Assessment of Agroecological Zone-Based Management Strategies for Sustainable Development in Sri Lanka

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Abstract: Agroecological Zoning (AEZ) serves as a crucial framework for sustainable agricultural planning and resource management, integrating biophysical attributes and socio-economic factors. This paper explores the historical evolution and current state of AEZ in Sri Lanka, focusing on its application in addressing modern challenges such as climate change, crop suitability, and disaster management. The study evaluates the limitations of the existing zoning framework, emphasizing the need to incorporate advanced geospatial technologies, dynamic climatic data, and comprehensive water balance metrics. Recommendations include enhancing zoning criteria with projected climate scenarios and integrating traditional irrigation systems for resilience. By aligning Sri Lanka's AEZ practices with global standards, this study aims to ensure adaptive and sustainable agricultural systems that support food security and ecological preservation.

Keywords*: Agroecological Zoning, Climate Adaptation, Natural Resource Management.*

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I. INTRODUCTION

Agroecological zoning (AEZ) is a method that clusters land-use types into homogeneous areas based on biophysical attributes, facilitating sustainable resource planning (Quiroz et al., 2001). Agroecological Zoning (AEZ) provides a scientific foundation for resource management, agricultural production, and land-use planning, making it an essential tool for sustainable development (Sivakumar & Valentin, 1997). AEZ maximizes the use of natural resources while reducing environmental degradation by dividing land into homogeneous zones based on socioeconomic factors and biophysical qualities like soil properties, climate, and topography (FAO, 1996). Landscape and farm diversity, intercropping, crop and pasture rotation, the use of organic amendments, cover crops, and the reduction or avoidance of synthetic inputs are all examples of agroecological techniques. Agroecology has significant social components in addition to its technical components, including addressing social injustices, nonwage labor relations, participatory processes, community property and resource management, and co-creation of knowledge with farmers (Kerr et al., 2023). This approach matches the physical characteristics of land and its best uses by combining crop needs with climate and soil data. AEZ is essential for determining the potential for crop production, creating effective agricultural systems, and tackling the problems brought on by expanding population demands (Quiroz et al., 2001; Sivakumar & Valentin, 1997).

The field of agroecology has an extensive and distinguished history. The farming communities that have mastered the art of using their environment's resources to live, develop, and advance their civilizations have been and continue to be the most successful agro-ecologists (Panabokke, 1996). As a result, it demonstrates that this idea is not just a hypothesis but rather emerged from farmers' farming methods and was further developed to increase the sustainability and production of agricultural products (Kerr et al., 2023). Since the establishment of the agroecology concept in the early 1970s, different nations have developed their own national systems for identifying and designating their agroecological zones (Panabokke, 1996). The FAO Agroecological Zones Project 1978, which employed 12 primary climatic divisions for the tropics and subtropics and

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the length of growing periods to determine class boundaries at two levels of generalization, was more beneficial for international collaboration in agro-climatology (Panabokke, 1996).

This paper aims to review the evolution of the agroecological zoning concept in Sri Lanka, analyzing its historical development and the criteria that have shaped its application over time. The objectives include assessing the suitability of the current zoning system in addressing modern challenges, evaluating its compatibility with other international zoning systems, and providing recommendations for potential updates. By comparing Sri Lanka's AEZ framework with global practices, this study seeks to identify gaps and propose enhancements that ensure the zoning system remains effective and adaptable to changing socio-economic and environmental conditions.

The importance of AEZ has increased in Sri Lanka, a nation with a wide range of agroclimatic conditions and a heavy reliance on agriculture (World Bank; CIAT, 2015). It forms the basis of national policies and procedures that balance ecological preservation and development. (Panabokke, 1996). Considering its significance, Sri Lanka's present AEZ framework has several challenges when handling the complexities of modern natural resource management and sustainable development (Muthuwaththa & Liyanage, 2013). The need for improvement is highlighted by gaps in integrating developing technologies, limitations in data accuracy, and a lack of reactivity to dynamic elements like climate change (Dayawansa & De Silva, 2020)This study offers a thorough assessment of Sri Lanka's AEZ framework by reviewing the current standards and suggesting creative additions. It emphasizes the framework's applications in several industries and its vital role in enhancing livelihoods and fostering resilience in the face of global challenges.

