murrah, and Italian Mediterranean buffalo (river type), which can produce approximately 6 to 8 L of milk daily (*del Barrio 2016*).

In 2017, the buffalo population in the Philippines was reported to be approximately 2.88 million heads, translating into a volume of 144,410 MT (*Philippine Statistics Authority [PSA] 2018b*), with an estimated economic value of PhP 12.59 billion (*PSA 2018a*) (1 US$ = PhP 48.121). According to the *National Dairy Authority* (*2018*), the dairy sector experienced one of its highest year-on-year growth rates in volume (22,756 MT) and value (PhP 809.33 M), at rates of 8% and 13% respectively, within the livestock sector for that year. However,the total production volume was not as high as those recorded in 2010 and 2011, when buffalo production volumes were approximately 148,020 MT and 147,520 MT, respectively (*PSA 2018b*).

Spatial and temporal variability in buffalo production has been observed, with disparities evident across different provinces and regions. As of January 2019, the national buffalo inventory was estimated at 2.87 million heads. The Bicol Region, Western Visayas, and Central Luzon were identified as the top contributors, accounting for 29.4 % of the total buffalo population in the country. These regions also have the highest concentration of carabao in backyard farms. Conversely, commercial farm buffalo inventories were highest in the Cagayan Valley, Central Luzon, and Eastern Visayas, representing a significant portion of the total commercial stocks. Among the 16 regions, CALABARZON (Region IV-A) ranked eighth in total and backyard production (6.18%) and fourth in commercial production (5.89%), with Laguna province accounting for 21.9% of the region's buffalo inventory (*PSA 2019*).

The observed variability in buffalo production can be attributed to factors such as land use preferences and business strategies. However, challenges such as poor reproductive performance (*Duran and Duran 2017*), low productivity (*Domingo and Olaguera 2017*), high mortality rates (*Portugaliza et al. 2019*), inadequate marketing strategies (*Dulin et al. 2019*), and problematic financing mechanisms (*Haddad et al. 2017*) also significantly impede the development of buffalo potential. These issues are compounded by physical, environmental, and climatic conditions, as well as management practices. The importance of conducting site suitability analyses at the planning stage has been emphasized, as suitable conditions are essential for optimizing animal productivity (*Gerber et al. 2011; Qi et al. 2015; and Upadhyay et al. 2007*).

Multi-Criteria Decision Analysis (MCDA) has been widely adopted for assessing the suitability of areas for livestock production. This approach facilitates decision-making by incorporating multiple, complex criteria (*Antunes et al. 2016*). Among the various techniques of MCDA, the Analytic Hierarchy Process (AHP) is notably the most common due to its applicability in a range of practical scenarios (*Mu and Pereyra-Rojas 2017*). Furthermore, the integration of AHP with Geographic Information Systems (GIS) enhances the assessment of site conditions, both prior to project implementation and during monitoring phases (*Schmoldt et al. 2001*). GIS's ability to manage and process large volumes of diverse data types makes it an invaluable tool in this context (*Kennedy 2013*). Consequently, the synergy between AHP and GIS presents a beneficial methodology for developing dairy buffalo production suitability maps, necessitating a comprehensive evaluation of multiple factors. This study aimed to utilize an integrated Geographic Information System and Multi-Criteria Decision Analysis (GIS-MCDA) framework to assess site suitability for smallholder dairy buffalo production, providing a novel approach to enhancing dairy buffalo productivity and sustainability. Specifically, this research aimed to identify and categorize pertinent physical, environmental, and economic factors that influence the suitability of dairy buffalo sites. It also aimed to assess the relative significance of each factor using the AHP, generate a site suitability map through GIS-based weighted overlay analysis, and validate the results using the actual locations of existing dairy buffalo farms in the study area.

MATERIALS AND METHODS

Study Area

The study was conducted in the municipality of Magdalena, Laguna, Philippines, from January to November 2019. Magdalena is approximately 11 km from the provincial capital, Sta. Cruz and 105 km from the national capital, Metro Manila. Geographically, it is bounded by the municipalities of Sta. Cruz and Pagsanjan to the north, Liliw to the south, segments of Pagsanjan, Luisiana, and Majayjay to the east, and Nagcarlan, Pila, and Sta. Cruz to the west (**Figure 1**). Spanning a total area of 3,397.4 ha, Magdalena is administratively divided into 24 barangays.

According to the 2016 local survey, Magdalena hosts a population of 26,939, yielding a population density of approximately seven individuals per hectare (*Department of the Interior and Local Government [DILG] 2019*). The municipality's elevation profile varies significantly, ranging from 4.7 to 148.3 masl, as indicated in the Digital Elevation Model (DEM) obtained from the *National Mapping and Resource Information Authority [NAMRIA]* (*2015*).

The hydrology of Magdalena is notably defined by the presence of two principal watercourses: the Balanac and Maimpis Rivers, which predominantly flow through the eastern and southwestern sectors of the municipality, respectively. These rivers play a critical role in the local agriculture, supplying irrigation to vast areas before their eventual discharge into Laguna Lake. The agricultural landscape of Magdalena is predominantly characterized by perennial crops, which occupy approximately 66.7% or 2,266.1 ha of the municipal territory. This is complemented by areas designated for annual crop production, which account for 24.1% or 818.8 ha. Such distribution underscores Magdalena's significant reliance on and commitment to agricultural productivity, with nearly 90% of its land being dedicated to agricultural pursuits.

In addition to crop cultivation, the region also engages in animal husbandry, with a notable emphasis on dairy buffalo farming. This study specifically aimed to identify viable locations for establishing smallholder dairy buffalo farms. According to the Philippine Statistics Authority (*PSA 2019*), a dairy buffalo enterprise qualifies as a backyard or smallholder operation under any of the following conditions: it comprises no more than 20 adult buffaloes; it includes no more than 40 young adults; or it

