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Ecosystem Productivity and Carbon Dynamics in Keibul Lamjao National Park, Manipur, India: A Grey Relational Analysis Perspective

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Abstract

An in-depth understanding of carbon dynamics and ecosystem productivity is essential for conservation and management of different ecosystems. Ecosystem dynamics and carbon budget are assessed by estimating Net Ecosystem Production (NEP) across different global ecosystems. An ecological productivity assessment of forest and floating meadow ecosystems in Keibul Lamjao National Park (KLNP), Manipur, North East India was conducted using the multi-criteria decision-making process namely, Grey Relational Analysis (GRA). The analysis was performed on 24 selected criterions classified either as "higher-the-better" or "lower-the-better" based on their degree of influence on the carbon budget. Floating meadows exhibited a higher production of aboveground and belowground biomass and a higher total mortality and decay. Furthermore, the study found that floating meadows exhibited a higher soil organic carbon (SOC) and net soil organic matter (SOM) than the forest ecosystem. The forest ecosystem showed higher total respiration (R_T), heterotrophic respiration (R_H), and autotrophic respiration (R_A) than floating meadows. Floating meadows exhibited a higher net primary productivity (NPP) of 616.49 ± 33.87 $gCm^{-2}yr^{-1}$ than the forest ecosystem, which has a NPP of 566.64 ± 65.26 $gCm^{-2}yr^{-1}$. Similarly, Floating meadows have higher NEP (495.25 ± 36.46 $gCm^{-2}yr^{-1}$) than forest ecosystems (418.39 ± 65.76 $gCm^{-2}yr^{-1}$). These characteristics have a significant influence on the carbon budget in floating meadows as compared to forest ecosystems, as shown by larger values of Grey Relational Coefficient (GRC) in GRA. The Floating Meadows Ecosystem (0.82) obtained 54.72% percentage gain in GRG value with the forest ecosystem (0.53). This study might help in improving KLNP and other adjutant areas for conservation and management policies from the vital information given on the importance of wetlands in carbon dynamics and ecosystem productivity.

Keywords: Net Ecosystem Productivity; Carbon budget; Wetlands, Floating Meadows; Forest Ecosystem; Grey Relational Analysis

Introduction

Fundamental principles of ecosystem productivity and carbon dynamics are crucial in the study of ecological systems. An important focus of critical research is to examine the net ecosystem production (NEP) of major ecosystem types since it is essential for understanding the carbon budget and productivity of these natural systems. The NEP is obtained by subtracting the measure of heterotrophic respiration (R_H) from the total primary production (NPP) (Smith et al., 2010; Guo et al., 2021). Scientific studies on the processes beyond NPP, such as litter production, decomposition, and respiration, is necessary to deepen our understanding of ecosystem dynamics and the carbon budget (Randerson et al., 2002). The NEP is a numerical evaluation of an ecosystem's capacity to function as either a net carbon source or sink (Guo et al., 2021). Empirical studies have shown that climate change has a direct impact on ecosystem production (Boisvenue and Running, 2006; Catovsky et al., 2001) The analysis of the fluctuations in NEP may provide valuable insights into the adaptive mechanisms of ecosystems to climate change (Boisvenue and Running, 2006). Furthermore, NEP is linked to biodiversity and ecosystem productivity as it measures the overall feasibility of the ecosystem (Catovsky et al., 2001). Conducting a comprehensive analysis of NEP might improve comprehension of the ecological interdependence among biodiversity, production and carbon sequestration. In accordance with the findings of Carnell et al. (2018) and Pearse et al. (2017), elevated NPP values in wetlands suggest their role as substantial carbon sinks, with the ability to sequester CO_2 from the atmosphere and effectively alleviate the consequences of climate change. The ability of wetlands to sequester a greater amount of carbon per unit area compared to other ecosystems, such as forests; make this very relevant

(Chen et al., 2023). The carbon storage capacity of wetlands is determined by several factors, including hydrology, plant diversity and availability of nutrients and resources. To maintain their substantial potential for carbon storage and production, it is crucial to adhere rigorously to the effective management and conservation strategies (Bernal and Mitsch, 2012; Pearse et al., 2017). Recent scholarly research acknowledges wetlands as significant carbon reservoirs, suggesting that their ability to capture carbon may surpass that of land-based ecosystems (Li et al., 2022; Rogers et al., 2022). In contrast, the function of ecosystem respiration, including both autotrophic and heterotrophic respiration, is to facilitate the retrieval of carbon into the atmosphere, therefore exerting an impact on the overall carbon balance of ecosystems (Tang et al., 2022). An accurate prediction of how ecosystems respond to environmental changes, such as changes in land use and variations in temperature over the seasons, requires a comprehensive knowledge of the equilibrium among many physiological processes (Rogers et al., 2022; Lanceman et al., 2022). These concepts are directly applicable to the management of conservation and the formulation of climate policy, going beyond theoretical models. Implementing environmental restoration and conservation measures as well as improving the ability of wetlands to sequester carbon, would provide a nature-focused strategy to tackle climate change (Bernal and Mitsch, 2012; Zang, 2021). Integrating ecological productivity and carbon dynamics into climate research is crucial for developing potent measures to improve carbon sinks and alleviate the effects of climate change, ensuring the long-term viability of these vital ecosystems (Creed et al., 2022). The current understanding of the specific role of indicators such as NPP, soil organic carbon, soil respiration, litter production, and decomposition in the unique environment of Keibul Lamjao National Park (KLNP) of Manipur State which is part of Loktak Lake (Ramsar site), the only floating national park worldwide, is inadequate. The presence of this gap poses challenges to the development of effective conservation and management strategies for this unique environment.

The Grey Relation Analysis (GRA) technique a Multi-Criterion Decision Making (MCDM) approach was introduced by Julong (1982) for evaluating the relative importance of the various criterions/components within a same system and investigates uncertainty arisen by these components (Wang et al., 2019). This is particularly advantageous in situations where the data is not measured in a same scale or the interaction between components is not fully comprehended. GRA is a statistical method that is employed to assess and organize a variety of components by examining their relative significance and influence within a specific system. In a limited number of studies, GRA has been implemented to assess forest services, including water retention capacity (Huiwen et al., 2018; Saha et al., 2021), agricultural variety assessment (Zhang et al., 2018; Qazi et al., 2021) and watershed soil erosion risk management (Pandey et al., 2022). However, there is a significant lack of information regarding the application of such MCDM techniques in the study of ecological productivity and carbon dynamics. The aim of this study was to compare and contrast the primary indicators that influence the productivity and carbon dynamics of a variety of ecosystems, with a particular focus on forest and floating meadow ecosystems in Manipur North East India, following GRA method. In order to better understand the main elements that impact the performance of ecosystems and ecological processes, the present study employed GRA to analyze the variations in their carbon budgets.

Materials and Methods

Study Area

The study area (24°27′N - 24°31′N latitudes; 93°53′E - 93°55′E longitudes) lies in the south-east part of Loktak Lake in Bishnupur district, Manipur, North East India (Fig. 1). The National Park covers 40 km², with 26 km² being floating meadows locally known as Phumdi and 14 km² consisting of hills, hillocks with small woodlands and elevated areas of land that are frequently submerged during severe floods (Tuboi and Hussain, 2018). The region is characterized by three primary ecosystems i.e., floating meadows (phumdi), woodlands (hills and hillocks), and open-water ecosystems (Meetei et al., 2022). This is the only floating National Park in the world and serves as the habitat for an endangered deer species *Rucevus eldii eldii*, known as Sangai in Manipur state. The area is interspersed with hillocks. The highest elevation hillocks in the park are IB2 (843 m), Pabot (788 m), Chingjao (783 m) and Toya (779 m) above mean sea level (Tripathi et al., 2024). Over 185 varieties of grasses and sedges dominate the landscape, sometimes reaching heights of up to 12 m (Tuboi and Hussain, 2016). The maximum temperature (34°C) recorded during June-July, while the minimum temperature (4°C) observed during January nights (Tripathi et al., 2024). Approximately 1,392 mm of precipitation is received annually in this region. The hills provide refuge for Sangai deer and other large animals during the rainy season.

