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Contribution of Mangrove Ecosystem Services to Local Livelihoods in the Indian Sundarbans

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Abstract: Mangrove forests, apart from their carbon sequestration and coastal protection benefits, provide a wide range of ecosystem services to people in tropical developing countries. Local people living in and around forests in the developing tropics also depend heavily on these mangrove ecosystem services for their livelihoods. This study examines the impact of mangrove ecosystem services on the livelihoods of people in Indian part of the Sundarbans—the largest contagious mangrove forest on earth. To achieve this objective, a household survey was undertaken to gather data on the diverse range of provisioning and regulating ES local people derived from mangrove forests living near the Indian Sundarbans. Surveys were carried out in nine villages across the Kultali, Basanti, and Gosaba blocks, involving over one hundred respondents. Our study reveals the active participation of locals in gathering various ecosystem services, with fishing and crab collection being the most common in the area. Due to numerous challenges in the agricultural sector, such as soil salinity and frequent extreme weather events, people increasingly depend on non-farming incomes, particularly fishing. A questionnaire was used to assess the dependence of local people on different ecosystem services. Some villages, such as Amlamethi, Satyanarayanpur, Mathurakhand, Vivekananda Palli, and Second Scheme, demonstrated a higher reliance on forest ecosystem services compared to other villages. The study indicates that the contribution of ecosystem services sometimes surpasses traditional activities like farming and daily contractual work. River transportation emerged as the most crucial service, followed by freshwater, food, and fiber. While certain resources like fuel, natural medicine, and genetic resources may not be prioritized, they still hold significance within the community, contrasting with ornamental resources, which are considered the least important. Our findings underscore the importance of preserving natural services in the Sundarbans forest, highlighting the need to conserve the mangrove ecosystem services to ensure the long-term well-being of local communities.

Keywords: mangrove ecosystem; Sundarbans; ecosystem services; ES ranking; livelihood dependency

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1. Introduction

Mangrove forests hold immense ecological, economic, and social importance, making them a critical and irreplaceable ecosystem [1]. Mangrove forests are also essential for land reclamation, protecting the coastal ecosystem from storms and tidal surges, and

strengthening the socioeconomic status of coastal communities [2]. Their ability to stabilize the ecosystem by acting as fish nurseries, habitats for biodiversity, and sites for carbon storage is also well recognized [3]. Since the mangrove species' large, above-ground aerial root systems are particularly effective in attenuating wave activities by dissipating energy, this ecosystem has also been designated as the first line of defense against frequent natural disasters as well as hazardous events. Additionally, by absorbing and storing significant volumes of carbon dioxide, its ability to act as a carbon sink helps us to mitigate climate change [4]. Mangrove forests can absorb 97.57 t of carbon per hectare, or more than three times the capacity of non-mangrove forests, making them extremely effective carbon sinks on a global scale [3]. Fishing, honey collection, and fuel wood or timber harvesting from mangrove forests provide livelihood support to the inhabitants living in and near mangroves [2,5]. Furthermore, they directly improve cultural, life-sustaining, and well-being functions [5,6].

The Sundarbans is the largest contiguous mangrove forest on earth and is strategically situated where frequent man–sea interaction occurs, making it a vulnerable coastal zone in the world [7]. This vast delta is formed by the confluence of several rivers, including the Ganges, Brahmaputra, and Meghna, creating a unique and dynamic ecosystem [8]. Being regarded as a UNESCO World Heritage site, the Sundarbans is a stunning combination of ecological significance and essential livelihood support for millions of people [9]. Named after the "Sundari" (*Heritiera fomes*) trees that flourish in abundance, the Sundarbans mangrove forest covers an area of about 10,000 km^2, of which 62% (6200 km^2) is in Bangladesh and the remaining 38% (3800 km^2) in India [7]. This unique forest is rich in biodiversity and is home to approximately 1186 recognized species of flora and fauna [10]. The Sundarbans, a habitat of diverse flora and fauna, is now at risk of becoming extinct due to the overuse of timber and other natural resources along with intense human interference and climate change [11,12].

The idea of ecosystem services is a key framework that highlights the tangible and intangible benefits that ecosystems provide to humans [5]. It emphasizes the direct and indirect services that natural ecosystems contribute to human well-being, livelihoods, and quality of life. These services encompass a wide range of ecological processes and functions that support life on earth and sustain human societies. Booi et al. [13] conducted a systematic review of estuarine ecosystem services, noting the significant benefits they provide for human well-being and the stress from human activities and advocating for more research on estuary users' perceptions and the importance of estuaries. With the advancement of civilization, humans have tried to rely on nature for the provision of goods like food, timber, fuel wood, fiber, etc. [14]. The services received from such an ecosystem are nature-based, and these multiple ecosystem services interrelate in complex dynamic ways [15,16]. It has been found that the scale of different ecosystem services is highly variable in nature, e.g., a few ecosystem services, like food and timber, have great value compared to services like pollination or bioremediation [17].

Ecosystem services (ESs) have been defined from a variety of perspectives. The benefits people derive from the ecosystem include provisioning services, regulating services; and supporting services that enable the existence and functioning of ecosystem and cultural services that provide non-material benefits. According to the Millennium Ecosystem Assessment (2003, 2005) [18,19], these services collectively make up ecosystem services. According to this concept, ecosystem services also include benefits from nature like oxygen production, carbon sequestration, and aesthetic attractiveness.

Among the four groups of ecosystem services (ESs), provisioning and regulating services are most important as they underpin the renewable resources to define regional supply and demand dynamics of this region [20,21]. For this reason, these two services are discussed in this study. However, a number of threats and stressors, both of natural and anthropogenic origin, continue to affect the flow and quality of ecosystem services due to overuse and degradation. Akram et al. [22] reviewed the essential functions of mangroves in coastal ecosystems, identifying threats such as coastal development, aquaculture,

deforestation, climate change, eutrophication, and pollution, and called for coordinated stakeholder approaches to improve mangrove management. Getzner and Islam [23] revealed that the economic value of mangrove services is influenced by factors such as elicitation methods, types of services considered, and conservation status, recommending original valuation studies for accuracy. Currently, various primary and secondary factors, including biophysical (such as climate change, alterations in soil characteristics, inherent plant structure, composition, etc.) and anthropogenic (such as land degradation, changes in land use, etc.), predominantly contribute to the devaluation of ecosystem services [24,25]. Among the driving factors, human-induced land use change is the most important factor of the reduction in ES [26,27]. Some previous studies have already examined how changes in land use and land cover (LULC) have a greater impact on the decline of ecosystem services at regional or global scale [28,29].