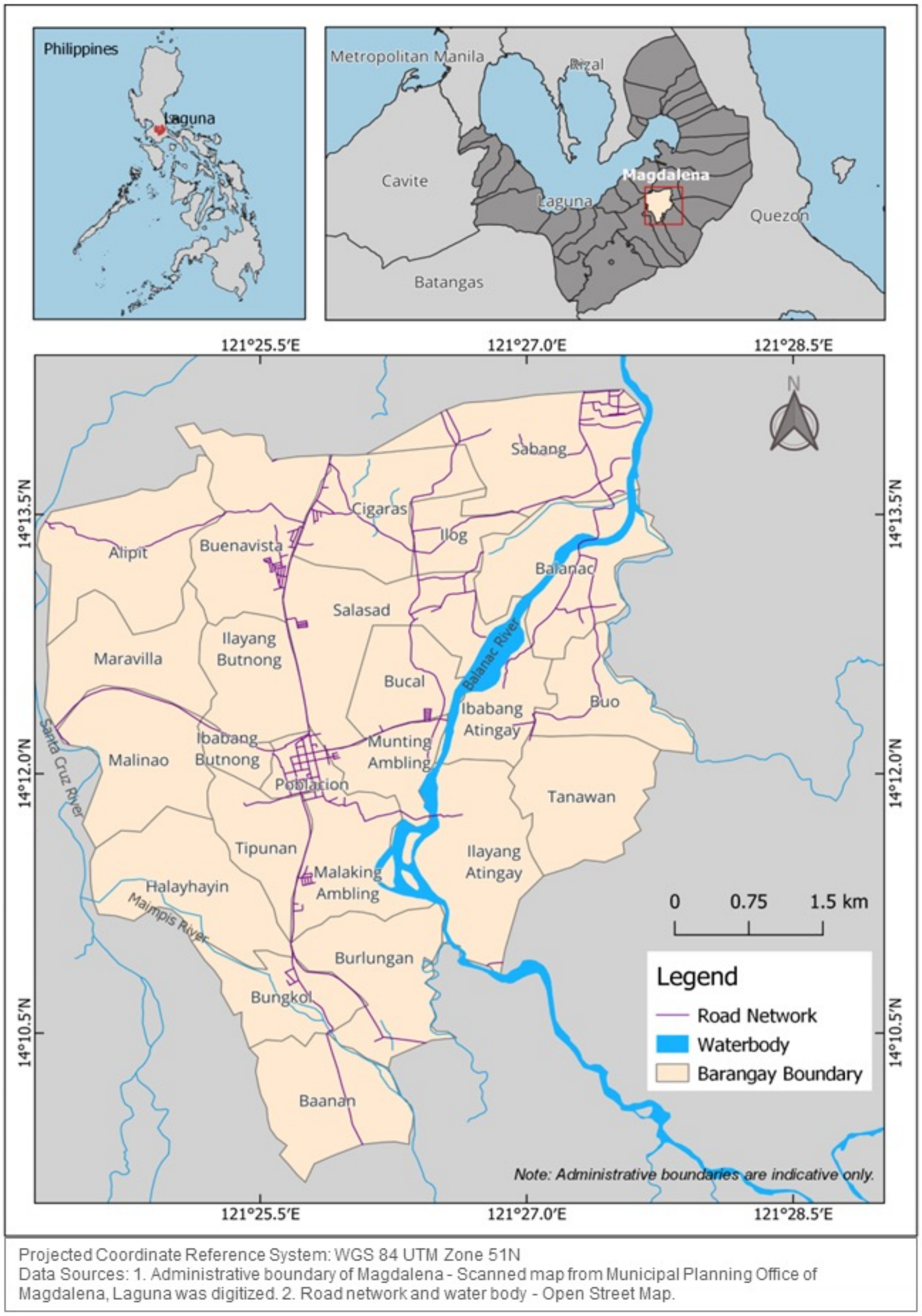

Figure 1. Map of Magdalena, Laguna, Philippines.

maintains a combination of up to nine adults and 21 young animals. Furthermore, in alignment with the Republic Act 7307 of 1992, also known as the Philippine Carabao Act, a smallholder is defined as a farmer possessing no more than 5 ha of land. Adhering to these descriptions, the stocking density for a smallholder dairy buffalo farm is determined to be a maximum of 20 buffaloes for every 5 ha, or equivalently, four buffaloes per hectare. This criterion is adopted to guide the assessment of land suitability for the development of small-scale dairy buffalo operations, reflecting both legislative and agricultural standards within the context of Philippine rural farming practices.

Site Suitability Analysis Framework

The methodology for site suitability analysis employed in this study was derived from the framework by *Wijayanto et al.* (*2015*). The initial phase involved defining the objective, which was to identify locations conducive for the establishment of smallholder dairy buffalo farms. To accomplish this, suitability criteria and corresponding thresholds were identified through an extensive review of existing literature and consultations with subject matter experts. Four primary suitability factors, including physical, agrometeorological, health and environmental, and economic, were identified. Each primary factor was dissected into ten specific sub-factors. These sub-factors include: slope of the land,soil texture, precipitation levels, temperature-humidity index, proximity to built-up areas, proximity to existing livestock and poultry operations, accessibility surface water sources, along with considerations for water source reliability and pollution risks, distance to the nearest road, and proximity to markets. Soil texture was included among the physical criteria to account for its significant role in forage production, which is crucial in supporting dairy buffalo nutrition and grazing potential (*Baldaccini and Vacca 2009*). The process of weighting involved the utilization of pairwise comparison to estimate relative importance, which was subsequently applied to their respective factor maps. To refine the accuracy of the suitability analysis, multiple iterations were conducted criteria thresholds until the derived overall suitability map met predefined standards of acceptance. The suitability map was considered acceptable when majority of the surveyed dairy buffalo farms intersected with moderately to highly suitable areas (*Layomi Jayasinghe et al. 2019*). This iterative approach ensured that the final suitability map accurately reflected the real-world distribution of viable locations for smallholder dairy buffalo farms.

Datasets and GIS Processing

The study used both vector and raster datasets, which were obtained from different sources including websites and different government institutions (**Table 1**). To ensure uniformity of all datasets, the projected coordinate reference system of the layers was set to WGS84 UTM Zone 51N (EPSG:32651), which uses meters as its linear unit. All datasets were reshaped from national to a municipal scale in Magdalena, Laguna. The boundary map of Magdalena was generated by georeferencing the NAMRIA administrative map and digitizing the polygons of each barangay on a scanned spot map provided by the Magdalena Municipal Planning Office.

All datasets of criteria were adjusted into a uniformed spatial resolution, which is the same as the spatial resolution of DEM data. The resolution of rainfall, temperature, and relative humidity datasets was adjusted by interpolation using the Kriging method (*Cao et al. 2009*). The temperature-humidity index was calculated following the method of *NRC* (*1971*) which uses dry bulb temperature and relative humidity as input parameters. All the GIS processing and analysis conducted in November 2019. Quantum GIS (QGIS) version 2.18 was utilized in processing the datasets (**Figure 2**).

Threshold Setting, Reclassification, and Standardization

The threshold or the values of the criteria by which an area is evaluated for its suitability were determined based on literature review and consultation with experts. The suitability class evaluation adapted from *FAO* (*1991*) was utilized then reclassified (**Table 2**).

Surface water was used in the analysis due to its accessibility, traditional use by smallholder farmers in Magdalena, and the availability of spatial data needed for GIS-based modeling. Deep wells, while viable, were excluded due to the absence of georeferenced data. In addition, although surface water bodies were considered

Table 1. Summary of datasets used for site suitability assessment of dairy buffalo production.