Sampling Methods

Stratified random sampling with proportional allocation was followed in the present study with two ecosystem types, viz., Floating Meadows and Forest ecosystems, as stratum.

Sampling sites were equally distributed in both the strata based on the area coverage of floating meadows and forest ecosystems.

Estimation of Biomass production

The harvest method developed by Anderson and Ingram (1993) was followed to quantify the above-ground biomass (AGB) in the floating meadows ecosystems. Plants were collected at regular intervals and separated into living and deceased tissue. Field-weighed above-ground components were subjected to oven-drying at 70°C until a constant weight was achieved for sub-samples. Subterranean portions with attached soil were brought to the laboratory, washed to eliminate soil, and visually examined for living (hyaline) and deceased (brown to black) roots and rhizomes. The samples were subjected to oven-drying at 70°C in order to quantify the live and dead biomass present below the surface. To determine the carbon content of both above and below-ground plant components, the ash content method (Negi et al., 2003) was followed. The computation of biomass production was based on the disparity in biomass between any two consecutive censuses.

The girth of all trees (≥30cm) and small trees (10-30cm) in the forest ecosystem was measured at 1.37m above the ground and converted to diameter at breast height (DBH). Nested quadrats of 3m × 3m for shrubs, leaf debris and deadwood, and 1m × 1m for herbs, were laid within the primary allotment of 31.62m × 31.62m to estimate other carbon pools. Herb quadrats were nestled within shrub quadrats that were positioned in two opposite corners of the tree plot. The herbs and shrubs within the sample plots were uprooted and fresh weight was recorded in the field. Leaf litter and fallen dead debris were collected from the 3m × 3m quadrats; a sub-sample was drawn and transported to the laboratory to estimate the dried biomass and carbon stock. Data were collected on the same sites twice over two years to estimate net primary productivity and biomass production. The following formulae were used to compute small trees biomass, deadwood biomass, AGB and carbon storage as well as below-ground biomass (BGB) and carbon storage.

$\mathrm{AGB} = 0.18\mathrm{DBH}^{2.16} \times 1.32$ (Nath et al., 2019)
$\mathrm{BGB} = \mathrm{AGB} \times 0.20\ (\mathrm{AGB} < 125\ \mathrm{Mg/ha})$ (Mokany et al., 2006)
$\mathrm{BGB} = \mathrm{AGB} \times 0.24\ (\mathrm{AGB} \geq 125\ \mathrm{Mg/ha})$ (Mokany et al., 2006)(
$\mathrm{AGBC} = \mathrm{AGB} \times 0.47$ (IPCC, 2006)
$\mathrm{BGBC} = \mathrm{AGBC} \times 0.205\ (\mathrm{AGBC} \leq 62.5\ \mathrm{Mg\ C/ha})$ (Mokany et al., 2006)
$\mathrm{BGBC} = \mathrm{ABBC} \times 0.235\ (\mathrm{AGBC} > 62.5\ \mathrm{Mg\ C/ha})$ (Mokany et al., 2006)
Deadwood, $V = \frac{L \times \pi \times (dm)^2}{4}$ (Du Cros and Lopez, 2009)

AGB (small tree) = 3.34 + 0.443 x $\ln(DBH)^2$	(Chaturvedi et al., 2012)

AGBC = Above Ground Biomass Carbon; BGBC = Below Ground Biomass Carbon; L= length; dm = mid-diameter

Estimation of Soil Organic carbon

Soil samples from 0-45cm depth were collected randomly from both the ecosystems. A soil corer with a predetermined volume was employed to obtain additional samples for bulk density from undisturbed sites. Walkley and Black (1934) wet oxidation method was followed to analyse SOC content. The following formulas were used to calculate soil bulk density (BD) and SOC:

BD (g/cm^3) = dry soil mass (g) / volume of soil corer (cm^3)

SOC = BD × depth × Organic carbon %

Estimation of Litterfall, Litter Production and Decay

The above-ground litterfall in the floating meadow ecosystems was measured at monthly interval using fifteen quadrats (50cm x 50cm). Root and rhizome litter (below-ground litter) was collected from fifteen additional quadrats of the same size that were laid near the above-ground quadrats already laid under stratified sampling scheme. Following Anderson and Ingram (1993), belowground litter (dead rhizomes and roots) was identified. Until a consistent weight was attained, all samples were oven-dried at 70°C to quantify biomass. Litterfall in the forest ecosystem was quantified by fixing ten litter traps (1m x 1m) with perforated nylon net bottoms that were set up at random. Litter was collected monthly, oven-dried at 80°C, and weighed to determine its dry weight. To quantify standing fine roots with a diameter of $\leq$2mm for below-ground production, sequential soil coring was used (Assefa et al., 2017) Following Anderson and Ingram (1993), fine roots were identified as either live or dead. Intact soil cores were collected from a depth of 40 cm using a 6.6 cm stainless steel corer (Assefa et al., 2017), and subsequently separated into 10cm depth increments. A mixture of fine roots from each depth was prepared, oven-dried at 80°C and weighed. The Max-Min approach was employed to determine the annual fine root production ($g\ m^{-2} year^{-1}$).

In the forest ecosystems, 60 nylon bags (15cm × 15cm, 1mm mesh) were stuffed with ten grams of air-dried aboveground (AG) and belowground (BG) litter and placed above the soil. Similarly, in the floating meadow ecosystems, 60 nylon bags were stuffed with ten grams of air-dried AG and BG litter and placed over dense vegetation. After collecting, the litter bags were carefully cleaned of soil particles and oven-dried at 70°C until a constant weight was achieved. Monthly mass loss (g) was estimated by subtracting the remaining litter mass in each bag from the preceding month measured mass. The mass loss over time was calculated using the negative exponential decay model (Olson, 1963).

Estimation of Total Respiration (R_T)

The alkali absorption approach proposed by Keith and Wong (2006) was used to determine the total soil respiration (R_T) (gCm^{-2}) at seasonal intervals. Each ecosystem was equipped with chambers of 30cm diameter, 8.5cm height and covering a surface area of $0.07065m^2$. The chambers were inserted into the layer of litter and topsoil to a depth of about 1.5cm. In order to reduce disruption, chambers were positioned many weeks before measurements and left exposed for 24 hours. Prior to measurement, the existing vegetation inside the chambers was clipped at ground level. Fifty grams of oven-dried soda-lime granules were carried to the field on secured petri dishes, then unshielded and wet with 8ml of fine spray to initiate CO_2 absorption. The petri dishes were kept above the litter surface through the use of wire stands mounted inside the chambers. Following a 24-hour period, the Petri dishes were collected, securely fastened and transported to the laboratory. Similarly, the blank chambers were set up with sealed bottoms, to avoid ambient CO_2 absorption and chamber leakage. This method is based on CO_2 adsorption by soda lime as shown by weight increase.