The Sundarbans mangrove forest is renowned for providing significant ESs (e.g., fishing, honey, crab, fuelwood, lumber, and tourism), which help to support almost 20 million residents of this area [5]. To improve the overall socio-ecological state of mangroves and manage Sundarbans's natural resources, a variety of information on different ESs is essential [30]. Mohamed [31] assessed perceptions of mangrove ecosystem services (MESs) in Zanzibar's Chwaka and Menai Bays, finding significant differences in awareness of regulating and supporting services between wards and stressing the need for sustainable management frameworks. Nyangoko et al. [32] found that local community perceptions of mangrove ecosystem services (MESs) in the Rufiji Delta varied by site, influenced by distance to mangroves, residence time, gender, and local management performance, emphasizing the importance of understanding local preferences for effective conservation. Azad [33] highlighted the heavy dependence of Shymnagar Upazila's residents on the Sundarbans mangrove ecosystem for resources like fuelwood and aquatic products, noting limited access to disaster warnings and medical treatment and suggesting alternative livelihoods to reduce dependency. Collectively, these studies underscore the crucial role of mangroves and estuaries in supporting human livelihoods and coastal health, while highlighting the need for tailored conservation strategies, increased awareness, and sustainable management practices to address site-specific challenges and threats.

Through a questionnaire survey, the current study aims to specifically assess the diverse range of ESs in the Indian Sundarbans, their contribution to local livelihoods, and a ranking of ESs based on their importance to the community. Very limited research has so far been carried out to determine how much the local people in the Indian part of Sundarbans depend on ecosystem services to support their way of life. Keeping this in mind, the following objectives were set for the current study:

(a) To assess the contribution of Sundarbans's diverse ecosystem services on the livelihoods of local people.
(b) To rank the ecosystem services based on their importance to the local people of the Sundarbans.

The paper makes an effort to show how various ecosystem services affect the way of life of people living in the fringe areas of the Sundarbans mangrove forest and assess the importance of the Sundarbans forest in delivering valued regulating and provisioning ecosystem services. The organization of the paper includes an introduction section followed by a methodology describing data collection and data analysis procedure, a results section outlining our study findings, a discussion section based on the results, and finally our conclusions.

2. Materials and Methods

2.1. The Study Area

The Ichchamati–Raimangal River in the east, the river Hugli in the west, and the Bay of Bengal in the south define the northern boundaries of the Indian Sundarbans Delta (ISD), which is located between 21°40′04″ and 22°09′21″ N latitude and 88°01′56″ and 89°06′01″ E longitude [8]. The Sundarbans Biosphere Reserve generally consists of 4200 km^2 of mangrove reserve forest and 5400 km^2 of non-forest inhabited territory in the

districts of the North and South 24 Parganas of West Bengal [34]. The Sundarbans National Park, which has a core area of 1330 square kilometers and is part of the Sundarbans Reserve Forest, was added to the UNESCO World Heritage List in 1987. In November 2001, it received recognition on a global scale through UNESCO's MAB (Man and Biosphere) Program [35]. The Sundarbans Delta consists of three divisions, namely the western, the middle, and the eastern regions (Figure 1). The delta is characterized by a hot and humid climate. May is the hottest month, with temperatures exceeding 40 °C, and January is the coldest, with temperatures as low as 10 °C [36]. The region receives an annual average rainfall of 1800–1900 mm, mainly from the south-west monsoons which start in the latter half of June and withdraw by mid-October. Pre-monsoon rains are received during March–April [36]. The Sundarbans Delta is prone to extreme storm events which are frequent during the pre-monsoon period, and from September through November [9].

