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Effect of seasonal snow on the start of growing season of typical vegetation in Northern Hemisphere

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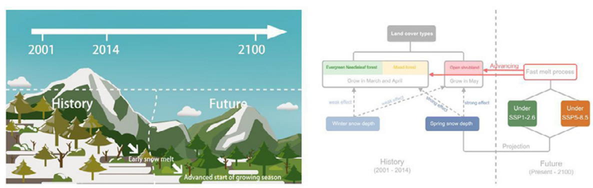
HIGHLIGHTS

- Start of the growing season (SGS) showed obvious advanced in the past years.
- SGS was more closely related with spring snow depth than winter snow depth.
- Different climate conditions will enhance the discrepancy of vegetation changes.

GRAPHICAL ABSTRACT



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ABSTRACT

Under global warming, seasonal snow takes faster melting rate than before, which greatly changes the hydrological cycle. In this study, by targeting three typical seasonal snow-covered land types (i.e., open shrubland, evergreen needleleaf forest and mixed forest) in the Northern Hemisphere, the start of growing season (SGS) has been found obviously advanced in the past years, greatly contributed by the faster melting rate of seasonal snow. It is manifested that significantly positive correlation has been found between SGS and May snow depth for open shrubs, March and April snow depth for evergreen needleleaf forests and March snow depth for mixed forests. However, such close association is not appeared in all the climate conditions of same vegetation. In the future, as the rate of melting snow becomes faster in the high emission of greenhouse gasses than the current situation, continuously advanced SGS will accelerate the change of vegetation distribution in the Northern Hemisphere. These findings offer insights into understanding the effect from seasonal snow on vegetation and promote the sustainable utilization of regional vegetation in the Northern Hemisphere.

1. Introduction

Snow is one of the major controlling factors of phenology due to its impacts on regional water cycle and soil nutrient influx, which ultimately impacts vegetation growth (Yu et al., 2013; Slatyer et al., 2021). A downward trend of snow cover extent was observed during the Northern Hemisphere (NH) spring and summer in the last two decades (Bormann et al., 2018; Y.L. Wang et al., 2018). The annual mean snow depth decreased at a rate of 0.06 cm yr^{-1} in the NH, accompanied by reduced duration of snow cover from 1992 to 2016 (Xiao et al., 2020). Such changes of snow cover have strongly altered the soil water budget. During the melting period, soil water content is generally high, driven by the melting, soil texture and topography (Zhang, 2005). The changes of soil temperature and water content are primary drivers of many ecosystem processes, such as the seasonal variation in soil respiration rate (Borken and Matzner, 2009).

Numerous studies showed that earlier snowmelt was consistently associated with advanced spring phenology in plants, thus prolonging the growing season and increasing the productivity (Aurela et al., 2004; Wipf and Rixen, 2010; Pulliainen et al., 2017; Slatyer et al., 2021). Deeper spring snowpack and later snowmelt may delay the onset of spring vegetation growth and shorten the growing season (Chen et al., 2011; Cooper et al., 2011; Xie et al., 2020). In some areas of northern Europe, the green-up onset date may be delayed by heavy snow and insufficient winter chilling, possibly attributed to the positive North Atlantic Oscillation phase (Nordli et al., 2008; Richardson et al., 2013). For the alpine steppes in the Tibetan Plateau, the negative correlation between snow cover duration and the onset of growth was highly significant (X.Y. Wang et al., 2018).

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Table 1
Definitions of the four regions used in this study.

Region	Longitude/Latitude
North America (NAM)	180°–25°W, 45°N–70°N,
Europe (EU)	25°W–60°E, 45°N–70°N
Central Asia (CAS)	60°E–90°E, 45°N–70°N
East Asia (EAS)	90°E–180°, 45°N–70°N

As the snow effect on phenology has obvious regional characters, previous results mainly focused on their local relationship. At large scales, studying the effect of snow on phenology is also attractive. In the NH, there are different land cover types, predominated by evergreen needleleaf, mixed forest and shrublands. As the spatial distribution of climate condition is different in each continent, the responses of spring phenology to snow by these three typical vegetation types show notable differences. Therefore, it is necessary to investigate the spatio-temporal change of typical vegetation, and compare these response differences from the start of growing season (SGS) to snow changes over different regions of North America, Europe, Central Asia, and East Asia. As the high emission of greenhouse gases will accelerate the decreasing rate of snow depth based on model simulations, related vegetation changes will likely appear in the future.

2. Materials and methods

2.1. Materials

In the mid-to-high latitudes of the NH, the impacts of snow cover dynamics on vegetation show large differences among boreal biomes (Eugster et al., 2000). Open shrubs, mixed forests and evergreen needleleaf forests are widely distributed in 45°N–70°N, covering 18.49%, 13.75% and 5.15% of the region, respectively. These three vegetation types not only cover large area in the mid-to-high latitudes of the NH, but also are widespread in the North America, Europe and Asia, so that we can compare the relationships between the start of growing season and snow depth of different regions. Besides, the three selected vegetation types were highly sensitive to snow changes compared with other vegetation types in the NH. In this study, we select the area where the distributions of these three major land cover types are stable from 2001 to 2014 based on the Moderate Resolution Imaging Spectroradiometer (MODIS) land cover data (MCD12C1). The region with stable biome is defined as the grids with the same land cover type in both 2001 and 2014. The study area is divided into four geographical regions given in Table 1. The latitude and longitude ranges of the four subregions are also listed in Table 1.

The MCD12C1 Version 6 data contains 17 land cover types, including 11 natural vegetation classes, 3 developed and mosaicked land classes, and 3 non-vegetated land classes. The data we selected covers the period from 2001 to 2014 at a resolution of 0.05° × 0.05° and yearly interval (Friedl et al., 2010). Compared with the Advanced Very High-Resolution Radiometer data, the enhanced spectral, spatial, radiometric, and geometric qualities of the MODIS data provide a greatly improved basis for monitoring and mapping global land cover. Therefore, the land cover maps based on the MODIS are useful at regional and global scales (Liston et al., 2007; Friedl et al., 2010).

