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Climate extremes limiting the growth of East Asian mangroves for future nature-based solutions

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Abstract. Mangroves represent distinctive coastal ecosystems that offer ecological benefits, notably through their high carbon sequestration rates. However, their resilience to extreme climate events remains uncertain. Here, we investigate the response of mangroves in East Asia to climate variability by employing the remote-sensing derived normalized difference vegetation index as a proxy for mangrove health. We found East Asian mangrove growth has positive relations with temperature and solar radiation, particularly in cumulative anomalies on seasonal time scales. These findings are extrapolated to future projections by the Earth system modelling to explore not only existing mangroves but also potential habitats. While shifts in wintertime isotherms indicate northward expansion of mangroves under global warming, low solar radiation events associated with aerosol emissions in East Asia could remain as a limiting factor for their growth. This study underscores the importance of climate extremes in practical planning for future mangrove conservation, restoration, and migration, which are considered effective nature-based climate solutions.

1 Introduction

Mangroves are vital intertidal ecosystems that provide a wide range of ecosystem services, including the provision of food and timber, coastal protection, pollution mitigation, biodiversity conservation and carbon sequestration (Barbier et al., 2011). As a crucial component of blue carbon ecosystems, mangrove forests—often described as coastal guardians—are one of the most carbon-rich ecosystems, storing on average ~1,000 Mg C ha^{-1}, with 49–98% carbon stored in the soil (Donato et al., 2011). This carbon storage capacity is roughly five times greater than that of terrestrial tropical forests (Donato et al., 2011). Despite their ecological and climatic significance, mangrove areas have experienced a substantial decline of 30–50% over the past fifty years, primarily due to anthropogenic pressures such as aquaculture expansion, overharvesting and land encroachment (Duke et al., 2007). This degradation has led to the loss of ecosystem services, notably the reduction in coastal

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protection against storm surges and tsunamis (Gultom et al., 2021; Xu et al., 2024). Consequently, mangrove management and restoration have been recognized as a key nature-based climate solution (NBCS) for climate change mitigation (Macreadie et al., 2021). For example, Indonesia has set an ambitious target to rehabilitate 600 kilo hectares (kha) of mangroves, achieving ~30% of this goal to date (Sasmito et al., 2023). Also, China has increased its mangrove coverage by 17% from 2001 to 2015 through concerted restoration efforts (Jia et al., 2018). Although these restoration initiatives have slowed the rate of mangrove loss in recent years, future changes in mangrove habitat suitability are expected to be more complex, driven by diverse factors such as land use change, sea level rise, and extreme weather events (Goldberg et al., 2020; Friess et al., 2022b). Among these, extreme weather events, including heatwaves and storm surge, have contributed to approximately 11% of total mangrove losses, highlighting their importance (Goldberg et al., 2020). Yet, their impacts on mangrove ecosystem under a changing climate remain less understood.

Mangroves predominantly inhabit tropical and subtropical coastal zones between 30°S and 30°N latitude (Jia et al., 2023). In East Asia, mangroves are found mainly in southeastern China and the southern islands of Japan (Kainuma et al., 2013). While this region comprises only 0.1–0.2% of global mangrove coverage (Jia et al., 2023; Kainuma et al., 2013), its carbon sequestration potential and restoration capacity are highly significant. It was reported that mangroves in China store about 355±82 MgC ha^{-1}, while in Japan, coastal ecosystems including mangroves are estimated to contribute up to 12% of the national carbon sink (Liu et al., 2014; Kuwae et al., 2023). Some of the regions in South Korea already have semi-mangroves (e.g. *Hibiscus hamabo* and *Paliurus ramosissimu* in Jeju Island), and ongoing research is exploring the potential for true mangrove introduction to the Korean peninsula to cope with climate crisis (Lee and Baral, 2023; Lee et al., 2023). However, our understanding remains limited regarding whether future climate change will create favourable conditions for mangrove expansion, not only within their current habitats but also in newly suitable areas resulting from potential northward range shifts under greenhouse gas-induced warming. Accurately projecting the regional carbon sink potential of mangroves is therefore essential for informing Nationally Determined Contributions (NDCs) and supporting the achievement of carbon neutrality goals for countries in East Asia.

Given that plant species distributions are strongly governed by climate zones, the current and future distribution of mangroves is particularly sensitive to temperature, which serves as a primary determinant of both habitat suitability and growth (Osland et al., 2017). While the influence of climate variables such as temperature, solar radiation, and precipitation on plant growth and productivity is well recognized, the magnitude, seasonal variability, and lagged responses can vary substantially across regions (Ding et al., 2020; Nemani et al., 2003). Nevertheless, there is a paucity of long-term, quantitative studies that comprehensively assess the role of these climatic factors in mangrove growth, as most existing research has relied on experimental, field, or remote sensing data of a relatively short period (Chen et al., 2017; Luo and Chui, 2020; Zheng et al., 2016a). For mangroves, freshwater acquisition mechanisms are more complex, including root uptake from a saline environment and foliar water absorption (Reef and Lovelock, 2015), which makes precipitation insufficient as a standalone factor representing water availability. Therefore, this study focused on evaluating the impacts of temperature and solar radiation on mangrove health and further assessed the future growth potential of East Asian

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mangroves under projected climate scenarios. The insights gained from this research are expected to provide a scientific basis for evidence-based conservation and restoration strategies targeting mangrove ecosystems.

2 Methods

2.1 Datasets

The mangrove distribution data were obtained from Global Mangrove Watch (Bunting et al., 2022), which has a relatively long time span that covers our research period. The mangrove growth dynamic was assessed based on Normalized Difference Vegetation Index (NDVI), a widely used index for quantifying vegetation health and density using remote sensing spectrum (Tran et al., 2022). Based on the optical properties of vegetation photosynthesis, NDVI is calculated as followed.

$$NDVI = (\rho NIR - \rho RED)/(\rho NIR + \rho RED)\ , \quad (1)$$

where ρNIR is the surface reflectance in the near infrared band, and ρRED is the surface reflectance in the red band. In this study, NDVI data was obtained directly from remote sensing dataset MODIS Vegetation Indices (MOD13Q1) Version 6.1 from 2001 to 2022 (Didan, 2021), with a composite of every 16 days for temporal resolution and a spatial resolution of 250 meters. Climatology data, mean temperature and surface solar radiation downwards were obtained from European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) for climatic analysis (Hersbach et al., 2023), with the time range from 2001 to 2022 and the spatial resolution at 0.25°×0.25°. The reanalysis data provides spatiotemporally continuous datasets compared with observational data, especially helpful for the analysis on mangroves as they are located in the intertidal areas. Total bright sunshine, defined as the sum of the time for which the direct sunshine irradiance exceeds 120 W/m^2, was obtained from Hong Kong Observatory (https://www.hko.gov.hk/sc/index.html). The future projections for climate condition were investigated in 28 coupled Earth System Models incorporated in the Coupled Model Intercomparison Project Phase 6 (CMIP6). Here, the historical and Shared Socioeconomic Pathway 1-2.6 and 3-7.0 were resampled into the 0.25°×0.25° resolution. The models used are listed in the Table S2.

