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Links between Nordic and Arctic hydroclimate and vegetation changes: Contribution to possible landscape-scale nature-based solutions

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Abstract

In Nordic and Arctic regions, the rapidly warming climate sustains hydroclimatic and vegetation changes in the landscape. There is evidence for an increase in vegetation density in some regions, a trend that is expected as a response to increasing temperature and precipitation. If the hydroclimatic changes are linked to vegetation response, it could be viewed as a landscape-scale nature-based solution (NBS) that could moderate the runoff response, as denser vegetation should lead to increased evapotranspiration and lower runoff. In this paper, we investigate and compare hydroclimatic changes over a set of basins in the Nordic region and northwest America and compare with changes in vegetation density, analyzed using the normalized difference vegetation index (NDVI) for three time periods: 1973–1978, 1993–1998, and 2013–2016.

Over the period of the 1970s to 1990s, the hydroclimate became warmer and wetter and vegetation density increased, but over a later period from the 1990s to 2010s, vegetation density decreased, despite a continuing warming and wetting of the climate. Although there was a tendency for runoff to decrease in basins where vegetation density increased, the relation between precipitation and runoff was much stronger. Overall, we found weak evidence for vegetation density changes, driven by hydroclimate, to act as NBS on the landscape scale over the studied regions. However, as hydroclimatic changes interact with vegetation changes and their ensuing hydrological responses in complex ways, more detailed investigations are needed to determine the potential NBS effect on the landscape scale across Nordic and Arctic regions.

KEYWORDS

hydroclimate change, nature-based solutions (NBS), NDVI, Nordic and Arctic regions, vegetation change

1 | INTRODUCTION

Hydroclimatic change in the Nordic and Arctic regions has hitherto been much more intense than the global average, and substantial changes have been documented (Gisladottir, Arnalds, & Gisladottir, 2005; Karlsson, Bring, Peterson, Gordon, & Destouni, 2011; Prowse, Bring, Mård, & Carmack, 2015; Prowse, Bring, Mård, Carmack, Holland, et al., 2015; Rennermalm, Bring, & Mote, 2012;

Sjöberg, Frampton, & Lyon, 2013). Both temperature and precipitation are increasing, because the capacity to hold water vapor increases with higher temperatures (Francis et al., 2009).

In cool temperate, subarctic, and Arctic climates, higher temperature and precipitation typically enhance vegetation productivity and diversity (Francis et al., 2009). Therefore, with ongoing warming, the vegetation distribution is expected to shift northward in latitude and upward in altitude (Kapfer, Grytnes, & Hédl, 2017). Furthermore, general greening, or increased vegetation density, can be expected in northern and Arctic landscapes, when not considering other drivers that modify vegetation, such as anthropogenic land management. These changes have been investigated throughout the Arctic (e.g., Myers-Smith et al., 2015; Naito & Cairns, 2011). For tundra landscapes, the term 'shrubification' is used to describe the increasing propensity for shrub vegetation growth in landscapes that were previously dominated by open tundra (Pearson et al., 2013; Tape, Sturm, & Racine, 2006).

However, changes in vegetation type and density are not only a response to climate change, they also feed back to the local landscape and the climate system. One example is the feedback between forest canopy and the energy and water cycle (Betts, Falloon, Goldewijk, & Ramankutty, 2007; Dale, 1997; Jia et al., 2014). Vegetation canopy cover has a major impact on transpiration (the less canopy, the less transpiration). Evapotranspiration, in turn, is responsible for the link between the water and energy cycle and connects the terrestrial and the atmospheric system (Bring et al., 2016). This link between landscape development and hydrology has also been investigated in northern and Arctic regions (e.g., Jaramillo, Prieto, Lyon, & Destouni, 2013; Karlsson, Jaramillo, & Destouni, 2015). In general, increasing vegetation density should lead to less runoff, as more water is stored and transpired back to the atmosphere by plants. Although effects are often more complex, with local controls on hydrology determining the actual response, there is some evidence for such links, both in northern and Arctic regions (Mård et al., 2017) and elsewhere (Buendia, Batalla, Sabater, Palau, & Marcé, 2016; Cox, Sarangi, & Madramootoo, 2006; Yang & Lu, 2017).