II. HISTORICAL DEVELOPMENT OF AGROECOLOGICAL ZONING IN SRI LANKA

Since ancient times, Sri Lanka has been recognized as an agricultural nation (FAO, 1999). As a result, the economy and way of life of the Sri Lankan people are closely linked to this agroecological zoning concept (World Bank; CIAT, 2015). Agroecological zoning (AEZ) in Sri Lanka has undergone significant changes over the last few decades (Fig 1), to adapt to new agricultural practices, climate, and technological innovations improves. In its very inception, AEZ was broad-based on climatic regions, mainly wet and dry zones demarcated based on rainfall patterns (FAO, 1996).

Sri Lanka is a tropical country influenced by a monsoonal seasonal climate (Shiromani Priyanthika Jayawardena et al., 2022). It is divided into three major climate zones, the Wet Zone, the Dry Zone, and the Intermediate Zone. Before implementing a comprehensive agroecological zoning system, Sri Lanka historically relied on simple classifications known as agro-climatic zones like many other countries. The country's climate was split into two zones up to 1956 based only on yearly rainfall (Panabokke, 1996). The wet Zone receives more than 75 inches of rainfall annually, and the Dry Zone receives less than 75 inches. Although this classification provided a fundamental comprehension of climatic diversity, it was not sufficiently detailed to address the complex structures of ecosystems and agriculture (Punyawardena B.V.R., 2010).

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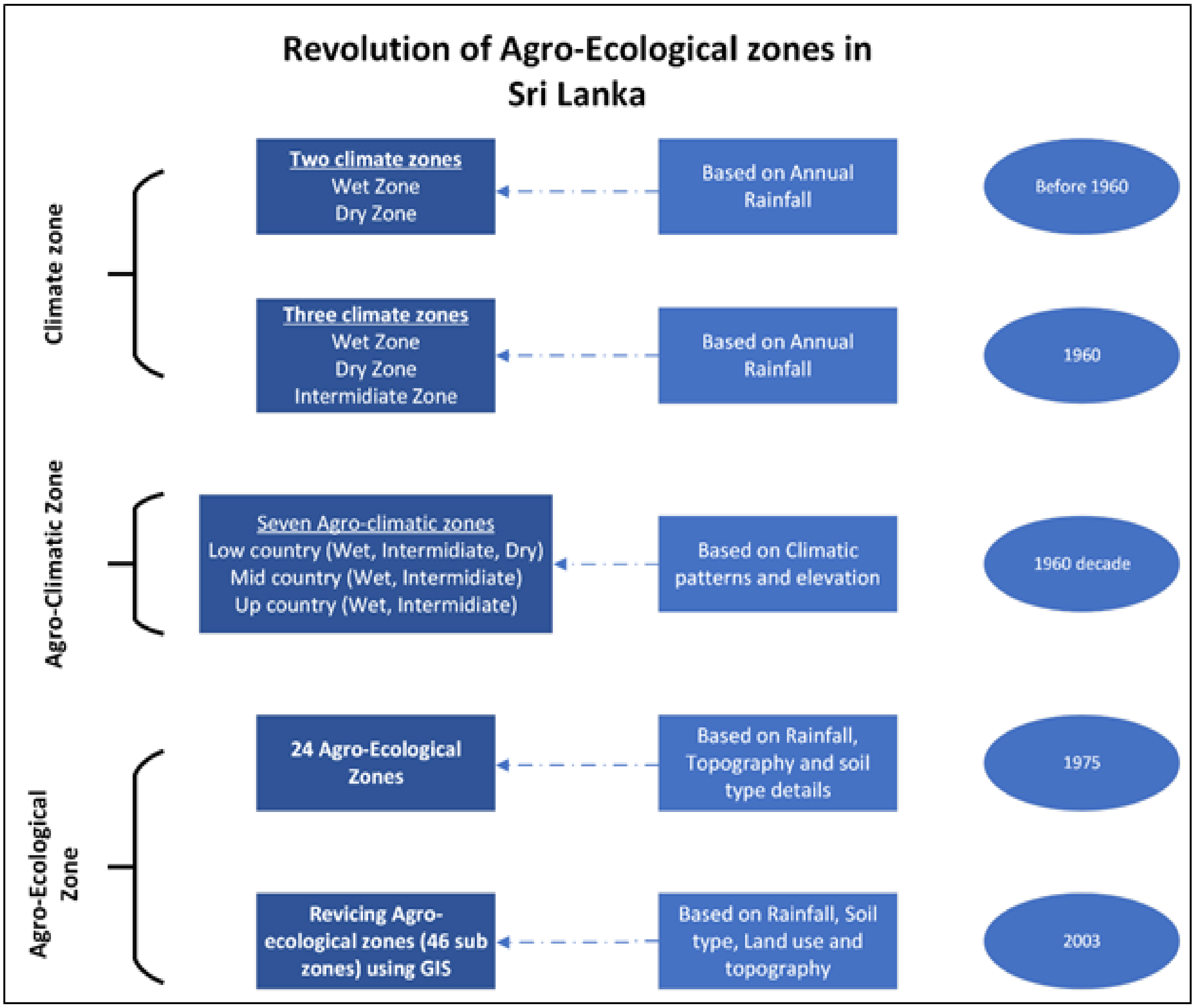