The monthly snow depth data used in this study are from the ERA5-land reanalysis dataset, covering a period from 1950 to present on 0.1° × 0.1° grid. The dataset provides a large number of land variables at hourly interval, combining model outputs with observations. This reanalysis is selected due to its enhanced resolution compared to the ERA5, which is the fifth generation of atmospheric reanalysis of the global climate produced by the European center for Medium-Range Weather Forecasts (ECMWF). SGS data used in this study were estimated by Wang et al. (2019) from the GIMMS3g dataset according to five widely used phenology retrieval methods.

We used 13 models used in the Coupled Model Intercomparison Project phase 6 (CMIP6) under shared socioeconomic pathways (SSPs) for the period 2015–2100 to evaluate the possible impacts of spring snow depth on SGS (Table 2). SSP1–2.6 and SSP5–8.5 were selected, representing the low end and high end of the range of future forcing pathway, respectively. The multi-model ensemble mean for snow depth is calculated according to each weight of the models provided by Zhong et al. (2022). Their study evaluated snow depth simulations from 22 CMIP6 models by comparing them to high quality observational dataset for the period of 1955–2014 across high-latitude regions of the NH, which includes our study area.

2.2. Methods

We used simple linear regression to identify the linear relation between SGS and winter/spring snow depth of three types of vegetation over each region, and the season in which the snow depth is more closely related to SGS of three vegetation types in each region. The Pearson correlation analysis is the correlation used to explore the relationship between SGS and snow depth of different months (March, April and May).

3. Results

3.1. Distributions of land cover types during 2001–2014

Fig. 1(a) shows the distributions of three land cover types based on the period of 2001–2014, covering a wide area across the mid-to-high latitude of the NH. The open shrublands were mainly distributed in northern Canada and northern Russia; evergreen needleleaf forests were mostly concentrated in southern Canada and northern Europe; and mixed forests primarily covered the southeastern part of Canada and were also located in some regions closed to 60°N of Eurasia. Fig. 1(b) shows the changes of the typical vegetation by comparing their distributions in 2001 and 2014. It is obvious that large tracts of evergreen needleleaf forests disappeared in North America (NAM); and the decrease of mixed forest mainly occurred over Europe (EU) and central Asia (CAS). The new mixed forests majorly appeared in the southeastern part of NAM. For open shrubs, they changed mostly in the mid-to-high latitude of East Asia (EAS).

Changes in the area for these three -types of vegetation in the zonal direction are illustrated in Fig. 2. The contraction of open shrublands mainly appeared around 60°N–70°N in NAM and EAS. The area of evergreen needleleaf forests concentrated in the 45°N–55°N region of NAM decreased significantly, while a slight increase of evergreen needleleaf forests can be found in 55°N–60°N of NAM and in 60°N–65°N of EU. The obvious decrease of mixed forest was majorly located in the mid latitudes of CAS and EAS. Compared with the evergreen needleleaf forests and open shrubs, the mixed forests took an obvious increase in the latitudes between 45°N and 50°N of NAM, and weak decreases over 50°N–60°N of EU, CAS and EAU. From the comparison over the four regions, the typical vegetations of NAM and EAS showed obvious changes. The decreased open shrubs were majorly located around the 70°N of EAS, but the evergreen needleleaf forests decreased in 45°N–50°N of NAM.

3.2. Distribution of SGS during 2001–2014

For the three typical vegetations, their SGSs were advanced. Combined with the distribution of vegetation in Fig. 1(a), Fig. 3(a) shows that SGS of open shrublands had the highest value from 130 to 160 days, which means SGS was in late-spring, even the start of summer. SGS of evergreen needleleaf forest and mixed forest were mainly around the 115 Julian day, which was in April, expect for EU with the earliest SGS. The trend of SGS illustrates that the extremely significant decrease was mainly in the open shrublands of the northern part of EAS (Fig. 3(b)). By contrast, an extremely significant increase was found in some small

Table 2
Climate models used in this study.

	Model	Institute	Country	Horizontal resolution (lon × lat)	Weight (%)
1	BCC–CSM2-MR	Beijing Climate Center (BCC)	China	1.1° × 1.1°	6.47
2	CAS-ESM2–0	Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP, CAS)	China	1.4° × 1.4°	7.13
3	CESM2-WACCM	National Center for Atmospheric Research (NCAR)	United States	1.25° × 0.94°	8.04
4	EC-Earth3	EC-Earth Consortium	Sweden	0.7° × 0.7°	6.95
5	EC-Earth3-Veg			0.7° × 0.7°	7.13
6	FGOALS-f3-L	Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP, CAS)	China	1.25° × 1.0°	7.35
7	GFDL-ESM4	National Oceanic and Atmospheric Administration (GFDL, NOAA)	United States	1.25° × 1.0°	8.07
8	IPSL-CM6A-LR	Institute Pierre Simon Laplace (IPSL)	France	2.5° × 1.27°	7.65
9	MIROC6	Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	Japan	1.4° × 1.4°	8.81
10	MRI-ESM2–0	Meteorological Research Institute, Japan Meteorological Agency (MRI, JMA)	Japan	1.1° × 1.1°	8.78
11	NorESM2-LM	Norwegian Climate Center (NCC)	Norway	2.5° × 1.9°	8.60
12	NorESM2-MM			1.25° × 0.94°	7.80
13	TaiESM1	Research Center for Environmental Changes, Academia Sinica (RCEC, AS)	China	1.25° × 0.94°	7.24