2.2 Pre-processing

NDVI pixels were further extracted for mangroves based on the following rules. First, we selected undisturbed mangrove stands that continuously maintained ≥60% canopy coverage during 1996–2020, ensuring that the NDVI values reliably represented mangroves. The coverage criterion aligns with protocols from previous related research (Zhang et al., 2024b), with the 60% coverage threshold derived from MODIS Land Cover Type Yearly Global product (MCD12Q1) classifications (Sulla-Menashe and Friedl, 2018). Second, pixels with NDVI ≤0.1 in more than one-third of temporal observations were excluded to minimize abnormal cases (Measuring Vegetation (NDVI & EVI), 2025). The filtered mangrove NDVI dataset was then used for subsequent analyses. The climatology data for the mangrove region were extracted without the coverage

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threshold rules, considering that the spatial resolution of the climatology data was coarser than that of the NDVI dataset. For forest extraction, we selected pixels for evergreen broadleaf forests that remained unchanged during 2001 to 2022 from MCD12Q1. These pixels were overlapped with a 2 km buffer around the undisturbed mangroves and intersected with the NDVI dataset to extract forest NDVI. The same filtering rules as for mangroves were applied. Both the NDVI data and the climate data were resampled to monthly intervals. The related process was conducted in ArcGIS Pro 3.0.0 and Python 3.

2.3 Regression-based sensitivity analysis

We applied linear regression to estimate the sensitivity of mangrove NDVI to different climate factors, with statistical significance assessed using a standard two-tailed Student's *t*-test. The analysis was conducted on monthly detrended anomalies of both NDVI (Y) and climate factors (X) to minimize the influence of long-term trends. To improve the readability and numerical precision of the results, the sensitivity coefficients were rescaled by factors of 100 for temperature and 1000 for solar radiation, yielding values within a single-digit range (<10).

2.4 Bootstrapping analysis for extreme cases and lag effect

The basic idea of bootstrapping is to resample the data through randomly picking thousands of times (10,000 iterations in this study) to regenerate an empirical estimate of the entire sampling distribution (Mooney et al., 1993). In this research, bootstrapping resampling was applied in both the extreme cases test and time-lagged effect analysis. For the extreme-case test, we examined the relationship between extremely low NDVI anomalies and extremely low values of climate factors, using monthly detrended anomalies. Specifically, the lowest 10% of NDVI anomalies were selected, and the corresponding climate data were evaluated against the bootstrapped climate distribution using a percentile-based test, with significance levels set at $P < 0.05$ or $P < 0.1$. The analysis was conducted at both the annual scale (Fig. 2c, 2e) and the seasonal scale, where boreal seasons (DJF, MAM, JJA, SON) were considered separately (Fig. 2d, 2f; Fig. S2). For the lag-effect test, we assessed the delayed influence of climate factors on mangrove growth. The analysis was based on boreal seasonal composites of detrended anomalies, with moving windows adjusted to represent different temporal lags. For example, for MAM NDVI: a 0-month lag corresponds to MAM NDVI vs. MAM climate factors, while a 1-month lag corresponds to MAM NDVI vs. FMA climate factors, with similar temporal offsets applied for other seasons and lag periods. The test was conducted by selecting the high and low NDVI cases (>+1 SD, <–1 SD), and evaluating the corresponding climate conditions against the bootstrapped climate distribution using the percentile method (Fig. 3). To further assess the importance of lag effects, we examined the difference in climate conditions between high and low NDVI cases (> +1 SD vs. < –1 SD), with significance again determined using the percentile method (Fig. S2).

2.5 Future projections in the sampled region

We adopted the critical biological temperature threshold of 10 °C in DJF, identified for mangroves in Fujian Province (Wang et al., 2022), as the criterion for projecting future mangrove expansion in East Asia. Two scenarios were selected for

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comparison: SSP1-2.6, representing a sustainable development pathway consistent with limiting warming to below 2 °C, and SSP3-7.0, reflecting a high-emission, regional-rivalry pathway with limited climate mitigation (Meinshausen et al., 2020). The DJF 10 °C isotherm is shown in Fig. 4a–b, comparing the historical baseline (2001–2022) with the late 21st century (2081–2100) under SSP3-7.0 and SSP1-2.6. The panels also illustrate differences in DJF temperature and solar radiation composites between the two scenarios. Low-temperature constraints are unlikely to remain a major limitation under future warming, while, in contrast, solar radiation is projected to decrease, motivating an assessment of how the frequency of low solar radiation events may change. To quantify this, we first identified the season during which solar radiation exerted the strongest influence on mangroves for each zone, based on the results in Fig. 3d. We then calculated the number of low solar radiation events in that season at the monthly scale, defining events as values below –1 standard deviation of the long-term mean, and expressed the frequency as rates per decade. This analysis was repeated for the historical (1940–2014), SSP1-2.6 (2015–2100) and SSP3-7.0 (2015–2100) periods, respectively (Fig. 4c–e). To address the confidence interval, we derived the event rate from ERA5 (1940–2024) and estimated 2.5th and 97.5th percentiles using bootstrap resampling. These values were used as the observational estimate for emergent constraint (EC), an approach that derives constraints by correlating model ensemble results with observational estimates (Winkler et al., 2019).

2.6 Future projection in the potential region

To assess the potential future expansion of mangroves at the northern limits in different countries (China, South Korea, and Japan) of East Asia, we adopted the 10 °C mean temperature threshold in DJF as the criterion. Potential habitats were identified through two steps: (1) selecting current non-mangrove shorelines at a spatial resolution of 0.25° × 0.25°, and (2) identifying regions where winter (DJF) mean temperatures are projected to reach ≥10 °C under SSP3-7.0 (2071–2100). We quantified historical-to-future changes in climatic factors on certain seasonal composites through a multi-model ensemble analysis under historical (1981–2100), SSP3-7.0 (2071–2100) (Fig. 5) and SSP1-2.6 (2071–2100) (Fig. S4). These results were compared with the statistically significant thresholds derived from the current northern distribution zone (Fig. 3a, 3d).

