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Distance to a River Modifies Climate Legacy on Vegetation Growth in a Boreal Riparian Forest

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Abstract: Inter-annual variability in growing season temperature and precipitation, together with snow coverage duration, determine vegetation growth in boreal ecosystems. However, little is known about the impact of concurrent and antecedent climate, particularly snow cover duration, on vegetation growth in a boreal riparian forest. Additionally, significant uncertainty exists regarding whether the distance to a river (as a proxy of groundwater availability) further modifies these climatic legacy effects on vegetation growth. To fill this knowledge gap, we quantified the responses of different vegetation types (shrub, deciduous coniferous and broadleaf forests) to concurrent and antecedent climate variables in a boreal riparian forest, and further determined the magnitude and duration of climate legacies in relation to distance to a river, using MODIS-derived NDVI time series with gridded climate data from 2001 to 2020. Results showed that higher temperature and precipitation and longer snow cover duration increased vegetation growth. For deciduous coniferous forests and broadleaf forests, the duration of temperature legacy was about one year, precipitation legacy about two years and snow cover duration legacy was 3 to 4 years. Further, distance to a river modified the concurrent and antecedent temperature and snow cover duration legacy effects on vegetation growth, but not that of precipitation. Specifically, temperature and snow cover duration legacies were shorter at the sites near a river compared to sites at greater distance to a river. Our research highlights the importance of snow cover duration on vegetation growth and that closeness to a river can buffer adverse climate impacts by shortening the strength and duration of climate legacies in a boreal riparian forest.

Keywords: boreal riparian forest; climate legacy; distance to river; NDVI

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1. Introduction

Boreal forests are sensitive to climate change [1,2]. As a large carbon pool of terrestrial ecosystems, climate-change-induced changes in boreal forest composition and functioning [3–5] may alter regional and even global carbon cycles. This in turn can further accelerate vegetation changes in a changing climate.

Temperature, precipitation and their interaction determine vegetation productivity of boreal forests [6,7]. In northern high latitudes, climate warming has been shown to advance spring budburst and delay autumn senescence, thereby increasing vegetation productivity [8–10]. The growth of coniferous trees is also precipitation-dependent, with enhanced aboveground biomass under increased precipitation [11,12]. Moreover, a shift in precipitation regime and warming can cause differential impacts on different vegetation types [13–15]. For example, drought resistance has been shown to decrease in the following order: forests > shrubs > grasslands [16].

In addition to temperature and precipitation, snow also influences plant growth in the high latitudes of the northern hemisphere, due its thermal protection and the supplement of snow melt water in the early growing season [17–19]. Extensive duration of snow coverage with low winter temperatures may delay snow melting and spring phenology in high-latitude regions, which can limit direct light availability for vegetation growth and development [20]. On the other hand, decreased snow cover duration and extent is likely to enhance the frequency of freeze-thaw cycles, which may result in reduced plant growth [21]. Under global warming, the duration, depth and spatial pattern of snow cover are changing [22,23], which can directly or indirectly affect vegetation growth [24]. However, compared with temperature and precipitation, studies quantifying the effect of snow cover duration on vegetation productivity in boreal forests are lacking.

The effect of climate on vegetation productivity/growth can be long-lasting, and this extended impact is commonly referred to as "climate legacy" or "climate memory" [25,26]. This has been shown for ecosystem structure and functioning [27–31]. Additionally, climate legacy is likely to vary among vegetation types. For example, the duration of climate legacies on most C cycle-related variables (i.e., gross primary production and net primary production) are about one year in grasslands [32,33], but several years in forests [34,35]. Previous studies typically only considered the short-term effect of snow cover (i.e., generally from the previous year) on vegetation growth, soil microbial community composition and diversity [36–38], with little consideration given to the extended impact of snow cover on vegetation growth in subsequent years, especially in riparian ecosystems. Hence, in addition to temperature and precipitation, this study quantified the extended impact of snow cover on vegetation growth in a boreal riparian forest where annual snow cover duration lasts for more than four months. Quantifying the magnitude and duration of antecedent climatic conditions can help us comprehensively understand the feedback of boreal riparian forest ecosystem processes and functioning to climate change, which is important for future vegetation/climate model development and nature resource management.

Altered precipitation and warming have been reported to have strong impacts on vegetation growth in riparian ecosystems [39,40]. The response of riparian vegetation to climate could be largely determined by water table depth, and rivers are likely to modulate climatic impacts via hydrological regulation [41,42]. This has been shown in studies conducted in tropical regions such as the Amazon riparian forests [43,44]. However, to our knowledge, such information is lacking for boreal zones. Therefore, this study investigated how distance from a river modulates the climate sensitivity and legacies of different vegetation types in a boreal zone.

In this study, we aimed to quantify: (1) the magnitude and duration of snow cover legacy on vegetation growth of different vegetation types in a boreal riparian forest, and (2) if and how distance to a river modifies the magnitude and time course of climate memories. This may be the case because during extended dry period or drought, in contrast to upland forests, riparian forests can access groundwater to alleviate water stress. Accordingly, we hypothesized that (1) snow cover, as well as temperature and precipitation have direct and carry-over effects on vegetation growth, and climate memories differ among vegetation types; and (2) climate memories are affected by distance to a river, implying a river buffering effect.

2. Materials and Methods

2.1. Study Area

The study area was in the Nanweng River National Nature Reserve (51°05′~51°39′ N, 125°07′~125°50′ E) in the southeast of the Daxing' an Mountains in China, with a semi-humid continental monsoon climate (Figure 1). It is warm and humid in summer, and cold and dry in winter. The growing season is from late April to September. The mean annual, growing season and winter temperatures are about −1.2, 12.3 and −14.7 °C, respectively. Snow cover duration spans from late October to March of the following year, on average about 138 days.