With strong climate warming in the past and in the projected future, this general tendency for increased vegetation density in northern and Arctic basins could be considered a nature-based solution (NBS) at the landscape scale, in that it modulates flow and alters the partitioning of precipitation into runoff and evapotranspiration. This could partly offset the effect of increasing temperature and precipitation (Mård et al., 2017). Thus, ignoring other changes in the landscape, the climate-driven change in northern and Arctic basins should lead to less runoff with increasing vegetation density in the basin. This large-scale NBS could consequently help to moderate effects of climate and anthropogenic change in northern and Arctic basins.

Although NBS have been increasingly promoted as a way of adapting human environments to climate and environmental hazards, they are typically investigated at small or local scales, such as urban regions, cities, or parts of cities (Keesstra et al., 2018). However, considering that future climate warming will also bring hydroclimate shifts that act on basin scales, it is relevant to consider the potential role of NBS on landscape scales. This potential role in modulating the increasing precipitation and runoff on drainage basin scales is an issue that has been much less explored.

Projected changes to northern and Arctic hydroclimate are already leading to substantial effects on ecosystems and human societies (Wrona et al., 2016). For instance, flows are generally increasing in response to increasing precipitation and moisture transport (Bring et al., 2016), which in turn affects infrastructure development (Instanes et al., 2016) and freshwater resources for both human, environmental, and industrial needs (Evengard, Berner, Brubaker, Mulvad, & Revich, 2011). If there is an overall effect of runoff modulation that accompanies an observed vegetation increase, it would be a relevant factor to consider when attempting to understand, predict, and plan for effects of climate change in northern and Arctic regions.

In this study, we investigate three research questions that pertain to northern and Arctic basins and the potential importance of vegetation changes as NBS at the landscape scale. First, we investigate hydroclimatic changes over a suite of basins with reliable hydrological records to determine changes in temperature, precipitation, and runoff. Second, we investigate changes in vegetation density over the same set of basins in order to determine whether there is a pattern of increasing vegetation density over time. Finally, we compare the vegetation density observations with hydroclimate data to determine whether the observed vegetation patterns are compatible with expected hydroclimate drivers and responses to landscape change.

2 | MATERIAL AND METHOD

2.1 | Study areas

To explore hydroclimatic changes in relation to vegetation changes, we selected river basins in Nordic and Arctic regions that have long-term records of discharge data available from the Global Runoff Data Centre (GRDC; based in Koblenz, Germany). We included basins comprising at least 50 years of data with less than 10% missing values. In the Nordic region, we investigated 36 river basins across Finland, Sweden, and Norway, located between approximately 57–70°N and 6–32°E and with a total area of 491,362 km^2 (Figure 1a). In northwest America, we investigated five river basins with a total area of 115,790 km^2 located between approximately 60–65°N and 136–159°W (Figure 1 b). We grouped the 41 basins into six study areas: northern Finland (five basins), southern Finland (eight), northern Sweden (seven), central Sweden (five), southern Sweden/Norway (11), and Alaska/Canada (five).

2.2 | Data and method

We investigated patterns in runoff and climate concurrent with vegetation observations over three time periods (1970s, 1990s, and early 2010s). These three time periods were chosen on the basis of the availability of satellite data for each river basin. The periods allowed a separation of the entire length of record into three distinctively different periods, separated from each other by 20-year intervals. In this way, we aimed to capture longer-term changes rather than shorter-term variability between years. For the 1970s, 1990s, and early 2010s, we used hydroclimate data for 1969–1978, 1989–1998, and 2007–2015, respectively. These years were selected on the basis of the maximum availability of runoff data. Furthermore, we chose to use slightly longer periods for hydroclimatic data in comparison with