3 Results

3.1 Spatial-temporal patterns of mangrove NDVI

Mangrove habitats were identified from the global mangrove distribution dataset and classified into three distinct latitudinal zones—northern, middle, and southern—based on both climate and dominant species composition across the natural latitudinal range of mangroves along the South China Sea (Zhao et al., 2024) (Fig. 1a, Table S1; Methods). Normalized Difference Vegetation Index (NDVI), one of the widely used indices for tracking vegetation dynamics (Tran et al., 2022), was used as the health indicator for mangroves in this study. Seasonal cycle of NDVI demonstrated clear phenological differences among these zones, consistent with previous studies indicating that, despite being evergreen, mangrove forests exhibit notable seasonal and spatial variability (Pastor-Guzman et al., 2018) (Fig. 1b). The northern zone has generally lower

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values, while the amplitude of NDVI fluctuation decreases progressively from north to south. While both the northern and southern zones exhibited synchronized timing of NDVI maxima and minima—typically with minimum values in winter and maximum values in summer, reflecting the seasonal cycle of temperature—the middle zone demonstrated a markedly different phenological pattern. Specifically, in the middle zone, NDVI minima occurred in April and maxima in October, indicating a shift in the seasonal cycle relative to the other zones. This divergence suggests that, whereas NDVI dynamics in the northern and southern zones are more aligned with temperature seasonality with a potential lag, in the middle zone, NDVI variations are more strongly synchronized with fluctuations in sunshine hours rather than temperature (Fig. S1). This pattern is likely attributable to the prevalence of cloud cover during the boreal spring associated with springtime mesoscale convective systems (Zhang et al., 2024a), which reduces incoming solar radiation and consequently limits photosynthetic activity and mangrove canopy development. Thus, solar radiation may act as a primary limiting factor for mangrove growth in the middle zone during this period, in contrast to the temperature-driven seasonality observed elsewhere. These findings are consistent with previous studies that have documented distinct spatial and temporal indicator patterns in mangroves across latitudinal gradients, reflecting the interplay of climatic drivers such as temperature and solar radiation (Songsom et al., 2019). Moreover, these phenological variations may also be influenced by species-specific responses during the temperature-sensitive winter-spring period, a timeframe during which NDVI dynamics have been shown to be particularly effective for species discrimination (Li et al., 2019). For example, Hainan in the southern zone hosts the highest mangrove species diversity, whereas the middle zone is predominantly occupied by *Sonneratia apetala.* and *Avicennia marina*, and the northern zone is mainly characterized by *Kandelia obovate* (Zhao et al., 2024). Annual NDVI distribution further reveals strong latitudinal dependencies, with higher and more clustered NDVI values observed at lower latitudes, reflecting more favourable conditions (especially temperature) for mangrove growth (Fig. 1c) (Chen et al., 2017). In the middle zone, the distribution of mean NDVI is relatively symmetric, while the maximum shows right skewness; in the southern zone, both mean and maximum are right-skewed. This indicates that growth in the middle zone is more stable than in the south, but in both regions the skewed maxima suggest potential for enhanced growth under suitable conditions. By contrast, the symmetric distribution in the northern zone implies limited growth potential, though overall stability is maintained.

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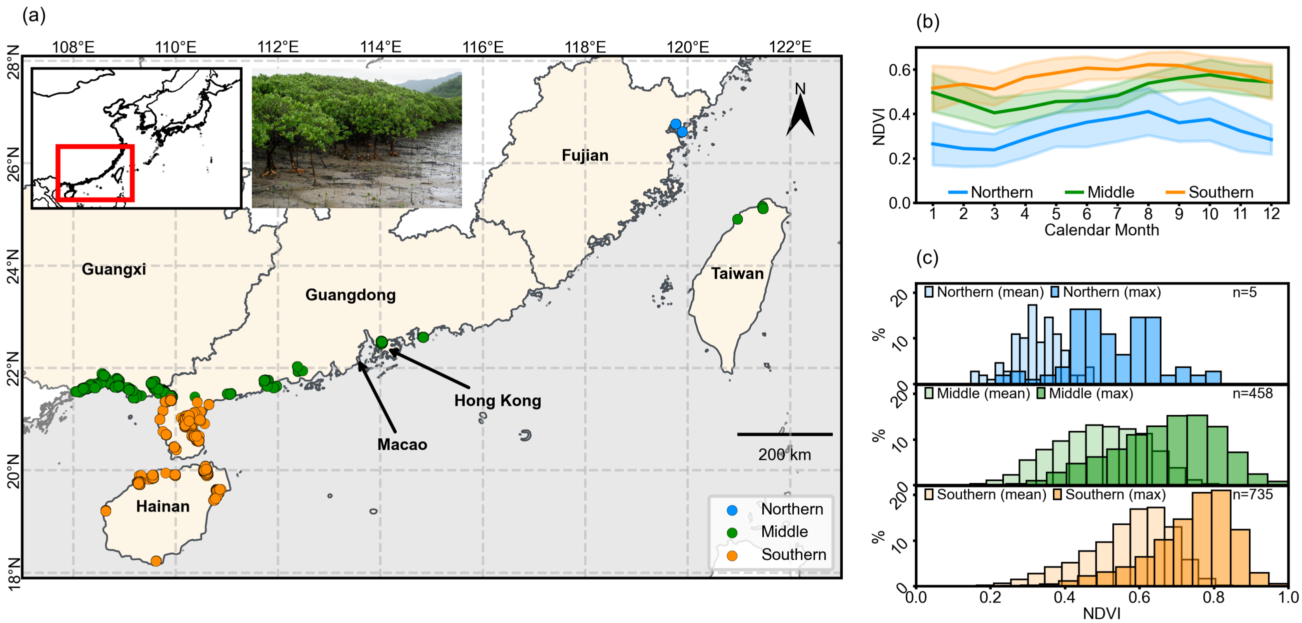

Figure 1. Spatial distribution of sampled mangroves with zone classification and NDVI characteristics. (a) Spatial distribution of sampled mangroves with a pixel resolution of 250 m. Sampling criteria required: (i) undisturbed mangrove stands maintaining ≥60% canopy coverage continuously from 1996 to 2020, and (ii) exclusion of pixels where NDVI ≤0.1 occurred in >1/3 of temporal observations (see Methods). Sampled mangroves were divided into three zones based on species composition, designated as northern, middle, and southern zones. (b) Seasonal cycle of sampled mangrove NDVI from 2001 to 2022. The light-shaded area represents the range of mean ±1 SD. (c) Histogram of yearly maximum and mean NDVI from 2001 to 2022. In the top right corner, *n* represents the number of pixels sampled for each zone.

3.2 Mangrove NDVI responses to temperature and solar radiation forcing

Linear relations between mangrove NDVI in each zone and climatic drivers are quantified to determine the sensitivity of mangrove NDVI to climatic drivers (see Methods). The sensitivity of mangrove NDVI to temperature does not have consistent patterns across three zones (Fig. 2a). Although temperature is widely recognized as the principal limiting factor influencing the global distribution of mangroves, this relationship is primarily reflected in the spatial distribution of species within our study region, which is shaped by species-specific thermal adaptation thresholds (Wu et al., 2018). However, the linear regression analysis did not detect the expected interannual NDVI response to temperature variations (Fig. 2a). In contrast, the sensitivity analysis indicates predominantly positive NDVI responses to solar radiation in the middle and southern zones, suggesting a broader influence of solar radiation on mangrove growth (Fig. 2b). While solar radiation is fundamental for plant photosynthesis, its role in shaping mangrove phenology has often been underemphasized or considered secondary in previous studies examining climatic controls on mangrove ecosystems (Luo and Chui, 2020; Poungparn et al., 2020; Songsom et al., 2019). Nevertheless, previous studies have highlighted the significant impact of solar radiation during specific phenological stages, such as seedling establishment and leaf senescence (Krauss et al., 2008; Sharma et al., 2012). Our findings extend this understanding by demonstrating a more general and consistent positive effect of solar radiation on

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mangrove NDVI, underscoring its importance as a key environmental driver of mangrove productivity across latitudinal gradients.