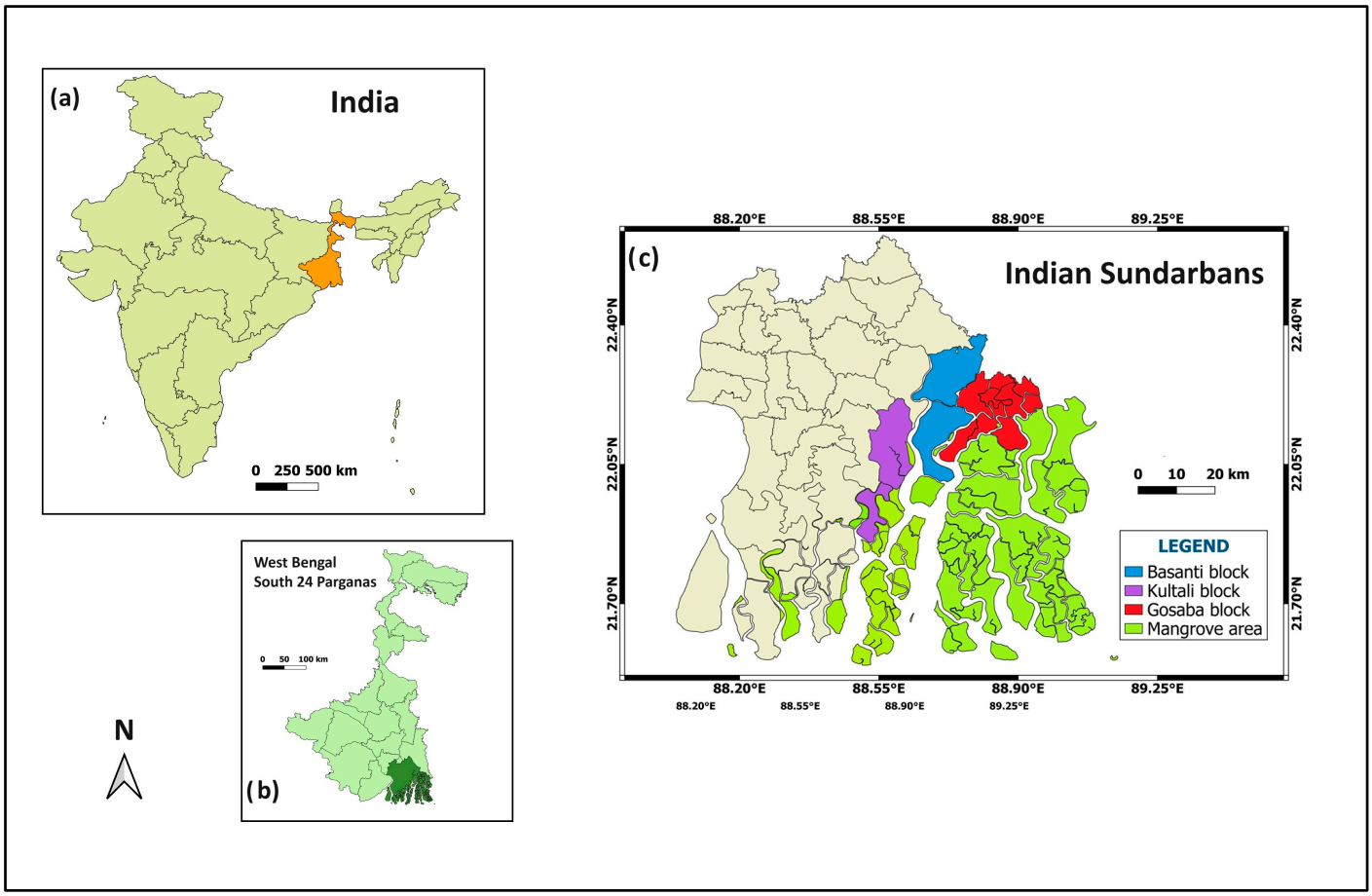

Figure 1. Location map of the study area: (**a**) India, (**b**) West Bengal and South 24 Parganas, and (**c**) Indian Sundarbans with the location of the three studied blocks.

2.2. Data Collection

A comprehensive household survey was undertaken to gather data on the diverse array of direct (provisioning) and indirect (regulating) benefits derived from the mangrove forests by local communities residing adjacent to the Indian Sundarbans. This survey aimed to assess the multifaceted contributions of these ecosystems to the livelihoods of the inhabitants. To ensure a representative sample, a stratified random sampling approach was employed for household selection in various villages across different locations within the Indian Sundarbans. This approach allowed us to capture the variation in ecosystem service perceptions and contributions across distinct geographical and socio-economic contexts. This sampling approach divides the target population into homogeneous, mutually exclusive segments. From each segment, a simple random sample is drawn. The samples

from the different strata are then combined to form a single sample. Stratified random sampling is a probability sampling technique where the characteristics of a specific variable are represented in the population concerning that variable. It advantages include reducing selection bias, effectively representing the population, requiring a sampling frame, and allowing for the estimation of random sampling errors [37]. A diverse range of participants were included in the survey to account for different age groups and gender perspectives. Respondents were randomly selected from three age categories: 15 to 30 years old, 31 to 60 years old (adult), and 61 years and older. This stratification helped to capture a comprehensive view of perceptions of ecosystem services across different generations. Structured questionnaire interviews were conducted as the primary data collection method. These interviews took place in various locations, including households, agricultural fields, and riversides, reflecting the diverse settings in which local interactions with the ecosystem occur. Additionally, separate group discussions were held specifically with women, recognizing their unique insights and roles within the community. The inclusion of separate discussions for women is significant due to the gender differentiated roles and responsibilities within these communities. Women frequently participate in distinct activities related to the use of mangrove resources and may have different viewpoints and experiences than men. We wanted to make sure that these special ideas were appropriately represented in our study, so we held separate group discussions. This approach acknowledges the importance of gender inclusivity in understanding the full spectrum of ecosystem services and their impacts on community livelihoods.

A total of 110 households were surveyed during the data collection period, which spanned from February 2022 to December 2022. This timeframe was chosen to account for potential seasonal variations in ecosystem service utilization and to capture a holistic picture of the annual patterns of resource dependence. It is worth noting that the surveyed villages predominantly rely on two primary sources of income: the collection of mangrove forest products as a primary source and the cultivation of various agricultural products as a secondary source. These livelihood dynamics underline the significance of mangrove ecosystems not only in terms of provisioning ecosystem services but also in supporting the broader socio-economic fabric of the communities.

2.3. Selection of the Villages

Nine villages, strategically chosen from different locations within the Indian Sundarbans, formed the focal points of this study. During the village selection process, paramount importance was given to proximity to mangrove regions and ease of accessibility of ecosystem services. As the vicinity of the mangrove forest region increases the probability of dependence on ecosystem services, the following villages were given preference for the selection of study regions: (i) Bongheri, East Gopalganj, Deulbari, and Binodpur from the Kultali block, (ii) Amlamethi, Satyanarayanpur, and Mathurakhand from the Gosaba block, and (iii) Vivekananda Palli and Second Scheme from the Basanti block. The respondents from each village belong to different occupational classes and income categories, and their level of dependence on forest products also varies from region to region. That is why a stratified random sampling technique was used to select the respondents. The total sample size was therefore 110 respondents, and the primary data was collected through household surveys.

2.4. Household Surveys

The questionnaire employed in household surveys was carefully designed to capture detailed perceptions of villagers regarding ecosystem services provided by the Sundarbans. It aimed to understand their significance in people's daily lives. The questionnaire was structured into sections covering the types of ecosystem services received from the mangrove forest, valuation of ecosystem services based on people's perceptions (on a scale of 0–5, where 0 means no value and 5 means highest value), income from ecosystem services and other occupational categories, frequency of use, dependency rate among households on ecosystem services (on a scale of 0–5, where 0 is the least dependency, and 5 is the most

dependency), and perceived importance of these services. This detailed approach ensured comprehensive data collection on the interaction between local communities and mangrove ecosystem services. This survey strategy incorporated a participatory methodology that combined comprehensive household surveys with individualized interviews. It ensured a comprehensive investigation of the subject matter. The study assessed the tangible contributions of ecosystem services to local livelihoods. The survey questionnaire focused on identifying the provisioning and regulating ecosystem services, specifically the products which are acquired and consumed by their families from the adjacent forest area. For a thorough analysis of the importance of different ecosystem services on local livelihoods, a participatory interview-based approach was adopted. The respondents, hailing from diverse categories within the studied households, were engaged in in-depth interviews. This method was designed to figure out their perceptions of the direct and indirect benefits that mangrove forests bring to their way of life. A comprehensive list of benefits derived from forest ecosystem services, accompanied by illustrative details, was presented to the respondents during the interviews. The question posed to them was structured to uncover the importance that they attributed to various ecosystem services within the context of their region. While the term "ecosystem service" was omitted in the field interactions to maintain accessibility, it assisted in categorizing and analyzing the data later in the results and discussion sections. To make it easier for the local people to understand, ecosystem services were described as benefits that directly and indirectly come from the forests. This approach facilitated a deeper and more subtle understanding of their relationships with the ecosystem. The interview forms were crafted in the local language, Bangla, to ensure respondents' ease of understanding.