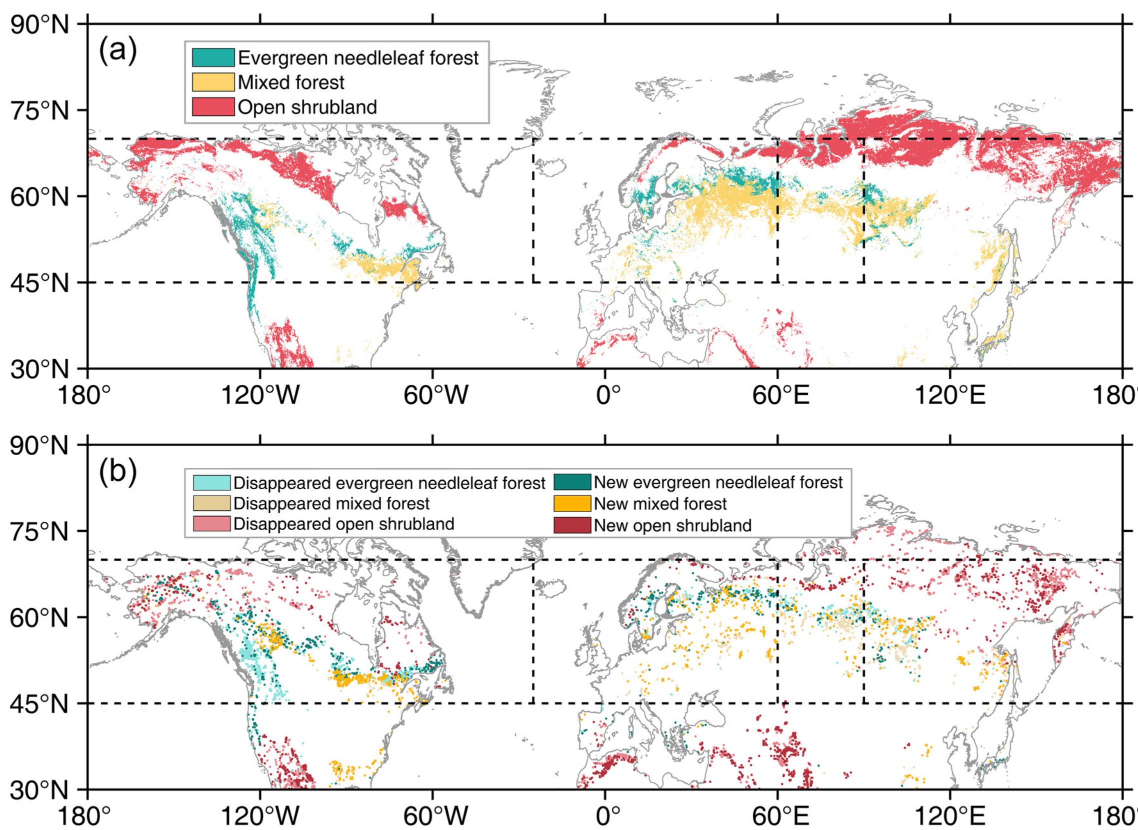

Fig. 1. (a) Distribution of stable evergreen needleleaf forests, mixed forests and open shrublands, and (b) changes of open shrublands (yellow), evergreen needleleaf forests (green) and mixed forests (red) in the four regions of the Northern Hemisphere during 2001–2014.

parts of the open shrublands in NAM and the far eastern part of EAS. An advanced trend of SGS for the evergreen needleleaf forest and mixed forest also occurred in EU, CAS and EAS.

3.3. Effect of snow depth on SGS

SGS is greatly influenced by snow depth. We calculated the relationship of SGS with snow depth in winter (Fig. 4) and spring (Fig. 5) to identify the impact of seasonal snow depth variation on vegetation growth. The results show that there was no statistically significant correlation between winter snow depth and SGS in the most typical vegetation of each region (Fig. 4). Only for the evergreen needleleaf forest in CAS, SGS exhibited a positive correlation with winter snow depth. In addition, negative correlation existed in the open shrublands of NAM and in the mixed forest of EAS (Fig. 4(h) and (i)).

There were, however, different degrees of positive correlation between SGS and spring snow depth in all areas. Most areas showed significantly positive correlation. For the evergreen needleleaf forest, the highest correlation coefficient appeared in CAS, which was up to 0.91 ($r = 0.91$, $P<0.01$), followed by NAM of 0.78, EAS of 0.77 and EU of 0.68

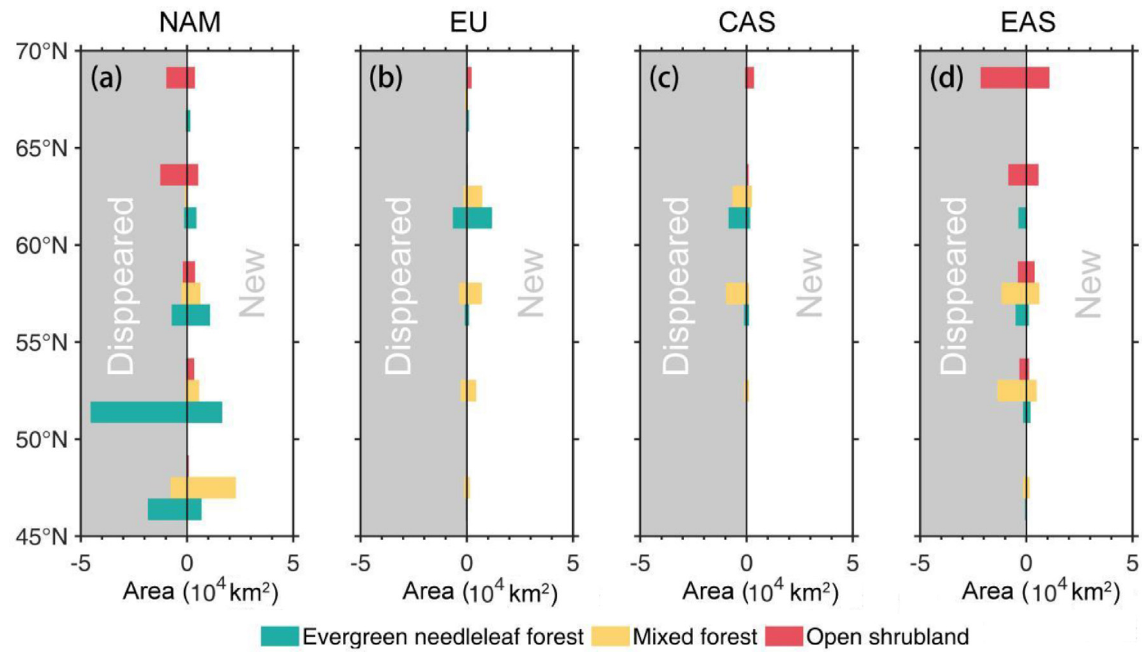

Fig. 2. Distribution of disappearance and new area of open shrubland (red), evergreen needleleaf forest (blue) and mixed forest (green) in the four regions during 2001–2014.

