

Response

We greatly appreciate the reviewer's thorough evaluation and constructive feedback. The comments have helped us significantly improve the scientific robustness and presentation of the manuscript. We have addressed each point in detail and revised the manuscript accordingly. A point-by-point response is provided below, with all modifications clearly indicated in the revised version.

Reviewer #1

This study applies a WRF–CMAQ modelling framework combined with multi-source emission inventories and high-resolution wetland maps to quantify nitrogen deposition in East Asian coastal wetlands and assess its impacts on carbon sequestration in different wetland types. The manuscript is logically organized and provides valuable model-based insights into source-specific nitrogen inputs and spatiotemporal deposition patterns. However, several methodological details, particularly the separation of ship and anthropogenic sources, the diagnosis of source-specific deposition fluxes, and the treatment of uncertainties, require clearer description before publication. At the same time, I think that the spatial distribution of nitrogen deposition should include the whole region, e.g. Yellow Sea, East China Sea. The manuscript has some originality and significance, but the writing is not rigorous enough, the arguments are not comprehensive enough, and the discussion is not in-depth enough. Careful revision is recommended.

1. The number of references cited throughout the manuscript is insufficient, and many places that should be supported by citations are not. For example, in lines 215–230, many key concepts and mechanisms are presented without referencing the relevant literature.

- Thank you for your suggestion. We conducted a full-text review and added citations of references in some places where literature support was needed. The number of references has increased from 69 to 108 now.

2. The discussion is not sufficiently in-depth.

- Thank you for your suggestion. Additional content has been added to our Results and Discussion, such as comparing the simulation results of the impact of ship emissions of nitrogen deposition in this study with other studies (Section 3.1). The reasons for the seasonal differences in nitrogen deposition in different coastal wetland areas were further discussed and summarized (Section 3.2). The changes of NPP in coastal wetlands of East Asia were discussed from the perspectives of seasonal differences, regional differences and differences among different types of wetlands (Section 3.3). For specific modifications, please refer to Results and Discussion.
- Section 3.1:

In summary, nitrogen deposition in East Asian coastal wetlands is shaped jointly by the type of emission sources and the chemical forms of nitrogen involved. Terrestrial anthropogenic emissions remain the primary contributor to total reactive nitrogen inputs, which is consistent with continental-scale assessments across China and other industrialized regions (Liu et al., 2024, 2013).

However, ship emissions also exert an important influence on coastal atmospheric chemistry, particularly through the formation of secondary particulate nitrate and ammonium. The simulated contributions of shipping in this study align with previous findings that reported substantial maritime impacts on coastal nitrogen aerosols. Evidence from regional atmospheric modelling consistently indicates that NO_x emissions of ships substantially elevate coastal nitrate concentrations, with increases of 20–30% reported for Chinese marginal seas (Lv et al., 2018), and analogous nitrate enhancements found in the YRD due to dense maritime traffic (Liu et al., 2016). Compared with these studies, our results reveal a comparable magnitude of ship-related nitrogen deposition, particularly for particulate NO_3^- -N and NH_4^+ -N in areas with intensive port activity. This consistency reinforces the emerging understanding that maritime transport represents a significant and spatially focused source of nitrogen enrichment in coastal boundary layers, complementing the broader and more diffuse contributions from land-based anthropogenic sources.

● Section 3.2:

Nitrogen deposition in coastal wetlands primarily occurs through two mechanisms: wet and dry deposition (Seinfeld and Pandis, 2016). Wet deposition involves the removal of atmospheric nitrogen compounds, both gaseous and particulate, via precipitation (such as rain or snow), occurring mainly through in-cloud (rainout) and below-cloud scavenging processes (Xu et al., 2020). In contrast, dry deposition refers to the direct transfer of nitrogen species to the Earth's surface in the absence of precipitation, facilitated by gravitational settling, turbulent diffusion, or gas absorption (Sutton et al., 1995). As previously outlined, nitrate (NO_3^- -N) and ammonium (NH_4^+ -N) constituted the dominant forms of nitrogen deposition in East Asian coastal wetlands, while the direct dry deposition of gaseous NO_x and NH_3 contributed only 6.63 % and 9.73 % of total deposition, respectively. Building upon this, the present study further investigated the seasonal variation in nitrate and ammonium deposition, distinguishing between wet and dry fluxes across six representative regions (Fig. 3). Overall, nitrate deposition consistently surpasses ammonium deposition in all regions, reinforcing its dominant role in nitrogen input. Moreover, wet deposition was identified as the primary contributor across all areas, significantly exceeding dry deposition, underscoring the critical influence of seasonal rainfall on nitrogen dynamics in these ecosystems.