Factors		Dataset	Format	Source
PHY	Slope	DEM	Raster	*NAMRIA* (*2015*)
	Soil texture	Soil series	Vector	*DA* (*2019*)
AGME	Precipitation	30-year monthly precipitation (1981-2010)	Raster	*Funk et al.* (*2015*)
	Temperature-Humidity Index	30-year ave. annual temp.and humidity (1971-2000)	Tabular	*ClimWat* (*2006*)
	Distance to SW (source)	Land use	Vector	*NAMRIA* (*2015*) and *OSM* (*2019*)
HAE	Distance to BUA	Land use	Vector	*NAMRIA* (*2015*)
	Distance to LPF	Land use	Vector	*NAMRIA* (*2015*) and *MAO* (*2019*)
	Distance to SW (pollution)	Land use	Vector	*NAMRIA* (*2015*) and *OSM* (*2019*)
ECON	Distance to road	Road network	Vector	*OSM* (*2019*)
	Distance to market	Coordinates	Vector	*MAO* (*2019*)

PHY – Physical, AGME – Agrometeorological, HAE – Health and Environmental, ECON – Economic, BUA – built-up areas, LPF – livestock and poultry farms, and SW – surface water

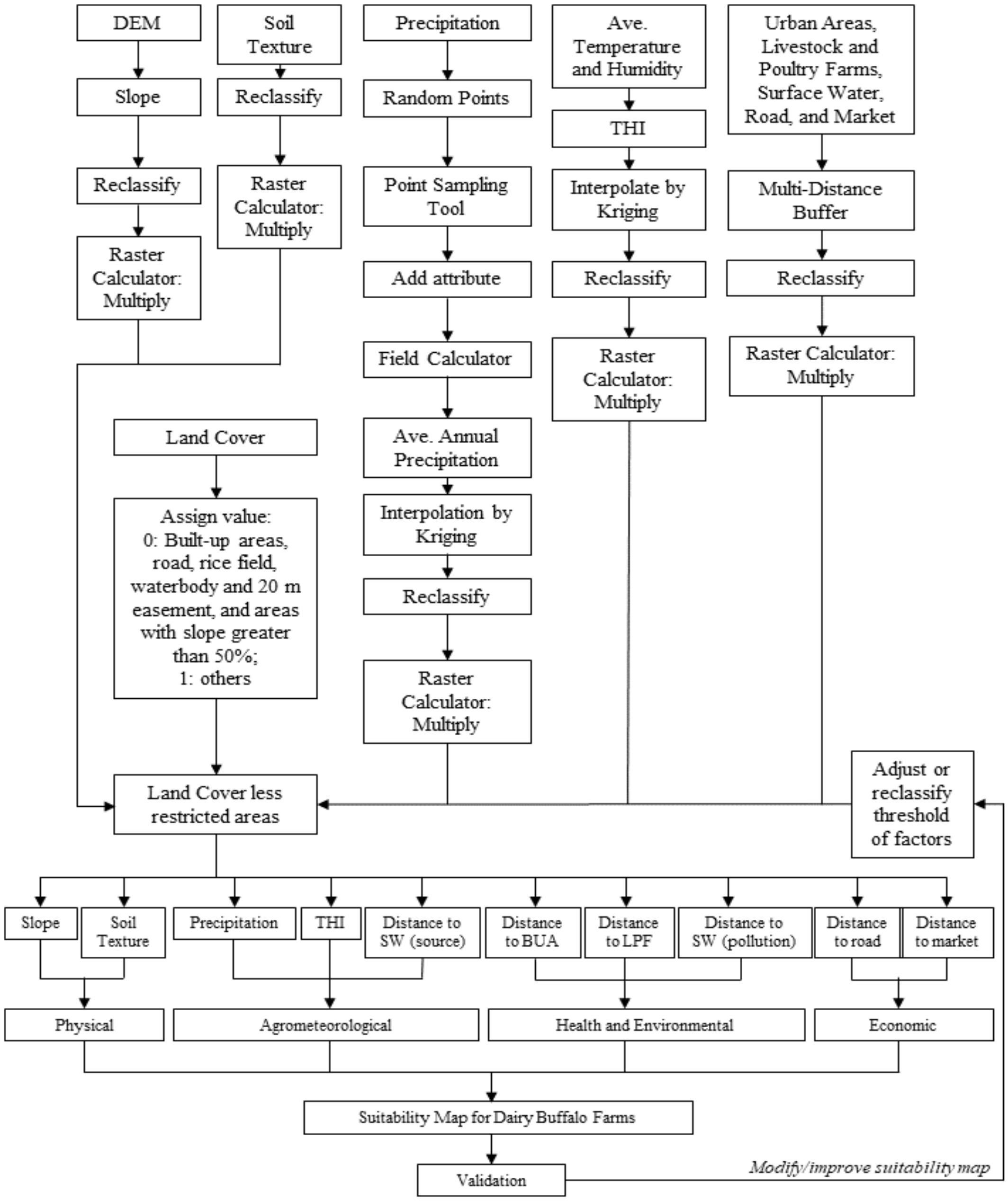

Figure 2. GIS processing flowchart for site suitability assessment of dairy buffalo production.

as crucial sources for both livestock drinking and forage production, their proximity also poses a pollution risk due to potential buffalo manure runoff. This dual role reflects the water–pollution nexus, where access to water must be balanced with environmental safeguards. To address this trade-off, Multi-Criteria Decision Analysis (MCDA) was employed to incorporate two contrasting criteria: one that favors proximity for accessibility (*Yan et al. 2017; Terfa and Suryabhagavan 2015*) and another that discourages over-nearness to protect water quality (*Basnet et al. 2001; Water Code of the Philippines 1976*). The MCDA framework enabled the integration ofthese competing factors into a unified suitability model.

Reclassification was performed to group classes with the same preference for dairy buffalo farms site selection. A linear function was used to assign preference values to different classes for all criteria allowing for standardization of each criterion. The number increases from 0 to 3 as the suitability also increases from not suitable to highly suitable, respectively (**Table 3**).

Analytic Hierarchy Process

The relative importance was assigned by using Delphi method (*Humphrey 1995*) in which representatives of experts from different fields or perspectives were interviewed face-to-face to compare the importance of the factors based on *Saaty* (*1980*) scale. The degree of consistency in the pairwise comparisons was assessed

Table 2. Summary of factors, criteria, and suitability classes for site assessment for dairy buffalo production.

Criteria	Suitability Characteristics				Reference
	Highly Suitable	Moderately Suitable	Marginally Suitable	Not Suitable	
Slope (%)	<10	10-18	18-50	>50	*Holechek (1988), Moog and Marbella (n.d.), and Revised Forestry Code of the Philippines (1975)*
Soil Texture	Loam	Sandy loam, silty loam, clay loam, silty clay loam, and sandy clay loam	Loamy sand, silty clay, and sandy clay	Sand, clay, and silt	*Baldaccini and Vacca (2009)*
Annual Precipitation (mm)	>1,100	900-1,100	<900	-	*Bizuwerk et al. (2005)*
Temperature-humidity index	<72	72 to 78	>78	-	*Dash et al. (2016)*
Distance to surface water (source) (km)	0.02-1	1-3	>3	<0.02	*Yan et al. (2017) and Water Code of the Philippines (1976)*
Distance to built-up areas (km)	>2.25	0.25-2.25	<0.25	-	*Basnet et al. (2001)*
Distance to existing livestock and poultry farms (km)	>6	0.1-6	<0.1	-	*Basnet et al. (2001)*
Distance to surface water (pollution) (km)	>1	0.1-1	0.02-0.1	<0.02	*Basnet et al. (2001) and Water Code of the Philippines (1976)*
Distance to road (km)	<0.5	0.5-3	>3	-	*Yan et al. (2017)*
Distance to market (km)	<1	1-5	>5	-	*Yan et al. (2017)*

Table 3. Reclassified value for each suitability class.