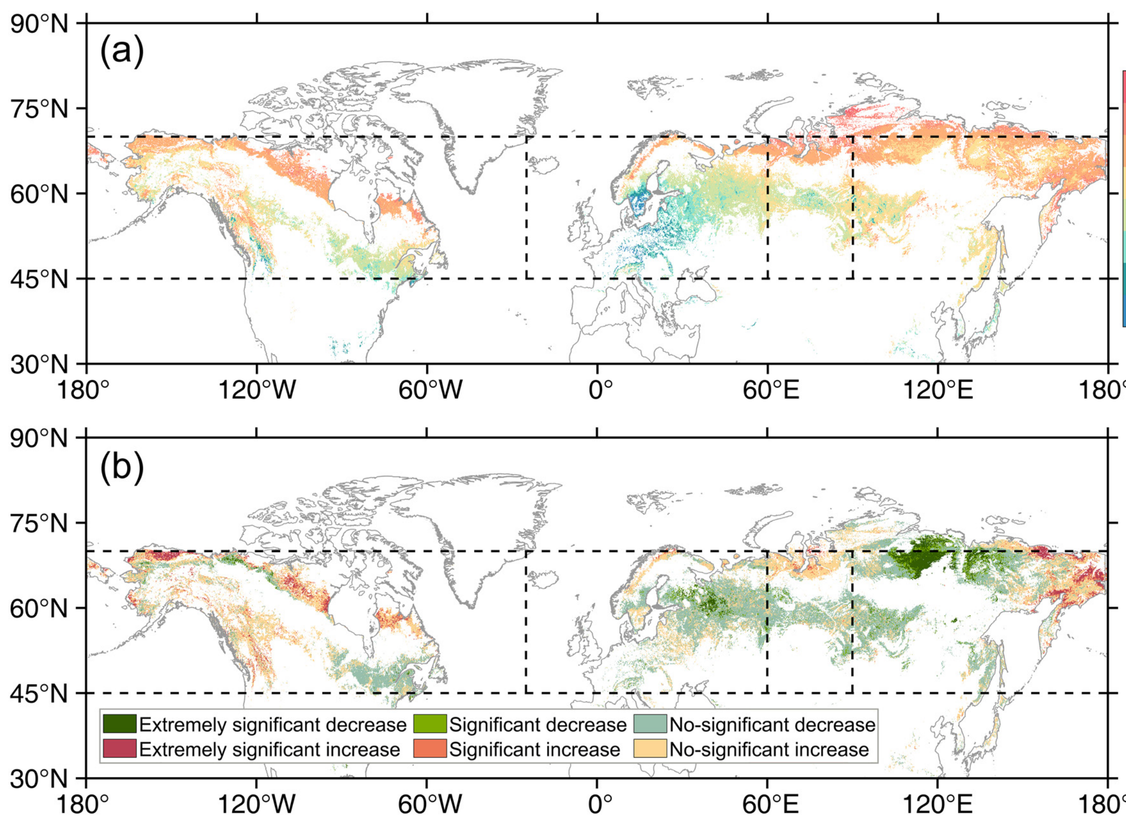

Fig. 3. (a) Distribution of SGS in units of day of year and (b) trend of SGS over open shrublands, evergreen needleleaf forests and mixed forests in the four regions during 2001–2014.

(Fig. 5(a)-(d)). In each region of mixed forest, SGS was significantly positively correlated with spring snow depth (Fig. 5(e)-(h)). SGS for open shrubs was also significantly postponed by the increased spring snow depth in EU and EAS in spite of no significant positive correlation in the other regions (Fig. 5(i)-(l)).

Considering the close relationship between spring snow depth and SGS, we further calculated the monthly effect of snow depth on SGS, which indicated that different sensitivities to changes in snow depth varied with biomes. For evergreen needleleaf forests and mixed forests, their SGSs were mainly concentrated in April, except in EAS in which

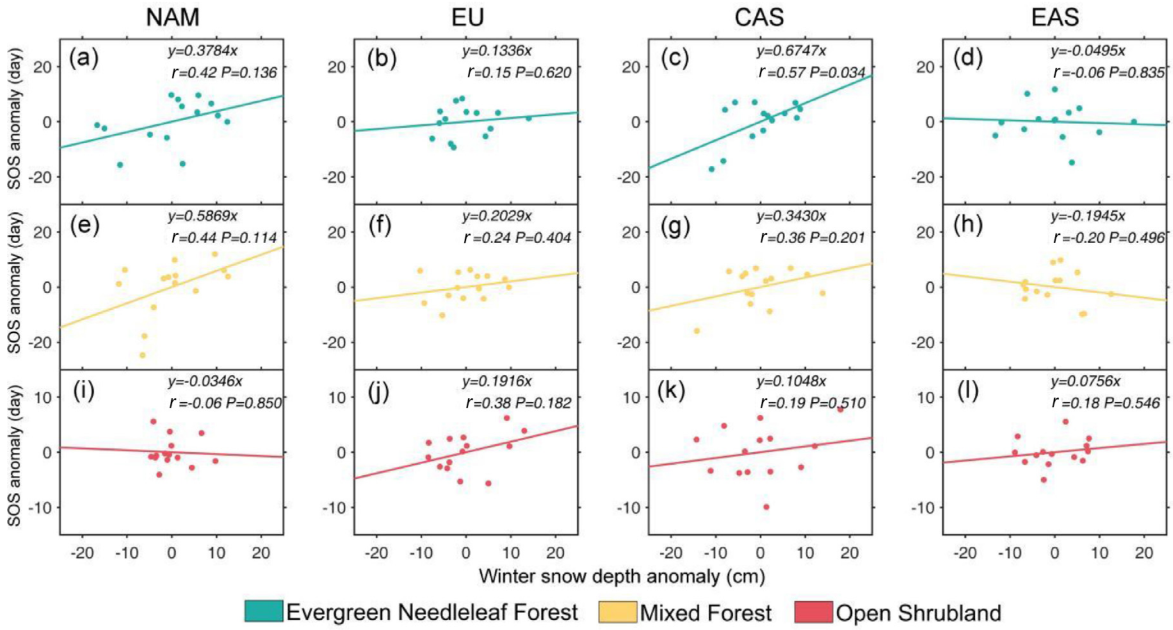

Fig. 4. Correlations between winter snow depth anomaly and SGS for different vegetation types in the four regions during the period of 2001–2014.