Fig 1-Revolution of Agroecological Zones in Sri Lanka

In 1956-1961, a transitional intermediate zone was identified in land use, forestry, hydrometeorology, and soil assessments carried out by the Canada-Ceylon Colombo Plan Project. Following a rigorous evaluation of agricultural land use, forest species distribution, rainfall statistics, terrain, and soils, the borders of these three zones, wet, intermediate, and dry zones were established (Panabokke, 1996). Although the climate of Sri Lanka was better understood due to this updated classification, its agriculture requirements were still not considered properly. As a result, agro-climatic zones were developed, emphasizing important climate factors that directly impact crop growth, like rainfall and ambient temperature. Since the atmospheric temperature in Sri Lanka is directly proportional to the elevation of the country (Panabokke, 1996), this classification further divided the country into three elevation-based zones. They are Low Country (elevation less than 300 meters), Mid Country (elevation between 300 and 900 meters), and Up Country (elevation above 900 meters). Combining these elevation zones with climate data, seven different agro-climatic zones are found. These include the Low Country Wet Zone, Mid Country Wet Zone, Up Country Wet Zone, Low Country Intermediate Zone, Mid Country Intermediate Zone, Up Country Intermediate Zone, and Low Country Dry Zone (Panabokke, 1996).

Although offering additional insights, the agro-climatic categorization was unable to assess Sri Lanka's agricultural potential adequately. This restriction prompted the creation of a more sophisticated agroecological zoning system in the 1970s, which was specific to regional conditions and inspired by an FAO methodology. Panabokke and Kannangara (1975) contributed to this development, by producing the first agroecological region map separating Sri Lanka into 24 agroecological zones. This classification was based on the 75% probability of monthly rainfall over 30 years, soil type, terrain, and land use. This classification paved the path for the current agroecological zoning system of Sri Lanka. The agro-ecological zones provided a strong framework for agricultural planning, resource management, and understanding the

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impacts of climate variability on Sri Lanka's agriculture (Panabokke, 1996).

III. CURRENT AGROECOLOGICAL ZONING CRITERIA IN SRI LANKA

The advancement of computer science and the introduction of Geographic Information Systems (GIS) provided the foundation for revising the agroecological region map in 2003 (World Bank; CIAT, 2015). In this new demarcation, the major zones demarcated in 1975 were considered and divided into different sub-zones, considering the area's wetness. The current agroecological zoning was created by the Natural Resource Management Center of Sri Lanka in Peradeniya, guided by Dr. Punyawardhana. The current agroecological zoning map consists of 46 zones, as shown in (Fig 2).