Suitability Class	Value
Highly Suitable	3
Moderately Suitable	2
Marginally Suitable	1
Not Suitable	0

and evaluated based on a consistency ratio index. The level of consistency was reasonably acceptable if the consistency ratio was equal to or less than 0.1 or 10% (*Saaty 1980*). The responses of the experts were inputted into the spreadsheet-based Analytic Hierarchy Process (AHP) application developed by *Goepel* (*2013*), which was used to calculate the weights of each factor. The weight of each factor was calculated using the geometric mean method (*Crawford and Williams 1985*). In instances where the consistency ratio was greater than 0.1, the pairwise comparison score was adjusted accordingly until the consistency ratio was acceptable. The weights provided by all the experts were consolidated using the weighted geometric mean to obtain the final weight for each factor. To determine the agreement of weights provided by the experts, the AHP consensus indicator (*Goepel 2013*) was calculated (**Table 4**).

Table 4. Interpretation of AHP consensus indicator (*Goepel 2013*).

AHP Consensus Indicator Value (%)	Interpretation
≤ 50	Very low (no consensus, diverse opinions)
50-65	Low (limited agreement)
65-75	Moderate (reasonable agreement)
75-85	High (strong agreement)
≥85	Very High (near-complete agreement)

Aggregation

Once the weights were associated with each factor map, the data layers were aggregated using a raster using a raster-based Weighted Linear Combination (WLC) method (*Malczewski 2011*) in QGIS. Each standardized raster layer, representing a factor or sub-factor, was multiplied by its respective weight using raster map algebra operations. These weighted rasters were then aggregated to generate the final suitability map. The WLC method was implemented using the raster calculator tool in QGIS, which can be represented by the equation of *Eastman et al.* (*1998*) as follows:

$$S = \sum_{i=1}^{n} W_i x_i \tag{1}$$

where: S is the suitability, W_i is the weight of factor i, and x_i is criterion score of factor i.

RESULTS AND DISCUSSIONS

Constraint Map

The constraints are defined as those permanent areas that are evidently not suitable for dairy buffalo farming and are prohibited by regulations or laws. These areas include road network, built-up areas, rice field and waterbody with 20-meter easement (*Water Code of the Philippines 1976*), and areas with slope of 50% or more (*Revised Forestry Code of the Philippines 1975*). While rice fields can provide a food source such as rice hay and are commonly used as wallowing or grazing grounds for buffaloes in the Philippines, their standing water conditions may support the proliferation of snails, the intermediate host of *Fasciola gigantica*, thereby posing a risk of fasciolosis (*Tum et al. 2004; Portugaliza et al. 2019*). Fasciolosis has been reported to significantly impair feed efficiency and milk production in infected lactating buffaloes (*Isah et al. 2019*). Recognizing this, the study cautiously considered rice field areas as potentially unsuitable due to elevated disease risk. Nevertheless, it is acknowledged that not all rice fields are infested, and effective preventive and control measures, such as strategic grazing, deworming, and snail control, can mitigate the threat of infection. The extent of the constraints or restricted areas is about 696.2 ha or 20.5% of thr total land area of Magdalena (**Figure 3**). The potential area for dairy buffalo production was obtained by subtracting the constraints from the total land area of Magdalena (3,397.4 ha). This area is equivalent to 2,701.3 ha or 79.5% of the whole municipality.

Factor Suitability Maps

Magdalena was classified as highly suitable for dairy buffalo production in terms of rainfall as the whole municipality received an annual rainfall ranging from 2,116 to 2,330 mm. On the other hand, the average monthly temperature-humidity index (THI) of the area is approximately 78.38 (**Figure 4**), which is categorized as mild stress level for buffaloes according to *Dash et al.* (*2016*). Thus, the municipality was classified as moderately suitable for dairy buffalo production in terms of THI. However, it is still important to note the variability of monthly THI, as some months (April to September) had THI values equal to or higher than 79. According to *Dash et al.* (*2016*), the buffalo may experience moderate stress during these months by showing symptoms of increased respiration rate, decreased dry matter intake, and decreased ratio of forage to concentrate intake. Nevertheless, these effects can be alleviated through providing shade, ventilation (e.g., fans), water misting systems, or access to wallowing areas.

The generated suitability map illustrated the following factors: slope, soil texture, temperature-humidity index, precipitation, land use, proximity to roads, proximity to markets, proximity to existing livestock and poultry farms, distance to surface water sources, and pollution risk (**Figure 5**). The slope suitability map shows that 86.14% (2,326.8 ha) of the potential area in Magdalena was highly suitable for dairy buffalo production because of its slope ranging from 0 to 10%. For the soil texture,25.5% (688.7 ha) of the potential area was moderately suitable because of its clay loam soil. These moderately suitable areas are in the eastern part of Balanac river and some portion on the southwest tail of the municipality. The remaining western portion of the municipality, which is about 74.5 % (2,012.6 ha) of the potential area, was highly suitable due to loamy soil texture.

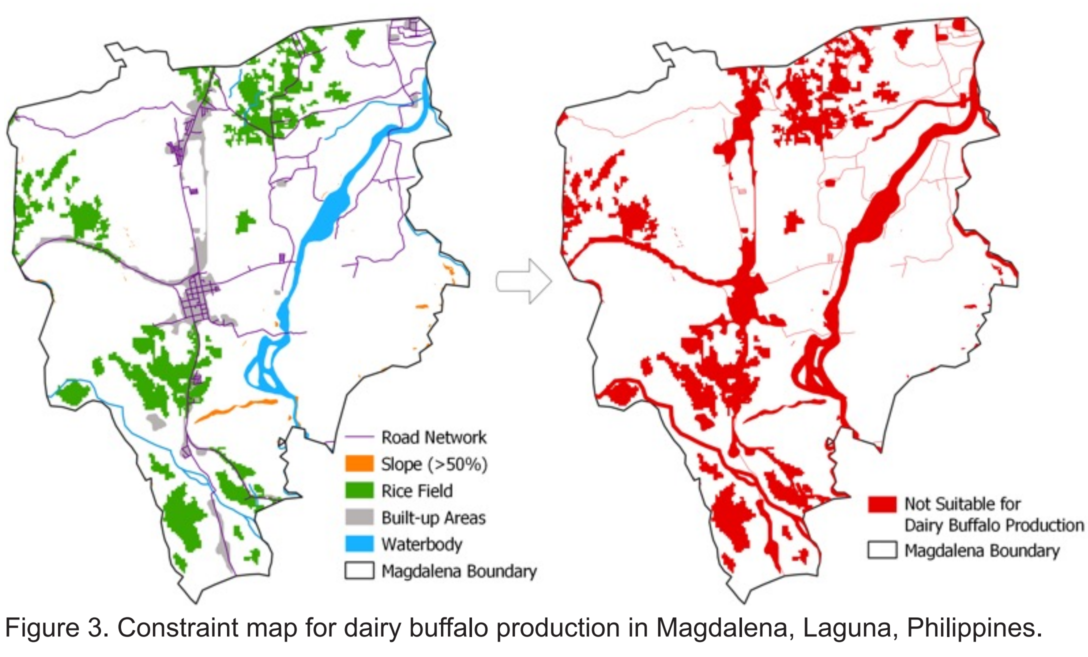

Figure 3. Constraint map for dairy buffalo production in Magdalena, Laguna, Philippines.

