Salinity-driven Model Development for Mangrove Biomass in the Indian Sundarbans

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Abstract
This study evaluates the impact of aquatic salinity on the Above Ground Biomass (AGB) of five dominant mangrove species namely *Sonneratia apetala*, *Avicennia marina*, *Avicennia alba*, *Avicennia officinalis*, and *Excoecaria agallocha*. The research was conducted across 24 stations in Indian Sundarbans with varying salinity profiles during 2024 to better understand the relationship between ambient aquatic salinity and mangrove biomass in terms of AGB values. Species-specific models were developed to analyse the response of AGB to salinity of the surrounding estuarine water, offering detailed insights into the tolerance and adaptability of each species under changing environmental conditions. The findings reveal that increased salinity adversely affects the AGB of all selected mangrove species, irrespective of their salinity tolerance. Thus, the research highlights the potential vulnerability of mangrove ecosystems to salinity changes caused by climate change, sea-level rise, and anthropogenic activities. Understanding these relationships is crucial for managing and conserving mangrove forests, which play a vital role in carbon sequestration, coastal protection, and supporting biodiversity. The study underscores the importance of strategic conservation efforts tailored to the salinity preferences of specific mangrove species to ensure their sustainability and ecological functionality.

Key words: Indian Sundarbans, Above Ground Biomass (AGB), mangrove species, aquatic salinity

Introduction

Mangrove forests, though covering just 0.1% of the Earth's surface (Hamilton and Casey, 2016), are vital ecosystems that play a significant role in mitigating and adapting to climate change. They are remarkable carbon sinks, storing up to five times more carbon per hectare than tropical rainforests (Donato et al., 2011). This exceptional ability to sequester carbon, coupled with their role in coastal protection and supporting biodiversity, underscores the importance of conserving these unique habitats. However, their position at the delicate interface between land and sea exposes mangroves to a variety of climate-induced stressors. Among these, sea-level rise and changing precipitation patterns stand out as critical challenges. These factors alter salinity levels in mangrove habitats, significantly impacting their growth and development. Elevated salinity levels can favour dwarf forms of mangroves (Feller, 1995; Ball, 2002; Lovelock et al., 2005; Mitra et al., 2010; Banerjee et al., 2010; Bhattacharjee et al., 2013; Mitra, 2013; Zaman et al., 2013; Mitra et al., 2015; Mitra and

Zaman, 2015; Banerjee et al., 2017; Mitra, 2018; Mitra and Zaman, 2020; Mitra et al., 2022; Mitra et al., 2023), disrupt essential physiological and functional processes, and, in extreme cases, lead to homeostatic collapse (Chowdhury et al., 2019).

While mangroves have evolved mechanisms to tolerate varying degrees of salinity and exhibit significant morphological plasticity (Vovides et al., 2014), the escalating rate of environmental change poses an unprecedented challenge. Projections like those of Sarker et al. (2021) predict a 50% increase in salinity levels in the Sundarbans by 2050, with potentially devastating consequences for mangrove ecosystems. Such an increase is anticipated to reduce ecosystem productivity by as much as 30%, threatening multiple ecosystem services these forests provide (Mitra, 2020). These projections highlight the urgent need for comprehensive studies to understand how salinity stress affects mangrove forests, particularly in terms of biomass accumulation and carbon storage capacity.

Tree size is a critical determinant in evaluating biomass and carbon stocks, as well as the overall response of ecosystems to environmental stressors. Large trees, often regarded as keystone species, are especially important because they contribute approximately 50% of forest biomass globally (Lutz et al., 2018). Their significant carbon sequestration potential and structural role within the ecosystem make them pivotal in maintaining ecological stability. Conversely, smaller trees, particularly in wetland forests, contribute to rapid growth and biomass accumulation, underscoring the importance of considering size-specific dynamics in ecological studies (Piponiot et al., 2022). This dichotomy between the roles of large and small trees is particularly pronounced in mangrove ecosystems, where abiotic factors such as salinity and biotic factors like species diversity and stand structure interact to shape growth dynamics.