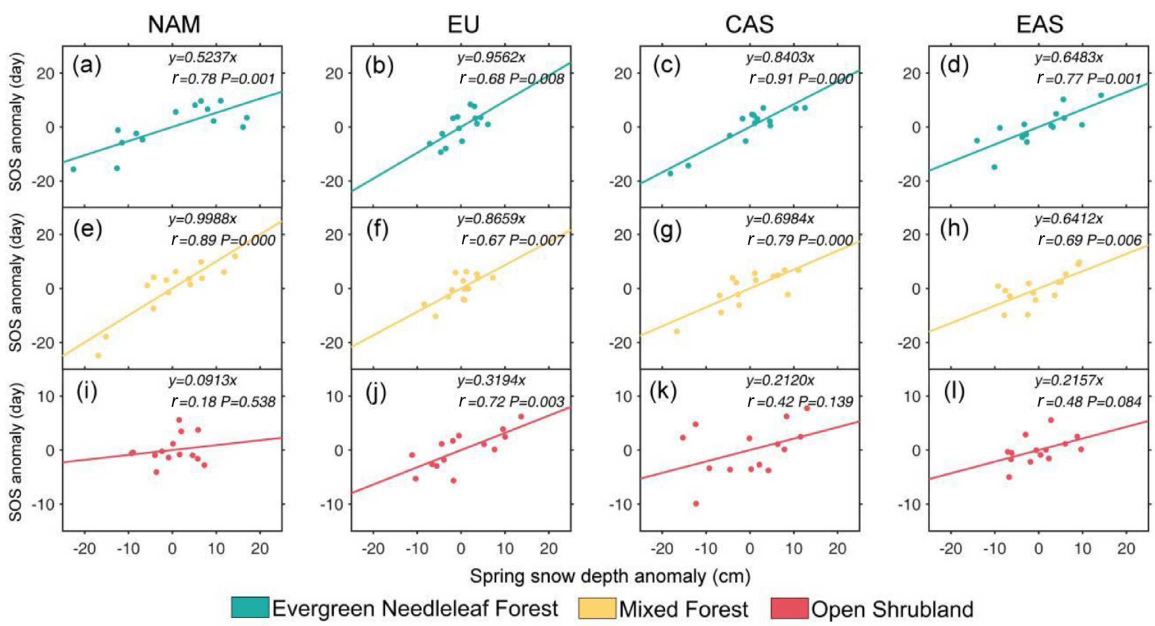

Fig. 5. Correlations between spring snow depth anomaly and SGS for different vegetation types in the four regions during the period of 2001–2014.

SGS was concentrated in late-April and early-May (Fig. 6(a)-(h)). The results also manifest that SGS concentrated in April received all the effect from the snow depth in March and April in the regions of NAM, EU and CAS (Fig. 6(a)-(h)). With respect to the correlation between SGS of open shrubs and snow depth in different months, SGS for open shrubs responded differently to the changes of mean snow depth in May, April and May compared with those for mixed forests. The effect of snow depth on SGS was only evident in May among these four regions, suggesting that the growth of open shrubs had a relatively faster response to the variation of snow depth.

The association between snow depth and SGS also showed spatial discrepancy. Combined with Fig. 2, the latitude of same vegetation had a range of climatic condition in the selected regions (Bienau et al., 2014; X.Y. Wang et al., 2018). For evergreen needleaf in the region with precipitation ranging from 650 to 950 mm, SGS of evergreen needleleaf forests was positively correlated with winter snow depth, while a weaker correlation was observed once the precipitation exceeded 950 mm or dropped below 650 mm (Fig. 7(a) and (d)). For mixed forests, positive correlation was mainly located in the warm region (> 5 °C) (Fig. 7(b) and (e)). However, nearly all the regions showed powerful correlations between SGS and spring snow depth for evergreen needleleaf forests and mixed forests, indicating that the relationship between spring snow depth and SGS in forests was less affected by hydrothermal conditions. In open shrublands, the positive correlation between SGS and winter/spring snow depth became stronger with increasing precipitation and temperature (Fig. 7(c) and (f)); and this positive relationship was more pronounced in spring. In these typical vegetations, the open shrublands showed obviously higher correlation in the area of precipitation