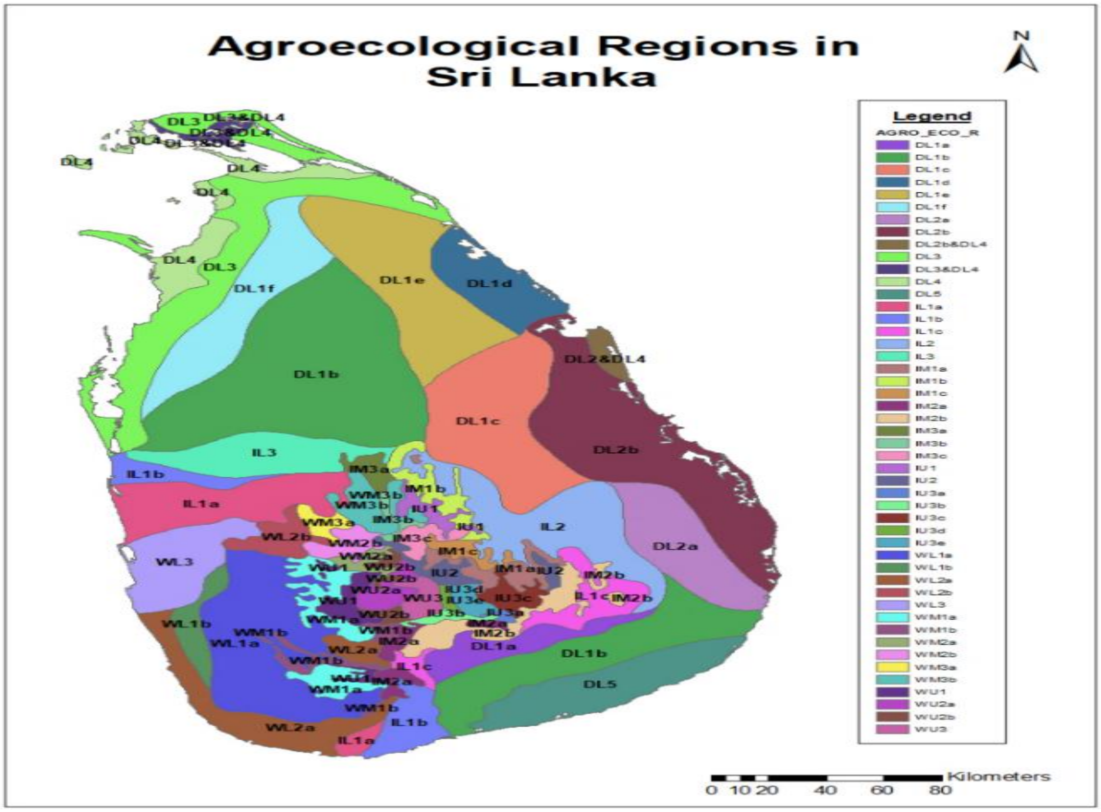

Fig 2- Current Agroecological Zones in Sri Lanka

The zoning criteria are mainly based on 4 parameters, annual rainfall, elevation, soil properties, and climate zone variation of Sri Lanka. The names of the zones reflect all these parameters in their name as mentioned in (Table 1). The climate zones were determined based on the monthly rainfall expectancy at the 75% probability level, calculated using data from 381 rain gauging stations distributed across the island (Panabokke, 1996).

Table 1-Current agroecological zoning criteria in Sri Lanka

Major Factor	Description	Symbol	Criteria
Climate Zone	Wet Zone	W	> 2500mm
	Intermediate Zone	I	1750mm – 2500mm
	Dry Zone	D	<1750mm
Elevation (Temperature)	Low Country	L	<300m
	Mid Country	M	300m – 600m
	Up Country	U	> 600m
Degree of wetness (Soil Category)		1 - 5	'1' represents the most favorable
Rainfall (Extreme) and other physical environmental factors		a - f	The degree of wetness decreases from 'a' – 'f'

(Source: Natural Resources Management Center, Sri Lanka)

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IV. APPLICATIONS OF AGROECOLOGICAL ZONING

Agroecological zones in Sri Lanka play a crucial role in various applications, including vegetation recovery assessment, food security analysis, and landslide susceptibility mapping. They are developed for decision-making purposes in different fields, especially agriculture. With the help of these agroecological zones, the Natural Resources Management Center of Sri Lanka has published a report on crop suitability recommendations for each GN division in Sri Lanka, considering the regional characteristics of each particular area (Natural Resources Management Center, 2015). The recommendations guide crop selection for each Grama Niladhari Division, focusing on economic viability, environmental sustainability, accessibility, and terrain adaptability, with considerations for commercialization and special regional niches.

These agroecological zones are useful for identifying high-risk areas of invasive species, as well as for identifying crop suitability areas. The invasive plants in Sri Lanka significantly affected in agriculture and food security of the country. The study Kariyawasam et al., (2017) used the Maxent model to identify suitable climate areas for these species under current climate scenarios, providing crucial data for land managers to implement timely control and management measures. In this study, having an agroecological zone system was very crucial to identify similar areas that have similar environmental characteristics to spread these invasive species (Kariyawasam et al., 2017).