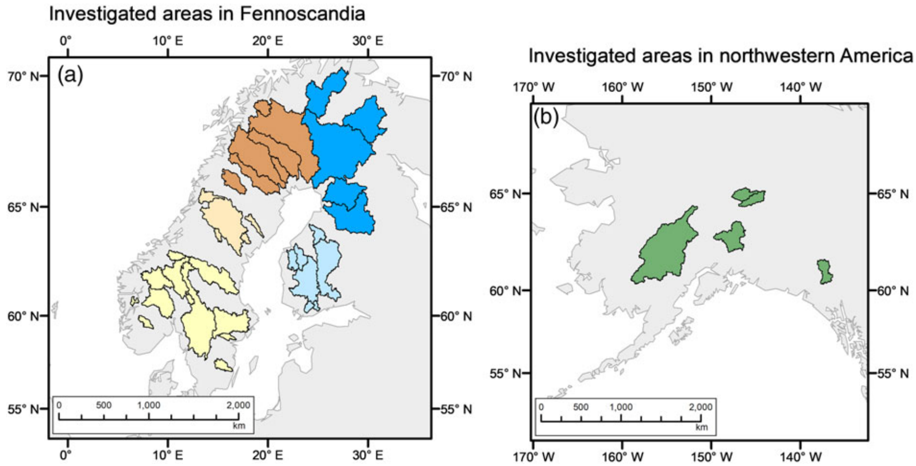

FIGURE 1 (a) Investigated areas in Fennoscandia, grouped into northern Finland (blue), southern Finland (light blue), northern Sweden (orange), central Sweden (sand), and southern Sweden/Norway (yellow); (b) investigated areas in Northwestern America, marked in green [Colour figure can be viewed at wileyonlinelibrary.com]

vegetation data, and we also chose to let these hydroclimatic data periods start somewhat earlier than the vegetation data periods. The reason for this was because changes in hydroclimate not only have an immediate impact of vegetation in the same year but can also affect the vegetation in the following years, for instance, through prolonged drought. In general, the subpolar, boreal, and cool temperate regions we investigate here have been shown to have the longest lag times from hydroclimatic change to vegetation response (Vicente-Serrano et al., 2013). We downloaded global gridded monthly average temperature and precipitation time series from the CRU TS 4.00 dataset (Harris, Jones, Osborn, & Lister, 2014) and extracted spatially averaged data for all basins. Runoff data were obtained from the GRDC (see Table S1 for a complete list of stations and GRDC codes). For temperature and precipitation data, mean annual values were calculated for each period and basin. For detection of changes in runoff, mean monthly river discharge was used together with basin area to calculate average annual runoff, which was averaged for each study area. Although it would have been possible to gather a wider set of climatic data and perform a full sensitivity and robustness analysis of the choice and quality of data, we considered such a comparison out of scope for the present study and chose to use the commonly investigated and widely acknowledged datasets listed above.

To identify vegetation changes, Landsat images were used to calculate the normalized difference vegetation index (NDVI) for each basin. The NDVI is a standard vegetation index based on the reflectance properties of areas with a vegetation cover (Rujoiu-Mare & Mihai, 2016) and has shown good accuracy for Nordic mountainous regions (Nordberg & Evertson, 2005). Satellite images from Landsat 2 and 3 were used to cover the study area for the 1970s (images selected from 1973 to 1978). The images from the Landsat Multispectral Scanner (MSS) on Landsat 2 and 3 have a resampled spatial resolution of 60 m. For the 1990s (images selected for 1993–1998), Landsat Thematic Mapper (TM) images with a spatial resolution of 30 m from Landsat 5 were used. Landsat 8 with the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) provided the satellite images for the early 2010s (images selected for 2013–2016), also with a spatial image resolution of 30 m. All satellite images were downloaded as a Level-1 product in GeoTIFF format from the United States Geological Survey Earth Explorer. Because the resolution of the satellite images from Landsat MSS-2 and MSS-3 are coarser than that from Landsat TM-5 or OLI_TIRS-8, the results for the first period may be less reliable. However, the magnitude of errors should be limited and tend to average out over basins, which were then also further aggregated into study areas. As cloud cover is a major limitation when using satellite data, we introduced a threshold to make sure we rejected images with high cloud cover, in order for these images not to confound our analysis. This threshold was set to 10%; thus, we only included satellite data with cloud cover of less than that number. We noted a relatively higher degree of cloud cover for the 1970s than for the other periods, but we were nevertheless still able to analyze a sufficient number of images to cover all basins. Here, we note also that the cloud cover threshold itself may be sensitive to the resolution of the sensor (Wielicki & Parker, 1992, Zhu & Woodcock, 2012), but this is an issue outside the scope of this study. To capture the main growing season, we selected imagery acquired between June and August and with a major proportion in July.