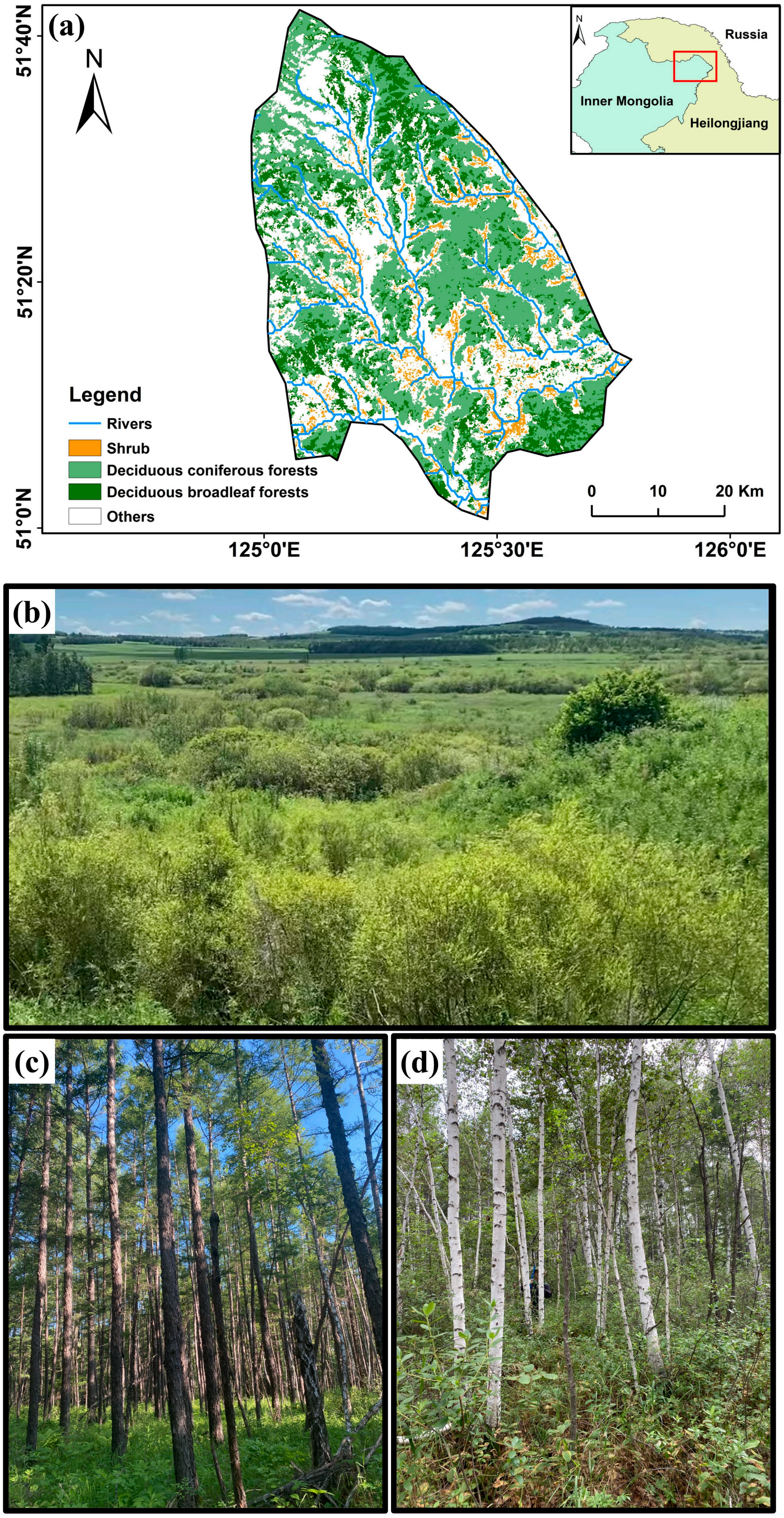

Figure 1. (**a**) Location of the Nanweng River National Nature Reserve and vegetation types (inset). Three types of vegetation (i.e., shrub, deciduous coniferous forests and deciduous broadleaf forests) obtained from the 2019 global land cover map (CGLS-LC100 Collection 3, with a spatial resolution of 100 m). (**b**) Photo of shrub at study area. (**c**) Photo of dominant species *Larix gmelinii* in the de-ciduous coniferous forest. (**d**) Photo of dominant species *Betula platyphylla* in the deciduous broadleaf forest.

The study area is in a permafrost region, with the depth of the active layer ranging from the soil surface to 0.8 to 1.4 m [45]. The main vegetation includes *Larix gmelinii*, *Betula platyphylla*, *Spiraea salicifolia*, *Rosa acicularis*, *Vaccinium uliginosum*, *Geranium maximowiczii*, *Sanguisorba parviflora* and *Sium suave*. The understory vegetation coverage was about 59–73%, and the canopy closure was about 31–67%. The soil is acidic with pH of 4.9–5.8, mainly dark brown soil, brown coniferous forest soil and gray forest soil. Soil EC was about 0.069–0.125 mS/cm. Soil organic carbon and nitrogen content at 0–10 cm was 5.8–33.2% and 0.7–2.4%, respectively.