The interplay between biotic and abiotic factors in mangrove ecosystems is complex. Species richness and structural heterogeneity have been shown to enhance ecosystem resilience and productivity. Diverse species assemblages promote complementary resource use and reduce competition, while structural heterogeneity provides stability under environmental stress (LaRue et al., 2019; Pretzsch et al., 2022). However, how these factors interact to influence mangrove productivity under salinity stress remains poorly understood. Salinity, a key player in the mangrove ecosystem, can directly affect mangrove physiology, influencing water uptake, nutrient acquisition, and photosynthesis. Meanwhile, biotic factors such as tree size distribution, stand density, and species composition play crucial roles in mediating ecosystem responses to salinity changes.

Understanding the mechanisms underlying these interactions is essential for evaluating the impact of salinity-induced stress on mangrove productivity. Current knowledge remains limited regarding the relative contributions of large, medium, and small trees to overall biomass in mangrove ecosystems. Moreover, the extent to which these contributions vary across salinity gradients is an area that demands further exploration. Addressing these knowledge gaps is vital for developing effective conservation strategies that account for the complex dynamics of mangrove ecosystems under changing environmental conditions.

To contribute to this understanding, we investigated the Above Ground Biomass (AGB) of five dominant mangrove species (*Sonneratia apetala*, *Avicennia marina*, *Avicennia alba*, *Avicennia officinalis*, and *Excoecaria agallocha*) across salinity gradients in the Indian Sundarbans. The study was conducted in 2024 across 24 stations representing high, medium, and low salinity zones. The primary objective was to assess how increasing salinity impacts the AGB of these species and to develop species-specific models to predict biomass changes under varying salinity conditions. The findings provide valuable insights into the resilience and vulnerability of mangrove species to salinity stress, contributing to broader efforts to conserve these critical ecosystems.

Our results indicate a significant shift in AGB from higher to lower values with increasing salinity, irrespective of the stations. This trend was consistent across all five species, highlighting the negative impact of salinity on mangrove productivity. The reduction in AGB with increasing salinity underscores the sensitivity of mangroves to changes in environmental conditions (Mitra, 2013). For instance, species like *Sonneratia apetala*, which typically exhibit high biomass under low salinity conditions, showed marked declines in AGB in high-salinity zones. Similarly, the AGB of *Excoecaria agallocha*, known for its wide salinity tolerance, was also negatively affected, albeit to a lesser extent. These observations suggest that even salinity-tolerant species are not immune to the adverse effects of elevated salinity levels.

The implications of these findings extend beyond individual species to the broader ecosystem. Reduced AGB translates to lower carbon storage capacity, compromising the role of mangroves as carbon sinks. This has significant ramifications for global climate change mitigation efforts, as mangroves are among the most efficient natural systems for carbon sequestration. Furthermore, declining biomass can affect the structural stability of mangrove forests, increasing their vulnerability to external disturbances such as storms and tidal surges. These changes could cascade through the ecosystem, affecting biodiversity, nutrient cycling, and the provision of ecosystem services.

Our study also highlights the importance of considering species-specific responses to salinity stress in mangrove conservation strategies. The differential impacts of salinity on AGB among the studied species underscore the need for targeted interventions that account for the unique ecological roles and tolerance thresholds of individual species. For instance, promoting the growth of salinity-tolerant species in high-salinity zones could help maintain biomass levels and ecosystem functionality. Similarly, efforts to reduce salinity stress through measures such as freshwater inputs (*via* channelizing harvested rain water) and habitat restoration could benefit sensitive species, enhancing overall ecosystem resilience (Banerjee et al., 2017).

Materials and methods

Site Selection

The study was initiated during 2024 with the selection of 24 sampling stations within the Indian Sundarbans (Table 1 and Fig. 1). At each station, 10 quadrats measuring 10 m × 10 m were randomly chosen. To identify the dominant tree species (*Sonneratia apetala*, *Avicennia marina*, *Avicennia alba*, *Avicennia officinalis*, and *Excoecaria agallocha*) in the study area, the mean relative abundance of each species was assessed. Only tree species with an abundance of at least 70% (based on population density) were considered for biomass estimation. Above Ground Biomass (AGB), encompassing the biomass of stems, leaves, and branches, was determined using standard procedures. For AGB assessment, individual trees of dominant species in each quadrat were evaluated, and the average biomass values for all quadrats per zone were expressed in tonnes per hectare.