The red and near-infrared (NIR) bands of the satellite image packages were processed in ArcMap (ESRI) version 10.4 where NDVI was calculated as follows:

$$NDVI = \frac{R_{NIR} - R_{RED}}{R_{NIR} + R_{RED}},$$

which is based on the reflectance in the red (R_{RED}) and near-infrared (R_{NIR}) bands of the electromagnetic spectrum by the green parts of the plants. The NDVI layers were combined into a mosaic and clipped to generate one NDVI layer for each basin and period. The NDVI values ranged from −1 to +1, with water, snow, and ice having a negative value, bare soil having a value around zero, and plants having a positive value (the greener the plants, the higher the NDVI value due to larger reflectance in the NIR band) (Lillesand, Kiefer, & Chipman, 2015). Five NDVI classes (I-V) were defined on the basis of this classification and a previous study by Al-doski, Mansor, and Shafri (2013) where Class I represents water, snow, and ice with a negative NDVI value (NDVI <0), Class II represents bare soils and areas with almost no vegetation

(NDVI 0.0–0.2), Class III represents sparse vegetation (NDVI 0.2–0.4), Class IV represents moderate vegetation (NDVI 0.4–0.6), and Class V represents areas with dense vegetation (NDVI >0.6).

3 | RESULTS

3.1 | Hydroclimatic changes

Table 1 and Figure 2 show mean annual temperature (T), mean annual precipitation (P), and mean annual runoff for the six study areas in the periods 1969–1978, 1989–1998, and 2007–2015. A temperature increase was seen for all study areas. When comparing the average temperature between 1970s and 2010s, the highest increase in average temperature was seen in northern Finland (1.38°C) and the lowest increase in southern Sweden/Norway (0.90°C). On average, the temperature increase for northern Finland corresponded to 0.37°C/decade. Southern Sweden/Norway showed the lowest rate of temperature increase, 0.24°C/decade.

Annual precipitation increased in all study areas from the 1970s to the 2010s, from 38 mm in Alaska/Canada to 130 mm in southern Sweden/Norway. In all areas but one (southern Sweden/Norway),

TABLE 1 Mean annual temperature (T), mean annual precipitation (P), and mean annual runoff for the six area groups and their study periods investigated

	T (°C)			P (mm yr^{-1})			Runoff (mm yr^{-1})		
	1969–1978	1989–1998	2007–2015	1969–1978	1989–1998	2007–2015	1969–1978	1989–1998	2007–2015
Northern Sweden	−2.19	−1.33	−0.96	604.48	670.60	664.51	489	562	553
Central Sweden	0.60	1.39	1.74	708.44	782.27	767.67	524	635	646
Southern Sweden/Norway	2.68	3.22	3.58	731.58	797.85	861.95	499	560	605
Northern Finland	−0.64	0.09	0.75	500.26	555.12	595.61	337	376	376
Southern Finland	3.50	4.25	4.77	510.18	566.97	590.92	256	284	299
Alaska/Canada	−5.09	−4.10	−3.82	279.20	315.82	316.88	298	340	353