While temperature does not show a significant linear relationship with NDVI variations, previous studies provide evidence of cold damage from in-situ field studies (Chen et al., 2017; Zheng et al., 2016b). To investigate non-linear response and impacts from climate extreme events, we further employ a bootstrapping resampling approach to determine the influence of climate conditions when extreme values of NDVI occur (the lowest 10% of NDVI anomalies) statistically and quantitatively. Analysis of the annual NDVI range reveals a marginally significant association with temperature in the southern zone (*P*=0.07, Fig. 2c) and significant associations with solar radiation in both the southern and the middle zones (*P*=0.00 and 0.00, Fig. 2e), indicating that instances of extremely low NDVI are correlated with extreme climatic conditions. Further analysis based on seasonal ranges (December–January–February, DJF; March–April–May, MAM; June–July–August, JJA; September–October–November, SON) reveals additional spatial and temporal patterns (Fig. 2d, f and Fig. S2). In the middle zone, both temperature and solar radiation exhibit significant relations with NDVI during MAM (*P*=0.04, Fig. 2d; *P*=0.01, Fig. S2d), coinciding with a pronounced NDVI decline during winter-to-spring transition (Fig. 1b). This underscores the critical role of the MAM season in mangrove growth in this region. In the southern zone, significant associations with both climatic factors were observed during JJA (*P*=0.06, Fig. S2b; *P*=0.02, Fig. S2e), consistent with the prevalence of thermophilic stenotopic species in this area (Wu et al., 2018). Although a previous study has reported that the 2008 chilling event resulted in widespread defoliation and even dieback of mangroves in the middle and southern zones (Chen et al., 2017), our analysis detects significant relations only with solar radiation (*P*=0.03 and 0.03, Fig. 2f), rather than with temperature. This discrepancy may be attributable to limitations in data resolution or the possibility of delayed temperature effects on mangrove health.

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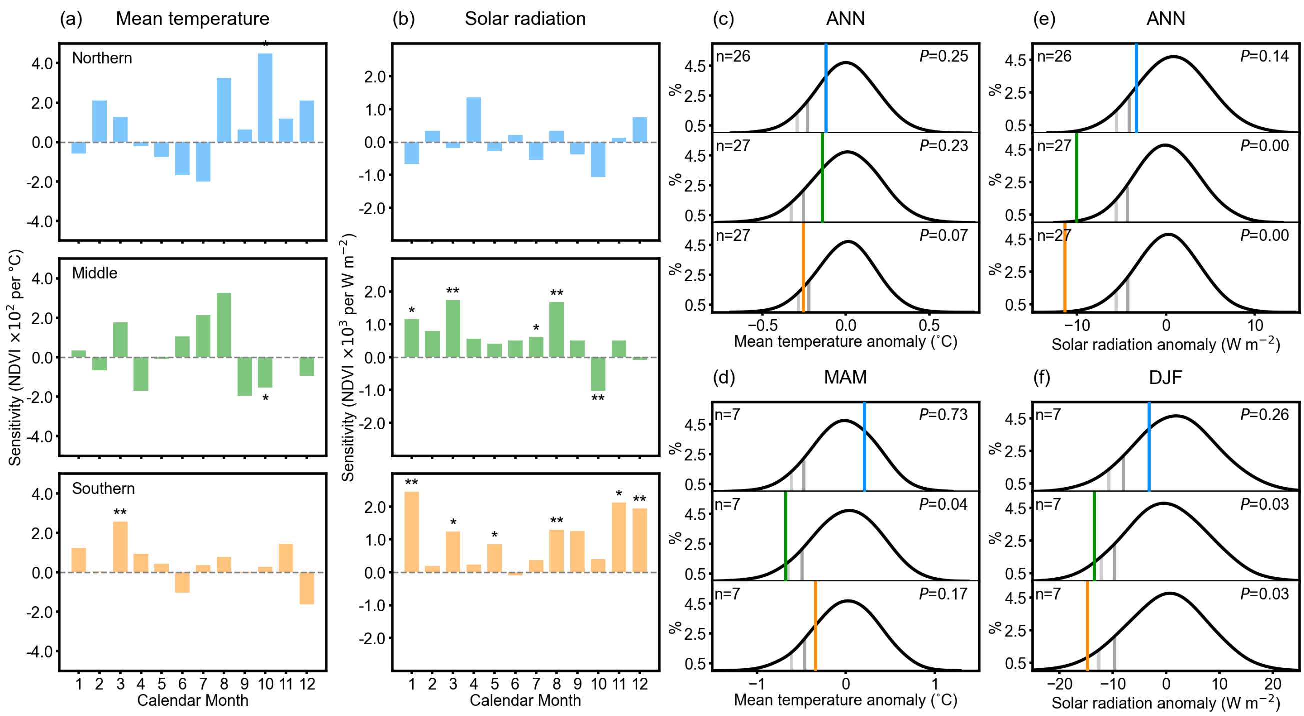

Figure 2. Simultaneous impact of mean temperature and solar radiation on mangrove growth. Sensitivity of mangrove NDVI to mean temperature (a) and solar radiation (b). Sensitivity is defined as the linear regression slope between monthly NDVI anomalies and climatic anomalies. One asterisk (*) indicates a *P*–value less than 0.1, and two asterisks (**) indicate a *P*–value less than 0.05. Bootstrap distributions for mean temperature and the significance test for extreme low cases are shown for annual (c) and MAM (d), while results for solar radiation are presented for annual (e) and DJF (f). Light grey lines represent *P*=0.05, and dark grey lines represent *P*=0.1. In the top left corner, n represents the number of cases selected. In the top right corner, *P* indicates the *P*–value result for the cases. Different colours indicate different zones: blue for the northern zone, green for the middle zone and orange for the southern zone.