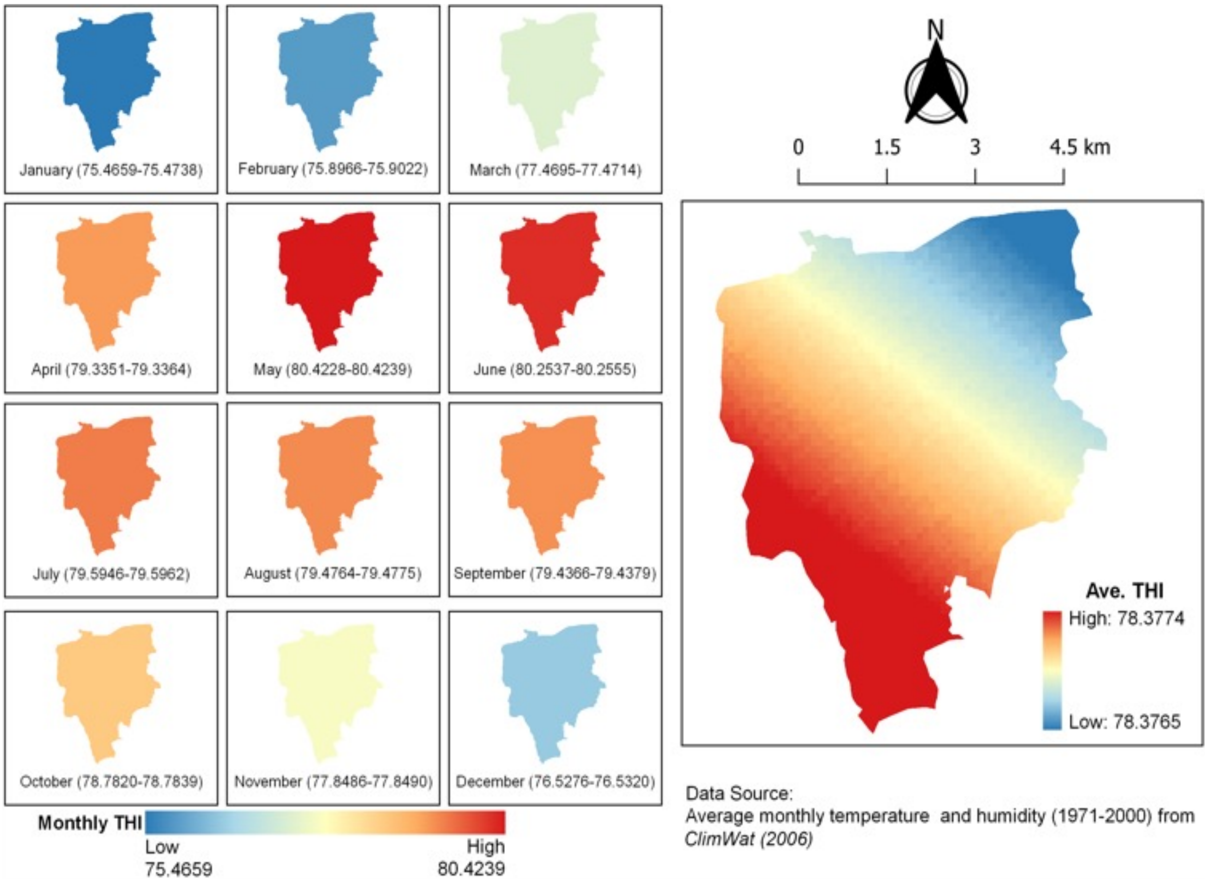

Figure 4. Temperature-humidity index map of Magdalena, Laguna, Philippines.

When surface water bodies, including rivers, streams, and creeks, located inside and outside the municipal boundary were buffered, 78.59% (2,122.9 ha) of the potential area was considered as highly suitable since these areas are within the 20 m to 1 km zone measured from the border of the surface water. When built-up areas were buffered by 250 m, 26.09% (704.8 ha) of the potential area was marginally suitable for dairy buffalo production. The majority of the potential area (1,979.9 ha or 73.30%) was moderately suitable or within the 25 m to 2.25 km range buffer. Only the remaining 16.5 ha (0.61%) located in the eastern boundary of Barangays. Tanawan and Buo were considered highly suitable since these areas are at least 2.25 km away from built-up areas. On the other hand, when medium-large scale livestock and poultry farms were buffered by 100 m, 1.7% of the potential area or equivalent to 45.9 ha was marginally suitable for dairy buffalo production. The remaining 2,655.4 ha (98.3%) was moderately suitable or within the 100 m to 6 km buffer distance.

Meanwhile, about 266.2 ha (9.85%) were found to be marginally suitable when an 80 m distance to surface water was buffered, as this area is a possible source of water pollution due to potential proliferation of buffalo manure. Nevertheless, the actual risk largely depends on the waste management practices employed in the farm, and proper interventions can significantly mitigate pollution impacts. Moderately suitable (100 m to 1 km away from a waterbody) areas were estimated at 1,856.7 ha (68.73%). A total of 578.4 ha (21.41%) was classified as highly suitable areas or at least 1 km away from the rivers.

In terms of access to transport routes, about 671.2 ha (24.85 %) of the potential area were moderately suitable or with a distance to road of 500 m to 3 km. Highly suitable areas or those with a distance to road of less than 500 m were 2,030.1 ha (75.15 %). Moreover, the distance of the farm to the market is considered because dairy milk should be delivered as timely as possible to preserve the quality of the milk and for it to be processed immediately. The extent of the area classified as moderately suitable or with a distance to market of 1 to 5 km is 2,225.9 ha (82.40%). However, it is important to note that travel time over 1 to 5 km distances may take less than an hour, depending on road conditions, which is well within the 2-4 hour window required to preserve raw milk quality. Hence, decision-makers may consider these areas as favorable options if road accessibility and condition permit timely delivery. On the other hand, about 475.4 ha (17.60%) were classified as highly suitable areas or within 1 km distance to the market.