2.2. Random Site Selection

To quantify the impact of climate variables on different vegetation types, we first randomly selected study sites based upon vegetation type, elevation, and distance to river. Vegetation types were extracted from a global land cover map at 100 m spatial resolution (Figure 1, CGLS-LC100 Collection 3), which is a new product in the portfolio of the Copernicus Global Land Service (CGLS) [46]. Three land cover types were considered, including shrub, deciduous coniferous forests (DCF) and deciduous broadleaf forests (DBF). Elevation information was collected from SRTM V3 (SRTM Plus), provided by NASA JPL at a resolution of 1 arc-second (approximately 30 m) [47]. To minimize the elevation-induced impact on vegetation, only relatively flat areas (i.e., elevation ranging from 400 to 700 m) were considered. The river distribution data was downloaded from a global river widths and depths database, which was based on hydraulic geometry equations and the HydroSHEDS hydrography dataset [48]. Using these data sources, we divided the entire study area into 500 $\times$ 500 m grids using the fishnet method in ArcGIS 10.7, and extracted the center point of each grid unit. Then, the shortest distance from each of the center points to the nearest river was calculated and grouped by distance. We only considered two groups (i.e., relatively close to the river (within 1 km) and further away (2–3 km)), to have two distinct distances. Close to the river (<1 km) was primarily influenced by running water, and 2–3 km from a river were mainly dependent upon seasonal precipitation and snow input. Thus, 50 sites from each vegetation type (shrub, deciduous coniferous forest, and deciduous broadleaf forest) and at each distance from a river were expected to be selected. But only 29 sites in shrublands were found 2–3 km away from a river, therefore we obtained 279 sites in total.

2.3. MODIS Derived NDVI Time Series

Normalized difference vegetation index (NDVI) was used to reflect vegetation growth [49,50]. We chose the Moderate Resolution Imaging Spectroradiometer (MODIS)-derived NDVI time series due to its excellent temporal and spatial coverage and because it is a good proxy of photosynthetic capacity and vegetation biomass [51]. We downloaded daily near-infrared reflectance (bands 1: 620–670 nm) and red reflectance (bands 2: 841–876 nm) from the MCD43A4 (V6) product (with a spatial resolution of 500 m) [52]. Bands 1 and 2 were used to calculate the daily NDVI using the Equation (1) [50] from which annual maximum NDVI was obtained.

$$\mathrm{NDVI} = (\mathrm{band2} - \mathrm{band1})/(\mathrm{band2} + \mathrm{band1}) \tag{1}$$

2.4. Climate Data

Monthly maximum and minimum temperature, and total precipitation input from 2001 to 2020 was obtained from TerraClimate [53], which is a monthly climate dataset for global terrestrial surfaces. Considering that the growing season generally spans from April to September in the region [54], we calculated the average temperature and total precipitation over these months. Snow phenology data derived from the China's National Cryosphere Desert Data Center (http://www.ncdc.ac.cn (accessed on 26 May 2022)) was used to obtain information on snow cover duration (October to March of the following year) from 2000 to 2020 for the study area [55].

2.5. Methodology

The overview of the methodology for this study is shown in Figure 2. We used the stochastic antecedent model (SAM) under a Bayesian framework [56] to determine legacy effects of temperature, precipitation and snow cover duration on vegetation growth, using the EcoMem package [57] in R [58]. The SAM approach allows us to estimate the effect and cumulative importance of current and antecedent climate on vegetation growth.