Table 1 Stations selected in Indian Sundarbans based on aquatic salinity

Station in western sector (Mid- saline zone)	**Station in central sector (High- saline zone)**	**Station in eastern sector (Low- saline zone)**
Muriganga (Stn. 1)	Saptamukhi (Stn. 2)	Arbesi (Stn. 8)
Jambu Island (Stn. 22)	Thakuran (Stn. 3)	Jhilla (Stn. 9)
Lothian Island (Stn. 23)	Herobhanga (Stn. 4)	Pirkhali (Stn. 10)
Sagar Island (Stn. 24)	Ajmalmari (Stn. 5)	Panchamukhani (Stn. 11)
	Dhulibasani (Stn. 6)	Harinbhanga (Stn. 12)
	Chulkati (Stn. 7)	Katuajhuri (Stn. 13)
	Matla (Stn. 15)	Chamta (Stn. 14)
	Chhotahardi (Stn. 19)	Chandkhali (Stn. 16)
		Goasaba (Stn. 17)
		Gona (Stn. 18)
		Bagmara (Stn. 20)
		Mayadwip (Stn. 21)

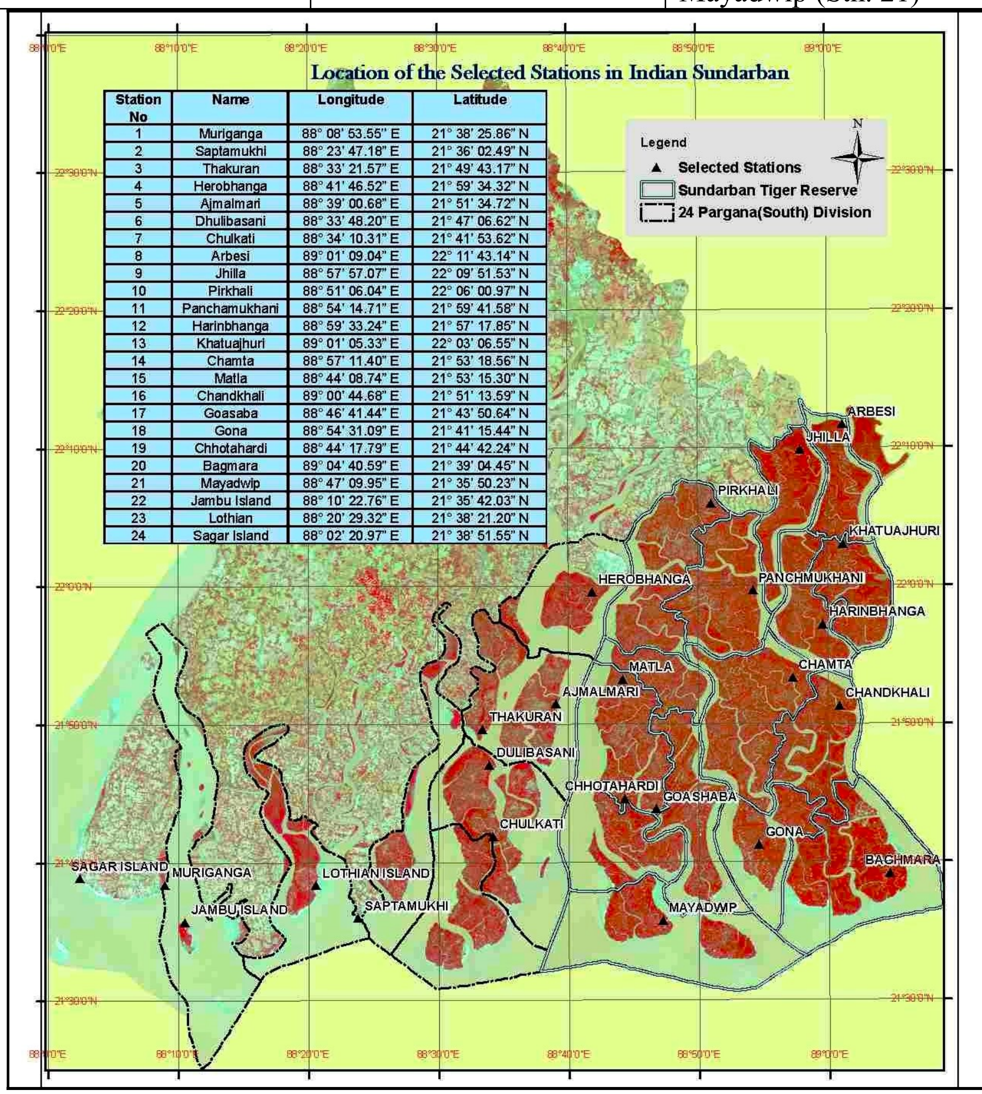

Fig. 1. Map showing 24 selected stations in Indian Sundarbans

Stem Biomass estimation

The stem volume of each of the selected species in every quadrant (10m × 10m) was estimated using the Newton's formula (Husch et al., 1982).

$$\mathbf{V = h/6\ (A_b + 4A_m + A_t)}$$

Where, V is the volume (in m^3), h is the height measured with laser beam (BOSCH DLE 70 Professional model), and A_b, A_m, and A_t, are the areas at base, middle and top respectively. Specific gravity (G) of the wood was estimated taking the stem cores by boring 4.5 cm deep and compared with the standard data of FAO (https://www.fao.org/3/w4095e/w4095e0c.htm). This was converted into stem biomass (B_S) as per the expression $B_S = GV$. The stem biomass of individual tree was finally multiplied by the number of trees of each species in all the selected quadrants and the mean values were expressed in t ha^{-1}.

Branch Biomass estimation

The total number of branches irrespective of size was counted on each of the sample trees. These branches were categorized based on basal diameter into three groups, *viz.* < 6 cm, 6–10 cm and > 10 cm. The leaves on the branches were removed by hand. The branches were cut in to pieces and oven-dried at 70°C overnight in hot air oven to remove moisture content if any present in the branches. Dry weight of two branches from each size group was recorded separately using the equation of Chidumaya (1990).