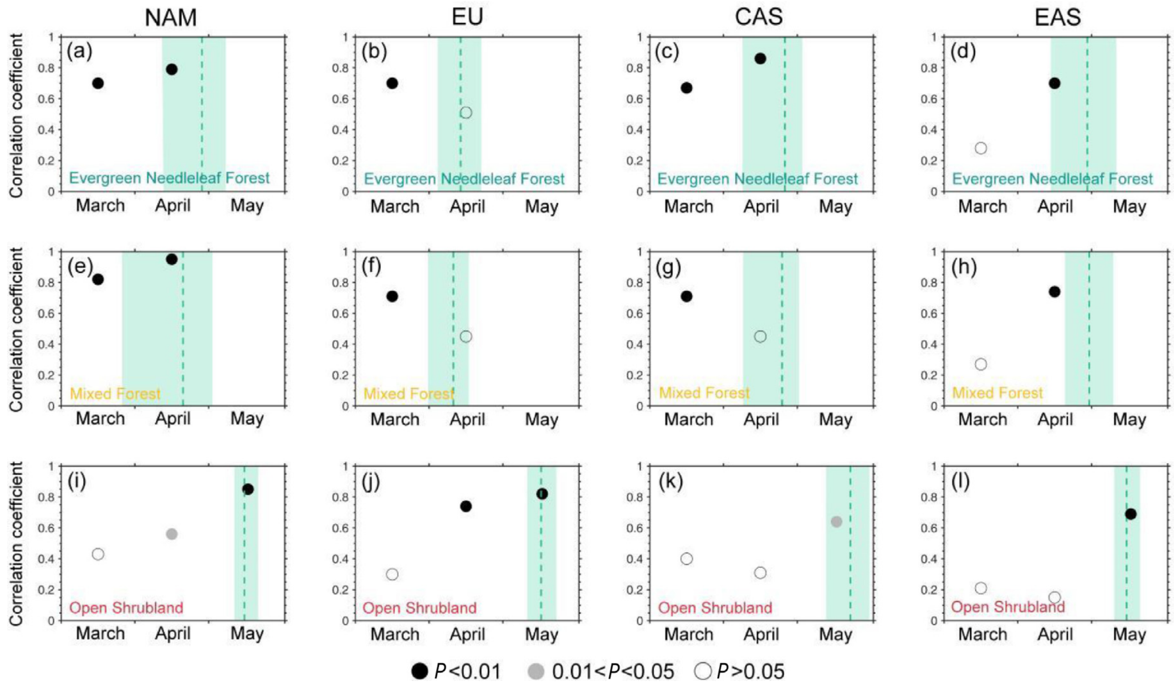

Fig. 6. Correlation coefficient between snow depth and SGS in March, April and May of open shrublands, evergreen needleleaf forests and mixed forests in the four regions. Green dashed line is the mean of regional SGS, and green shading is the variation range of SGS.

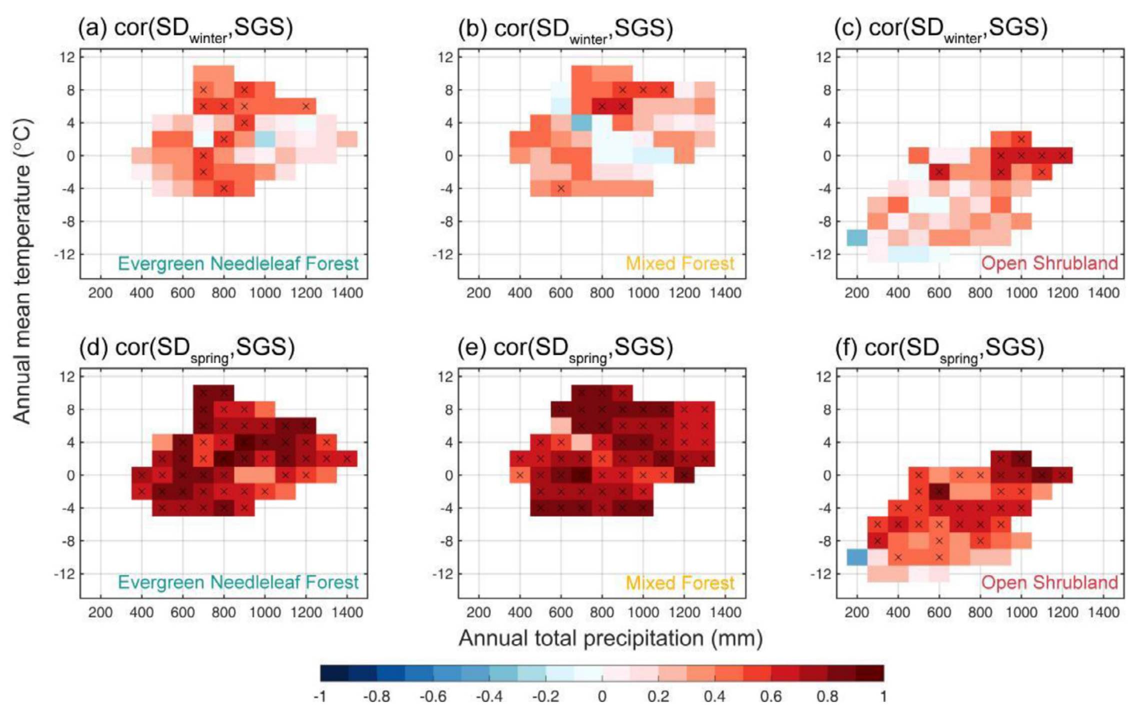

Fig. 7. Variation in the correlation between winter/spring snow depth and SGS along multi-year-averaged temperature and precipitation gradients for evergreen needleleaf forests, mixed forests and open shrublands from 2001 to 2014 over the mid-to-high latitudes of Northern Hemisphere. Black cross indicates significance at the 90% confidence level.

larger than 800 mm/yr and temperature higher than 2 °C than that in the other areas. Such discrepancy implies that snow effect on SGS in the climate condition of high temperature and high precipitation was much quicker than that of low temperature and less precipitation. In winter, the evergreen needleleaf forest was sensitive to the precipitation in the range of 600–800 mm/yr, the mixed forest had the highest value located in the mean temperature from 4 to 8 °C and the precipitation from 700 to 1,000 mm/yr, and the sensitive climate condition of open shrublands is in the mean temperature from −4 to 4 °C and precipitation from 900 to 1300 mm/yr (Fig. 7(a), (b), (c)). These sensitive regions had obvious response on SGS to the snow changes in winter.

As the melting of snow depth in the past decades became faster, the trend of annual mean snow depth experienced a spatial decrease, while the elevated snow depth can be seen in the western part of NAM and the