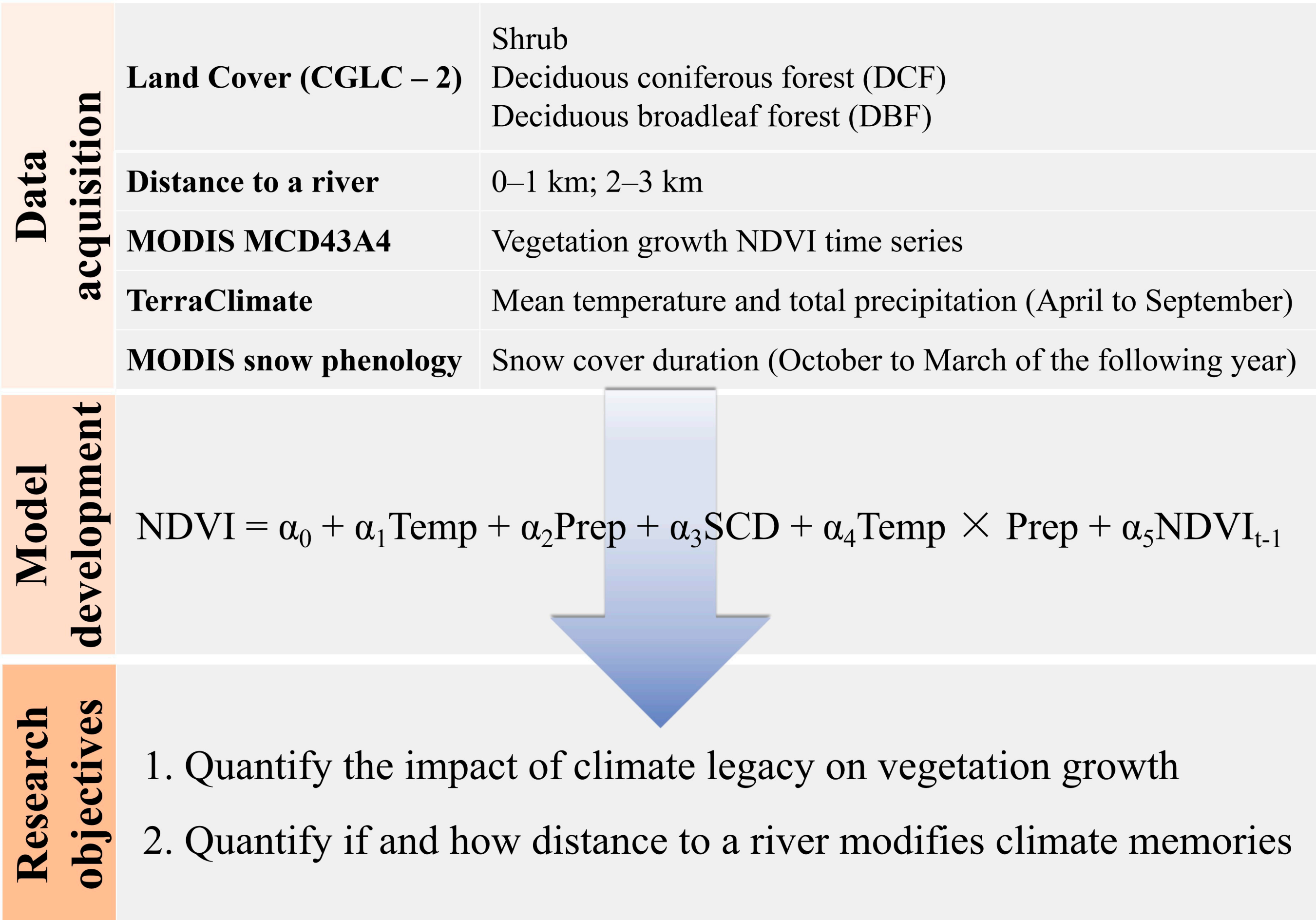

Figure 2. Flowchart for analyzing climate legacy on vegetation growth used in this study.

A linear equation was built, and the explanatory variables were mean temperature and total precipitation over the growing season and their interaction, as well as snow cover duration. Additionally, NDVI ($NDVI_{t-1}$) of the previous year was included as the proxy of endogenous growth and was referred to as the autoregressive term. We did not use winter temperature as an explanatory variable because it was significantly correlated with snow cover duration (general linear regression model: $F_{1,5578} = 216.9$, $p < 0.001$) to avoid multicollinearity. We preformed SAM modeling to quantify climate memories for each vegetation type (shrub, deciduous coniferous forest, and deciduous broadleaf forest) and each distance to river (0–1 km and 2–3 km), respectively. The maximum length of climate legacies for precipitation, air temperature and snow cover duration were set at five years (year 1–5) into the past [35,59,60]. Together with climate data of the concurrent year (year 0), climate over the preceding six years is assumed to affect vegetation growth. Then, each year is assigned with a random weight which illustrates the contribution from each year considered, and these weights can be summed to 1. All weights together demonstrate the temporal features of the climate memory. The linear equation for climate memory is:

$$\mathrm{NDVI} = \alpha_0 + \alpha_1\mathrm{Temp} + \alpha_2\mathrm{Prep} + \alpha_3\mathrm{SCD} + \alpha_4\mathrm{Temp} \times \mathrm{Prep} + \alpha_5\mathrm{NDVI}_{t-1} \quad (2)$$

where Temp and Prep are mean temperature and the total precipitation during the growing season, respectively. SCD is snow cover duration. Temp × Prep indicates the interaction between mean temperature and total precipitation during the growing season. NDVI_{t-1} is NDVI from the previous year.

For each SAM model, we ran three parallel Markov Monte Carlo (MCMC) chains for 15,000 iterations each. After an initial burn-in period (5000 iterations), we thinned the chains by 10, and about 1000 relatively independent samples were produced from the posterior distribution. After assessing model convergence, we summarized the marginal posterior distributions (the posterior means and 95% CIs) and importance weights for the ecological memory parameters. If the 95% CIs of the ecological memory parameters do not contain zero, then the climate variable has a positive or negative effect on vegetation growth. Cumulative importance weights greater than 0.5 over the past five years reflect persistent impacts of climate variables on vegetation growth, which can be referred to as the timescale of the legacy effect for the climatic driver.

3. Results

3.1. Vegetation Growth in Response to Temperature, Precipitation and Snow Cover Duration

The response of vegetation growth to concurrent and antecedent climate variables differed among vegetation types (Figure 3). Generally, growing season temperature and precipitation, as well as snow cover duration positively affected forest growth whereas shrub growth was determined only by precipitation and snow cover duration. Further, a significant negative interaction between temperature and precipitation was found for all vegetation types, suggesting enhanced vegetation growth under warm and dry conditions.

Figure 4 shows the length and strength of climate legacies. Temperature legacy lasted for one year in deciduous coniferous forests, whereas there was no temperature legacy in shrublands. The duration of precipitation legacy was approximately one year for deciduous coniferous forests and deciduous broadleaf forests which was much shorter than that for shrublands where it was more than four years. The legacy of snow cover duration in coniferous forests and deciduous broadleaf forests was three to four years.