$$\mathbf{B_{db} = n_1b_{w1} + n_2b_{w2} + n_3b_{w3} = \Sigma\ n_ib_{wi}}$$

Where, B_{db} is the dry branch biomass per tree, n_i the number of branches in the i^{th} branch group, b_{wi} the average weight of branches in the i^{th} group and i = 1, 2, 3, …..n are the branch groups. The mean branch biomass of individual tree was finally multiplied with the number of trees of each species in all the plots for each site and expressed in t ha^{-1}.

Leaf Biomass estimation

For leaf biomass estimation, one tree of each species per quadrant was randomly considered. All leaves from nine branches (three of each size group) of individual trees of each species were removed and oven dried at 70°C and dry weight (species-wise) was estimated. The leaf biomass of each tree was then calculated by multiplying the average biomass of the leaves per branch with the number of branches in that tree. Finally, the dry leaf biomass of the selected species (for each quadrant) was recorded as per the expression:

$$\mathbf{L_{db} = n_1L_{w1}N_1 + n_2L_{w2}N_2 + \ldots\ldots\ldots n_iL_{wi}N_i}$$

Where, L_{db} is the dry leaf biomass of selected urban species per plot, n_1..….n_i are the number of branches of each tree of the species, L_{w1}…….L_{wi} are the average dry weight of leaves removed from the branches and N_1……N_i are the number of trees per species in the quadrants. This exercise was performed for all the sites and the mean results were finally expressed in t ha^{-1}.

Statistical analysis

To determine the impact of salinity on mangrove AGB, a polynomial regression model of quadratic order was chosen to capture the nonlinear relationship. The quadratic model was selected based on its ability to fit the observed trends, where AGB typically peaks at lower salinity levels and declines at extremes. Model selection was guided by statistical criterion like coefficient of determination (R^2). This approach ensures an optimal balance between simplicity and accuracy in representing the salinity-AGB relationship.