2.5. Data Analysis

The information collected from the surveyed households was carefully reviewed and processed in a meticulous data-cleansing process. The analysis focused on examining the utilization of ecosystem services provided by the households and their perceived significance in terms of indirect contributions. The surveyed households provided valuable insights into their engagement with various provisioning and regulating ecosystem services. To establish the most commonly utilized ecosystem services, the percentage of households receiving and utilizing at least one service was calculated. Standard analytical techniques were employed for data analysis. Quantitative data, such as the patterns of ecosystem service utilization and the proportion of household income derived from forest resources, were analyzed using basic arithmetic operations such as sum and average. Subsequently, the processed data were synthesized into tables, charts, and diagrams using Microsoft Excel (version 2021) software.

In addition to these analyses, we conducted a one-way analysis of variance (ANOVA) using the latest version of R software (version 4.4.1) to determine if there were any significant differences in the utilization of ecosystem services among different villages. The ANOVA results indicated significant differences, prompting further analysis using Duncan's multiple range test (DMRT) to identify specific groupings. These statistical analyses provided a deeper understanding of the variations in ecosystem service utilization, highlighting the most and least utilized services and their corresponding villages.

3. Results

3.1. Ecosystem Services Received from the Indian Sundarbans

Understanding the array of ecosystem services received by local communities in the Indian Sundarbans region is of immense importance for assessing their contribution to livelihoods. This region offers a large number of provisioning ecosystem services that sustain local livelihoods. These services cover a wide variety of resources, many of which are interlinked to the day-to-day existence. From honey collection to fishery and fuelwood extraction, the provisioning services not only meet material needs but also bear cultural and traditional importance. People collect honey every year during the summer months,

like April, May and June. The West Bengal Forest Department plays a crucial role in monitoring the procedure of honey collection so that the environment is protected. The Forest Department used to issue passes to a limited number of persons for a specified timespan to ensure the least disturbance to nature. Fishing, which is important for people's livelihoods, happens in sync with the tides. It is influenced by spring tides and moon phases, which change the amount that is gathered at different periods. Both freshwater and tidal river water fishing contribute significantly to the local diet and economy, with the monsoon period yielding the highest catch. Engaging in provisioning and fuelwood collection carries legal implications. Our study brings to light that the current situation necessitates well-balanced forest resource management. The prohibition of fuelwood harvesting has sparked discussions about feasible sustainable options and encouraged cooperation between policy makers and the local populace.

Beyond provisioning, the Sundarbans region presents regulatory ecosystem services that support the well-being of its inhabitants. These services, i.e., flood regulation, coastal protection, climate regulation, and carbon sequestration, which are often less prominent but equally vital, contribute to the resilience of the ecosystem.

3.2. Local Dependence on Ecosystem Services

The interaction with the local people revealed that soil salinity in the region hampers crop growth, resulting in unsatisfactory agricultural yields, further worsened by the fact that a majority of agricultural laborers lack land ownership. Consequently, the adjacent mangrove forest area has evolved into a vital buffer zone, essential for their survival. For many of these communities, non-agricultural sources of income, primarily tied to fishing and related activities in rivers and creeks, are pivotal to their way of life. However, the unique status of the Sundarbans as a biosphere reserve and protected area under the IUCN category introduces constraints on the collection of various ecosystem services from the forest. Certain exemptions have been established, allowing for the collection of specific animal-based services such as honey, fish, and crabs.

The analysis of this study involved administering a questionnaire comprising 20 questions during the survey. The respondents from each village provided individual rankings on a scale of 0 to 5, representing their level of dependence on ecosystem services. These individual rankings were then aggregated and averaged to yield an overall ranking, encapsulating the community's perspective on their reliance on these services. The results unveiled distinctive patterns of dependency on ecosystem services among the surveyed villages. Villages like Amlamethi, Satyanarayanpur, Mathurakhand, Vivekananda Palli, and Second Scheme demonstrated remarkably high reliance on ecosystem services, with dependence levels ranging between 66 and 76% (Figure 2). In contrast, residents of East Gopalganj and Bongheri indicated a moderate level of dependency, with values of 50 and 35%, respectively. Deulbari and Binodpur exhibited relatively lower levels of reliance, with percentages of 28.4 and 25%, respectively (Figure 2).

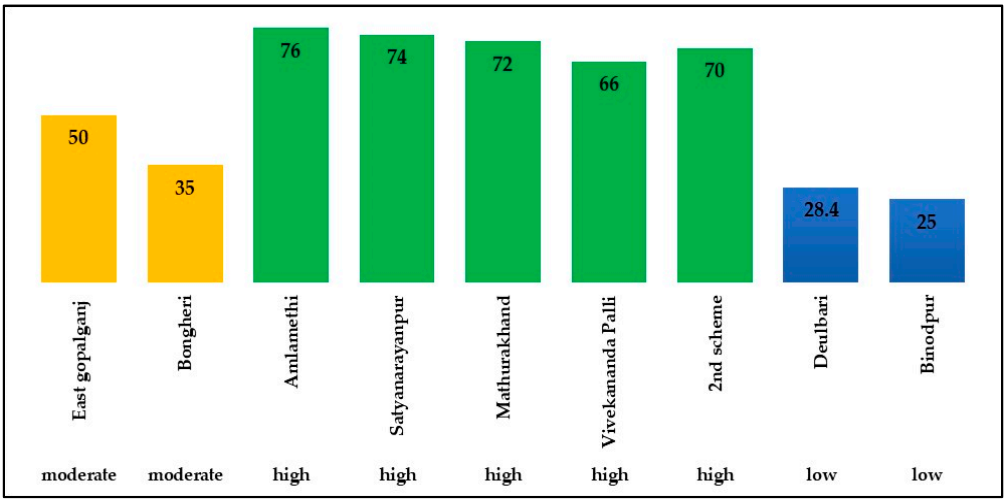

Figure 2. Dependency (%) of the people in the studied villages around the Indian Sundarbans on ecosystem services.

3.3. Contribution of ESs to Annual Household Income

The study focused on assessing the contribution of Ecosystem Services (ESs) to annual household income in the Indian Sundarbans region. The objective was to understand the extent to which ESs contribute to household incomes in the region and how this contribution compares to other sources of income, such as agriculture and daily wage labor.