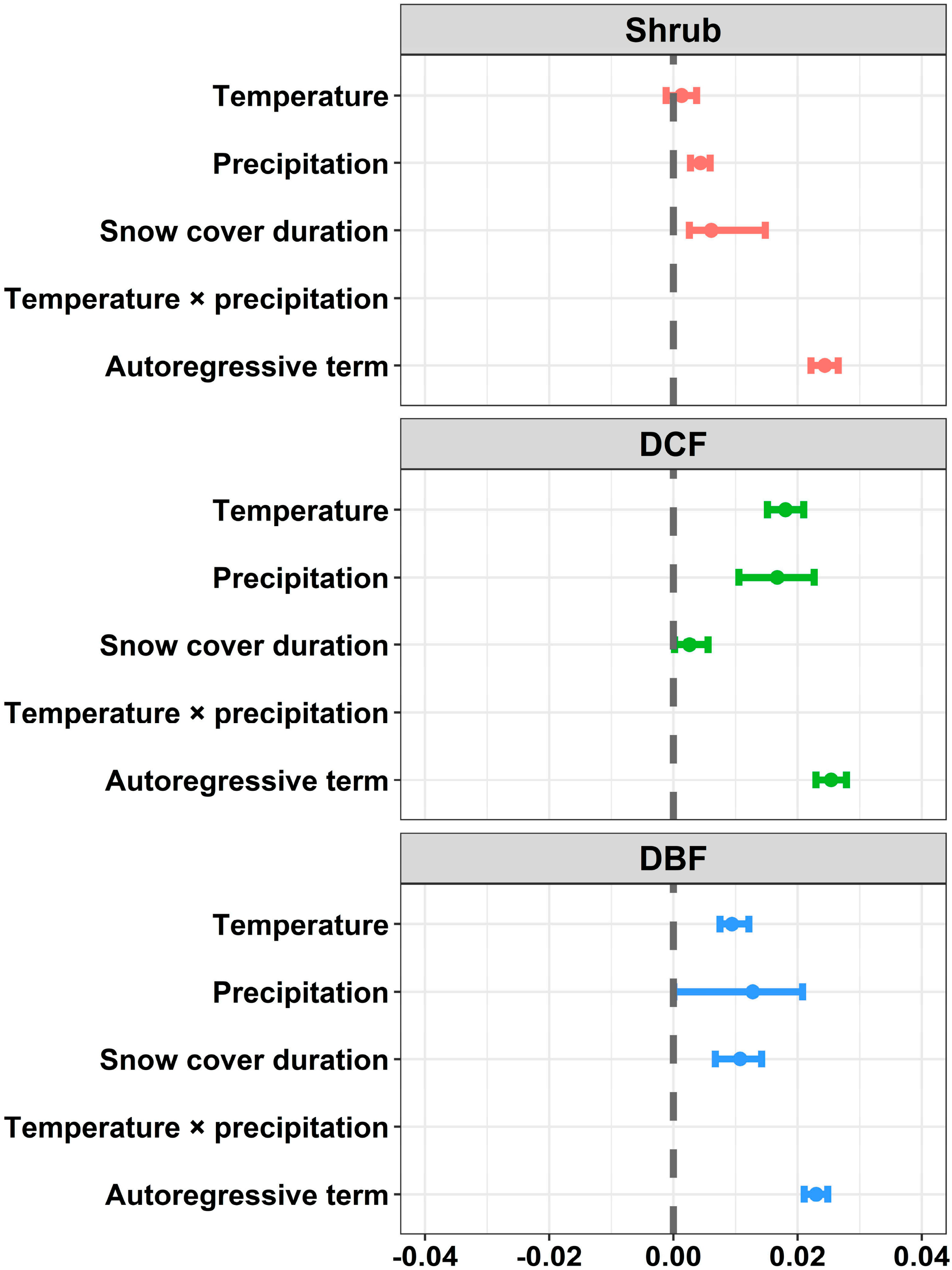

Figure 3. Posterior means values (points) and 95% credible intervals (CIs; horizontal lines) for antecedent climatic variables (i.e., temperature, precipitation and snow cover duration) and their interaction (temperature × precipitation) for three vegetation types (different colors represent different vegetation types, with red for shrub, green for deciduous coniferous forest (DCF), and blue for deciduous broadleaf forest (DBF)). The vertical dotted line indicates the zero line, and 95% CIs that overlap the zero line denote parameters that are not statistically different from zero.