Net Primary Productivity (NPP) and Net Ecosystem Production (NEP)

The following equations were followed to calculate the NPP and NEP:

$$\text{Litter Production}_{AG} = \Delta\ \text{Litterfall}_{AG} + \text{Decay}_{AG}$$

$$\text{Litter Production}_{BG} = \Delta\ \text{Litterfall}_{BG} + \text{Decay}_{BG}$$

$\text{Decay} = \text{Litterfall}\ (e^{-kt})$ where k is decay rate at time t.

$$\text{Mortality}_{AG} = \Delta\ \text{Dead biomass}_{AG} + \text{litterproduction}_{AG}$$

$$\text{Mortality}_{BG} = \Delta\ \text{Dead biomass}_{BG} + \text{litterproduction}_{BG}$$

$$\text{NPP}_{AG} = \Delta\ \text{Live biomass}_{AG} - \text{Mortality}_{AG}$$

$$\text{NPP}_{BG} = \Delta\ \text{Live biomass}_{BG} - \text{Mortality}_{BG}$$

$$R_H = \text{Decay}_{A+B} - \Delta\text{SOC}$$

$$R_A = R_T - R_H$$

Net soil organic matter (SOM) = Litter production - R_H

$$\text{NEP or Carbon Budget} = \text{NPP} - \text{R}_\text{H}$$

The subscript AG and BG represents the ‘Above Ground’ and ‘Below Ground’ respectively and Δ indicates net changes in a year.

Grey Relational Analysis (GRA)

A comparative ecological performance of floating meadows and forests is assessed using GRA (Fig. 2). For this purpose, 24 important characters were used to determine their relative importance and aggregate impact on ecosystem functioning (Table 1). The variables were classified as either "higher-the-better" or "lower-the-better" based on their ability to contribute to the carbon budget. Variables such as AGBC, BGBC and NPP were classified as "Type -A" (higher-the-better) because they tend to be associated with improved carbon storage and production, all of which have a positive impact on the carbon budget. Variables such as Total Respiration (R_T), Decay, and Mortality were categorized as "Type-B" (lower-the-better) since higher values in these parameters often indicate more carbon loss; less carbon storage efficiency and resultant lower NEP (Table 1).

The standardized transformation to normalize the various scales of measurement of the characters was carried out using the following formulae for each of the two categories of characters. Eq. (1) and (2) were used for Type-A and Type-B, respectively. Using equation (3), the Grey Relational Coefficient was calculated from normalized data to quantify the relation between the performance of each ecosystem and the ideal (reference) performance.

Type-A Character $X_i = \frac{X_i - \min_i X_i}{\max_i X_i - \min_i X_i}$ (1)

Type-B Character $X_i = \frac{\max_i X_i - X_i}{\max_i X_i - \min_i X_i}$ (2)

Grey Relational Coefficient, $\xi_i = \frac{\Delta_{min} + d\Delta_{min}}{\Delta_{X_i} + d\Delta_{max}}$ (3)

where, Δ_{X_i} represents absolute deviation of X_i from the ideal performance. Ideal performance of Type A and Type B are 1 and 0 respectively. $d \in [0,1]$ is a distinguishing coefficient which expand or compress the range of the grey relational coefficient. In this study, the results are based upon d= 0.5.

An equal weight (w_i) of 1/24=0.042 was assigned to each character X_i of each component, resulting in a total weight of 1 for all characters. The Grey Relational Coefficients were used to generate grey relational grades (GRG) using Eq. (4) and the performance of each ecosystem was determined based on these GRGs.

$$GRG(X_i) = \sum_i w_i \xi_i \tag{4}$$

Ecosystems are classified based on their Grey Relational Grades (GRG), which enables a comparison assessment of their ecological performance. A high GRG for an ecosystem, i.e., closer to one, indicates better overall performance in terms of the carbon budget.

Results

Biomass Production

The maximum 2,814.99 ± 22.06 gCm^{-2} AG live biomass was recorded during the post-monsoon season (Fig.3). However, the lowest 213.59 ± 18.07 gCm^{-2} biomass was recorded during the winter season. AG dead biomass exceeds 752.99 ± 3.20 gCm^{-2} during the pre-monsoon season and falls below 616.05 ± 8.91 gCm^{-2}during the winter season. The monsoon season showed maximum 2,132.44 ± 22.76 gCm^{-2} BG live biomass, while the lowest 1,502.02 ± 13.15 gCm^{-2} BG live was recorded in winter season. The highest 796.46 ± 12.71 gCm^{-2} BG dead biomass was recorded during the post-monsoon season while lowest 657.12 ± 14.66 gCm^{-2} was recorded during the winter season. From 2022 to 2023, forest ecosystem components showed an overall increase in biomass production. In 2022, the tree biomass was 141.08 ± 16.55 Mg ha^{-1} and in 2023, it increased to 156.16 ± 17.30 Mg ha^{-1} (Table 2). The herb biomass increased from 2.06 ± 0.29 Mg ha^{-1} to 2.15 ± 0.30 Mg ha^{-1}, while the shrub biomass increased from 2.64 ± 0.25 Mg ha^{-1} to 2.76 ± 0.26 Mg ha^{-1}, reflecting similar trends. The biomass of litter also increased slightly from 1.06 ± 0.03 Mg ha^{-1} to 1.17 ± 0.03 Mg ha^{-1}. The deadwood biomass grew from 12.77 ± 3.98 Mg ha^{-1} to 13.44 ± 4.08 Mg ha^{-1}. Similarly, the biomass of small trees rose from 28.63 ± 4.03 Mg ha^{-1} to 29.53 ± 4.16 Mg ha^{-1}. A notable increase in the AG biomass was observed from 188.26 ± 14.36 Mg ha^{-1} in 2022 to 205.23 ± 14.90 Mg ha^{-1} in 2023. Similarly, BG biomass increased from 45.18 ± 3.44 Mg ha^{-1} to 49.25 ± 3.57 Mg ha^{-1}. The total biomass production of 1,608.10 ± 28.48 gCm^{-2} yr^{-1}in the floating meadows ecosystem was considerably higher than the 984.66 ± 67.63 $gCm^{-2}yr^{-1}$ in the forest ecosystem (Table 3). In the present study, the AG and BG production in the floating meadows was recorded to be higher than that of forest ecosystem.

Litterfall, Litter Production and Decay

The BG litterfall in the floating meadows were higher, especially during the monsoon and pre-monsoon seasons, with an estimated value of 722.735 ± 5.79 gCm^{-2} and 707.876 ± 5.32 gCm^{-2} respectively (Fig. 4). The maximum 217.704 ± 5.12 gCm^{-2} aboveground litterfall was observed during the post-monsoon season. AG litterfall in the forest ecosystem was at peak during the pre-monsoon season with an estimated value of 256.761 ± 1.17 gCm^{-2}, while maximum 133.407 ± 0.08 gCm^{-2} BG litterfall was estimated during the monsoon season. The total 294.21 ± 1.31 gCm^{-2} yr^{1} litterfall in the forest ecosystem was marginally higher than that of the 269.93 ± 7.74 gCm^{-2}yr^{1} in the floating meadows. However, 210.23 ± 1.17 gCm^{-2}yr^{-1} AG litterfall estimated in the forest ecosystem was higher than the 108.13 ± 2.79 gCm^{-2}yr^{-1} estimated in the floating meadows, while the BG litterfall estimated to be 161.80 ± 6.71 gCm^{-2}yr^{-1} in the floating meadows was higher than that of forest ecosystem. Both, the floating meadows and forest ecosystems revealed almost similar estimates of total litter production. The former has an annual litter production of 439.03 ± 12.53 gCm^{-2}yr^{-1}, while the latter has an annual litter production of 448.32 ± 1.90 gCm^{-2}yr^{-1} (Table 3). Although the forest ecosystem has a larger AG LP (321.69 ± 1.70 gCm^{-2}yr^{-1}) but the floating meadows have a higher BG LP (260.68 ± 10.81 gCm^{-2}yr^{-1}). The floating meadows have a comparatively higher decay rate of 169.10 ± 4.78 gCm^{-2}yr^{-1} compared to the forest ecosystem, which has a total decay rate of 154.11 ± 0.69 gCm^{-2}yr^{-1}). The floating meadows exhibited a higher BG decay of 98.88 ± 4.10 gCm^{-2}yr^{-1} whereas in the forest ecosystem AG decay rate was estimated at 111.46 ± 0.62 gCm^{-2}yr^{-1} which was higher than the floating meadows (Table 3). The floating meadows had considerably greater total mortality of 715.32 ± 20.42 gCm^{-2}yr^{-1} as compared to the 498.86 ± 9.95 gCm^{-2}yr^{-1} in the forest ecosystem (Table 3). The overall AG mortality rates were higher in the floating meadows as compared to the forest ecosystem.