3.3 Time-lagged effect of climate drivers on seasonal composite NDVI

While we found that NDVI extreme cases are linked to climatic anomalies simultaneously (Fig. 2), we further investigate the potential lagged effect of climatic variables using seasonal composite NDVI and anomalous case detection (defined as NDVI anomalies exceeding ±1 standard deviation) in order to quantify the legacy effect on East Asian mangroves (Ding et al., 2020**)**. Time-lagged effects are critical for elucidating climate-vegetation interactions, as they reveal the influence of climatic factors over extended temporal scales (Yuan et al., 2022). Our results indicate that NDVI during MAM tend to have significant dependence on preceding winter temperatures (Fig. 3a, c). High MAM NDVI cases in northern zone are significantly linked with temperature anomalies occurring simultaneously and 1–3 months prior (Fig. 3a), while low MAM NDVI cases in the middle and southern zones also demonstrate lagged temperature effects (Fig. 3c). MAM represents a crucial period for the initiation of mangrove growth (Fig. 1b), and transitions in the mangrove life cycle often require the accumulation of favorable climatic conditions, as described by the concept of accumulated temperature (Wen et al., 2019). Although mangrove species in the northern zone (e.g., *K. obovata*) are relatively cold-tolerant, higher winter temperatures

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are still preferable. It is reported that low winter temperatures can induce persistent metabolic stress and impair the recovery of photosynthetic capacity, resulting in subtle but long-lasting impacts on mangrove growth (Zheng et al., 2016b). Our findings are consistent with field surveys conducted approximately one month after the 2008 winter chilling event, which documented significant mangrove defoliation in middle and southern zones, with severe dieback observed in the southern zone, particularly among non-native species such as *S. apetala* (Chen et al., 2017). Furthermore, our analysis highlights the importance of high temperature for mangrove growth during SON, as evidenced by significant short lag (≤1 month) effects (Fig. 3a). This phenomenon likely reflects temperature-induced shifts in phenology, as temperature is a key determinant of the timing of peak growing seasons in mangroves (Songsom et al., 2019). More broadly, increasing temperature can extend the growing season and enhance photosynthetic activity (Peng et al., 2011). Consistently, high SON temperatures may lengthen the growing season of mangroves in northern zone, while in southern zone they may raise potential productivity, as indicated by the positive skewness in Fig. 2c. The observed variation in temperature sensitivity among zones underscores the influence of species composition on climatic responses (Wu et al., 2018).

Low solar radiation events during DJF in the low-latitude zone are significantly associated with low NDVI (Fig. 2f), indicating that the influence of radiation in winter is primarily simultaneous. Beyond the winter period, however, the impact of solar radiation on mangroves is primarily evident through lagged responses. For high NDVI cases, elevated solar radiation is significantly associated with JJA in the northern and middle zones (lags 0–2 months; Fig. 3b), and with SON in the southern zone (lag 1 month), highlighting the importance of these transitional seasons. In contrast, low NDVI cases exhibit divergent lagged responses: northern zone shows a 2-3 month lag to radiation deficits in SON; the middle zone shows a 1-month lag in MAM; and southern zone demonstrates immediate (lag-0) response to JJA solar radiation (Fig. 3d). These patterns may reflect the decoupling of carbon assimilation and utilization during certain developmental stages, such as MAM, when photosynthetic products are used primarily for growth and reproduction (Trugman and Anderegg, 2024), and in JJA when mangroves prepare for their peak growing season. In addition, increased solar radiation during late winter has been shown to advance the onset of the growing season in spring (Li et al., 2021). During inter-seasonal transitions (i.e., MAM→JJA and JJA→SON), the role of solar radiation becomes particularly pronounced, potentially influencing the timing of both the peak and termination of the growing season. It has been reported that the cumulative and lagged effects of temperature and solar radiation on vegetation vary in magnitude depending on temporal and spatial factors (Ding et al., 2020), and our findings demonstrate that such effects are also evident in mangrove ecosystems. In particular, the consistent significance of both temperature and solar radiation during the JJA→SON transition highlights this period as especially important for sustaining mangrove growth. The relative importance of mean temperature and solar radiation for mangrove growth is further summarized in Fig. S3.

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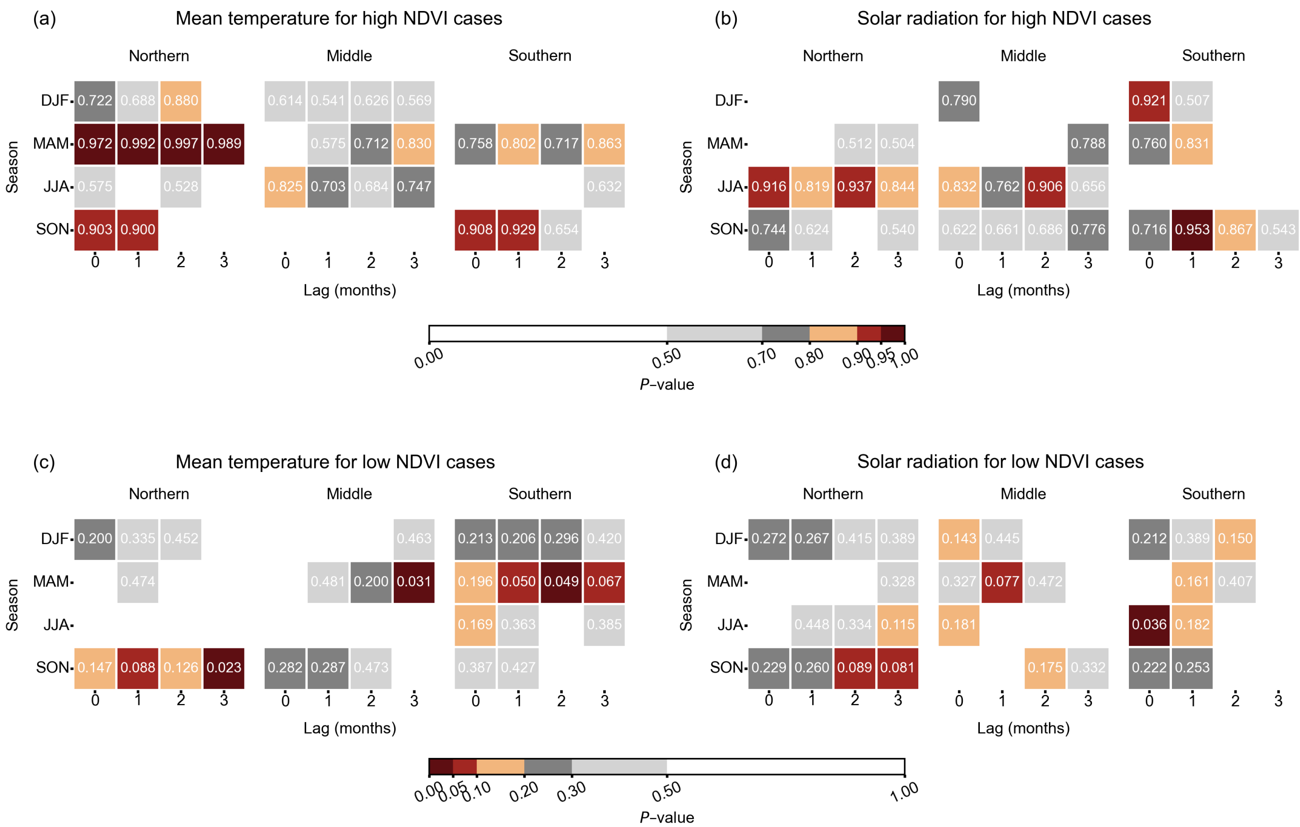

Figure 3. Time-lagged effect of mean temperature and solar radiation on mangrove growth at the seasonal composite. Significance test for high NDVI cases to mean temperature (a), solar radiation (b). Significance test for low NDVI cases to mean temperature (c), solar radiation (d). Lags (τ) on the *x*-axis represent a three-month period that occurs τ months prior to a given season (*y*-axis). Statistical significance here ($P<0.05/P>0.95$) indicates that mean temperature/solar radiation demonstrates a strong lagged correlation with the high/low NDVI extremes with certain months of time lags.