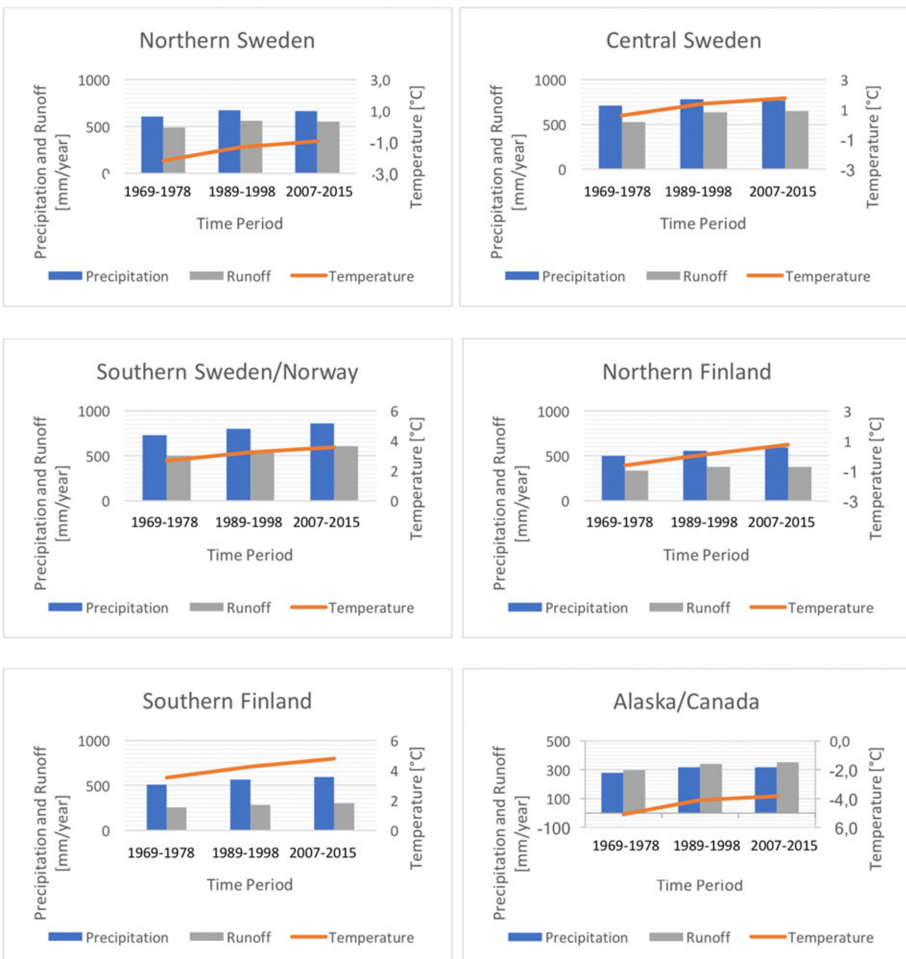

FIGURE 2 Changes in average annual precipitation [mm/yr], average annual runoff [mm/yr], and average annual temperature [°C] over the three investigated periods in the 1970s, 1990s, and 2010s for northern Sweden, central Sweden, southern Sweden/Norway, northern Finland, southern Finland, and Alaska/Canada [Colour figure can be viewed at wileyonlinelibrary.com]

the increase in precipitation was higher from the 1970s to the 1990s than from the 1990s to the 2010s.

Mean annual runoff increased from the 1970s to the 2010s. The greatest increase was observed for central Sweden where annual runoff increased by 32.6 mm/decade. Southern Sweden/Norway also showed a strong increase with 28.2 mm/decade. The smallest increase was observed for Finland. Except for southern Sweden/Norway, the majority of the increase in runoff was observed from 1970s to the 1990s. Between 1990s and 2010s, a much smaller increase was noted, and for northern Finland and northern Sweden even a slight decrease (−0.1% and −1.6%, respectively). Considering all basins and periods, average runoff was strongly correlated with precipitation (Pearson $r = 0.78$, $p < 0.001$; Figure S1).

To further explore the robustness of these changes and put them in a longer-term perspective, we also investigated changes when considering all years during the entire period 1969–2015. This investigation supported the indications of increasing values across all hydroclimatic variables, albeit with some variations. For temperature, trend slopes were positive and significantly different from zero for all study areas ($p < 0.05$). For precipitation, trends were positive and slopes significantly different from zero for Alaska/Canada, northern Finland, southern Finland, and southern Sweden/Norway ($p < 0.05$), but not significantly different from zero for northern and central Sweden ($p > 0.05$). For runoff, trends were significantly different from zero for Alaska/Canada, northern and central Sweden, and southern Sweden/Norway ($p < 0.05$), but not significantly different from zero for northern and southern Finland ($p > 0.05$).