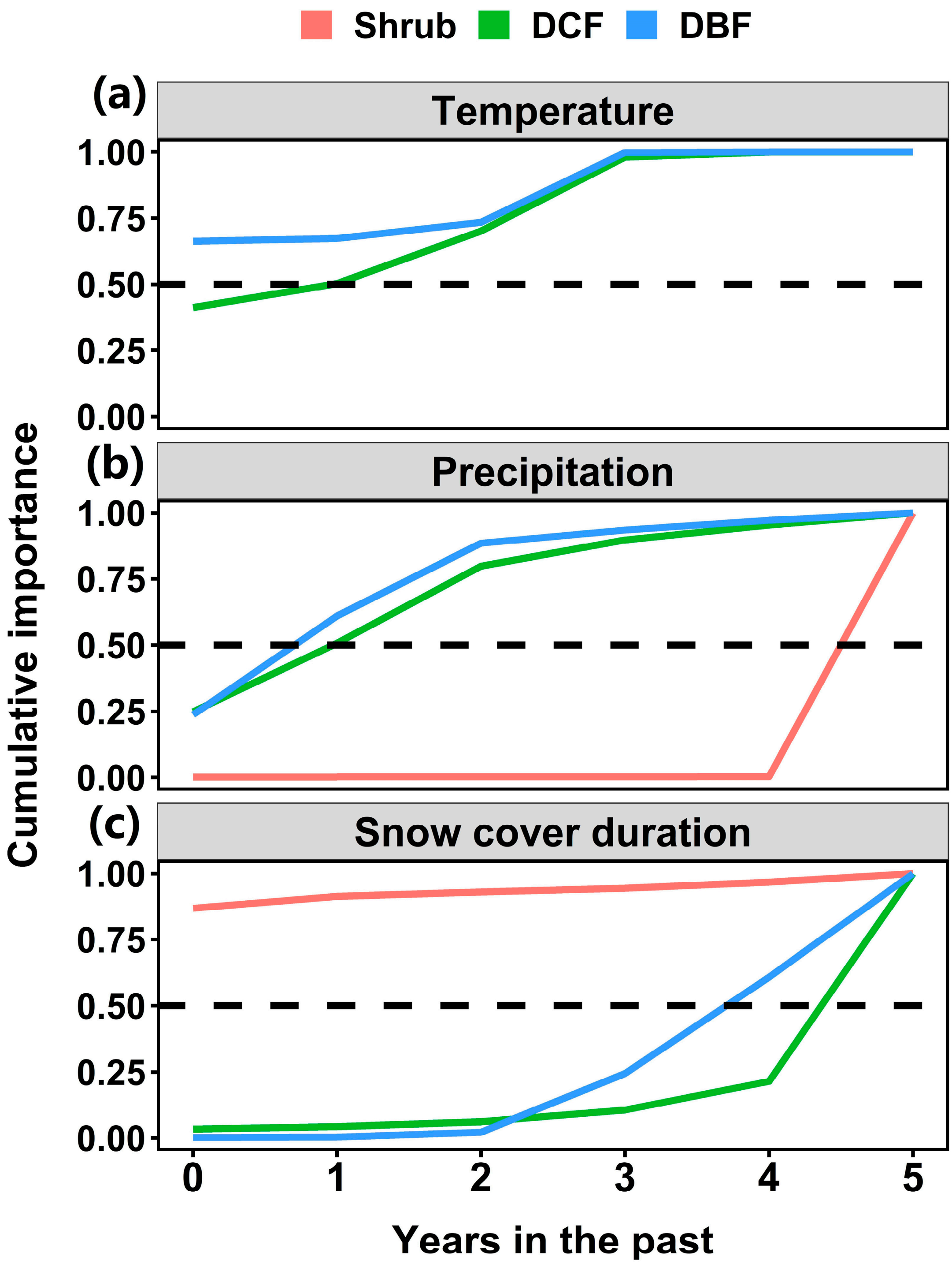

Figure 4. Cumulative importance of antecedent temperature (**a**), precipitation (**b**) and snow cover duration (**c**) on different vegetation types. Equivalent to 'cumulative probabilities', climate effects experienced over the concurrent year and past five years (x-axis) account for cumulative importance (y-axis) of the climate covariate to NDVI. The posterior mean cumulative importance is shown for each antecedent climatic variable, with different colored lines representing different vegetation types. Only vegetation types responding to climate variables in Figure 3 are included. The dashed line at a cumulative importance of 0.5 indicates the threshold for the critical lag period. The time when the cumulative importance crosses this line is considered the timescale of the memory effect for each vegetation type and for the climatic driver. DCF and DBF are deciduous coniferous forest and deciduous broadleaf forest, respectively.

3.2. Distance to a River Modifies the Importance and Duration of Climatic Legacy

Perpendicular distance to a river only modified the responses of vegetation growth to current and antecedent temperature in shrublands, but had no effect on forest growth (Figure 5). Specifically, shrub growth relatively close to a river (approximately 0–1 km) was no affected by temperature fluctuations; whereas they influenced shrub growth at sites further away from river (approximately 2–3 km).

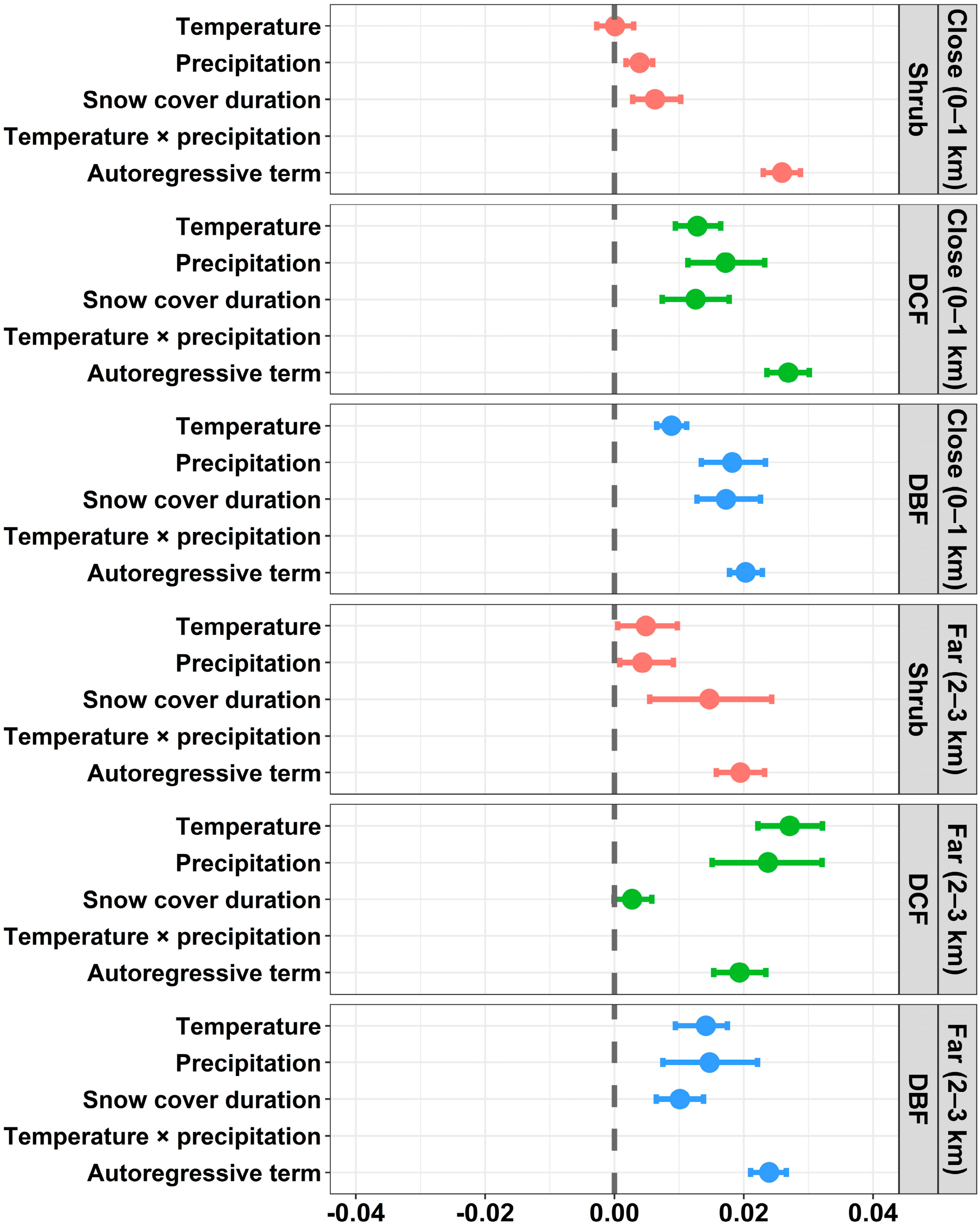

Figure 5. Posterior mean coefficient values (and 95% credible intervals) for antecedent climate effects (e.g., temperature, precipitation, snow cover days) and their interactions (temperature × precipitation) for different vegetation types by distance to a river (close represents close to a river (<1 km); far represents 2–3 km away from a river). The vertical dashed line at estimate = 0 is depicted (i.e., no significant effect).