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Seasonal patterns of total nitrogen deposition also vary substantially across coastal regions (Fig. 4). For instance, in the YRD, the dry deposition of nitrate nitrogen reached its peak during autumn, amounting to approximately 7139.55 tons. This enhancement is consistent with the seasonal intensification of fossil fuel combustion and industrial activity in eastern China, which maintains high NO_x and oxidized nitrogen levels over the region (Sun et al., 2022). At the same time, meteorological conditions characteristic of autumn, including a shallower planetary boundary layer, more frequent stagnation, and reduced convective mixing, favour the accumulation and near-surface conversion of NO_x to nitrate aerosols (Zang et al., 2022). In contrast, ammonium nitrogen dry deposition in the same region does not demonstrate a similar autumnal peak. This discrepancy is likely attributable to its stronger association with agricultural sources and their seasonally variable application cycles. (Kong et al., 2019; Liu et al., 2011).

In the BG, a distinct seasonal profile was observed. Here, dry deposition of both nitrate and ammonium nitrogen peaked in winter, which were 1667.85 tons and 322.32 tons respectively. This wintertime enhancement is consistent with the dominant influence of the East Asian winter monsoon,

which transports NO_x and NH₃-containing air masses from mainland China and Indochina toward the northern South China Sea and BG (Shah et al., 2020). This seasonal enhancement was likely driven by a combination of long-range pollutant transport via the East Asian winter monsoon, frequent atmospheric inversion events, and limited vertical mixing along the coast, all of which amplify nitrogen loading during the winter season (Lao et al., 2021).

Regarding wet deposition, a more consistent pattern was observed in the BS, YRD, PRD, and BG wetlands. In these regions, spring and summer seasons exhibited significantly higher deposition fluxes compared to autumn and winter. This seasonal increase aligns with enhanced convective activity and frequent rainfall events that facilitate the scavenging of soluble nitrogen compounds from the atmosphere (Tomczak et al., 2025). In contrast, Kyushu Island and the KP demonstrated relatively minor seasonal variations in wet deposition fluxes for both nitrate and ammonium nitrogen, indicating a more uniform annual distribution. This smooth intra-annual profile was likely attributable to the maritime climate characteristic of these island regions, which features moderate temperature gradients and evenly distributed precipitation throughout the year (Zhao et al., 2015; Morino et al., 2011).

Overall, nitrogen deposition in East Asian coastal wetlands shows clear spatial and seasonal heterogeneity. Across all six regions, wet deposition contributes more to total nitrogen input than dry deposition for both nitrate and ammonium, indicating that precipitation plays a dominant role in transporting reactive nitrogen to coastal surfaces. Seasonal differences are particularly evident in spring and summer, when wet deposition fluxes markedly exceed those in autumn and winter. By contrast, dry deposition exhibits more region-specific behaviour; for example, the YRD shows a distinct autumn maximum in dry nitrate deposition, whereas the BG experiences its highest dry deposition in winter. These variations correspond closely to the differing meteorological conditions and emission intensities observed across regions and seasons. In areas such as Kyushu and the Korean Peninsula, seasonal differences in wet deposition remain relatively small, consistent with the more uniform precipitation and air-mass conditions characteristic of these maritime locations. Taken together, the results indicate that nitrogen deposition in coastal wetlands is shaped by both regional atmospheric environments and seasonal shifts in wet and dry deposition processes, with each region exhibiting a distinct seasonal signature.