Results

The AGB of mangroves displayed a consistent trend across all three salinity zones, regardless of the species. The highest AGB was observed in the low saline zone, followed by the mid saline and high saline zones. The zone-wise monthly variations in AGB for every species based on salinity are illustrated in Figs 2–6. Additionally, the specific months during which the AGB for each species reached its minimum and maximum values across the three salinity zones have been identified and highlighted during the study period.

In the low saline zone, *A. officinalis* showed the highest AGB in December (43.21 t/ha), while *E. agallocha* exhibited lowest value of 31.91 t/ha in January 2024.

In the mid saline zone, the AGB of *E. agallocha* was lowest in January (22.65 t/ha) and highest value showed in *A. officinalis* (41.62 t/ha) during December 2024.

In the high saline zone, *E. agallocha* recorded the lowest AGB (8.71 t/ha) in January 2024 and highest value in *A. officinalis* (26.01 t/ha) during December 2024.

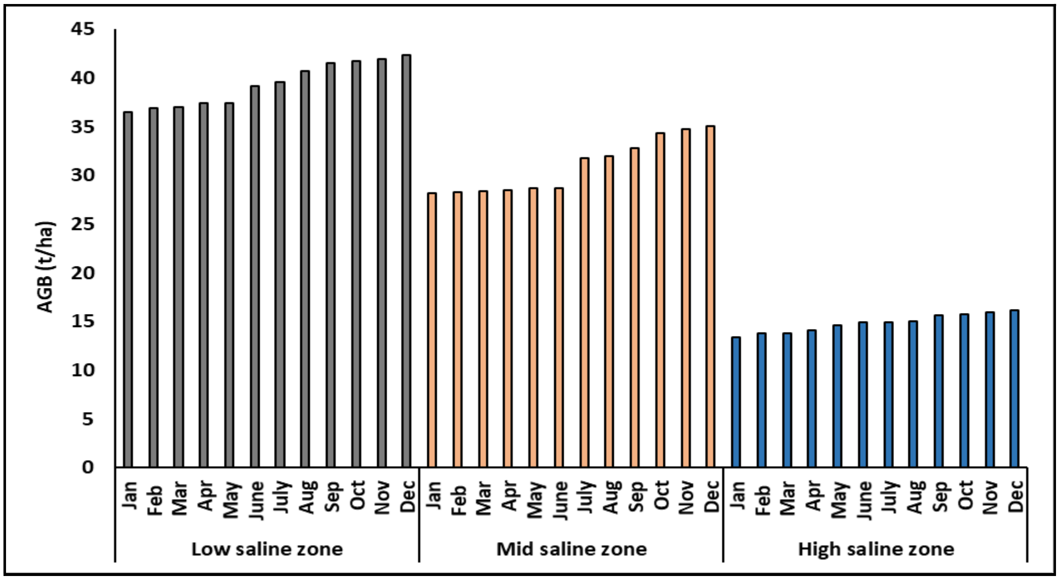

Fig. 2. Monthly variation of AGB (in t/ha) for *S. apetala* in 3 different salinity zones