3.2 | Vegetation changes

Vegetation changes were detected for all 41 basins during the observation period (Figures 3 and 4). From the 1970s to the 1990s, an increase in moderate vegetation was observed for all six study areas, particularly for northern Finland, northern Sweden, and central Sweden, where only a small share of land was covered with moderate vegetation during the 1970s. These three study areas also had much higher area coverage of snow, ice, and water and areas of bare soil or almost no vegetation compared with the other study areas. This can be an indicator of high cloud cover, because clouds reflect more solar radiation in the NIR bands and thereby lower the NDVI. An increase in moderate vegetation was also observed for the other study areas (southern Sweden, southern Finland, and Alaska/Canada), where the percentage of nonvegetated area was much lower in the 1970s. For these three study areas, moderate vegetation increased from about 42% to 55% from the 1970s to the 1990s. The dense vegetation class also increased during this period, except for northwest America, with the highest increase in southern Finland and southern Sweden/Norway (from about 6% to 15% and 4% to 10%, respectively). For all six study areas investigated, a decline in areas with sparse vegetation and no vegetation coverage was observed from the 1970s to the 1990s.

Vegetation change differed between the 1990s and 2010s, compared with 1970s to 1990s. For example, about 50–58% of the land was covered with moderate vegetation in the 1990s, which decreased to 8–33% in the 2010s. The strongest decline was observed in North America, northern Finland, and northern Sweden. In contrast, a large increase in sparse vegetation was detected for all areas, from 15–34% of the land in the 1990s to 57–74% in the early 2010s. The areas with almost no vegetation and bare soil increased from about 7% to 10% during the same time period. Furthermore, almost no dense vegetation was detected in the 2010s: Only a minimal proportion was observed in southern Finland and southern Sweden (0.2% and 0.1%, respectively).

3.3 | Relationship between hydroclimate and vegetation

Figure 5 shows the relationship between total average runoff and share of vegetation in the classes sparse, moderate, and dense vegetation, for all study areas and periods. With sparse vegetation, runoff tended to be higher (+1.4 mm per percent increase). In contrast, for moderate and dense vegetation, runoff decreased as the share of the density classes in the basin increased, that is, with more moderate and dense vegetation there was less runoff (−1.5 mm and −9.0 mm per percent increase, respectively). However, as variability was quite high overall, none of the relations were statistically significant ($p > 0.05$ for all vegetation density classes). To further test the robustness, we also investigated the same relationship as in Figure 5 when pooling all the individual basins (40 in number), except one outlier basin in Alaska that had runoff values more than twice as high as any other basin. The overall pattern for this test was similar (Figure S2; runoff changes of +0.7, −1.2, and −5.0 mm per percent increase, respectively). In this case, the relations were substantially stronger, but however were still not statistically significant ($p > 0.05$ for all vegetation density classes).

4 | DISCUSSION

With this study, our overarching aim was to explore links between hydroclimate and vegetation changes in Nordic and Arctic regions. Principally, we aimed to investigate whether vegetation changes act as a landscape-scale NBS that moderates the proportion of precipitation turning into runoff.

4.1 | Hydroclimate changes

Our first question concerned hydroclimate changes. The results show that temperature increases were overall consistent, with mean values of 0.90°C and 1.38°C observed for northwest America and the Nordic region, respectively, between the 1970s (1969–1978) and the 2010s (2007–2015). In general, the results showed a northward increase in the rate of mean annual temperature change in the Nordic region, and all study areas except southern Sweden and Norway experienced a temperature increase higher than the global average (0.25–0.27°C/decade; Hartmann et al., 2013) between 1979 and 2012. In northwest America, an above average temperature increase of 0.34°C/decade was detected. These results are in line with previous findings of higher temperature increase in the Nordic regions (ACIA, 2005).