Disaster management is another important field of study that uses agroecological zoning systems in Sri Lanka (Chithranayana & Punyawardena, 2008). According to past studies, different agroecological zones have different patterns of catastrophe risk and recovery. For example, these places differ in terms of vegetation regeneration and landslide susceptibility, with recovery times often lasting three to five years (Premawansha et al., 2024). Similarly, drought vulnerability differs significantly between agroecological zones. For example, the Yala season makes the Dry Zone especially vulnerable to droughts, whereas the Wet Zone has comparatively less drought occurrences (Chithranayana & Punyawardena, 2008). These findings highlight how important agroecological zones are for determining hazards specific to a given area and creating efficient, locally specific disaster management plans.

V. RECOMMENDATIONS FOR ENHANCING AGROECOLOGICAL ZONING CRITERIA

It is anticipated that future agricultural production risks will rise as a result of global climate change (Ratnayake et al., 2023). Recent advances in climate modeling have made possible the development of advanced models that incorporate satellite data and other environmental parameters to analyze past, present, and future climate activities, such as rainfall, maximum and minimum temperatures, evaporation, and evapotranspiration (Kattsov et al., 2013). These models provide important information on the long-term patterns and dynamic nature of climate systems. The agroecological zoning system in Sri Lanka is mostly based on historical climate data gathered from a few chosen stations that reflect various climatic conditions throughout the country (Muthuwaththa & Liyanage, 2013; Panabokke, 1996)This approach, however, is limited by its reliance on past data and does not fully account for the rapid and ongoing changes in the country's climate. Due to the acceleration of climate change, future conditions are anticipated to deviate greatly from past patterns. Hence, it is important to include projected climate scenarios in the delineation of agroecological zones.

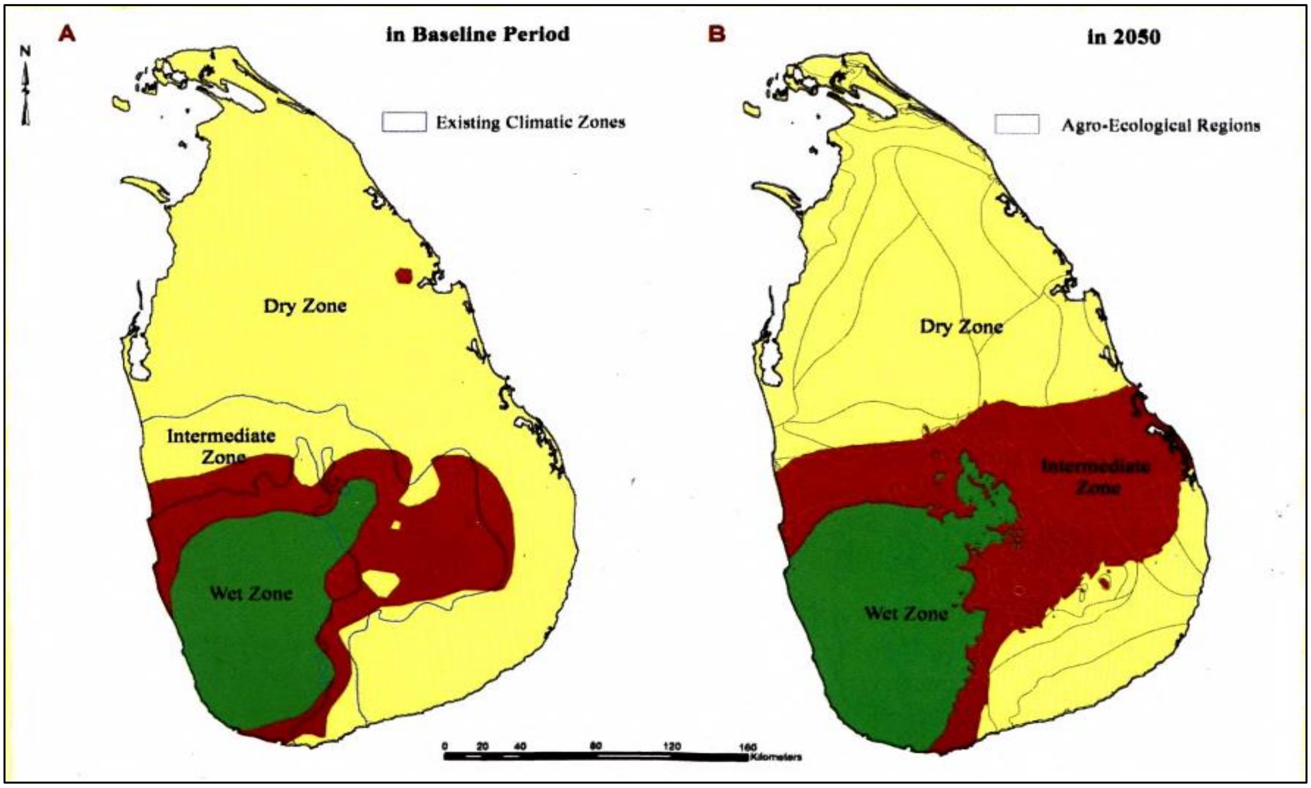

Fig 3- Changes in Climate Zone Boundaries by 2050
Source: (Muthuwaththa & Liyanage, 2013)