● Section 3.3

Utilizing remote sensing data and ecological model outputs from six representative coastal regions in East Asia, this study systematically evaluates the seasonal dynamics of NPP and CO₂ fixation across three wetland types (mangrove forests, salt marshes, and tidal flats) during spring, summer, autumn, and winter (Fig. 5). Among these wetland types, mangrove forests exhibited superior performance across all metrics, highlighting their crucial role as “blue carbon” ecosystems with significant carbon sequestration potential, consistent with previous global syntheses of mangrove carbon cycling (Alongi, 2014). During summer, mangrove forests in PRD received an average solar radiation of 1749.29 MJ m⁻² and APAR of 743.45 MJ m⁻², resulting in a high mean NPP of 776.16g C m⁻² approximately. Corresponding CO₂ fixation and O₂ release reached 2783.31 g m⁻² and 3244.35 g m⁻² respectively (Fig. 5a, Fig. 5b and Table S4), exceeding those in other regions. These values are on the same order of magnitude as those reported for highly productive mangrove stands in subtropical and tropical regions (Sun et al., 2024). FPAR for mangrove forests remained stable around 0.85 throughout the year, indicating a pronounced advantage in light use efficiency. This

advantage arises from mangrove forests' evergreen habit, complex canopy structure, and higher water availability, which sustain efficient photosynthesis under high temperature and humidity conditions (Barr et al., 2013). Tidal flats, characterized by sparse or exposed vegetation cover, demonstrated the weakest carbon sequestration metrics. In winter, for example, APAR in tidal flats of the BS can decrease to 37.2 MJ m⁻², with NPP falling to 14.5 g C m⁻², and CO₂ fixation and O₂ release declining to 51.9 g m⁻² and 37.9 g m⁻², respectively. These low values align with the consistently low FPAR (<0.1), reflecting the limited photosynthetic contribution of tidal flats. Seasonally, carbon sequestration exhibited peaks during the summer across all wetland types, primarily driven by maximal solar elevation angles, extended daylight hours, and increased radiation intensity. For example, the highest NPP of mangrove forests in summer reached 776.16 g C m⁻², approximately double that of winter values. This pronounced seasonal variation is even more pronounced in salt marshes and tidal flats, where NPP approaches near-zero levels during autumn and winter. Notably, in regions such as the PRD, mangrove NPP in autumn slightly exceeds spring values, likely attributable to nutrient inputs from post-typhoon events and heavy rainfall that temporarily enhance photosynthetic efficiency and biomass accumulation. (Qiu et al., 2019). Regional disparities in seasonal responses further underscore wetland ecosystems' sensitivity to localized climate and hydrological factors.

3. The manuscript lacks comparison with other related studies.

- Thank you for your suggestion. In Section 3.1, we added the contribution of ship emission inventories to other studies for comparison. Also, we have added comparisons with other studies in the discussion sections of Sections 3.1 and 3.2.

In summary, nitrogen deposition in East Asian coastal wetlands is shaped jointly by the type of emission sources and the chemical forms of nitrogen involved. Terrestrial anthropogenic emissions remain the primary contributor to total reactive nitrogen inputs, which is consistent with continental-scale assessments across China and other industrialized regions (Liu et al., 2024, 2013). However, ship emissions also exert an important influence on coastal atmospheric chemistry, particularly through the formation of secondary particulate nitrate and ammonium. The simulated contributions of shipping in this study align with previous findings that reported substantial maritime impacts on coastal nitrogen aerosols. Evidence from regional atmospheric modelling consistently indicates that NO_x emissions of ships substantially elevate coastal nitrate concentrations, with increases of 20–30% reported for Chinese marginal seas (Lv et al., 2018), and analogous nitrate enhancements found in the Yangtze River Delta due to dense maritime traffic (Liu et al., 2016). Compared with these studies, our results reveal a comparable magnitude of ship-related nitrogen deposition, particularly for particulate NO₃⁻-N and NH₄⁺-N in areas with intensive port activity. This consistency reinforces the emerging understanding that maritime transport represents a significant and spatially focused source of nitrogen enrichment in coastal boundary layers, complementing the broader and more diffuse contributions from land-based anthropogenic sources.

4. In Figure 2, the N and E (north and east) indicators are missing from the map.

- The N and E (north and east) indicators are added in the Figure 2.