Soil Respiration and Soil Organic Matter

The soil organic carbon (ΔSOC) of the floating meadows ecosystem was estimated at 47.50 ± 0.71 gCm^{-2}yr^{-1}) while in the forest ecosystem it was 12.71 ± 0.58 gCm^{-2}yr^{-1} (Table 4). The forest ecosystem revealed a slightly higher Heterotrophic Respiration (R$_H$) rate of 141.39 ± 0.72 gCm^{-2}yr^{-1} compared to the 121.23 ± 4.64 gCm^{-2}yr^{-1} in the floating meadows (Table 4). In the forest ecosystem total respiration (R$_T$) rate of 265.28 ± 3.99 gCm^{2} yr^{-1} and 123.88 ± 4.15 gCm^{-2}yr^{-1} autotrophic respirations (R$_A$) was estimated. In contrast, the floating meadows have a lower R$_T$ value of 225.07 ± 1.83 gCm^{-2}yr^{-1} and 103.83 ± 5.04 gCm^{-2}yr^{-1} R$_A$ which is in line with their higher ΔSOC. The net soil organic matter (Net SOM), which was determined as the differences between total LP and R$_H$, indicates that floating meadows accumulate a higher amount of organic matter (317.79 ± 7.96 $\mathrm{gCm^{-2}yr^{-1}}$) than the forest ecosystem (306.92 ± 1.54 $\mathrm{gCm^{-2}yr^{-1}}$) (Table 4).

Net Primary Productivity and Net Ecosystem Production

The total NPP in the floating meadows was estimated to be 616.49 ± 33.87 g C $\mathrm{m^{-2}}$ $\mathrm{yr^{-1}}$ which was slightly higher than the forest ecosystem where it was estimated at 566.64 ± 65.26 g C $\mathrm{m^{-2}}$ $\mathrm{yr^{-1}}$ (Table 3). However, the below ground NPP (230.38 ± 24.47 g C $\mathrm{m^{-2}}$ $\mathrm{yr^{-1}}$) in the floating meadows was significantly higher than the 171.55 ± 11.88 g C $\mathrm{m^{-2}}$ $\mathrm{yr^{-1}}$ estimated in the forest ecosystem. Moreover, the NEP value of 495.25 ± 36.46 g C $\mathrm{m^{2}}$ $\mathrm{yr^{-1}}$ in the floating meadows was noticeably higher than the 418.39 ± 65.76 g C $\mathrm{m^{2}}$ $\mathrm{yr^{-1}}$ in the forest ecosystem (Table 4). The spatial distribution of NEP across KLNP revealed a comparable heterogeneity. The majority of the higher productivity region was observed in the west-central portion of the park, which is dominated by tall grass and thick mats (Fig. 5).

Grey Relational Analysis

The Grey Relational Coefficients (GRCs) for each ecological parameter are presented in Fig. 6, which emphasizes their relative impact on the carbon budget in the forest ecosystems and floating meadows. The floating meadows ecosystem has maximum GRCs of 1.000 for parameters like AGBP, BGBP, Total BP, AGLP, Total LF, Decay AG, Mortality AG, NPP BG, Total NPP, SOC, RT, RA, SOM and NEP. On the other hand, BGLF, BGLP, Decay BG, Total Decay, Mortality BG, Total Mortality, NPP AG, and RH showed the highest GRCs of 1.000 in the forest ecosystem. The ecosystems were ranked using the GRGs, which were calculated using the GRCs. The state of contributing more to the carbon budget can be observed by the highest GRG value, 0.82, which is close to the ideal GRG value 1. Further, the percentage gain in GRG value of floating meadows with forest ecosystem is 54.72% which is comparatively very high. The floating meadows ecosystem with rank 1 has a more substantial relationship with the carbon budget than the forest ecosystem (Table 5).

Discussion

The seasonal variation in the estimated biomass observed in floating meadows provides information on the complex ecological processes of carbon distribution in wetland ecosystems. The maximum AG live biomass accounted in the post-monsoon season, along with the highest BG live observed during the monsoon season, highlights the crucial influence of seasonal water availability and nutrient dynamics on plant biomass production.

The assimilation of nutrients may be facilitated by elevated water levels, which in turn accelerates the growth rates of wetland plants. The contrasting trends in dead biomass, with higher AG dead biomass during the pre-monsoon season and BG dead biomass during the post-monsoon season, indicate varying decomposition rates and accumulation of organic matter over various seasons. The accumulation of dead biomass during the pre-monsoon season may indicate a phase of senescence and nutrient recycling, whereas the rise in BG dead biomass during the post-monsoon season can be ascribed to increased microbial activity and decomposition processes facilitated by desired moisture levels in the soil (Dolinar et al., 2015; Overbeek et al., 2019). The concurrent increase in AG biomass and BG biomass is consistent with well-documented trends in forest ecosystems, where the accumulation of biomass is influenced by a variety of factors, including stand age, environmental conditions and carbon allocation dynamics (Wang et al., 2023; Zhang et al., 2015a). Furthermore, determining the relationship between the aboveground and belowground components is essential for comprehending the ecosystem function, as a single alteration may impact the other through litter supplies and root interactions (Hyodo et al., 2016). In comparison to the forest ecosystem, the floating meadows stored more biomass both above and below ground. This trend aligns with research indicating that wetlands, especially those composed mostly of herbaceous plants, often exhibit greater biomass output as a result of their rich nutrient settings and hydrological factors that promote plant development (Stagg et al., 2017).

The total litterfall of the forest ecosystem (294.21 ± 1.31 $gCm^{-2}yr^{-1}$) is marginally higher than that of the floating meadows (269.93 ± 7.74 $gCm^{-2}yr^{-1}$). These results correspond to other studies that indicate that forest ecosystems often generate a greater amount of aboveground litter due to their complex structure and larger biomass (Shen et al., 2019). More precisely, the amount of AG litterfall in the forest ecosystem (210.23 ± 1.17 $gCm^{-2}yr^{-1}$) was comparably higher than that in the floating meadows (106.11 ± 4.22 $gCm^{-2}yr^{-1}$). These findings align with the results of (Neumann et al., 2018) who observed that forest litterfall is mostly characterized by leaf and branch inputs, suggesting the productivity of tree canopy. The ecological importance of belowground biomass in wetlands is highlighted by the higher BG litterfall in floating meadows compared to forest ecosystems. Previous studies have shown that plants in wetlands may adjust to their hydric environment, resulting in improved carbon dynamics and enhanced productivity (Gorham et al., 2012). Higher AG LP values were observed in forest ecosystems, however, higher BG LP was recorded in floating meadows. This variation in production highlights the fundamental ecological principles that many ecosystems use to make the most of the resources at their disposal. This trend corresponds with other studies that suggest that wetlands, particularly floating meadows, allocate a higher proportion of biomass to below-ground structures as a result of the need to access water and nutrients in saturated soils (Stagg et al., 2017). The total rate of decay in floating meadows exceeded that in the forest ecosystems, demonstrating the significant production and accumulation of organic matter in wetland ecosystems (Bernal and Mitsch, 2012).