Using projected climatic data would improve the accuracy and durability of these zones and enable them to represent future circumstances more accurately. For example, the study by Muthuwaththa & Liyanage, (2013) compared the current agroecological zoning system, which uses 30 years of historical data to base it on a baseline period of 1970–2000, with climate model estimates for temperature and rainfall in 2050. This study emphasizes the differences between zoning based on historical data and future estimates, highlighting the necessity of thoroughly revising agroecological zones (Fig 3). Adopting a technique that considers climate model projections and offers a precise, modern description of these zones is crucial to overcoming these obstacles. A strong and forward-looking strategy is essential to guaranteeing the applicability and usefulness of agroecological zones in agricultural planning, resource management, and climate adaptation given the notable geographical and temporal variability in Sri Lanka's climate.

The water balance equation, a basic idea in hydrology that encapsulates the interdependent elements of the water cycle, is a crucial instrument for assessing agricultural water supplies and requirements (Bhagat, 2014). This equation encompasses precipitation (P), potential evapotranspiration (PE), changes in storage (ΔS), and runoff (R), represented as:

$$P = PE + \Delta S + R$$

where ΔS accounts for variations in soil moisture, groundwater, and reservoir storage (Soczyńska et al., 2003).

The current methodology primarily takes precipitation and, to a lesser extent, soil moisture (wetness) into account when sub-zoning in the framework of Sri Lanka's agroecological zoning (Table 1). Rainfall is useful for agriculture, but its effectiveness is dependent on how it interacts with every element of the water balance equation, not just precipitation. For example, agricultural water availability is directly impacted by the ratio of soil moisture retention to evapotranspiration, whereas irrigation and water security are influenced by runoff and water storage capacity (Ingrao et al., 2023). Therefore, to guarantee sustainable agricultural operations, a thorough agroecological zoning method needs to consider all these elements.

Irrigation has always been essential to Sri Lankan agriculture, especially in paddy farming (Panabokke & Jyothi, 2010). A key component of agricultural sustainability has been the implementation of small-scale runoff water harvesting systems in micro-watersheds, like those in Asian and Mediterranean nations (Ratnayake et al., 2021). The tank-based irrigation system used in Sri Lanka, mostly in the Dry Zone, is one of the world's oldest and most advanced agricultural systems (Abeywardana et al., 2019). This system, which dates back to the time of ancient kingdoms, is made up

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of more than 10,000 man-made tanks that were cleverly built in shallow valleys to store and control water for paddy farming (Abeywardana et al., 2019). These tanks not only mitigate seasonal flooding and droughts but also ensure year-round water availability for domestic use, livestock, and agriculture (Geekiyanage & Pushpakumara, 2013). The innovative water resource management techniques of the past are reflected in this time-tested Tank Cascade System (TCS), which allows for continuous paddy farming during the wet and dry seasons (Geekiyanage & Pushpakumara, 2013).

Achieving the Sustainable Development Goals (SDGs), especially SDG-2 (Zero Hunger) and SDG-6 (Clean Water and Sanitation), requires the restoration and integration of historic irrigation systems into contemporary farming methods (Ratnayake et al., 2021). Enhancing surface and groundwater management requires community involvement, particularly in developing nations where resource shortages frequently threaten agricultural sustainability (Ratnayake et al., 2021). Therefore, a more comprehensive framework would be produced by integrating these conventional irrigation techniques and the ideas of water balance into agroecological zoning requirements. This strategy would provide food and water security in the face of climatic variability by strengthening agricultural resilience and optimizing water resources.