The study explored how ESs contribute to the household income of each village. The highest reliance on ESs was observed in villages like Amlamethi, Satyanarayanpur, Mathurakhand, Vivekananda Palli, and Second scheme of Gosaba, as well as the Basanti block, in which ES constituted 100% of the household income (Table 1). This highlights the dominance of ecosystem services as the sole income source in these communities, underscoring their direct dependence on the surrounding environment. Similarly, East Gopalganj exhibited a substantial contribution of 61% from ESs, indicating a significant reliance on these services (Figure 3). Bongheri and Deulbari villages also depended on ES, to a lesser extent, with contributions of 20 and 19%, respectively (Figure 3). The variation in these percentages suggests varying degrees of reliance on ecosystem services, likely influenced by factors such as geographical location, available resources, and local economic activities. On the other end of the spectrum, Binodpur village of the Maipith coastal area in Kultali displayed the lowest contribution of ES to annual household income, accounting for only 14% (Figure 3). The results of the study indicated that the contribution of ESs to the total annual household income exhibited a range from Rs. 17,333 to Rs. 43,000 across the surveyed villages (Table 2). This range reflects the variability in the dependence of households on different types of ecosystem services. The data highlighted that ES plays a substantial role in supporting the livelihoods of the local communities in the Indian Sundarbans. When examining the combined results for all nine villages, it was revealed that ES accounted for approximately 47% of the total household income (Table 2). This finding draws attention to the importance of ecosystem services as a key income source for households in the region. In comparison, income from agriculture contributed to 25% of the average annual household income, while daily wage labor constituted 28% (Table 2). This suggests that ESs are a significant income source that compete with the traditional livelihood activities in the study area.

Table 1. Households fully dependent (i.e., 100% income) on different ecosystem services in the study villages around the Indian Sundarbans.

Villages	No. of Households Completely Dependent on ESs
Amlamethi	10
Satyanarayanpur	10
Mathurakhand	10
Vivekananda Palli	10
Second Scheme	10
East Gopalganj	8
Bongheri	6
Binodpur, Maipith Coastal	6
Deulbari	6

Table 2. Average annual household income (in INR, Indian Rupees) from different sources in the surveyed villages around the Indian Sundarbans.

Villages	Income from ESs	Income from Agriculture	Income from Wages	Total Income (INR)
Amlamethi	43,000	0	0	43,000
Satyanarayanpur	41,300	0	0	41,300
Mathurakhand	40,000	0	0	40,000
Vivekananda Palli	26,900	0	0	26,900
Second Scheme	35,000	0	0	35,000
East Gopalganj	35,000	22,500	0	57,500
Bongheri	27,917	42,500	67,500	137,917
Binodpur, Maipith Coastal	17,333	62,667	43,667	123,667
Deulbari	19,417	24,750	60,000	104,167
Overall	31,763.0	16,935.0	19,018.56	67,717.0

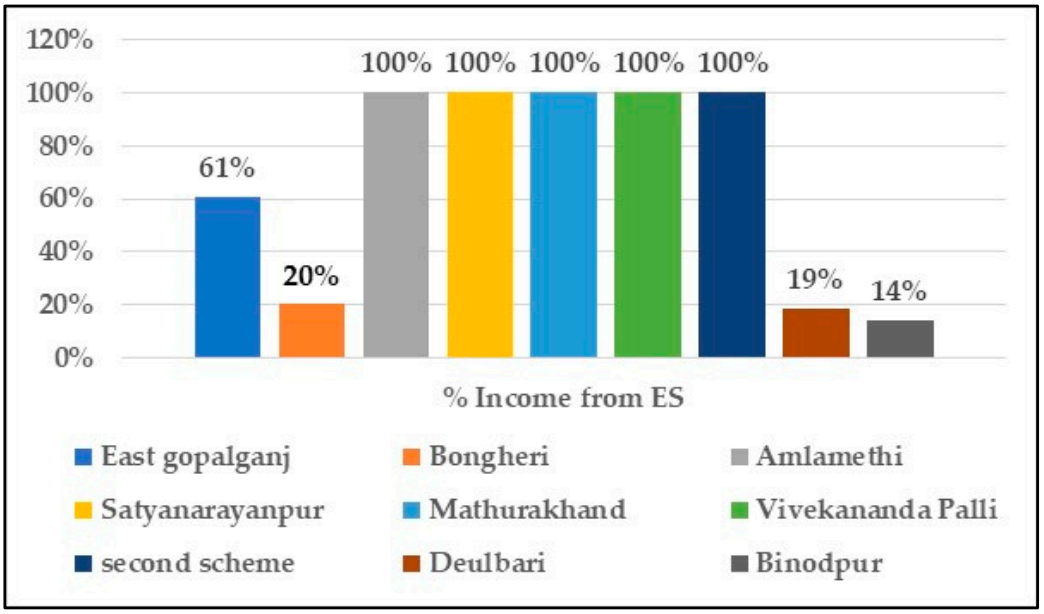

Figure 3. Percentage income from different ecosystem services in our study villages in the Indian Sundarbans.

3.4. Ranking of Provisioning Ecosystem Services

Our survey aimed to assess the perceived importance of different provisioning ecosystem services (PESs) among individuals in a particular village. Provisioning services are ecosystem services that directly provide goods such as food, water, fiber, and fuel, which are essential for human well-being. The survey utilized a scaled value ranging from 0 to 5

to capture the perceived importance of each PS, and these values were then weighted based on individual sample sizes to calculate a weighted mean for each service (Figure 4).

The study results revealed the relative ranking of various provisioning services based on the weighted means obtained from the questionnaire responses. This ranking shed light on the services that the surveyed individuals perceive as most vital for their well-being.

1. River transportation: river transportation emerged as the provisioning service perceived as the most important by the respondents, with a weighted mean of 3.71.
2. Fresh water: fresh water ranked as the second most important provisioning service, with a weighted mean of 3.24.
3. Food and fiber: food and fiber, encompassing the availability of edible resources and materials for textiles and other uses, achieved a weighted mean of 3.18, placing it as the third most important provisioning service.
4. Fuel, natural medicine, and genetic resources: the survey respondents perceived fuel, natural medicine, and genetic resources as relatively important provisioning services, with weighted means of 2.79, 2.27, and 2.24, respectively.
5. Pharmacological resources and shade/shelter provision: Pharmacological resources and shade/shelter provision were ranked lower in perceived importance by the respondents, with weighted means of 2.16 and 2.14, respectively. While these services might be of less immediate significance, they could still contribute to the overall well-being and resilience of the community.
6. Ornamental resources: Ornamental resources received the lowest ranking in terms of perceived importance, with a weighted mean of 0.99. This suggests that the community places minimal importance on services related to aesthetic enjoyment and ornamental resources in their daily lives.