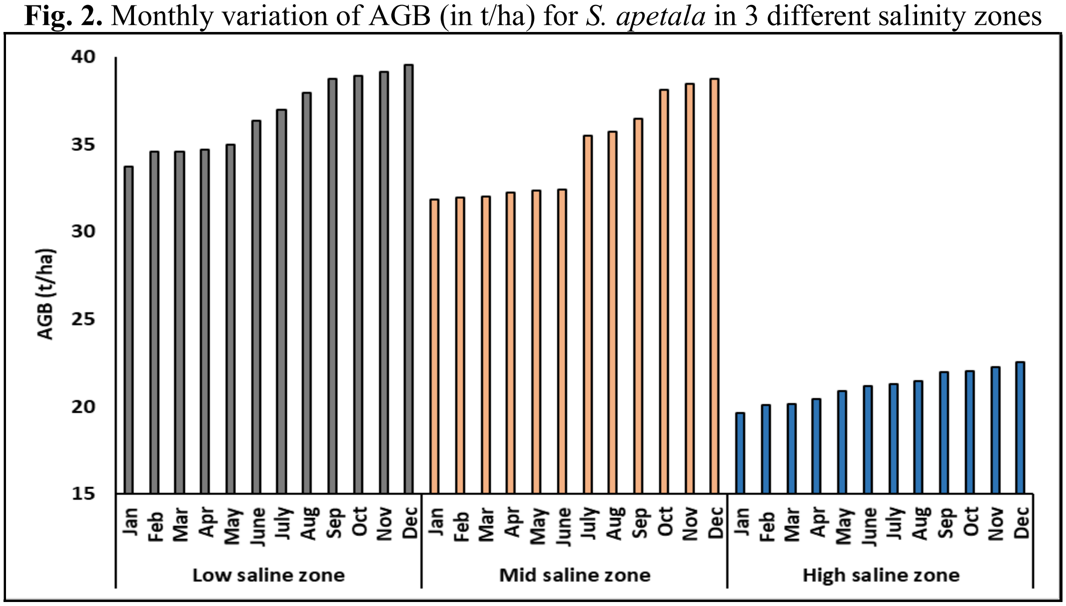

Fig. 3. Monthly variation of AGB (in t/ha) for *A. marina* in 3 different salinity zones

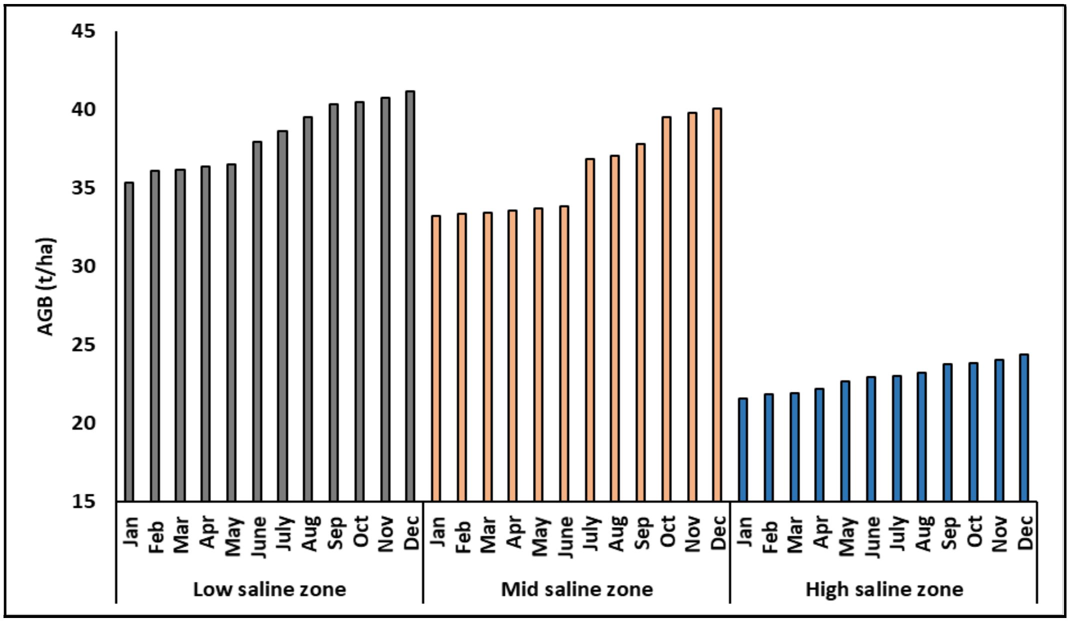

Fig. 4. Monthly variation of AGB (in t/ha) for *A. alba* in 3 different salinity zones