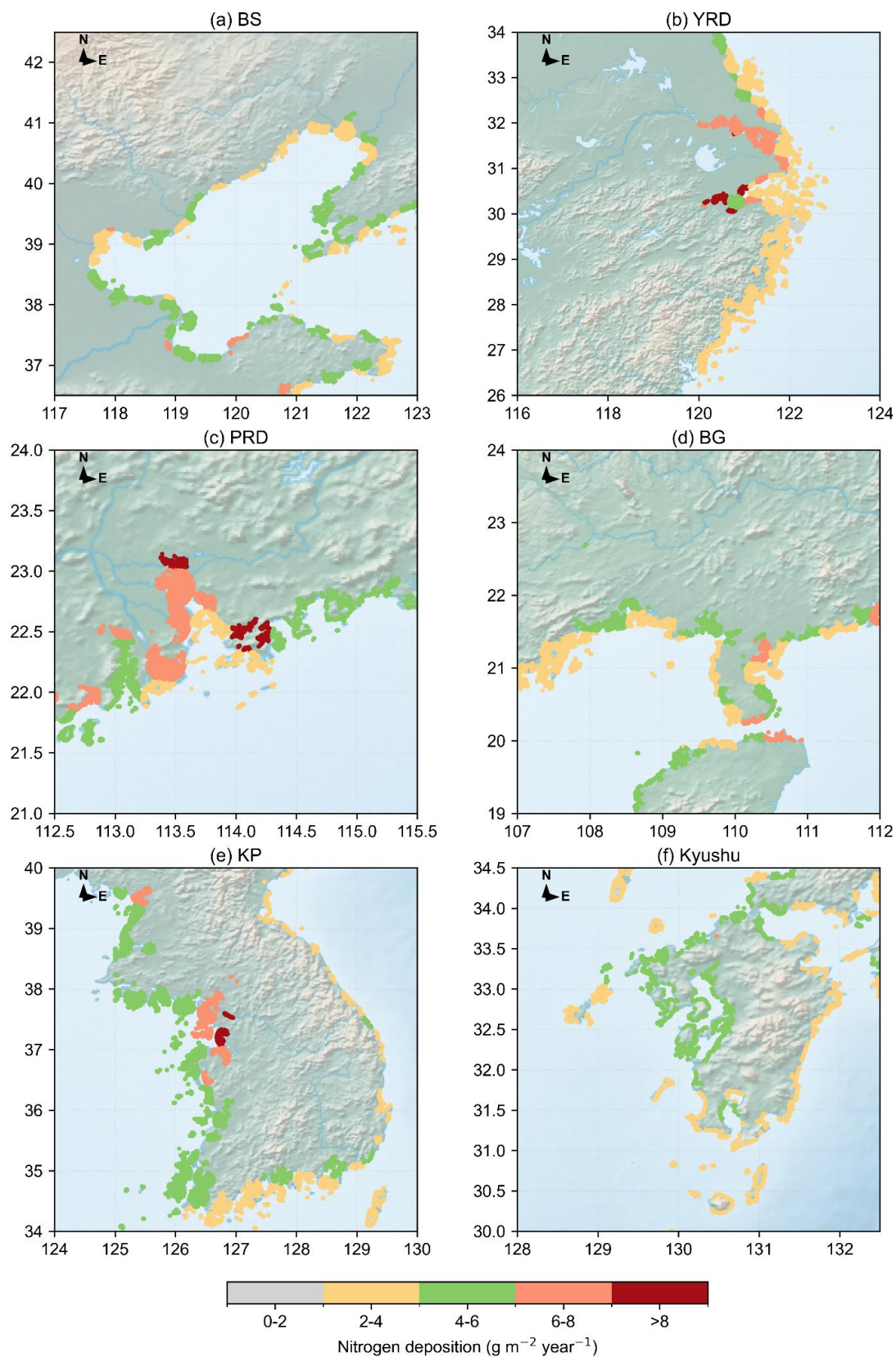


Figure 2. Spatial Distribution of annual total atmospheric nitrogen deposition in coastal wetlands across different regions of East Asia (g N m⁻² yr⁻¹).

5. In Table 1, there is an extra horizontal line under “Anthropogenic”.

- Thank you for your suggestion. The table seems to have extra line segments due to the issue of page spread. We have adjusted this table.