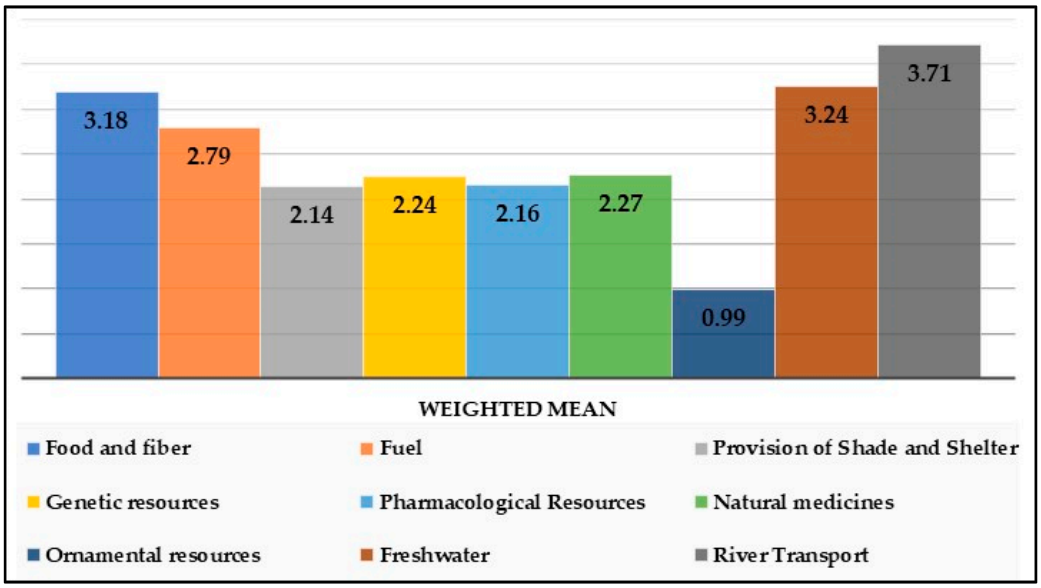

Figure 4. Perceived weighted mean value of different provisioning ecosystem services, as collected in our study villages around the Indian Sundarbans.

The results of our ANOVA revealed significant differences in the utilization of these provisioning ecosystem services among the surveyed households. For provisioning ecosystem services, the calculated F-value for the treatment effect was 16.02, which was significant at level $p < 0.05$. It confirms the presence of substantial variation in the utilization of ecosystem services among the different villages. The analysis shows that the treatments, representing different ecosystem services, have a significant impact on the mean utilization values, with the mean values for the treatments ranging from 1.01 to 3.73. This variation highlights the differing levels of reliance on various services among the villages, with river transport showing the highest mean utilization (3.73) and ornamental resources the

lowest (1.01) (Figure 5). The standard error (S.E.) for perceived mean value of provisioning ecosystem services ranges from 0.17 to 0.51, indicating the precision of the mean estimates, while the coefficient of variation (CV) is 23.58%, reflecting the relative variability in the utilization of provisioning ecosystem services among the studied villages. These findings underscore the diversity in the reliance on various provisioning ecosystem services among the villagers. River transport, fresh water, and food and fiber emerge as the most critical services, likely reflecting their essential roles in the daily lives and economic activities of the households. Conversely, ornamental resources had the least utilization, suggesting that these services are less integral to households' economic well-being.

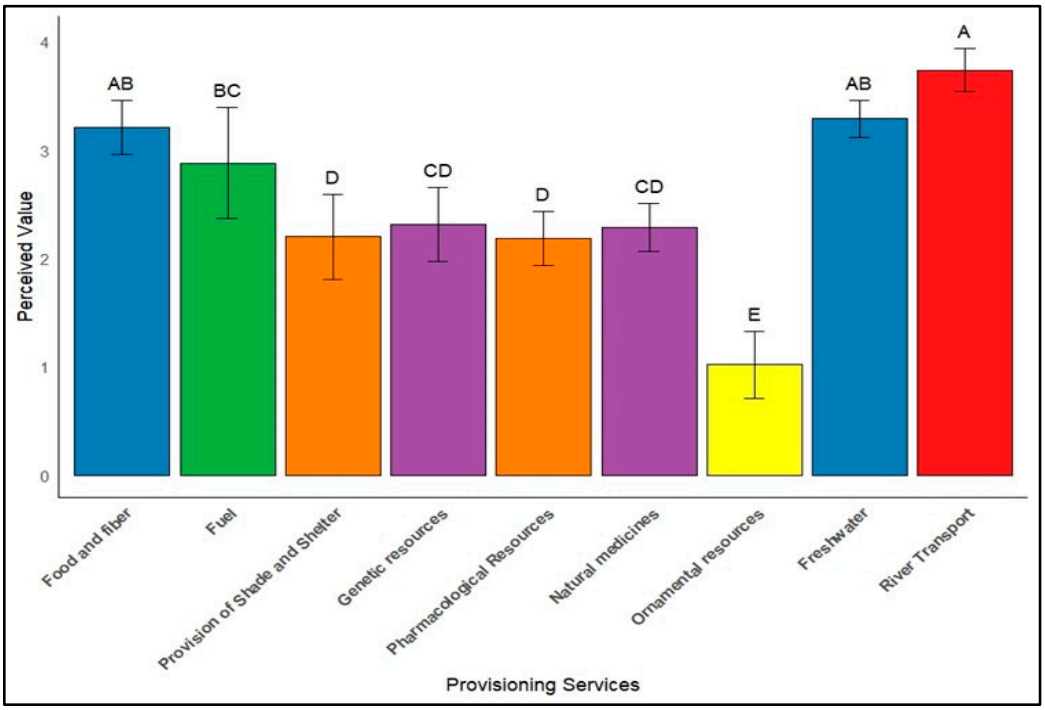

Figure 5. Utilization of provisioning ecosystem services among our surveyed villages in the Indian Sundarbans (bars with different letters indicate statistically significant differences, and bars with the same letters are not significantly different).

3.5. Ranking of Regulatory Ecosystem Services

Like the provisioning ecosystem services survey, this survey aimed to assess the perceived importance of various regulatory ecosystem services (RESs) among the respondents. Regulatory services encompass ecosystem functions that help regulate environmental processes, such as climate regulation, water purification, and disease control. The survey utilized a scaled value ranging from 0 to 5 to capture the perceived importance of each RES component, and these values were weighted based on individual sample sizes to calculate a weighted mean for each service. The study results provide insights into how the surveyed individuals perceive the relative importance of different regulatory ecosystem services based on their weighted mean values (Figure 6).