The higher amounts of soil organic carbon (ΔSOC) and soil organic matter (SOM) in floating meadows indicate that wetland soils have a greater capacity to store carbon as compared to the forest ecosystems. These observations are in congruence with other studies that emphasize the exceptional ability of wetlands to capture organic carbon as a result of their distinct hydrological conditions and plant dynamics. For instance, Zhang et al. (2015b) reported that wetlands have a higher capacity to store plant organic carbon in their soils which is essential for efficient carbon sequestration. Moreover, it has been noted that the species richness and structural complexity of floating meadows may improve carbon storage since the diverse plant communities that make up these ecosystems aid in the build-up of organic matter (Cunha et al., 2012).

Soil respiration differs with ecosystem types and environmental conditions (Peri et al., 2015). Ecosystem respiration depends on autotrophic and heterotrophic activities and both of these are regulated primarily by organic inputs, soil temperature and soil moisture (Wei et al., 2010). Heterotrophic respiration derives from the mineralization of soil organic matter (Fang et al., 2005; Reichstein et al., 2005), and hence litter inputs are likely to play a key role. Indeed, Bond-Lamberty et al. (2004) found a significant correlation between total detritus inputs and heterotrophic respiration. Although soil temperature and moisture are the primary factors influencing heterotrophic respiration, the physiology related to autotrophic respiration may also have a significant impact on root respiration (Tang and Baldocchi, 2005). The lower R_T, R_A, and R_H in the floating meadows are consistent with their higher soil organic carbon values. This suggests that these ecosystems retain a greater amount of carbon in the soil rather than emitting it as CO_2 (Zhang et al., 2015b). The distinctive characteristics of wetland habitats, including persistent inundation and reduced temperatures, might restrict microbial activity, thereby impacting the total rates of soil respiration (Zhang et al., 2015b). The observed higher ΔSOC and SOM values in the floating meadows substantiate the notion that wetland ecosystems are efficient in storing carbon over time. Bernal and Mitsch (2012) suggest that wetlands can accumulate significant quantities of organic carbon by limiting decomposition activities and preserving plant organic matter.

The wetlands exhibit a broad range of variation in net primary production (Peregon et al., 2008). The NPP value of 619 ± 33.87 g C m^{-2} $year^{-1}$ in floating meadows is within the range reported in previous studies. The NPP of temperate peatlands, such as those found in the Sanjiang Plain in Northeast China, ranges from 590 to 1260 g C m^{-2} $year^{-1}$ (Xing et al., 2015). Numerous field studies have demonstrated that the NPP of marshes and wetlands in Northern America and Europe falls within the range of 400 to 1000 g C m^{-2} yr^{-1} (Peregon et al., 2008). The findings of Devi and Yadava (2009) of NPP values for semi-evergreen tropical forests in Manipur and (Nayak et al., 2012) on the inter-annual variability of NPP across various land cover types, including forests are in conformity with the estimates of the present study of net primary productivity of forests. However, it is less than the results reported by Baishya and Barik (2011) on a old *Pinus kesiya* forests in Northeastern India. A notable disparity in NEP values between floating meadows and forest ecosystems underlines the necessity to take into account the structure and composition of the ecosystem type when assessing carbon dynamics. The distinctive features of peatlands, such as their hydrological and vegetational composition are imperative for their efficient capacity to fix carbon (Koehler et al., 2011; Ward et al., 2013; Gavazov et al., 2018;). Temperate freshwater wetlands have been demonstrated to have significantly higher rates of carbon sequestration than temperate forests which support their critical function as carbon sinks (Pearse et al., 2017) The significant ability of wetlands to capture carbon is often ascribed to waterlogging conditions, which hinder the breakdown processes and hence enable the gradual build-up of organic matter (Nahlik and Fennessy, 2016; Chimner et al., 2023). This characteristic is critical to the long-term viability of wetlands and their influence on global carbon cycles.

In most parameters, the Grey Relational Coefficients (GRC) of floating meadows exceeded the forest ecosystems, indicating a more significant influence of these factors on the carbon budget. Parameters such as AGBC, BGBC, NPP and SOC are of significant importance in the floating meadows, suggesting a more robust carbon storage and nutrient cycling framework in this ecosystem. The Grey Relational Grades (GRGs) derived from the Grey Relational Coefficients offer critical information on the closeness of ecosystems to the optimal GRG value of 1, indicating their impact on the carbon budget. In the comparison between the forest ecosystem and the floating meadows ecosystem, the floating meadows ecosystem demonstrated a higher GRG value of 0.82, thereby being at the highest rank of 1. This greater GRG value indicates a more pronounced correlation with the carbon budget in comparison to the forest ecosystem with a GRG value of 0.53. This suggests that the floating meadows ecosystem has a greater impact on carbon storage and productivity. The findings emphasized the importance of wetlands in the process of carbon storage and subsequent enhancements in ecological production (Pearse et al., 2017; Chen et al., 2023). Wetlands are recognized for their ability to act as carbon sink, therefore, assisting in the mitigation of the impacts of climate change (Zhang et al., 2015b). A higher GRG rating for the floating meadows ecosystem indicates that it has a greater potential for enhancing the carbon budget than the forest ecosystem in the Keibul Lamjao National Park, Manipur. The outcomes of this study provide crucial information for improving conservation efforts and management approaches. By prioritizing ecosystems with higher GRGs, such as floating meadows, park managers may maximize carbon storage capacity while also improving ecological sustainability. Adopting this approach is critical for responsible environmental management and effective climate change mitigation, ensuring that the Keibul Lamjao National Park plays an important role in carbon dynamics on a global and regional scale.

Conclusion

The present study has elucidated the complex interplay between carbon dynamics and ecosystem productivity in the floating meadows and forest ecosystems of the Keibul Lamjao National Park. The findings highlight the substantial influence of the structure and composition of ecosystem types on the functions and carbon budget. As compared to the forest ecosystem, the floating meadows ecosystem had better carbon storage and productivity, as shown by its higher values of NEP and SOC. The Grey Relational Analysis further emphasized the relative importance of many ecological parameters. The floating meadows ecosystem has the strong carbon storage capacity and ecosystem productivity, as revealed by a higher Grey Relational Coefficients (GRCs) in parameters such as AGBP, BGBP, SOM, and NEP. The higher Grey Relational Grade (GRG) of the floating meadows as compared to the forest ecosystem suggests a significant relationship with the carbon budget, emphasizing the critical role of wetlands in ecosystem productivity and carbon dynamics. Furthermore, the findings provide considerable insights for conservation strategies, indicating that prioritizing the protection and management of floating meadows might optimize carbon sequestration and improve ecological sustainability.

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Author contribution K.B.M.: Conceptualization; Methodology; Data collection; Formal analysis; Investigation; Visualization; Data curation; Writing – original draft. M.T.: Visualization; Manuscript editing. G.C.: Conceptualization; Methodology: Formal analysis: Validation; Writing – review and editing; D.M.: Visualization; Manuscript editing. K.G.: Conceptualization; Methodology; Supervision; writing – review and editing.

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Data availability statement: Data will be made available on reasonable request

Declarations

Ethical approval The authors confirm that all studies described in this manuscript were carried out in an ethical and responsible manner, adhering fully to all pertinent codes of experimentation and legislation.

Competing Interests The authors declare no competing interests.