6. Does “total nitrogen deposition” refer only to inorganic nitrogen deposition, or to the sum of inorganic and organic nitrogen deposition?

- The relevant explanations have been added to the methodology.

In this study, total nitrogen deposition refers exclusively to total inorganic nitrogen (TIN), defined as the sum of oxidized inorganic nitrogen species (NO_2 , NO , NO_3^-) and reduced inorganic nitrogen species (NH_3 and NH_4^+).

7. Why choose 1, 4, 7, 10 to represent spring, summer, autumn, and winter instead of 12-2 to represent winter, and 3-5 to represent spring? Because this is not the result of a post-sampling experiment, so I think it's better to choose three months to represent a season.

- On one hand, in this study we have to do a series of sensitive simulations for different emission categories in our experimental designs, the simulation of continuous months would require a lot of computational costs, which was not feasible in practical study. On the other hand, the selection of January, April, July and October to represent winter, spring, summer and autumn follows a widely adopted practice in regional atmospheric modeling studies that require seasonally representative simulations rather than continuous multi-month runs. These four months are commonly used as seasonal proxies because they correspond to the midpoint of each climatological season and minimize transitional effects associated with monsoon onset and withdrawal. Our goal was to capture the characteristic meteorological conditions, emission patterns and deposition behaviors of each season through independent simulations. January, April, July and October provide the most stable representation of seasonal atmospheric states while avoiding inter-month variability associated with early or late seasonal transitions. This approach is consistent with numerous WRF-CMAQ and regional climate studies that adopt single-month seasonal proxies when performing factorial or scenario-based experiments rather than long continuous runs. For this reason, we have added the following explanations of limitations in the methodology:

The use of a single representative month for each season is a methodological simplification relative to full three-month seasonal simulations. This choice was dictated by the factorial experimental design, which required independent simulations under two emission scenarios, and by the associated computational demands. Although this single-month representation is widely adopted in regional atmospheric modelling studies and has been demonstrated to capture the characteristic meteorological and chemical features of each season (Wu et al., 2021; Li et al., 2018), it inevitably introduces some degree of uncertainty related to intra-seasonal variability. Future work involving continuous multi-month simulations for each season would help further constrain this uncertainty.

8.I think the methods section does not clearly explain how different emission sources are distinguished. This may cause readers to question the robustness of your source-specific results.

- Thank you for your suggestion. We have added explanations on how to distinguish different emission source areas in the methodology. Specifically as follows:

In developing the emission inventories, this study explicitly separated terrestrial anthropogenic sources from marine ship emissions to enable a source-specific attribution of atmospheric nitrogen inputs to coastal wetlands. The land-based anthropogenic emissions for China were derived from the Multi-resolution Emission Inventory for China (MEIC), while emissions for other Asian regions were based on the MIX Asian inventory (Yue et al., 2017). Ship emissions were calculated using a bottom-up method based on AIS data with a fine resolution, following established practices for high-resolution marine emission modelling (Jiang et al., 2024; Fan et al., 2016). Based on the inventory of land-based anthropogenic, two parallel emission scenarios were constructed. The first scenario included both land-based anthropogenic and marine ship emissions (with shipping scenario). The second scenario excluded all ship emissions (without-shipping scenario). The contribution of shipping to nitrogen deposition was quantified by comparing the deposition fields simulated under these two scenarios.

9.The seasonal differences are not discussed in sufficient detail. For example, in lines 307–309: “In other words, even within regions that share similar latitudinal positions and ecological characteristics, the ratio of dry to wet deposition can exhibit significant variation due to differences in atmospheric circulation patterns, precipitation regimes, and land-sea interactions.” You could try to incorporate backward trajectory analysis and precipitation data (if available) to support and deepen this discussion. There are also no relevant references cited here.