1. Erosion control: Erosion control emerged as the most highly ranked regulatory ecosystem service, with a weighted mean value of 3.73. This result suggests that the surveyed individuals recognize the crucial role of ecosystems in preventing soil erosion, which is essential for maintaining soil quality, agricultural productivity, and preventing sedimentation in water bodies. The high value indicates the perceived significance of erosion control for the community's well-being.
2. Soil retention: Soil retention was ranked second in perceived importance among the regulatory ecosystem services, with a weighted mean of 3.38. This underscores

the community's recognition of the importance of natural habitats in retaining soil, preventing land degradation, and ensuring the resilience of the local landscape.

3. Water regulation and gas regulation: Water regulation and gas regulation tied in perceived importance, each obtaining a weighted mean value of 3.16. These services play a vital role in maintaining balanced water cycles and regulating gases like carbon dioxide and oxygen in the atmosphere. Their relatively high ranking underscores their influence on ecosystem health and human well-being.
4. Nutrient regulation and pollination: Nutrient regulation and pollination were ranked next, with weighted mean values of 3.12 and 2.88, respectively. Nutrient regulation involves the maintenance of nutrient cycles in ecosystems, which is essential for sustaining plant growth and ecosystem productivity. Pollination, while ranking lower, was still recognized as important for supporting agricultural production and biodiversity.
5. Climate regulation: Climate regulation also received a weighted mean value of 2.88, placing it in the same range as pollination. This service refers to ecosystems' role in regulating climate patterns, which has broad implications for weather patterns, temperature moderation, and climate change mitigation.
6. Natural hazard regulation and pest disease regulation: The surveyed individuals ranked natural hazard regulation and pest disease regulation as relatively less important, with weighted mean values of 2.79 and 2.72, respectively. While these services might not be top priorities, they still play roles in reducing the impacts of natural disasters and controlling pests and diseases that could harm both ecosystems and human activities.

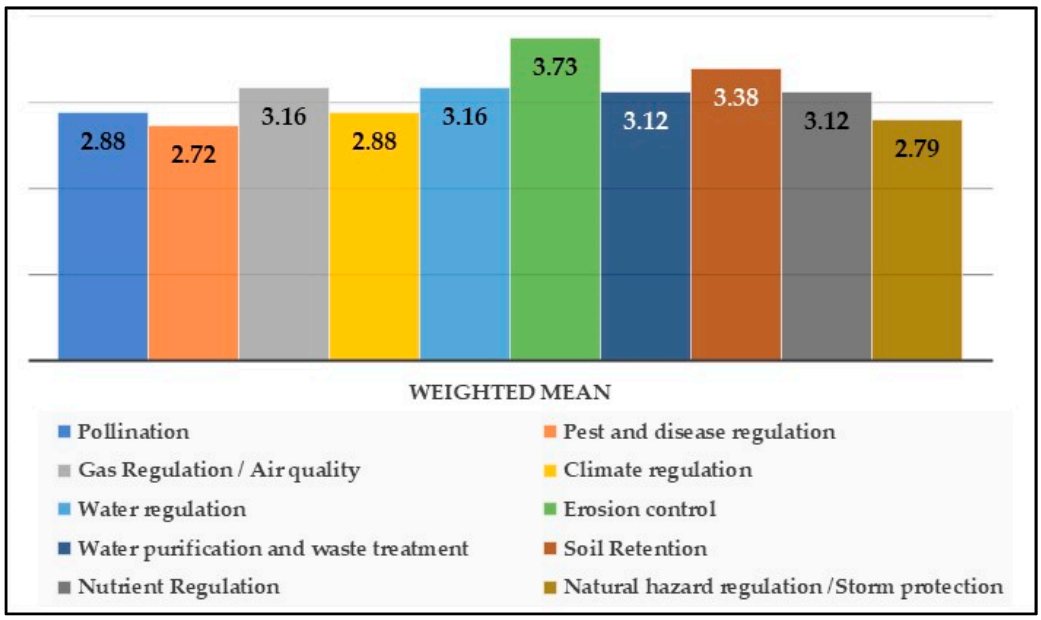

Figure 6. Perceived weighted mean values of different regulatory ecosystem services collected in the study villages around the Indian Sundarbans.

For regulating ecosystem services, the ANOVA indicated significant differences in utilization among the surveyed villages. The calculated F-value of 3.54 for the treatment effect, with a significance level of 0.00111 ($p < 0.05$), confirmed the presence of significant variation in the utilization of regulating services among the different villages. The analysis revealed that the treatments, representing different regulating ecosystem services, have a substantial impact on the mean utilization values, with the mean values for the treatments ranging from 2.75 to 3.72. This variation highlights the differing levels of reliance on various services among the households, with erosion control showing the highest mean utilization (3.72) and pest and disease regulation the lowest (2.75) (Figure 7). The standard error (SE)

values for the treatment means range from 0.161 to 0.264, indicating the precision of the mean estimates, while the coefficient of variation (CV) is 15.16%, reflecting the relative variability in the utilization of regulating services among households. The critical difference (CD) value of 0.442 provides a threshold for determining significant differences between treatment means. Additionally, the standard error of the mean (SE(m)) is 0.156, which helps in assessing the accuracy of the samples' mean estimates.