The duration of temperature legacy was about one year in deciduous coniferous forest that were far away a river (Figure 6). Precipitation legacy was approximately one year for deciduous coniferous forest and deciduous broadleaf forest, irrespective of distance to a river. The duration of snow cover legacy was generally shorter for sites that were close to a river in all three vegetation types compared to sites far from a river, indicating that the growth of vegetation far from a river was more dependent on snow cover.

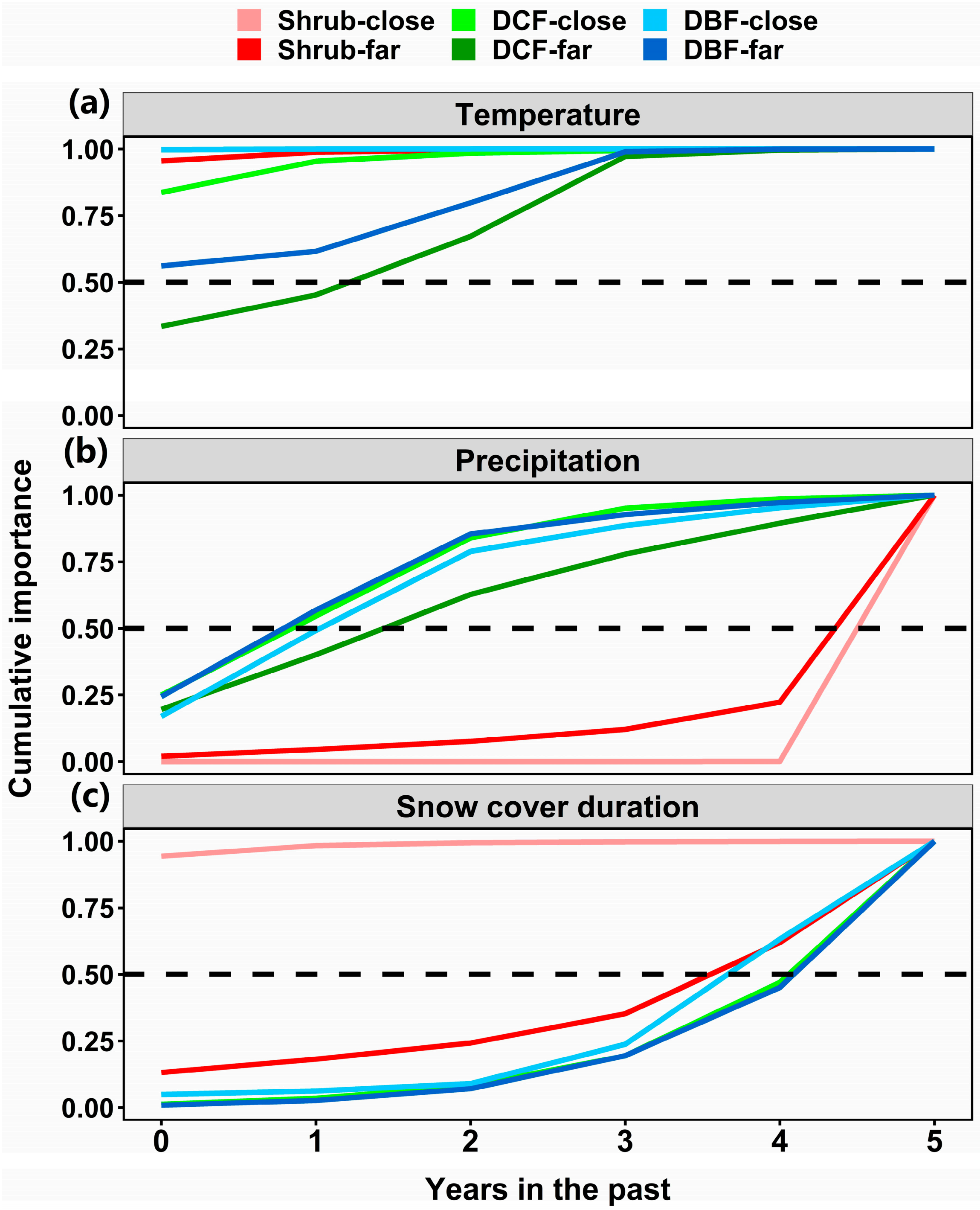

Figure 6. The cumulative importance for vegetation types at different distances from rivers of antecedent climate effects (temperature (**a**), precipitation (**b**) and snow cover days (**c**)). Only vegetation types responding to climate variables in Figure 5 are included. The timescale (legacy 'length') is based on when the cumulative importance weights reach 50% (dashed horizontal line).

4. Discussion

This study quantified the response of different vegetation types to concurrent and antecedent climate variables in a boreal riparian forest and further determined the magnitude and time course of climate legacy in relation to distance to a river. We showed that increasing concurrent and antecedent temperature, precipitation and snow cover duration promoted vegetation growth. The duration of temperature legacy and precipitation legacy was about one year for the most of the vegetation types. In contrast, the legacy effect of snow cover duration on growth varied among vegetation types, lasting from three (deciduous broadleaf forest) to four years (deciduous coniferous forest). Therefore, the first hypothesis (snow cover, as well as temperature and precipitation have direct and carry-over effects on vegetation growth, and climate memories differ among vegetation types) can be partially accepted. Additionally, distance to a river modified the effect of concurrent and the duration of antecedent temperature and snow cover legacy on vegetation growth, but had no effect on precipitation legacy on vegetation growth. This finding partially confirms the second hypothesis (climate memories would be affected by distance to a river, implying a river buffering effect).