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Figures

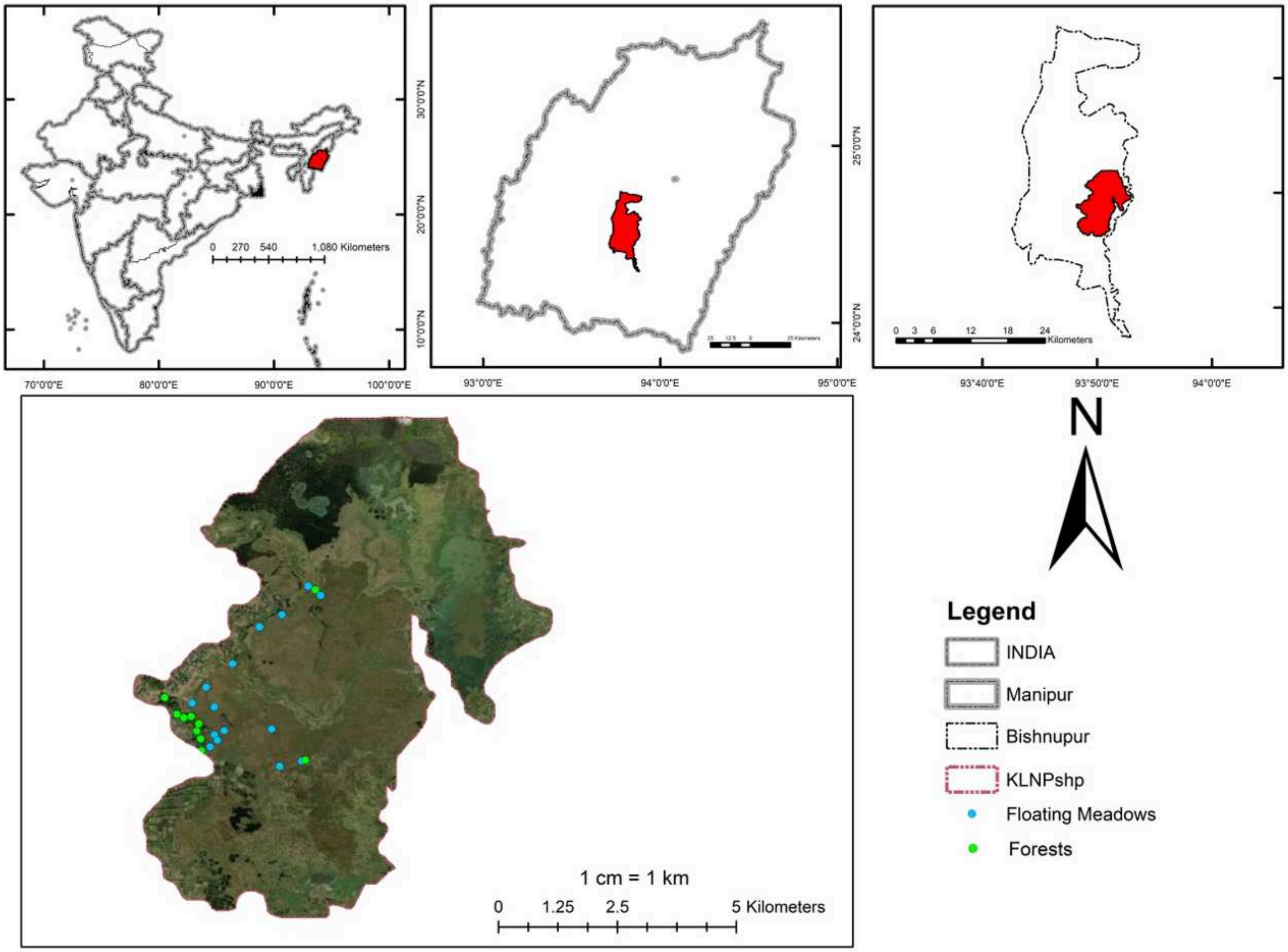

Figure 1

The map illustrates the study area to (a) India, (b) the boundaries of Manipur state, (c) Bishnupur district and (d) study area map of KLNP with sampling locations

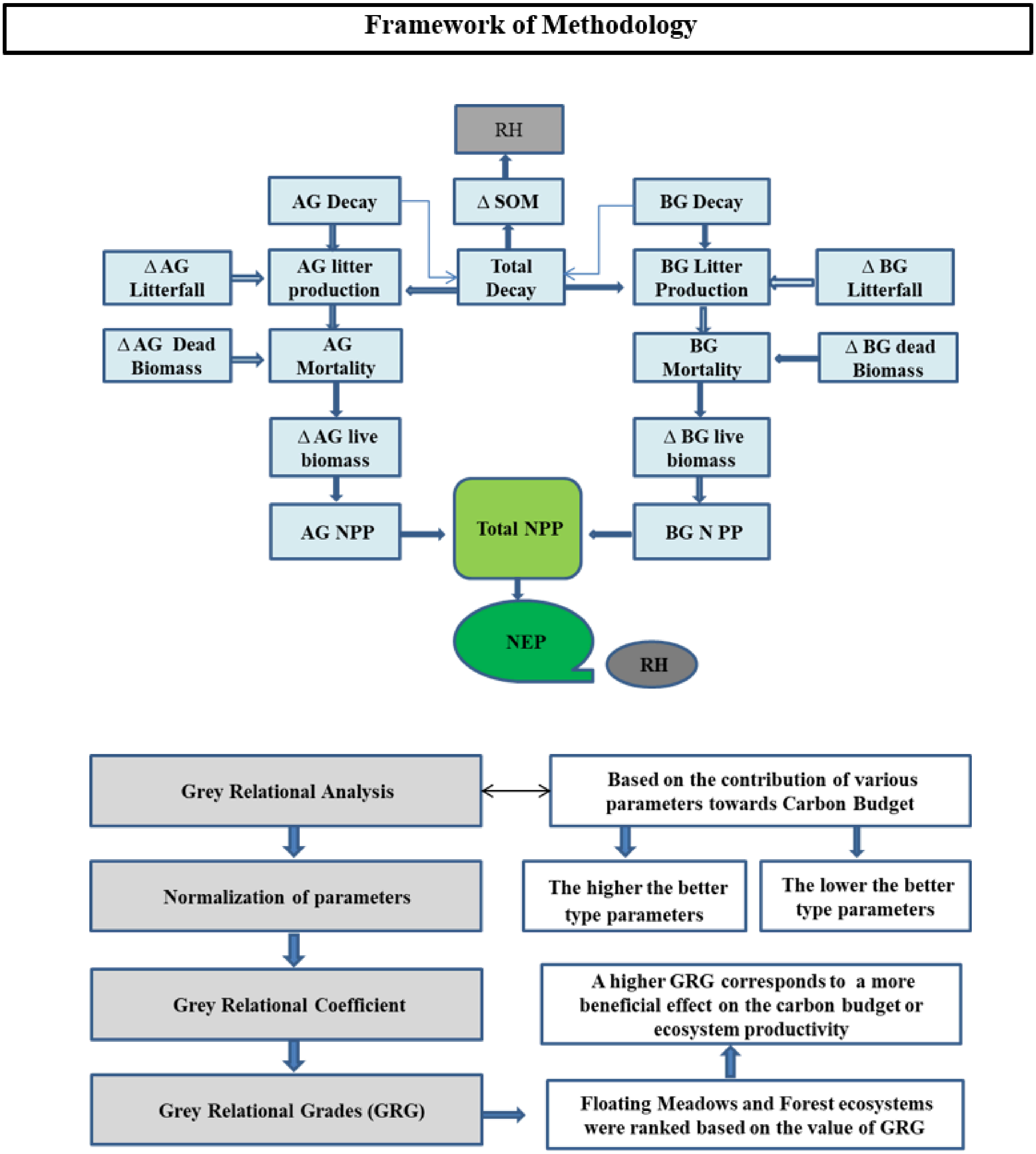

Figure 2

The methodology and conceptual framework for estimating NEP and ranking floating meadows and forest ecosystems of KLNP using GRA