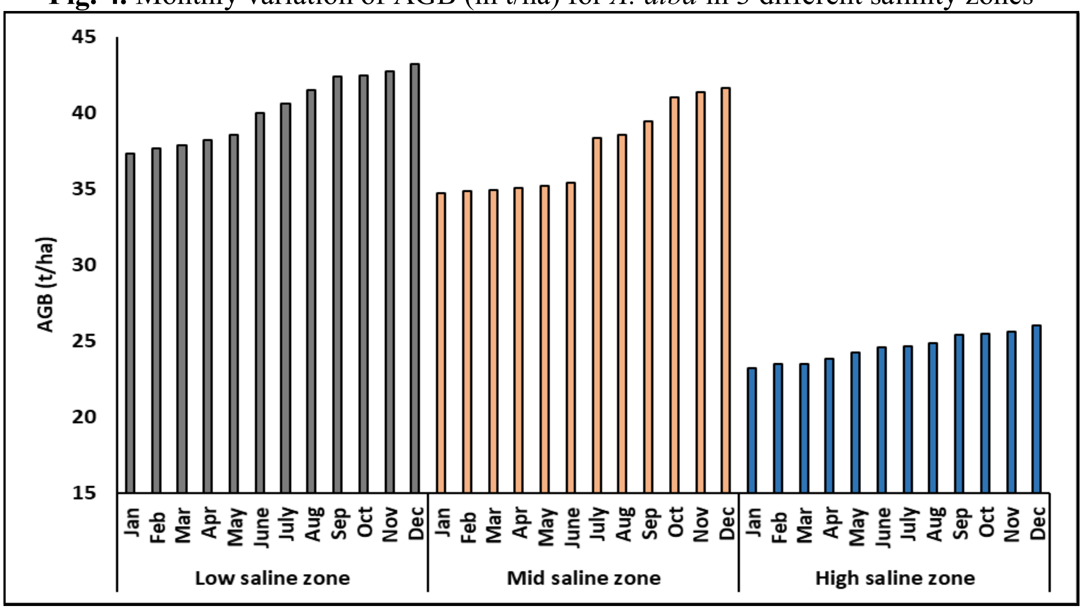

Fig. 5. Monthly variation of AGB (in t/ha) for *A. officinalis* in 3 different salinity zones

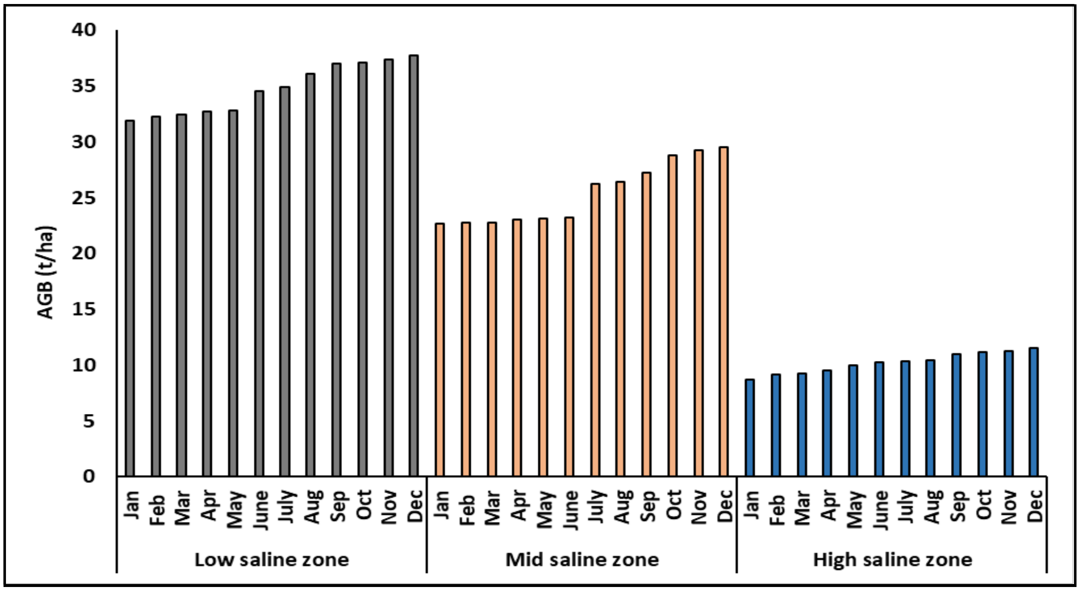

Fig. 6. Monthly variation of AGB (in t/ha) for *E. agallocha* in 3 different salinity zones

We also estimated species-wise AGB as a function of aquatic salinity through allometric equations. A second-order polynomial (quadratic) equation has been used for the five selected species thriving in three salinity zones (Table 2).

Polynomial models often provide a better fit than simple linear regression when the data show curvature, enabling more accurate predictions of biomass at varying salinity levels.