- We thank the reviewer for the insightful suggestion. We have now expanded the seasonal interpretation by incorporating mechanisms involving monsoon circulation, precipitation patterns, and marine air-mass transport, supported by relevant literature. Although backward-trajectory analyses were not conducted within the current study, we now cite previous trajectory-based studies over Kyushu and coastal Japan that demonstrate the influence of clean maritime inflow on nitrogen deposition patterns. This revision strengthens the mechanistic understanding of seasonal variability and improves the robustness of our interpretation. The specific modifications are as follows:

In other words, even within regions that share similar latitudinal positions and ecological characteristics, the ratio of dry to wet deposition can exhibit significant variation due to differences in atmospheric circulation patterns, precipitation regimes, and land-sea interactions (Zhao et al., 2017; Zhang et al., 2006). For example, the annual dry and wet sedimentation fluxes of nitrate nitrogen and ammonium nitrogen in Kyushu of Japan are 183.92 tons, 337.05 tons, 15.45 tons and 49.24 tons respectively. Nitrogen deposition over Kyushu is generally lower than that observed in heavily industrialized regions of China, a pattern supported by nationwide monitoring records showing comparatively modest wet and dry nitrogen inputs across Japan's coastal zones (Itahashi et al., 2021; Morino et al., 2011). These studies attribute the lower levels of nitrogen deposition largely to weaker local emission sources and the dominant influence of maritime air masses, which

dilute atmospheric reactive nitrogen prior to deposition. This relatively low input of nitrogen is likely a consequence of limited industrial emissions coupled with the predominant influence of clean maritime air masses originating from upwind oceanic regions. (Hayashi et al., 2021; Kiriya et al., 2021).

10. it is better to use “Autumn” rather than “Fall.”

- Thank you for your suggestion. The relevant expressions in the manuscript have been corrected in full.

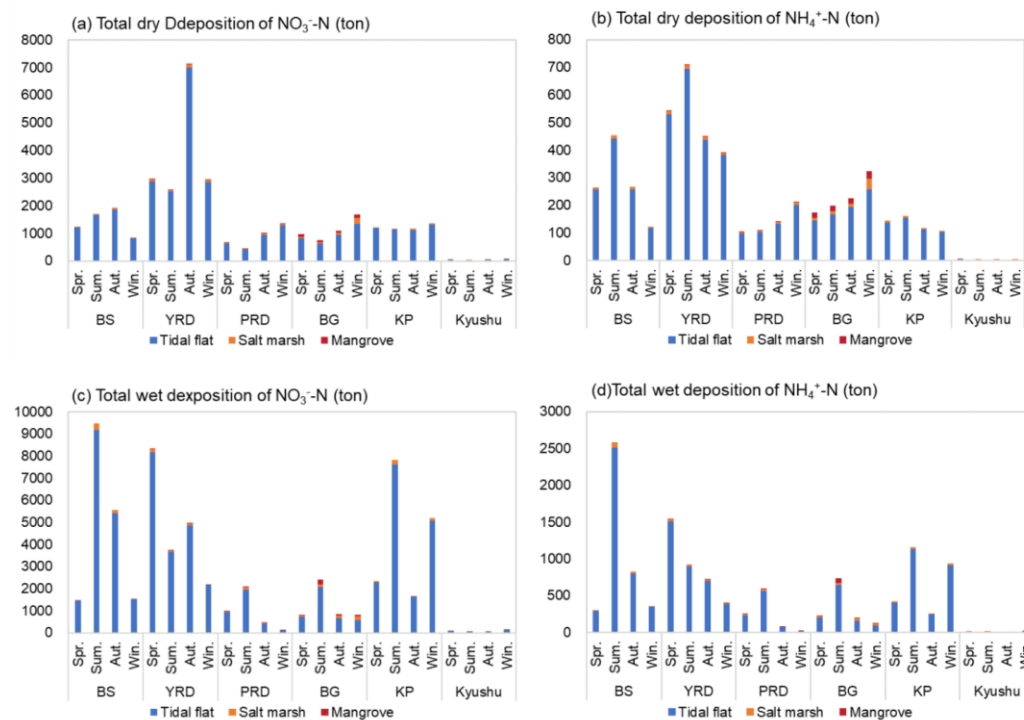


Figure 4. Seasonal Characteristics of Total Nitrogen Deposition in Six Typical Regions. (a) and (c) show the total dry and wet deposition of nitrate nitrogen in different typical regions across different seasons; (b) and (d) show the total dry and wet deposition of ammonium nitrogen in different typical regions across different seasons.

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