3.4 Climate-driven mangrove habitat potential expansion

Our findings highlight that temperature and solar radiation are significantly associated with regulating mangrove growth. Anticipated alterations in these climatic factors under global warming scenarios are likely to substantially influence both the spatial distribution and growth dynamics of mangrove ecosystems. To evaluate these potential impacts, we utilized multiple Coupled Model Intercomparison Project Phase 6 (CMIP6) models to project future changes in mangrove dynamics across East Asia, where mangrove distribution is primarily constrained by minimum winter temperature thresholds (Osland et al., 2017). Compared with SSP1-2.6, SSP3-7.0 shows higher temperatures but lower solar radiation toward the end of the century, mainly due to stronger aerosol emissions under this fossil-fuel-dominated scenarios (Kim et al., 2024; Turnock et al., 2020). In Fujian Province, the critical biological threshold for mangrove survival is approximately 10˚C during winter (Wang et al., 2022). Climate model projections suggest that, under continued warming, this thermal boundary will progressively shift poleward (Fig. 4a-b). Given that winter warming is a dominant driver of poleward mangrove migration in

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East Asia (Osland et al., 2017), this could allow mangroves to expand into previously unsuitable coastal zones, including northern Zhejiang Province of China, the southern coast of South Korea, and parts of Japan, by the end of the 21st century. Particularly in southeastern China, the natural northern limits of mangroves in Fujian Province are projected to migrate further northward under future climate senarios (Wang et al., 2022). Among the various mangrove species, *K. obovata*, which exhibits the highest cold tolerance, is expected to be the first to establish along the southern coast of South Korea when the mean surface temperatures reach 10.4˚C in winter (Nam et al., 2024).

However, projected changes in solar radiation may pose emerging risks to mangroves in the studied regions. We conducted a comparative analysis of temperature and solar radiation during the same timeframes across different climate scenarios (Fig. 4a-b). Especially, we focused on the DJF season, where climatic factors could have a significant influence on NDVI in the subsequent seasons in the northern zone (Fig. 2f, Fig. 3a). A comparison between SSP3-7.0 and SSP1-2.6 scenarios reveals divergent climate trends: although SSP3-7.0 projects winter (DJF) temperatures approximately 1.5°C higher than those under SSP1-2.6, this warming is accompanied by reduced solar radiation availability during critical growth periods (Fig. 4a-b). Figure 4c-e illustrate trends in extreme low-radiation events for both SSP3-7.0 and SSP1-2.6 scenarios, for the selected seasons that are identified as important for NDVI in Fig. 3d. Under the SSP1-2.6 scenario, all three latitudinal zones exhibit declining trends in the frequency of such events. In contrast, the SSP3-7.0 scenario is characterized by increasing trends in low-radiation events across these zones. This is particularly notable given previous findings indicating a general increase in surface solar radiation over southeastern China under SSP3-7.0 conditions (Niu et al., 2023). Despite this overall trend, localized areas may still experience a heightened frequency of low-radiation anomalies. This suggests a potential ecological trade-off under SSP3-7.0 conditions: while elevated temperatures may facilitate mangrove poleward expansion and improve growth potential during the sensitive growing period, the concurrent rise in low solar radiation events could impose physiological or growth-related limitations. These contrasting impacts highlight the critical importance of climate change mitigation in securing favourable environmental conditions for future mangrove sustainability and expansion.

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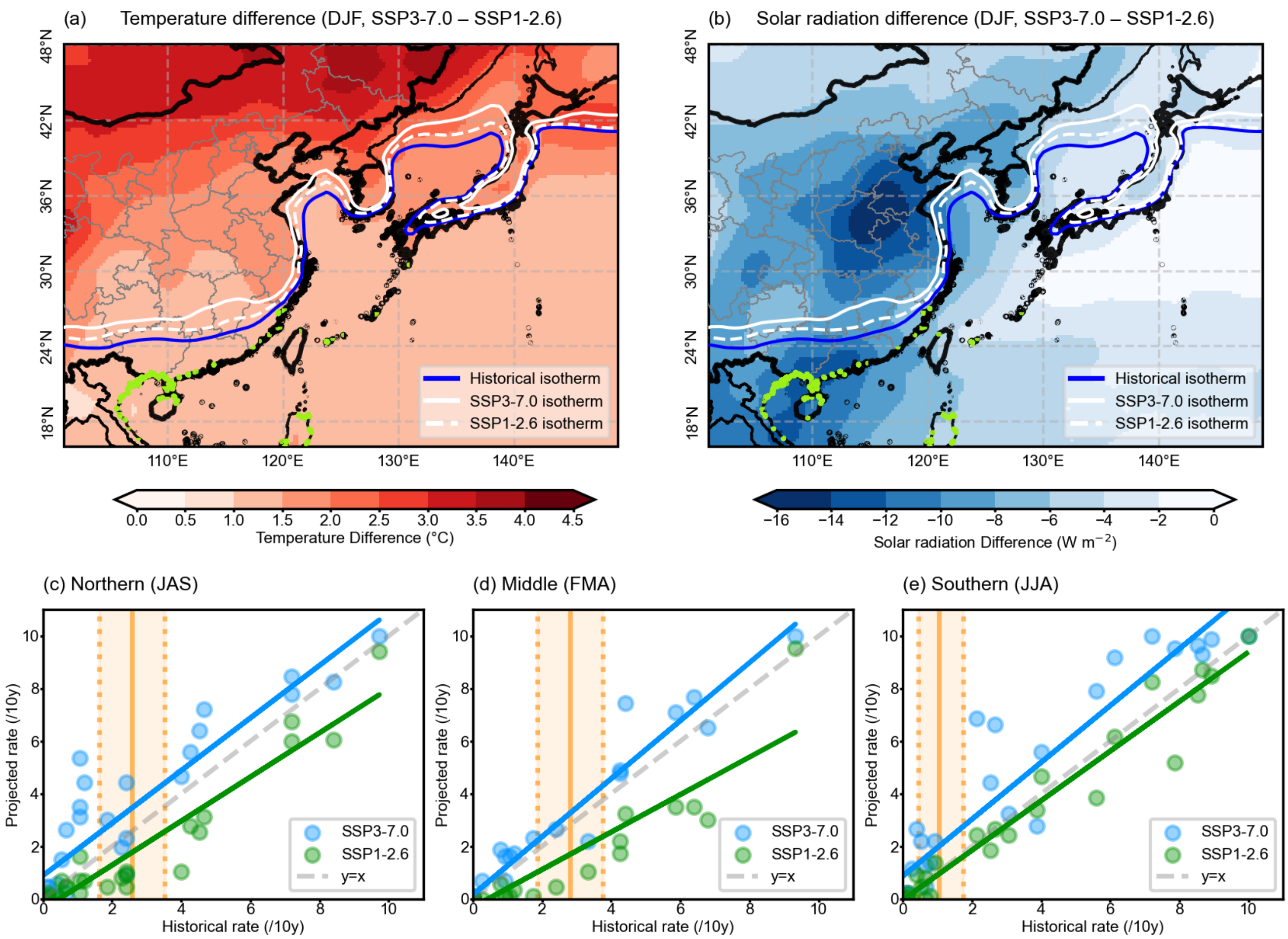