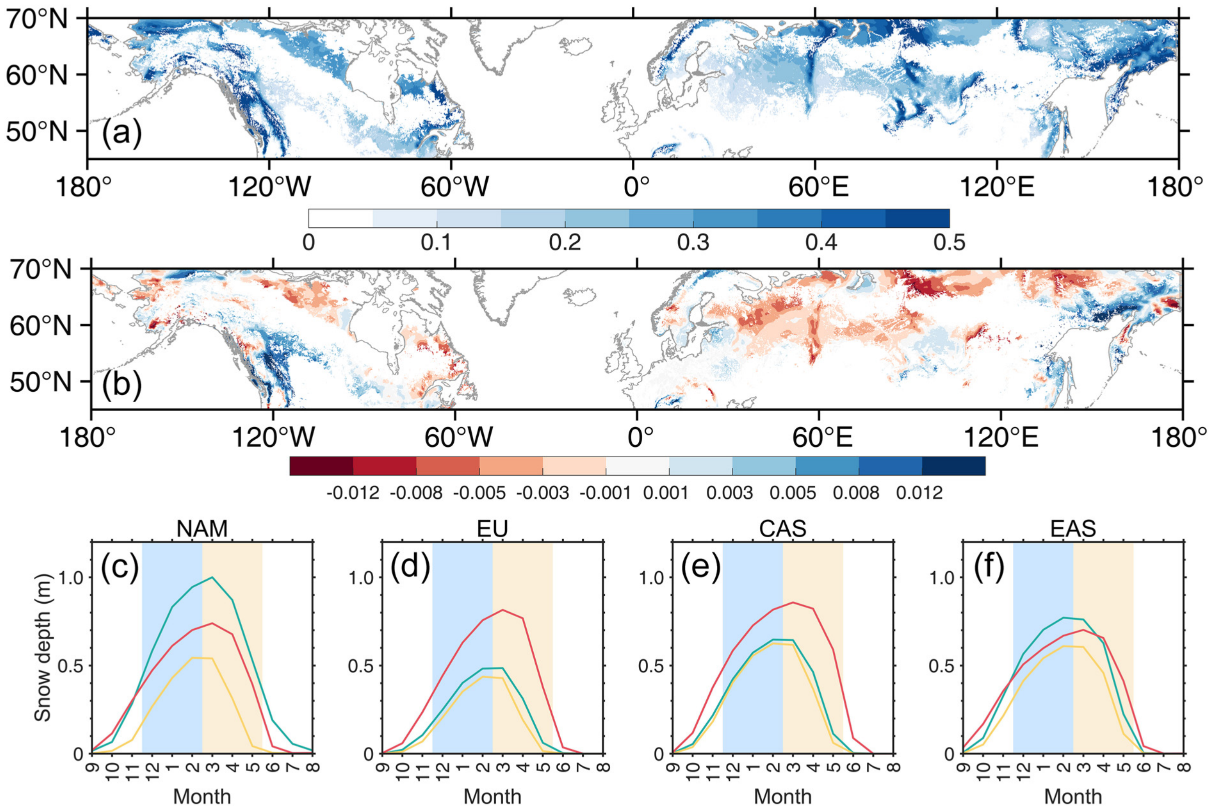

Fig. 8. (a) Multi-year-mean snow depth in units of m, (b) the trend of annual mean snow depth in units of m/10 yr, monthly variability of mean snow depth of open shrublands (yellow), evergreen needleleaf forests (green) and mixed forests (red) in the four regions of NAM (c), EU (d), CAS (e), and EAS (f) in 2001–2014. Light blue and yellow areas in (d)-(g) denote winter (December-February) and spring (March-May), respectively.

northeast part of EAS (Fig. 8(b)). Fig. 8(c)-(f) demonstrate the monthly variation of snow depth of the three land cover types in snow accumulation and snowmelt processes. The snow depth increased in winter (December to February) and decreased in spring (March to May), indicating snow accumulation was the winter hydrological process and spring was the snowmelt stage in the mid-to-high latitudes. The snow depth of open shrublands increased the earliest and had the highest values in EU and CAS, followed by those of evergreen needleleaf forests and mixed forests. After that, an accelerated decline of snow depth can be found in all land cover types. It is noteworthy that the snow depth of evergreen needleleaf forests was larger than those of mixed forests and open shrubs in NAM in both winter and spring; and the variation of snow depth in EAS was similar among the three biomes.

Given that the effect of spring snow depth on SGS was significant, projecting the change of SGS according to spring snow depth is beneficial to our understanding of the future change of snow-covered ecosystems under global warming. Two extreme scenarios (SSP1–2.6 and SSP5.8.5) were selected for comparing snow depth changes by different warming. Under SSP1–2.6, a slight decrease of spring snow depth will occur in all regions (Fig. 9(a)-(l) and (m)). When the radiative forcing reaches a high level (SSP5–8.5), spring snow depth will reduce up to 0.38 cm/yr and 0.37 cm/yr in evergreen needleleaf forests of NAM and open shrublands of EU, respectively (Fig. 9(a), (j), (n)). This dramatic reduction of snow depth in spring will advance SGS and constantly make positive contribution to the earlier leaf-out of plants.

3.4. Discussion

Our findings show that different vegetation had different responses to snow change. However, in general, SGS of these three vegetations showed more obvious positive correlation with spring snow depth than with winter snow depth in most regions. This also suggests that thicker snow cover in spring delayed the vegetation growth in evergreen needleleaf forest and mixed forest, which was probably caused by the reduction of soil respiration rate associated with the cooling effect of thick spring snow in forest ecosystem (Monson et al., 2006; Sullivan et al., 2008; Peng et al., 2010). Besides, the significant correlations between SGS and spring snow depth in EU and EAS echoes previous finding. A strong correlation existed between SGS and snow depth in shrublands, suggesting that underground thermal condition modulated by snow depth could exert a great influence on the leaf-out of shrubs (Korner and Basler, 2010; Peng et al., 2010). However, in the regions of NAM and CAS, such positive correlation was not significant. Our further analysis on the effect of snow depth of different month suggested that the discrepancy of sensitivity among these species was possibly the result of the difference of their root depth. A thinner snow layer in spring may bring about an earlier snow melting date and a higher spring air temperature, consequently causing a faster change of thermal condition of the root for open shrubs. By contrast, previous studies showed that spring snow was assumed to have a lagged effect on SGS for broad-leaf deciduous forests (Yu et al., 2013) which probably also existed in evergreen needleleaf forests and mixed forests. These findings are crucial to develop science-based policies that can prevent adverse vegetation phenology changes and preserve ecosystem services considering the notable effect of snow depth on SGS under the threats posed by ongoing climate change (Guan et al., 2015).