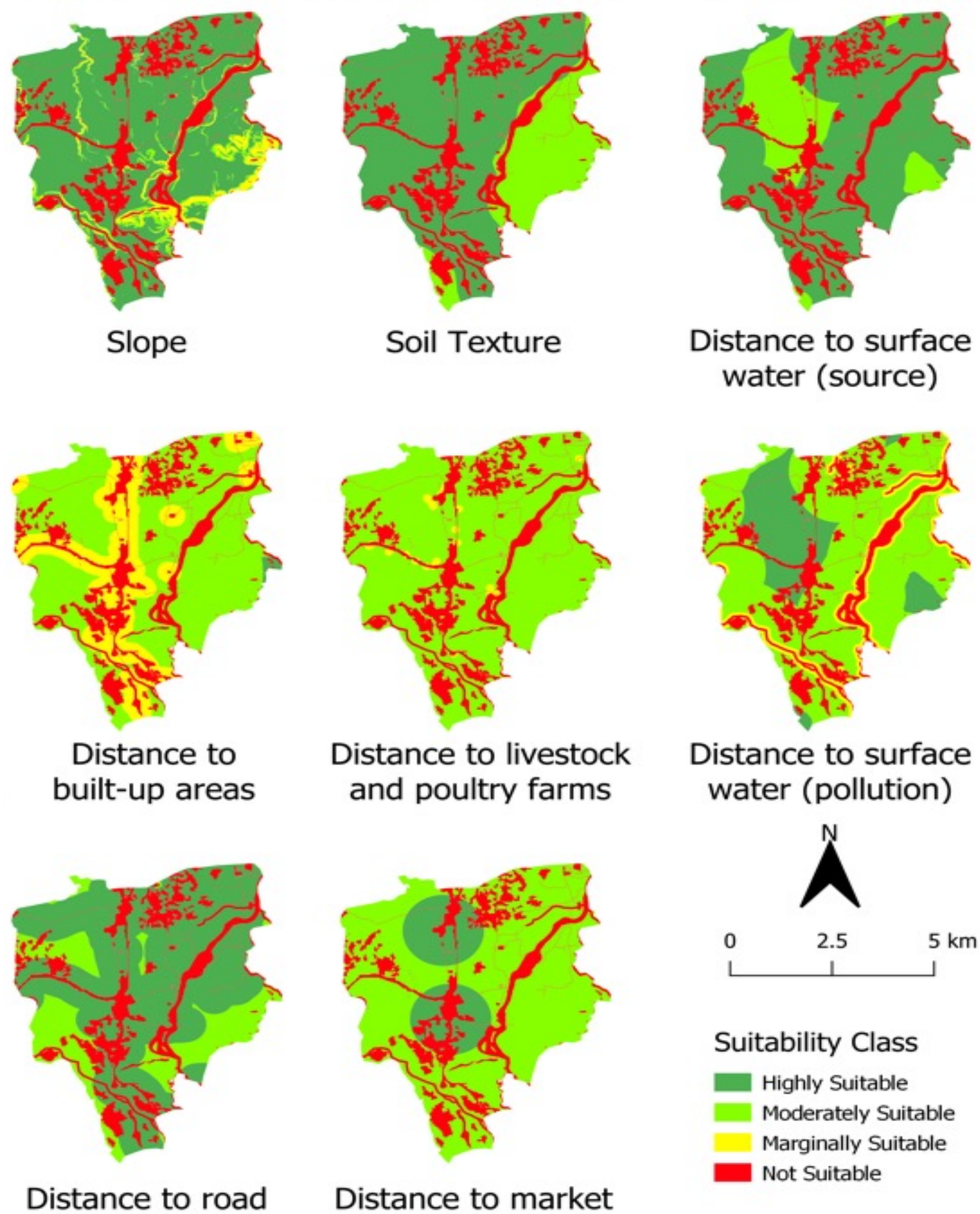

Figure 5. Factor suitability maps for dairy buffalo production in Magdalena, Laguna, Philippines.

Estimation of Weights for Overlay Analysis

The weights needed in overlaying the maps were determined by consolidating the scores estimated by the experts during the pairwise analyses comparison (**Table 5**). Five experts were consulted for this process. An expert from the Philippine Carabao Center - University of the Philippines Los Baños (PCC-UPLB), Municipal Agricultural Officer of Magdalena, Laguna a farmer-scientist who has significantly contributed to improving the productivity of the dairy buffalo farming community in Magdalena, Laguna, through his expertise and innovation, an animal science professor of UP Los Baños, and a Researcher from School of Environmental Science and Management, also from UP Los Baños.

It was observed that the economic factor has the highest weight (47.91%), followed by the agrometeorological factor (22.12%), the health and environmental factor (22.10%) and the physical factor (7.87%). The consensus of the group inscoring this set of factors was high (81%). All of them gave the highest weight to the economic factor except for the third expert, who considered health and environmental factors to be the most important. This is because the goal of agricultural development, such as dairy buffalo enterprises in rural areas, is not only to encourage diversification among marginalized farmers but also to improve the local economy (*Boori et al. 2015*).

For the physical factor, the consolidated weights were 54.37% for slope and 45.63% for soil texture. The

Table 5. Weights of factors provided by the experts and their consensus.

Factors	Weight (%)						Consensus	
	1	2	3	4	5	Consolidated	%	Interpretation
Physical	4.0	11.3	4.7	15.1	5.9	7.87	81.0	High (strong agreement)
Agrometeorological	9.9	21.1	29.8	15.1	30.9	22.12		
Health and Environmental	23.8	6.2	39.8	18.3	30.9	22.10		
Economic	62.3	61.3	25.7	51.6	32.4	47.91		
Consistency Ratio (%)	10.0	5.0	9.0	3.0	0.0	1.20		
Slope	80.0	75.0	16.7	50.0	50.0	54.37	66.3	Moderate (reasonable agreement)
Soil Texture	20.0	25.0	83.3	50.0	50.0	45.63		
Precipitation	13.9	13.2	19.5	20.0	22.9	17.77	95.8	Very High (near-complete agreement)
Temperature-humidity index	8.8	17.4	8.8	20.0	7.5	11.71		
Surface water (source)	77.3	69.4	71.7	60.0	69.6	70.52		
Consistency Ratio (%)	6.0	8.0	10.0	0.0	8.0	5.00		
Distance to built-up areas	8.1	41.3	41.3	14.3	45.5	28.54	70.4	High (strong agreement)
Distance to livestock and poultry farms	18.8	26.0	26.0	42.9	45.5	34.99		
Surface water (pollution)	73.1	32.7	32.7	42.9	9.1	36.47		
Consistency Ratio (%)	7.0	6.0	6.0	0.0	0.0	0.20		
Distance to road	16.7	50.0	87.5	50.0	50.0	51.68	65.7	Moderate (reasonable agreement)
Distance to market	83.3	50.0	12.5	50.0	50.0	48.32		

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consensus for these two factors was moderate or around 66.3%. Two experts considered the two factors to be equally important; two experts believed that slope is more important than soil texture, while the other expert considered soil texture is more important than slope. Higher weight to be given to slope because of its effect on landslide susceptibility (*Sangchini et al. 2016*), which influences the forage production or the grazing capacity (*Holechek 1988*). Nevertheless, soil texture is also an important factor and sometimes assigned a higher weight than slope (*Basnet et al. 2001*) since the characteristic of the soil significantly affects the yield of the forage being produced (*Charman and Murphy 2007*).