Two important factors in the water balance equation, runoff and evapotranspiration, are not adequately taken into consideration by Sri Lanka's present agroecological zoning regulations (Panabokke, 1996). These elements should be incorporated into the zoning framework for a more comprehensive approach, as they have a major impact on agricultural output and water availability. Human civilizations developed around these essential water sources, and Sri Lanka's vast network of river basins has been essential to the survival of its people from ancient times (Katupotha & Gamage, 2020). There are 103 river basins in the country, of which 29 (15 perennial and 14 seasonal) run straight to the sea. The remaining basins drain into lagoons. These river basins' yearly runoff varies greatly, from 100 to 6,000 acre-feet (yearly Total Runoff in 1,000 Ac. ft.), highlighting the regional variety in the water supply (Katupotha & Gamage, 2020). The potential for agriculture and water management techniques in various areas is directly impacted by this unpredictability. To better represent the hydrological features of each area, runoff should be included in agroecological zoning (FAO, 1996).

Evapotranspiration, another crucial component, is influenced by a region's topography, climatic conditions, and crop types (Tabari & Hosseinzadeh Talaee, 2014). It greatly influences the amount of water needed for agriculture by determining how much water is lost to the atmosphere through evaporation and plant transpiration. The precise computation of evapotranspiration for regions is made possible by recent developments in satellite remote sensing, which yield accurate and spatially resolved data (Xiao et al., 2024). A better understanding of local water demands and more effective agricultural planning would be made possible by including evapotranspiration in agroecological zoning (FAO, 1996).

Incorporating land use and land cover (LULC) data into the agroecological zoning criteria is essential for more accurate and efficient planning (FAO, 1996). About 40% of Sri Lanka's land area is used for agriculture, with the remaining 30% being made up of forests and wildlife reserves (Mapa et al., 2002). The remaining land comprises private lands, water bodies, and built-up areas (Mapa et al., 2002). Since the main objective of agroecological zoning is to enable effective agricultural planning, it is crucial to recognize and eliminate areas that are inappropriate for farming, such as built-up areas, forests, and wildlife reserves.

Ecosystem balance, carbon sequestration, and biodiversity protection all depend on forests and wildlife reserves (Buotte et al., 2020), yet built-up regions are incompatible with agriculture since they are used for urban and industrial reasons (Chen & Dong, 2024). By accurately mapping these non-agricultural zones, agroecological zoning can focus solely on the regions with agricultural potential. These zones can be successfully delineated using the precise and current LULC data provided by contemporary geospatial technology, such as remote sensing and GIS (World Bank; CIAT, 2015).

The Agroecological Zones (AEZ) methodology, developed by IIASA and FAO over 30 years, assesses agricultural resources and potential using increasingly detailed global databases (Fischer et al., 2012). The latest version, GAEZ v3.0, integrates updated crop simulations for 280 crops, water management techniques, and new datasets, including climate scenarios, soil and terrain data, irrigated areas, and population density. It also features a novel methodology for spatially downscaling agricultural statistics to assess global yield and production gaps. GAEZ v3.0 includes a comprehensive data portal and documentation for researchers, institutions, and organizations addressing sustainable land use, agricultural development, and food security (Fischer et al., 2012)A similar strategy can be modified for the agroecological zone re-demarcation procedure in the Sri Lankan context. By employing the data sets from this model, we could create a more comprehensive agroecological zoning system for the country, which can also be appropriately suited to the relevant locations.

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VI. CONCLUSION

Agroecological Zoning (AEZ) has played a pivotal role in sustainable agricultural planning, resource management, and addressing the socio-economic and environmental challenges in Sri Lanka. This study highlights the evolution of the AEZ framework from simplistic rainfall-based classifications to a sophisticated zoning system incorporating climatic, soil, and topographical factors. The current framework, developed with the aid of Geographic Information Systems (GIS), has provided significant advancements in agricultural planning, disaster management, and crop suitability mapping. However, challenges remain in its ability to adapt to dynamic environmental changes, including climate variability and land-use transformations. The study underscores the importance of integrating modern climate modeling, satellite-derived evapotranspiration data, and hydrological elements such as runoff into the zoning criteria. Furthermore, incorporating traditional water management systems like the Tank Cascade System can enhance agricultural resilience and water security. Future adaptations should focus on revising AEZ boundaries using projected climate scenarios, high-resolution geospatial data, and comprehensive water balance analyses to create a robust, forward-looking framework. By aligning Sri Lanka's AEZ system with global best practices, this study advocates for a holistic approach to agroecological management that fosters sustainability, food security, and ecological balance in the face of emerging challenges.

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