As the earlier start of the growing season is consistent with the descend of spring snow depth, a faster snow melting process will greatly contribute to the advance of vegetation growth. The melting snow induced changes in local water and energy systems. This process may off-

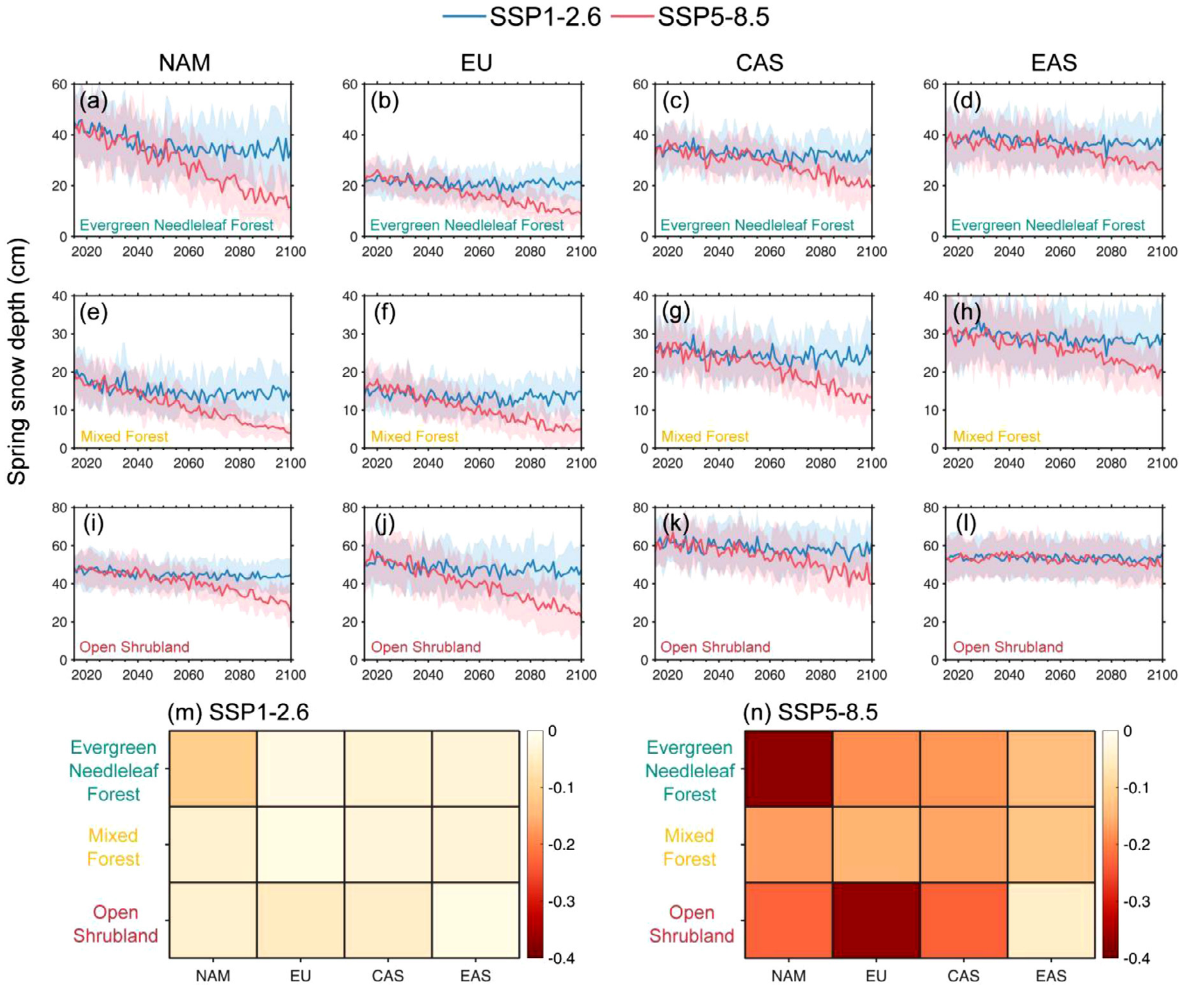

Fig. 9. (a)-(l) Changes in units of cm and (m)-(n) corresponding trends in units of cm/yr for spring snow depth of different land cover types (open shrublands, evergreen needleleaf forests and mixed forests) based on the period of 2001–2014 in the four regions for the projected period of 2015–2100 under the scenarios of SSP1–2.6 and SSP5–8.5. The trends are significant at the 95% confidence level in all regions.

set the beneficial effects of the earlier snowmelt to some extent and thus limit the productivity of vegetation during the growing season because the timing of snowmelt can influence water availability during the growing season; and late-season moisture limitation is also a risk from an early snowmelt (Slatyer et al., 2021), and takes a series of phenological changes, such as the degradation of plant and rapid recession of ecosystem productivity. The reduced seasonal snow brings a significant conservation challenge and seriously threaten the sustainability of the vegetation in the NH. As the ecological system is changing, its protection and sustainable development, especially in the regions with dramatic decrease of snow depth, needs more consideration of anthropogenic effect.

4. Conclusions

Climate changed dramatically during the past decades. Seasonal snow is one of the most important climate factors because of its roles in energy and water balances, which can affect local ecological system. By using reanalysis and remote sensing data during 2001–2014, we show that spring snow depth was significantly positively correlated with SGS. And SGSs of needleleaf forests, mixed forests and open shrubs responded to the change of snow depth in March, April and May. Furthermore, the open shrubs obviously decreased over high-latitude area to the north of mixed forests and evergreen needleleaf forests. According to the variation of spring snow depth simulation form the CMIP6, we can see the constant reduction in most of our study area under SSP1–2.6 and SSP5–8.5. Under the most aggressive scenario of SSP5–8.5, snowmelt will increase the risk of soil freezing and root mortality.

In general, this study provides important information for understanding the spatio-temporal pattern of snow depth in mid-to-high latitudes of the NH in the past and future, as well as the different responses of SGS of different vegetation to snow depth. The discrepancy in regional warming will result in an obvious change in vegetation distribution and shorten the process of snow melting. Such a connection between snow and vegetation will lead to a new performance in the regional energy and water cycle. Our findings will help support decision makers to deepen the understanding of the risk of fast snow melting to vegetation growth, thus alleviating the impact of global warming on the ecosystem by taking effective measures.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

Acknowledgments

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