4.1. Effects of Concurrent and Antecedent Temperature and Precipitation on Vegetation Growth

Our study area is permafrost, with permanently frozen soil from about 10 cm to 1 m depth [45]. As air temperature rises, the permafrost gradually thaws and snow melts. Therefore, the boreal forests are in a low temperature and moist conditions at the start of the growing season [61]. Hence, low temperature was likely limiting forest growth [62], particularly in early spring [63,64]. Indeed, the results of this study showed that increasing current and antecedent growing season temperature (from April to September) increased vegetation growth, particularly in the deciduous coniferous and broadleaf forests (Figure 3). This has been shown before for boreal forests [65–67]. As temperature rises, the growing season will start earlier and last longer, resulting in an extended growing period [68–70]. However, we did not find a significant temperature impact on shrub growth, possibly because shrubs are more influenced by microclimate, topography, and soil temperature than trees [71]. We found that the duration of temperature legacy of deciduous coniferous forest was about one year (Figure 4a).

Increasing growing season precipitation also promoted vegetation growth, indicating that water availability limited plant growth, likely later in the growing season. Previous studies have shown that precipitation legacy on vegetation growth lasted from several months to years, and forests generally had a longer precipitation legacy than shrublands [27,72–76]. However, in this study, the duration of precipitation legacy for deciduous and broadleaf coniferous forest was one year, whereas it was 5 years for shrubs (Figures 3 and 4b). This may be because trees have deeper roots than shrubs, which allows them to access water stored in deep soil or even ground water. Further, trees may also be able to use water stored in the trunk and roots. Thus, trees would be less reliant on rainfall in previous years. Shrubs on the other hand, with their shallower roots and lower aboveground biomass, would use less water in a given year and could therefore benefit longer from high precipitation in previous years.

4.2. Snow Cover Duration Legacy on Vegetation Growth

Snow cover can play an important role in the early phase of vegetation growth in the northern hemisphere [77–79]. Our results showed that increased snow cover duration increased vegetation growth (Figure 3). The extended snow cover duration is beneficial for vegetation productivity and health in the boreal riparian forest for several reasons. Firstly, longer snow cover duration, which is usually accompanied by greater depth of snow cover in our study area, suggests that a greater amount of snowmelt water is available in the subsequent growing season [80,81]. Therefore, once the ecosystem warms up in spring, snowmelt water can infiltrate into soils, directly increasing plant growth by improving water availability and indirectly by enhancing microbial activity [78,81]. Secondly, extended snow cover can protect soils from extremely low temperatures and strong winds [82–84]. In our study area, the average temperature in winter (late October to March of the following year) is approximately −14 °C. Therefore, the thermal insulation function of snow is important, particularly early in the growing season. Thirdly, areas covered with thick snow generally have a higher top soil temperature than areas with little or no snow [85], which can stimulate the decomposition of soil organic matter in spring, and promote both root growth and microbial activity [18].

Our results showed that the legacy effect of snow cover duration on vegetation growth varied among vegetation types (Figure 4c). Based on a study in interior Alaska, Wipf [86] suggested that shrubs would first be driven by snow melting time and secondly by accumulated temperature. Due to the low stature and shallow roots of shrubs compared to coniferous and broadleaf trees, they are likely more influenced by the insulating effect of snow cover in winter, and may benefit more from high water availability in the top soil early in the growing season [87].

4.3. River Modulates Climate Legacy

Our results show that distance to a river can modify the responses of shrubs to temperature (Figure 5). The growth of shrubs at sites adjacent to a river was less affected by temperature fluctuations than at sites further away. This may be because rivers can buffer temperature fluctuations [88], resulting in less variation in temperature at sites close to the river compared to those further away.

Our findings also revealed that distance to river did not alter the duration of precipitation legacy, but modified the duration of snow legacy (Figure 6b,c). It can be generally expected that sites become drier with increasing distance to river, and that vegetation is more dependent on growing season precipitation at sites further away from the river compared to those close to the river, thus that precipitation legacy differs. However, we did not observe this. In this ecosystem, plants may need only a certain amount of water from precipitation and deep soil for growth, and therefore may not respond to a greater amount of water due to the closeness of the river. This may be the adaptive mechanism of the vegetation at this site.

The duration of snow duration legacy was reduced at sites particularly close to river. As mentioned above, the extended snow cover duration likely enhanced vegetation growth because of the insulating effect of snow which protects soil and plants from freezing. This may be less important at sites close to the river because they remain warmer compared to sites further away.

5. Conclusions

This study showed that higher temperature and precipitation and longer snow cover duration increased vegetation growth. The duration of temperature legacy and precipitation legacy was about one year for all vegetation types, but snow cover duration legacy lasted from three (in deciduous broadleaf forest) to four years (in deciduous coniferous forest). Temperature and snow duration cover legacies were modified by the distance to a river. The legacy of snow cover duration was shortened at the sites near the river while the duration of precipitation legacy remained unchanged, which may be due to the insulation effect of snow cover on soil and the buffering effect of rivers on temperature fluctuations. These findings highlight the importance of snow cover duration on vegetation growth in the boreal riparian forest and that proximity of a river can further modify the response of vegetation growth to climatic conditions. These findings are useful for vegetation model development and to inform boreal forest management in the future. The current study emphasized the positive role of prolonged snow cover duration on vegetation growth, but in general the immediate and carry-over effects of snow cover were less investigated than the effect of temperature and precipitation legacies in boreal regions. Given the fact that climate change is highly likely to alter the duration and extent of snow coverage in this and other similar cold regions, extensive studies are required to better understand the effects of prolonged snow cover on boreal forest growth.

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