Figure 4. Mangrove dynamics driven by temperature and solar radiation in future scenarios. (a) Temperature difference in DJF for 2081–2100 (SSP3-7.0 – SSP1-2.6). (b) Solar radiation difference in DJF for 2081–2100 (SSP3-7.0 – SSP1-2.6). Green dots indicate the current distribution of mangroves in East Asia. Blue solid, white dashed, and white solid lines represent the 10 °C DJF isotherm for the historical period (2001–2022), and future projections under SSP1-2.6 and SSP3-7.0 (2081–2100), respectively. The rate of low solar radiation events simulated by 28 models for northern (c), middle (d) and southern (e) zones at significant influential seasonal composite. The season for each zone was selected based on the results in Fig. 3d, as the period during which low solar radiation can significantly influence NDVI. The rate for the historical (1940–2014; *x*-axis) period is shown against those for SSP1-2.6 (2015–2100; *y*-axis, green) and SSP3-7.0 (2015–2100; *y*-axis, blue). The orange solid line represents the rate of low solar radiation events of ERA5 (1940–2024), while the two orange dashed lines indicate the 2.5th and 97.5th percentiles of the rate after bootstrap resampling.

We assessed future changes in temperature and solar radiation across projected mangrove expansion zones in East Asia under the two climate scenarios. The potential impacts of high temperature and low solar radiation were evaluated using the thresholds derived from the Northern Zone in Fig 3a and 3d. CMIP6 models reproduced realistic ranges of mean temperature and solar radiation for the historical period, which largely encompass those of the observational dataset (Fig. 5, black lines and blue shading), supporting their use for future projections. Our results indicate a substantial increase in the frequency of

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days exceeding key high-temperature thresholds across the three regions (Fig. 5a–c), suggesting that thermal conditions will become increasingly favourable for mangrove expansion and growth. Although SSP3-7.0 projects lower levels of solar radiation compared to SSP1-2.6 during the DJF season (Fig. 4b), solar radiation during the important transitional season JAS does not show a significant decline relative to historical baselines, and the incidence of extreme low-radiation events remains limited (Fig. 5d–f). This indicates that, under the SSP3-7.0 scenario, the projected rise in temperature is likely to support mangrove range expansion and enhance overall growth potential, although sporadic low solar radiation events may still constrain productivity to some extent. In contrast, the SSP1-2.6 shows a more pronounced increase in mean solar radiation, particularly during this transitional season (Fig. S4d–f), providing even more favourable conditions for photosynthesis and growth. These findings underscore the ecological importance of climate change mitigation: efforts to limit global warming not only promote mangrove expansion into higher latitudes but also ensure improved solar energy availability to support sustained productivity.

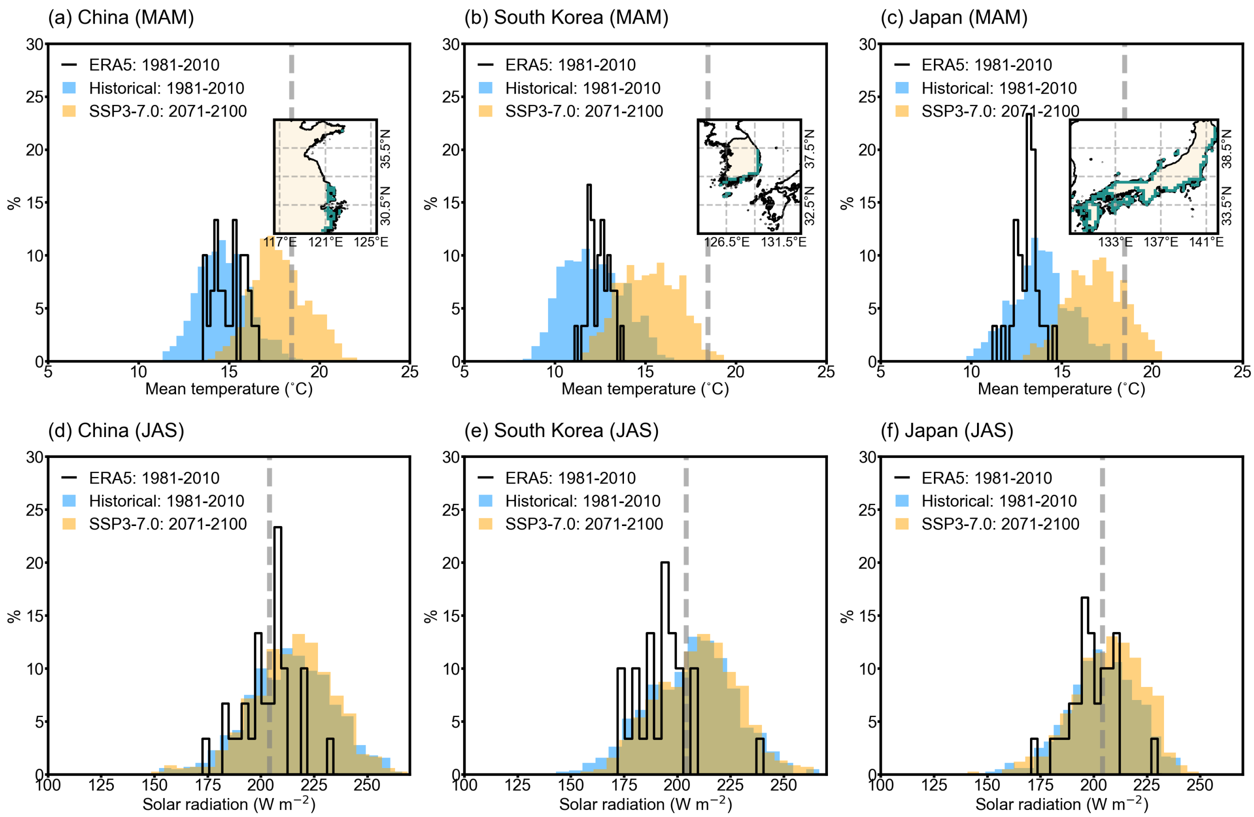

Figure 5. Changes in temperature and solar radiation in future potential mangrove habitats. Histogram of mean temperature comparing ERA5 (1981–2010), CMIP historical (1981–2010) and SSP3-7.0 (2071–2100) for future potential mangrove habitats in China (a), South Korea (b) and Japan (c). Same but for solar radiation in China (d), South Korea (e) and Japan (f). The grey dashed lines represent the threshold criteria for high mean temperature (top row) and low solar radiation (bottom row), using the northern zone as the reference standard. The maps delineate potential mangrove habitats under SSP3-7.0 by integrating: (1) current non-mangrove shorelines, and (2) projected expansion zones where winter (DJF) mean temperatures reach ≥10°C in SSP3-7.0 (2071–2100).