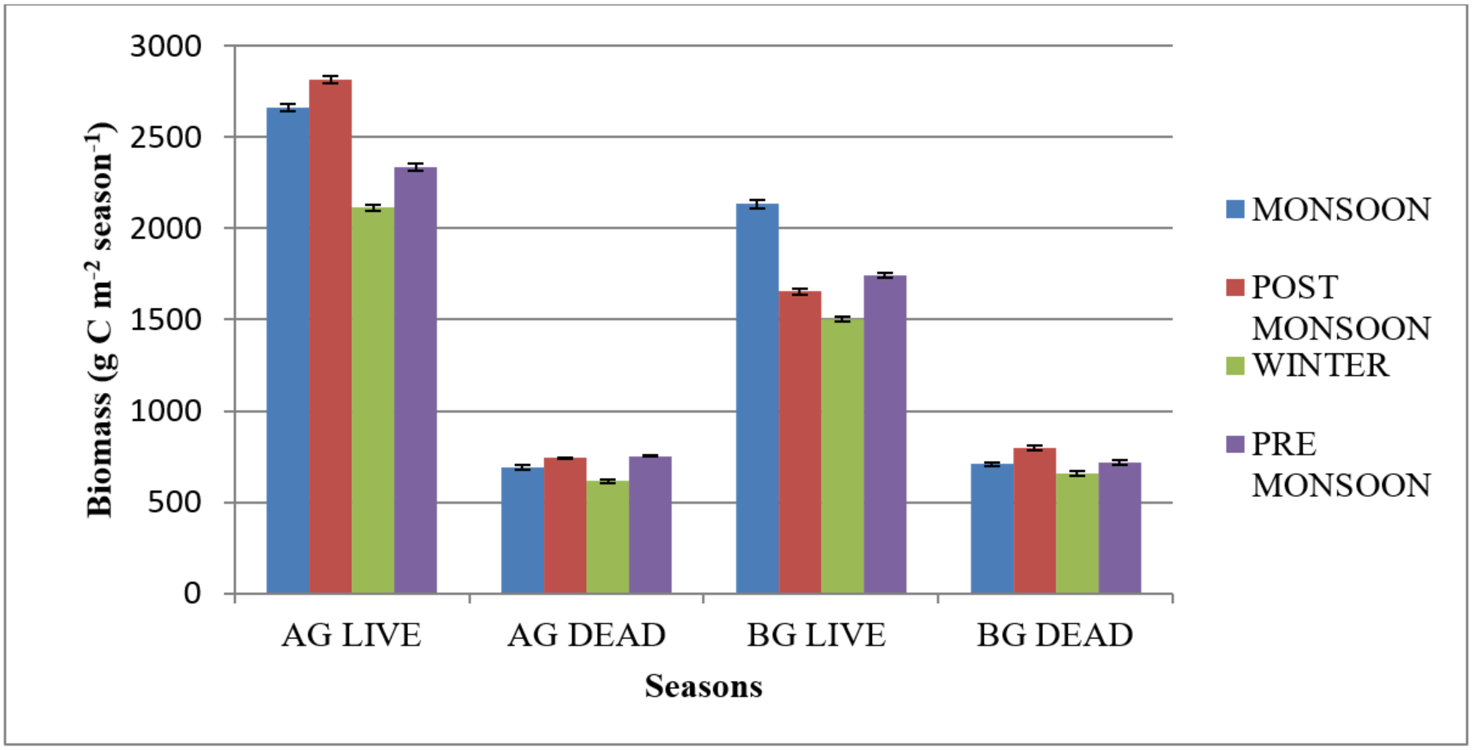

Figure 3

Seasonal distribution of Aboveground (AG) and Belowground (BG) live and dead biomass (g C m^{-2} $season^{-1}$) in floating meadows. Error bars indicate standard error of mean

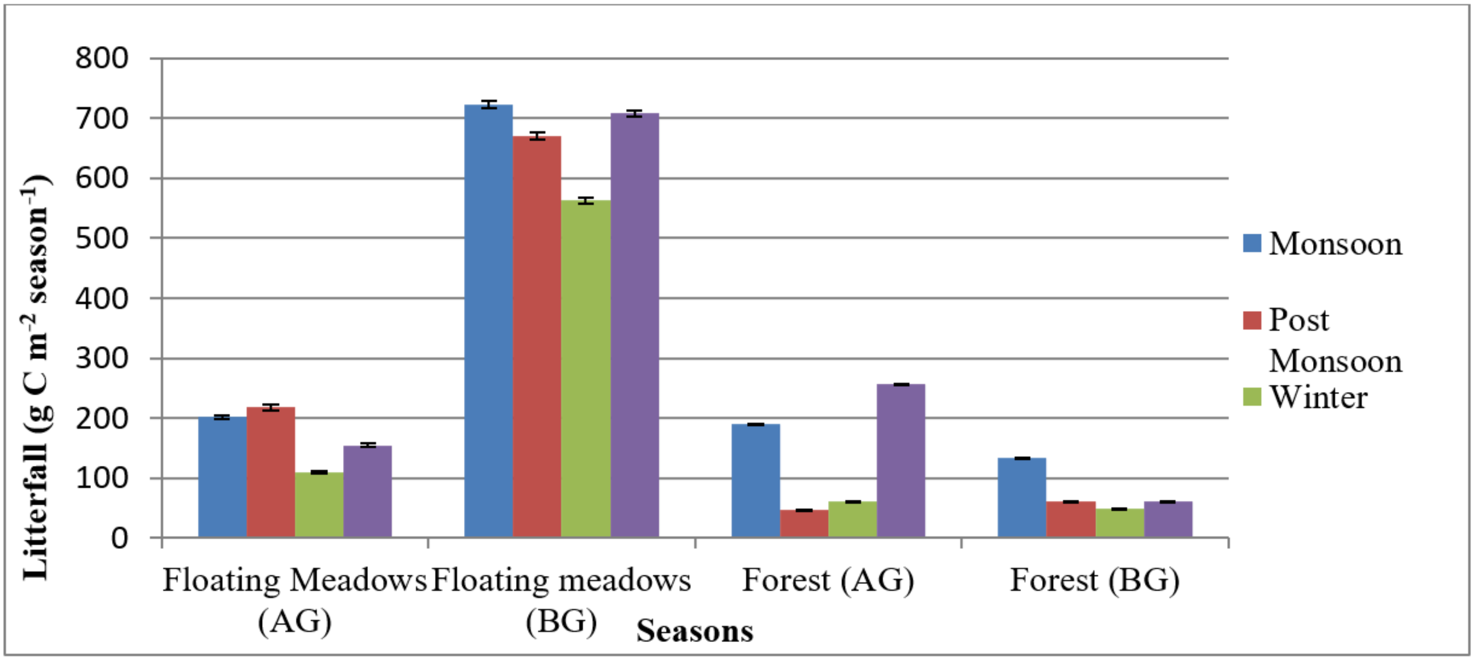

Figure 4

Seasonal litter biomass (gCm^{-2}) in floating meadows and forest ecosystems. Error bars indicate standard error of mean