Table 2 Species-specific polynomial model of selected mangrove species across three different salinity zones in Indian Sundarbans

Salinity Zone	Species	Equation	R^2
Low-saline zone	*S. apetala*	$y = 0.0885x^2 - 2.3233x + 52.52$	0.6641
	A. marina	$y = 0.0855x^2 - 2.2304x + 49.288$	0.6615
	A. alba	$y = 0.0842x^2 - 2.2042x + 50.766$	0.6589
	A. officinalis	$y = 0.0913x^2 - 2.3583x + 53.463$	0.6476
	E. agallocha	$y = 0.0883x^2 - 2.3196x + 47.9$	0.6707
Mid-saline zone	*S. apetala*	$y = 0.0359x^2 - 1.8569x + 52.326$	0.4752
	A. marina	$y = 0.0359x^2 - 1.8563x + 56.043$	0.4749
	A. alba	$y = 0.0359x^2 - 1.8553x + 57.406$	0.4747
	A. officinalis	$y = 0.0364x^2 - 1.8756x + 59.142$	0.4775
	E. agallocha	$y = 0.1093x^2 - 2.9302x + 42.264$	0.7610
High-saline zone	*S. apetala*	$y = 0.0168x^2 - 0.9849x + 28.418$	0.3761
	A. marina	$y = 0.0172x^2 - 1.0062x + 35.064$	0.3818
	A. alba	$y = 0.0171x^2 - 1.0066x + 36.897$	0.4050
	A. officinalis	$y = 0.0478x^2 - 1.156x + 30.768$	0.6210
	E. agallocha	$y = 0.1093x^2 - 2.9302x + 42.264$	0.7610

Discussion

High salinity exerts a dwarfing effect on the Above Ground Biomass (AGB) of mangroves, primarily by limiting their growth and structural development. Under saline conditions, mangroves allocate more energy to coping mechanisms like ion regulation, salt excretion, and osmotic balance, leaving less energy available for biomass production. This results in stunted growth, reduced height, and smaller canopy size. The dwarfing effect is particularly pronounced in species less adapted to high salinity, leading to diminished AGB (Mitra, 2013). This not only affects the productivity of the ecosystem but also compromises its ability to provide essential services like carbon sequestration and coastal protection. Thus, the dwarfing effect caused by salinity highlights the vulnerability of mangroves in high-salinity environments.

The observed pattern, where an increase in salinity leads to a reduction in biomass (AGB), reflects the physiological and ecological stress that mangrove species experience under higher salinity conditions. This relationship can be explained by few factors as stated here in points.

1. Osmotic Stress:

High salinity reduces the availability of water for uptake by plants due to osmotic imbalance. Plants must invest more energy in extracting water from saline environments, leaving less energy for growth and biomass accumulation.

2. Ion Toxicity:

Elevated salinity increases the concentration of sodium (Na^+) and chloride (Cl^-) ions, which can accumulate in plant tissues, disrupting cellular function, enzymatic activity, and photosynthesis, thereby stunting growth.

3. Nutritional Imbalance:

Excess salts can interfere with the uptake of essential nutrients like potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), which are critical for growth and development.

4. Energy Trade-off:

Mangroves under high salinity conditions must expend additional energy on physiological adaptations such as salt exclusion, secretion, or compartmentalization in vacuoles. This adaptation reduces the energy available for biomass production.

5. Reduced Photosynthetic Efficiency:

Stomatal closure is a common response to high salinity to minimize water loss. However, this also reduces the uptake of carbon dioxide, lowering photosynthetic efficiency and biomass production.

Conclusion

The present study provides critical insights into the impact of salinity on mangrove biomass in the Indian Sundarbans. By developing species-specific models, we have identified key trends and mechanisms underlying the response of mangroves to salinity stress. These findings have important implications for conservation and management, highlighting the need for proactive measures to mitigate the effects of climate-induced salinity changes. As the Sundarbans and other mangrove ecosystems face increasing pressure from environmental and anthropogenic stressors, understanding and addressing these challenges will be essential to ensure their long-term sustainability and the continued provision of their invaluable ecological services.

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