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4 Conclusions

Mangroves are increasingly recognized as a nature-based climate solution due to their distinctive ecological functions and carbon sequestration capacity. While countries in East Asia may consider mangrove restoration a strategic opportunity for climate change mitigation, on-the-ground afforestation efforts have faced numerous challenges. Specifically, unvegetated tidal flats are not counted toward NDCs, but areas colonized by mangroves, salt marshes, or coastal reeds are recognized as carbon sinks and thus included in NDC calculations. For this reason, East Asian governments are increasingly adopting the restoration and afforestation of such coastal wetland ecosystems as policy agendas. In this research, we further compared the lag-effect results between mangroves and the nearby forests (Table S3) and highlighted that mangroves tend to be more influenced by temperature during the MAM season. Previous research has reported that global mangroves are experiencing higher interannual variability in productivity in comparison with forests (Zhang et al., 2024b). This indicates that, when it comes to afforestation and restoration, mangroves may present more challenges than terrestrial forests due to the complexity of their habitats and higher sensitivity to climatic factors, which requires rigorous assessment at the beginning stage, coupled with adaptive management during the establishment. Field studies have reported low early success rates in mangrove restoration projects—ranging from 20–30% in China to 10–20% in the Philippines—attributed to a combination of biotic and abiotic stresses, including low temperatures, high salinity, and unfavourable hydrological and tidal conditions (Liao et al., 1996; Primavera and Esteban, 2008). Restoration potential must be evaluated based on species-specific adaptability, with a clear understanding of the risks associated with both over- and under-adaptation. For example, the introduction of the non-native species *S. apetala*, although initially favoured for its rapid growth and high tolerance, has raised ecological concerns due to its potential to outcompete native species (Zhu et al., 2022). Furthermore, *S. apetala* has exhibited considerable vulnerability, suffering severe damage or dieback during extreme cold events such as the 2008 chilling episode in Guangdong and Guangxi Provinces (Chen et al., 2017). It was also reported that mangrove resilience and resistance towards typhoon events varied with species (Gao et al., 2025). These early experiences underscore the importance of incorporating ecological suitability and climate resilience into mangrove restoration planning. Although our projections indicate considerable potential for poleward mangrove expansion due to temperature increases under future climate scenarios, successful restoration will require careful site selection that accounts for geographic, hydrological, and climatic variables, especially for solar radiation (Lewis et al., 2019). Ultimately, effective mangrove afforestation in East Asia calls for interdisciplinary collaboration (Friess et al., 2022a), integrating ecologically-informed species selection, robust planting and management protocols, and long-term monitoring with adaptive governance frameworks.

Our results indicate that, relative to the SSP1-2.6 scenario, mangroves are projected to face an increased risk of low solar radiation events under the SSP3-7.0 scenario. Previous studies have reported that under SSP3-7.0, global surface solar radiation declines by approximately 2.8 W m^{-2}, primarily due to the enhanced influence of aerosols (Song et al., 2025). While it has been suggested that the "diffuse fertilization effect"—an increase in diffuse radiation due to aerosols—can enhance vegetation productivity in some ecosystems (Mercado et al., 2009), the impacts of aerosols on mangrove

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photosynthetic efficiency remain uncertain. Although a rise in diffuse radiation may partially compensate for the reduction in direct solar radiation, evidence shows that reductions in aerosol concentrations, especially those achieved through air pollution control efforts, can positively influence ecosystem productivity. For example, ref. (Xue et al., 2020) reported a significant improvement in terrestrial ecosystem productivity in China following the implementation of air quality regulations in 2013. Nonetheless, some studies indicate that aerosol reductions may also induce unintended climatic consequences, such as regional warming and increased frequency of extreme weather events (Wang et al., 2023). These findings highlight the need for a nuanced approach to aerosol emission controls, including the prioritization of specific species such as black carbon, which is recognized as the second most potent anthropogenic climate forcing agent, exerting a positive radiative forcing of approximately +1.1 W m^{-2} (Bond et al., 2013). Future research should aim to quantitatively assess the net balance between natural carbon sinks and anthropogenic mitigation efforts, with consideration of compound climate drivers rather than isolated variables. While elevated temperatures and enhanced solar radiation may promote mangrove growth to some extent, associated environmental changes—including shifts in precipitation, evaporation rates, and salinity—introduce substantial ecological complexity (Ward et al., 2016). Moreover, large-scale climate anomalies may exacerbate these uncertainties. For instance, a widespread mangrove dieback event occurred in the Gulf of Carpentaria between late 2015 and 2016, coinciding with a strong El Niño that brought extreme heat, low precipitation, and suppressed sea level rise (Duke et al., 2017; Kim et al., 2025). The anticipated increase in frequency and intensity of extreme weather events and climate oscillations could introduce compounded stressors that challenge mangrove resilience in the future (Lovelock et al., 2022). Taken together, these findings suggest that while climate change presents opportunities for mangrove expansion and enhanced productivity, it simultaneously poses significant challenges. Balancing these dual outcomes will require integrated, multidisciplinary approaches that account for both anthropogenic and natural climate dynamics.

Data Availability

All datasets used in this study are publicly available. Mangrove distribution data was obtained from Global Mangrove Watch (https://zenodo.org/records/6894273). Land cover type data were obtained from MODIS Land Cover Type Yearly Global product (MCD12Q1) (https://www.earthdata.nasa.gov/data/catalog/lpcloud-mcd12q1-061). Remote sensing data for NDVI was obtained from MODIS Vegetation Indices (MOD13Q1) Version 6.1 (https://www.earthdata.nasa.gov/data/catalog/lpcloud-mod13q1-061). Climatology data were obtained from European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) (https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=overview). Data for total bright sunshine was obtained from Hong Kong Observatory (https://www.hko.gov.hk/sc/index.html). Earth System Models data were obtained from Coupled Model Intercomparison Project Phase 6 (CMIP6) (https://aims2.llnl.gov/search).

Author contributions

RC conducted the data analysis and completed the manuscript. JK and HK contributed to the conceptualization and development of the research idea. JC, BL, SJ, and GS provided critical revisions and editorial support throughout the manuscript preparation.

Competing interests

The authors declare that they have no conflict of interest.

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