Meanwhile, the consensus of the rating provided by the experts for the agrometeorological factors (17.77% for rainfall; 11.71% for THI; and 70.52% for distance to surface water as a source) was very high at about 95.8%. All of them gave the highest weight to the distance to surface water as a source, which is similar to the study of *Sarl and Ceylan* (*2017*). Surface water is a valuable resource as it can provide not only the water requirements of forage but also of the livestock (*Terfa and Suryabhagavan 2015*).

The AHP consensus indicator value of the consolidated weights for environmental factors was high at 70.4%. The distances to built-up areas, livestock and poultry farms, and surface water, as possible pollution zones, have weights of 28.54%, 34.99%, and 36.47%, respectively. A study on livestock site suitability analysis by *Peng et al.* (*2014*) showed that farm proximity to surface water in relation to pollution also received the highest weight compared to the other two factors.

For the economic factors, the consolidated weights were 51.68% for distance to road and 48.32% for distance to market. The AHP consensus was moderate with a value of 65.7%. Three of the experts gave 50% to both factors, while the other two assigned slightly varied proportions based on their assessments. Overall, the consensus of the experts ranged from moderate to very high, which justified the acceptability of the weights used in overlaying the maps.

The weights of the sub-factors were multiplied by the corresponding major factors to calculate the final weight for each factor map (**Table 6**). The top sub-factors were attributed with weights of 0.2476 for distance to road and 0.2315 for distance to market. This was followed by distance to surface water as source (0.1560), distance to surface water as pollution (0.0806), and distance to livestock and poultry farms (0.0773). Three of the lowest factors are rainfall (0.0393), soil texture (0.0359) and THI (0.0259). The results were similar to that of *Peng et al.* (*2014*), wherein economic and agrometeorological factors, such as distance to road and distance to surface water as a source had the highest weights, while physical factors, such as slope and soil characteristics, had lower weights.

Overall Suitability Map and Validation

The overall suitability map (**Figure 6e**), was generated by combining the physical, agrometeorological, health and environmental, and economic factor maps using the

Table 6. Hierarchy of site suitability evaluation for smallholder dairy farms in Magdalena, Laguna, Philippines and the weights of the evaluation factors.

Factor Weights		Sub-Factor Weights		Final Weights
Physical	0.0787	Slope	0.5437	0.0428
		Soil Texture	0.4563	0.0359
		Precipitation	0.1777	0.0393
Agrometeorological	0.2212	THI	0.1171	0.0259
		Distance to SW (source)	0.7052	0.1560
Health and Environmental	0.2210	Distance to BUA	0.2854	0.0631
		Distance to LPF	0.3499	0.0773
		Distance to SW (pollution)	0.3647	0.0806
Economic	0.4791	Distance to road	0.5168	0.2476
		Distance to market	0.4832	0.2315

weighted sum analysis in GIS. The weights of the respective factors were 0.0787, 0.2212, 0.2210, and 0.4791. Eighty-six percent or 2,326.3 ha of the potential area of 2,701.3 ha area in Magdalena was highly suitable for dairy buffalo production (**Figure 6a**). About 264.9 ha (9.81%) was moderately suitable, and 110.1 ha (4.08%) was marginally suitable. It was observed that this percentage distribution of suitability class had the same pattern as that of the slope suitability map (**Table 7** and **Figure 5**). However, the percentage of moderately suitable areas found in the physical suitability map was higher, while the percentage of marginally suitable areas was lower. The slope was weighted higher (0.5437) than the soil texture factor (0.4563) which in effect, influenced the shift of some marginally suitable areas to moderately suitable areas.

Seventy-eight percent (2.121.2 ha) of the potential area in Magdalena was highly suitable for dairy buffalo production while the remaining 21.47% (580.1 ha) was moderately suitable (**Figure 6b**). This is mainly influenced by the distance to surface water as the source suitability map, which had the highest weight (0.7052) among the agrometeorological factors.

Two percent (73.3 ha) of the potential area was marginally suitable for dairy buffalo production, while 97.29% (2,628.0 ha) was moderately suitable (**Figure 6c**). There were no highly suitable areas in terms of health and environmental factors. About 2,257.3 ha (83.57%) of the unrestricted area were moderately suitable and 443.9 ha (16.43%) were highly suitable for dairy buffalo production (**Figure 6d**). The economic factor map is a combination of the distance to road and market suitability map, with assigned weight equal to 0.5168 and 0.4832, respectively. It was observed from the overall suitability map that about 2,700.7 ha (99.98%) of the unrestricted area were highly suitable and 0.6 ha (0.02%) located in the barangays of Halayhayin

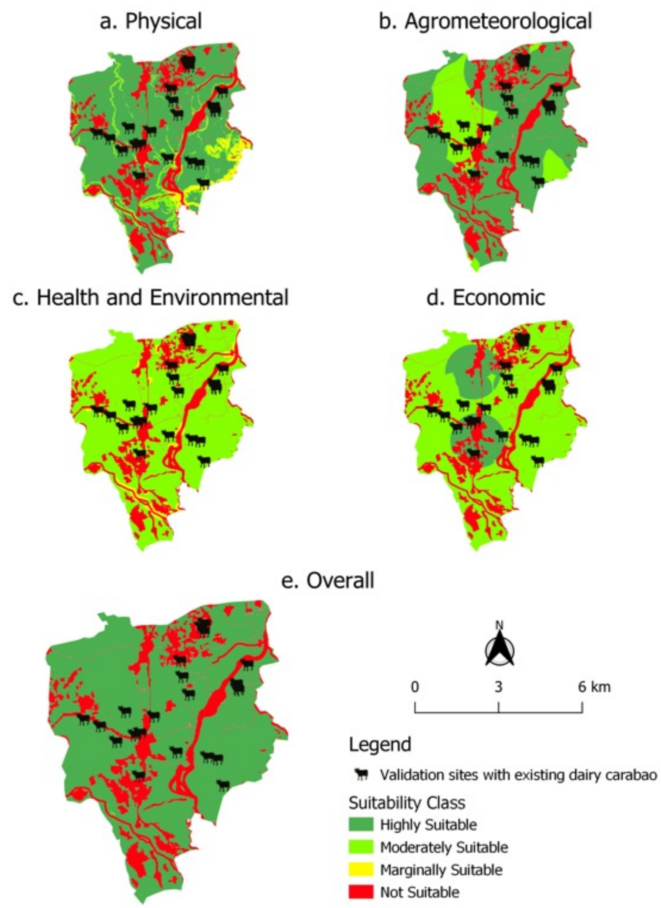

Figure 6. Overall suitability map of Magdalena, Laguna, Philippines with existing dairy carabao farms overlaid in 2019.

and Bungkol (**Table 8**) were moderately suitable for dairy buffalo production. Generally, the overall suitability map is highly influenced by the economic factors particularly the distances to road and market because these factors were given the highest weights by the experts (**Table 7**).