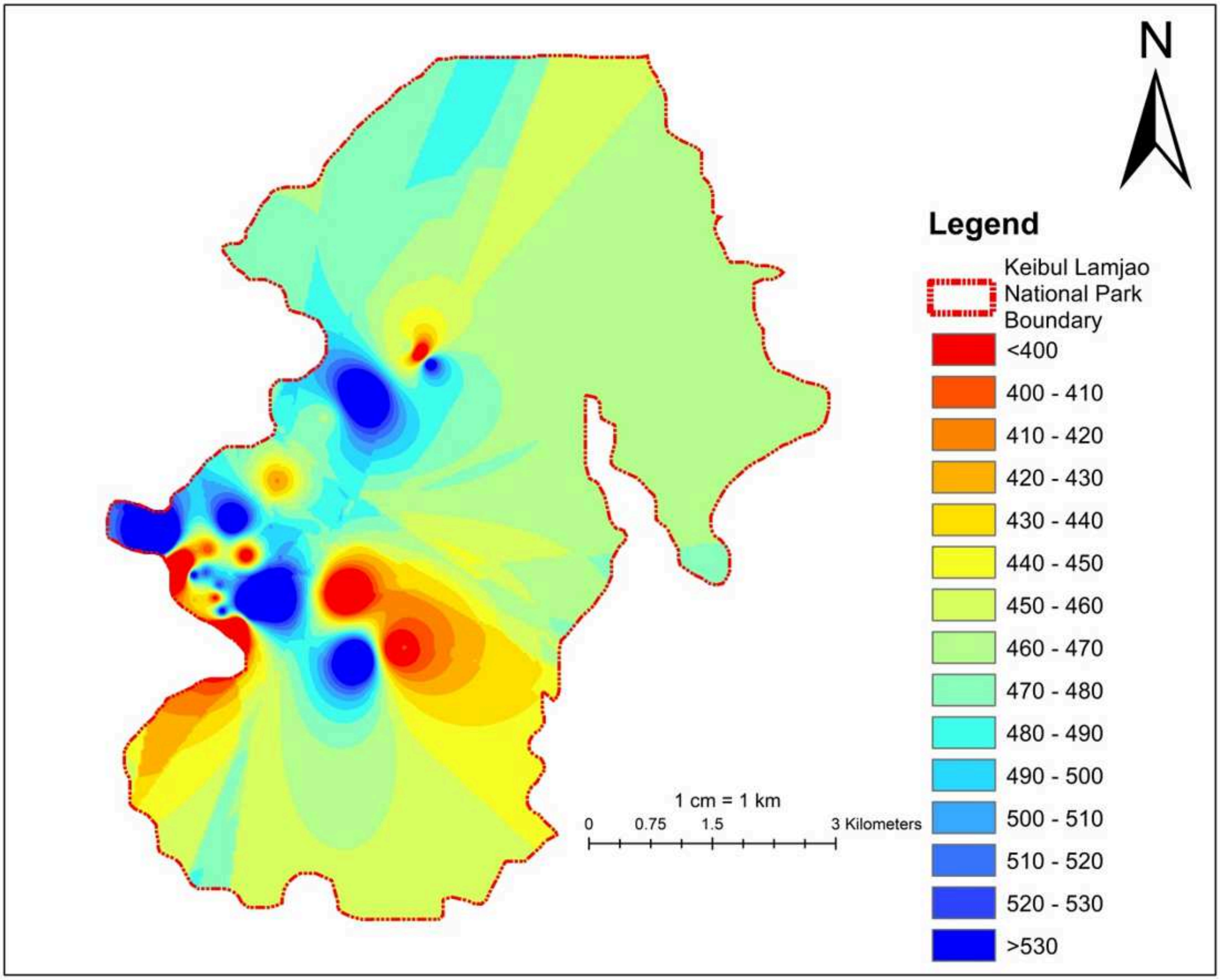

Figure 5

Spatial distribution of Net Ecosystem Production (NEP, $gCm^{-2}yr^{-1}$) across KLNP

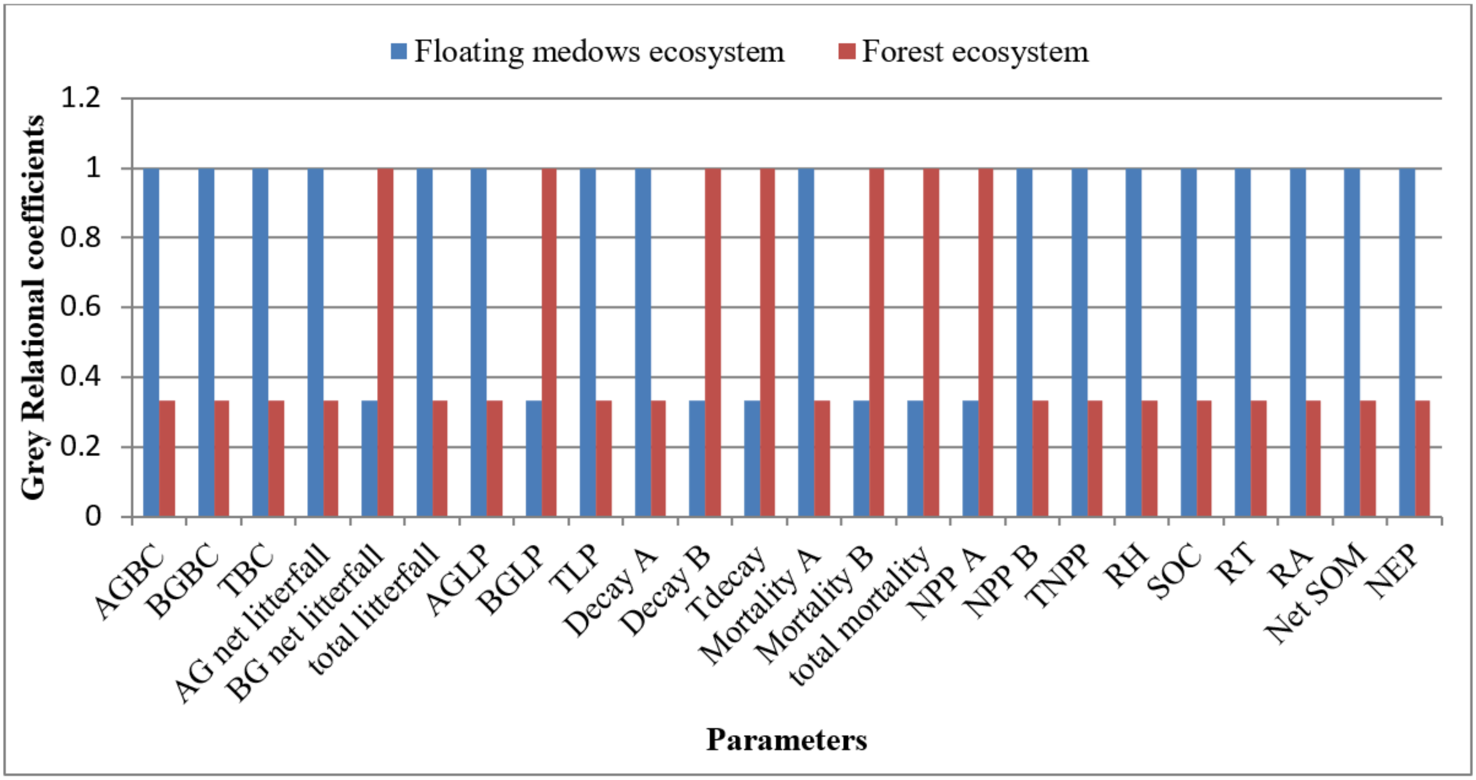

Figure 6

The Grey Relational Coefficients (distinguish coefficients =0.5) for both floating meadows and forest ecosystems across different parameters

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table.docx