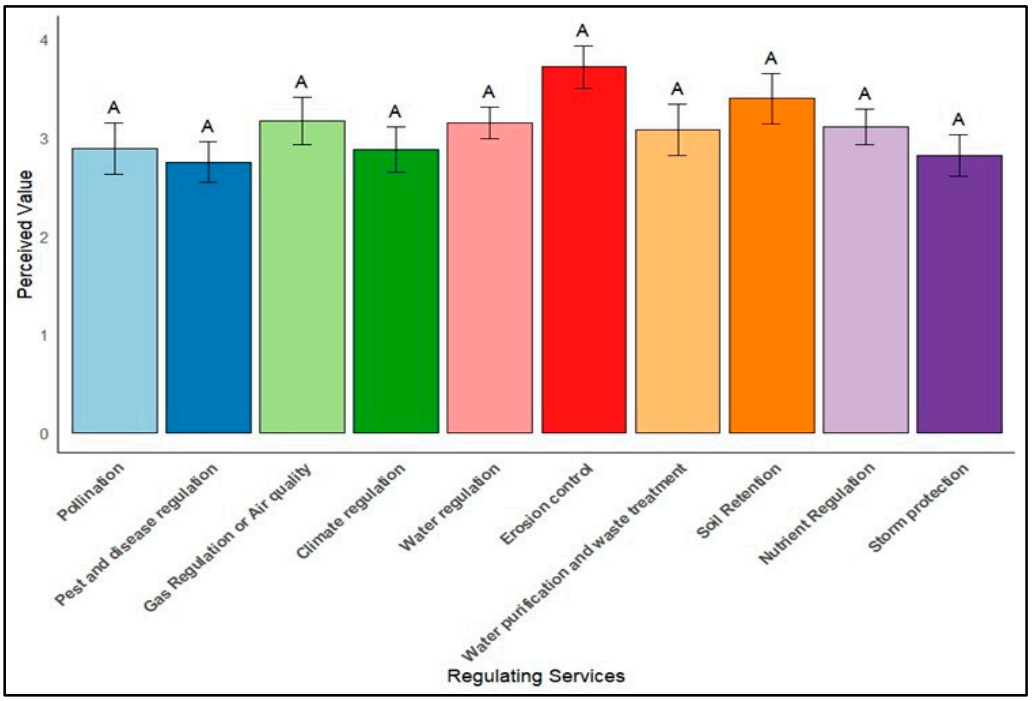

Figure 7. Utilization of regulating ecosystem services among our surveyed villages in the Indian Sundarbans (bars with different letters indicate statistically significant differences, and bars with the same letters are not significantly different).

4. Discussion

The study elucidates dependency on ecosystem services within communities residing in mangrove fringe areas of Indian Sundarbans, an area that is recognized for its diverse ecosystem services [38], and a similar observation was also made by Uddin et al. [5] in the Bangladeshi part of the Sundarbans. At the same time, the ability of this world-famous mangrove forest to provide critical ecosystem services has been declining over the past decades [39,40]. A study by Uddin et al. [41] showed how climate change has a direct impact on provisioning ecosystem services and forest-dependent livelihoods in Bangladesh Sundarbans.

Diversified sources of income exist here, and fishing and aquatic activities emphasize the diversified nature of livelihoods in the Sundarbans area [5]. The varying degrees of dependency among different villages show the complex interaction between natural resource availability, economic necessity, and local perceptions.

This study explores the intricate relationship between ecosystem services and household incomes in the Indian Sundarbans. The findings of the contribution of ESs to annual household income (Section 3.3) depict that households in these village may have diversified their income sources beyond ecosystem services, possibly due to local conditions, economic opportunities, or other factors. Similar findings have been mentioned in studies based on the Sundarbans region of Bangladesh [42,43].

The results of our study provide valuable insights into the community's priorities and perceptions regarding ranking of provisioning ecosystem services. The highest weighted mean value of river transportation suggests that the community highly values the availability of river transportation for their daily activities, which could include commuting, trade, and access to resources located across water bodies. The significance of this service

could be due to the practical and economic benefits it provides. The ranking of fresh water was next to river transportation, and it signifies the crucial role of clean and accessible freshwater sources for drinking, sanitation, and various domestic uses. The third most important provisioning service is observed to be food and fiber. It highlights the community's dependency on local ecosystems for sustenance and materials for daily life. The higher rankings of these three services reflect the direct link between them and residents' basic needs [43]. Services like fuel, natural medicine, and genetic resources also impart crucial roles in energy provision, traditional healthcare practices, and potential future benefits such as biotechnological advancements. Although not ranked at the top, these services are still considered valuable by the community. Some services like pharmacological resources, shade/shelter provision, and ornamental resources ranked lower. Despite their cultural importance, increasing reliance on chemically formulated medicines and concrete building materials as a result of modernization and technological advancements may have impacted the outcomes. These rankings of provisioning services can guide targeted interventions that aim to enhance the most valued services while also recognizing the potential significance of less emphasized ones.

The results of the regulatory ecosystem services survey offer valuable insights into the community's perceptions of the functions that ecosystems provide to regulate environmental processes. The higher rankings of erosion control, soil retention, water regulation, and gas regulation revealed the community's recognition of the importance of these services for ecosystem health and their own well-being. The lower rankings of services like natural hazard regulation and pest disease regulation might reflect the community's focus on services that have more immediate and direct impacts on their lives. However, it is important to recognize that even services perceived as less important still contribute to the overall functioning and resilience of ecosystems. Overall, these findings underscore the diversity in reliance on various ecosystem services among the villages of the studied blocks. Significant differences in service utilization highlight the need for tailored conservation and management strategies that address the specific needs and priorities of different villages. Identifying the most and least utilized services will enable policy makers and conservationists to allocate resources more efficiently, which will result in the sustenance and enhancement of the provisioning of these vital ecosystem services. The associated ANOVA and DMRT analyses provide comprehensive understanding of the utilization patterns of ecosystem services, offering valuable insights for informed decision making and effective ecosystem management.

Our study has several limitations that need to be acknowledged to provide context and direction for future research. One significant limitation is the absence of the impact of local market valuation of mangrove ecosystem services. Markets play a crucial role in how communities value and utilize these services, but this was not explored in this study. The inclusion of this aspect may improve the clarity of the study. While our study assessed the contribution of individual ecosystem services, it did not find out the potential synergistic effects of combination of these services. Different combinations of ecosystem services might yield varying outputs and benefits. Future studies may investigate these combinations to optimize stakeholder returns and enhance the overall value derived from mangrove ecosystems.

5. Conclusions

This study underscores the crucial perceptions and priorities of local communities regarding ecosystem services in the Indian Sundarbans region. The analysis revealed that provisioning ecosystem services heavily rely on food, river transportation, and fresh water and fiber. These services are frequently valued more than agricultural and daily wage work. Society also values services with positive externalities, such as erosion management, soil retention, and water and gas regulation, which are critical for preserving environmental stability and preventing natural disasters. While pest disease regulation was deemed less important, it was still included in the survey, because all these aspects are part of the different functionalities of the ecosystem, which is crucial for the community.

This study emphasizes the need to incorporate ecological services into people's living, coping, and survival methods in the Indian Sundarbans. By combining ecological knowledge with community views, this research contributes to our understanding of how people and their environment are connected and how ecosystem services are essential for daily life. These findings contribute to sustainable development and help to create plans to protect both nature and people's well-being in the Indian Sundarbans. Our results support the idea that understanding ecosystem services is vital for the local environment, and by understanding what people need from these services, we can build a future in which both communities and nature can prosper together.

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