The barangay with the largest suitable area was Alipit with 192.7 ha of highly suitable areas (**Table 8**). In contrast, Brgy. Poblacion had the smallest total area classified as highly suitable for dairy buffalo production. However, despite its limited size, approximately 14.0 ha within this barangay were identified as highly suitable, which decision-makers may still consider for development due to their favorable conditions for raising dairy buffalo.

With a total suitable area of 2,701.3 ha and a stocking density of four buffaloes per hectare, the number of buffalo that can be raised in Magdalena was estimated to be 10,805 heads. It is important to note, however, that the appropriate stocking density varies depending on the management system. While four buffaloes per hectare may apply under a grazing system without paddocks, a confined management system could accommodate 15-20 heads of buffaloes with a dedicated one hectare of forage area. This could serve as the baseline for planning the actual carrying capacity of the area for dairy buffalo production,

Table 7. Suitable areas for dairy buffalo production in Magdalena, Laguna, Philippines grouped by factors.

Factor	Marginally Suitable		Moderately Suitable		Highly Suitable	
	ha	%	ha	%	ha	%
Slope	177.7	6.58	196.7	7.28	2,326.8	86.14
Soil Texture	0.0	0.00	688.7	25.50	2,012.6	74.50
Precipitation	0.0	0.00	0.0	0.00	2,701.3	100.00
THI	0.0	0.00	2,701.3	100.00	0.0	0.00
Distance to SW (source)	0.0	0.00	578.4	21.41	2,122.9	78.59
Distance to BUA	704.8	26.09	1,979.9	73.30	16.5	0.61
Distance to LPF	45.9	1.70	2,655.4	98.30	0.0	0.00
Distance to SW (pollution)	266.2	9.85	1,856.7	68.73	578.4	21.41
Distance to road	0.0	0.00	671.2	24.85	2,030.1	75.15
Distance to market	0.0	0.00	2,225.9	82.40	475.4	17.60
Physical	110.1	4.08	264.9	9.81	2,326.3	86.12
Agrometeorological	0.0	0.00	580.1	21.47	2,121.2	78.53
Health and Environmental	73.3	2.71	2,628.0	97.29	0.0	0.00
Economic	0.0	0.00	2,257.3	83.57	443.9	16.43
Overall Suitability	0.0	0.00	0.6	0.02	2,700.7	99.98

Table 8. Suitable areas for dairy buffalo production at different barangays in Magdalena, Laguna, Philippines.

Barangay	Moderately Suitable Area (ha)	Highly Suitable Area (ha)	Total Area (ha)
Alipit		192.7	192.7
Salasad		189.3	189.3
Ilayang Atingay		180.5	180.5
Sabang		178.1	178.1
Buenavista		168.6	168.6
Tanawan		166.4	166.4
Malinao		160.8	160.8
Balanac		159.7	159.7
Halayhayin	0.5	133.6	134.1
Burlungan		126.8	126.8
Ibabang Butnong		116.3	116.3
Baanan		106.6	106.6
Maravilla		101.1	101.1
Buo		98.2	98.2
Malaking Ambling		95.9	95.9
Bucal		90.0	90.0
Cigaras		88.2	88.2
Ibabang Atingay		78.1	78.1
Bungkol	0.1	69.8	69.9
Munting Ambling		68.7	68.7
Tipunan		47.5	47.5
Ilog		43.9	43.9
Ilayang Butnong		25.8	25.8
Poblacion		14.0	14.0
Total Area (ha)	0.6	2,700.7	2,701.3

considering other land use conflicts, forage availability, and other factors not accounted for the computation.

To validate the AHP model, the location of the existing dairy farms was overlaid on the suitability maps (**Figure 6**). As recommended by *Layomi Jayasinghe et al.* (*2019*), model validation was performed by calculating the percentage of existing dairy buffalo farms intersecting with each of the modelled suitability classes. In terms of overall suitability, all the 25 surveyed dairy buffalo farms were in highly suitable areas (**Figure 6e**). However, in terms of economic suitability, only 20 dairy buffalo farms (80%) were within highly suitable areas, and the remaining five dairy farms (20%) were moderately suitable areas. Only one farm (4%) was in moderately suitable areas, while the remaining farms were in highly suitable areas. Moreover, 19 farms (76%) were in the highly suitable areas and six farms were in the moderately suitable areas, when overlaid with the agrometeorological suitability map (**Figure 6b**). Furthermore, all the surveyed farms were located in moderately suitable areas, as validated by the health and environmental suitability map.

CONCLUSIONS AND RECOMMENDATIONS

Site suitability analysis for dairy buffalo production is important for the development and future planning of the dairy buffalo sector in Magdalena, Laguna. This study utilized GIS processing and analysis in conjunction with the AHP technique to assess potential areas for dairy buffalo production. The selected evaluation criteria for site suitability assessment were based on physical, agrometeorological, health and environmental, and economic factors. As per the land characteristics and other requirements, the potential areas for raising dairy buffalo were classified as highly suitable (79.49%) and moderately suitable (0.02%) while the not suitable areas (696.2 ha) were 20.49% of the total area of the municipality. The findings emphasized the significant influence of economic factors, particularly access to roads and markets, on the spatial suitability of dairy buffalo farms. This highlights thec necessity of integrating infrastructure planning into agricultural development programs to support the growth of the dairy sector.

The model validation results showed that all the surveyed 25 smallholder dairy buffalo farms were in highly suitable areas. These dairy buffalo farms were found to be producing sufficient milk and earning profit from such production, hence, suggesting overall robustness of this model and the weights applied. The results of the study suggest that GIS and AHP model provided a useful decision-making approach to help dairy buffalo farmers and decision makers to carry out site suitability assessment.

Nevertheless, it is important to note certain limitations of the study. The suitability assessment was based on a set of ten criteria, yet other relevant factors such as land tenure status, forage productivity, climate variability beyond temperature, humidity, and precipitation, and socio-economic conditions of farmers were not integrated. Additionally, the validation process, while effective, relied solely on spatial overlap and did not assess the long-term performance or sustainability of existing farms. Future studies may consider collecting detailed production and socioeconomic data from surveyed farms, including average farm size, years in operation, milk production levels, and income. These indicators can offer deeper insights into the relationship between suitability levels and actual farm performance, thereby strengthening model validation. Incorporating time-series data to evaluate seasonal variability and using remote sensing for real-time monitoring of forage resources may also be considered. Integration of participatory GIS approaches can also enhance the model's applicability and accuracy at the community level.

Applying the GIS-AHP technique in the regional or national scale of site suitability assessment of dairy buffalo farms could be proposed in the future to mainstream this methodology in identifying suitable sites for dairy buffalo production and to calibrate and recommend the use of this tool in future projects of Philippine Carabao Center.

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