Similar to temperature, we noted an overall increase in mean annual precipitation between the 1970s and the 2010s. The highest increase (34.8 mm/decade) was found in southern Sweden and

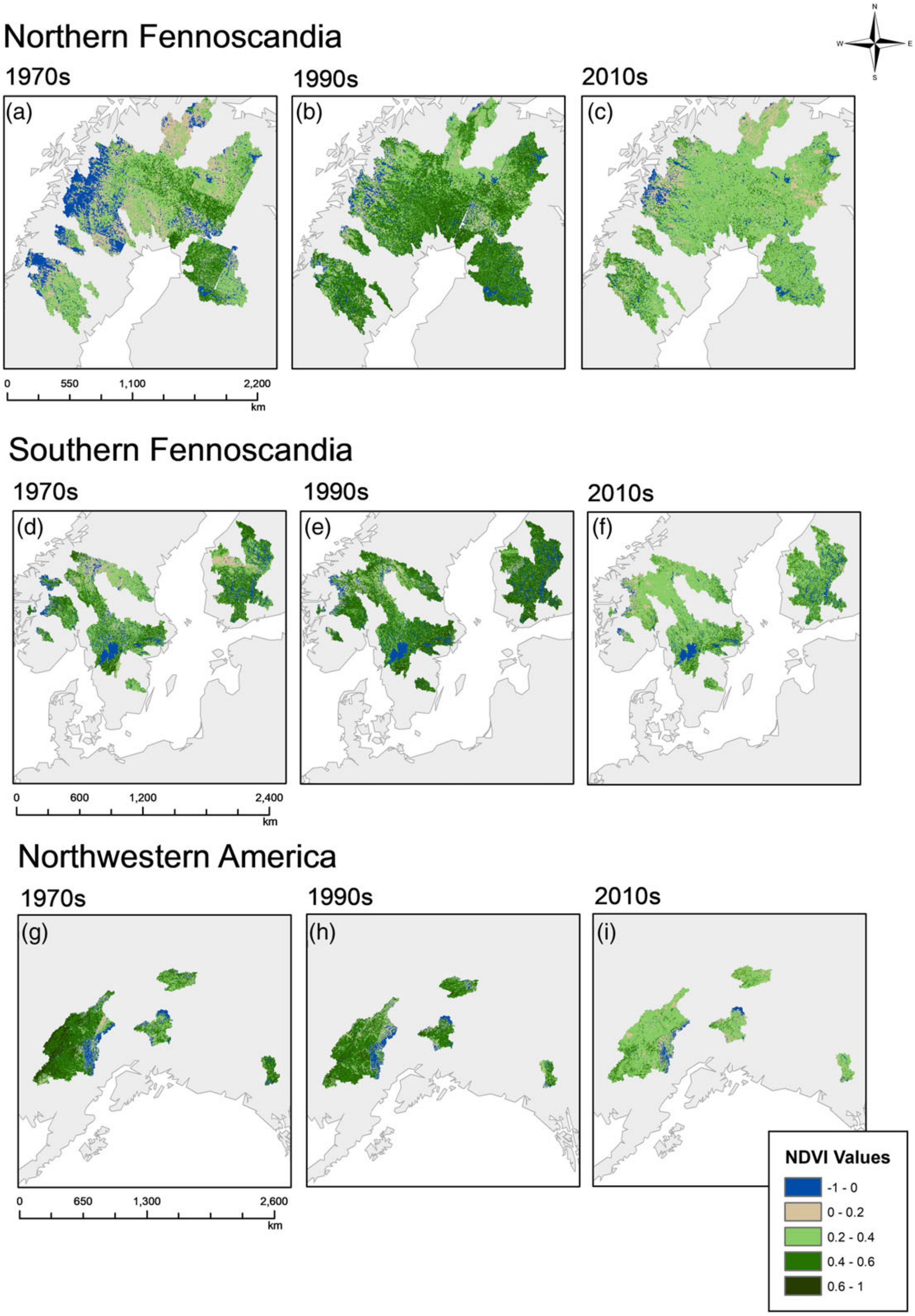

FIGURE 3 Vegetation changes in (a-c) northern Fennoscandia, (d-f) southern Fennoscandia, and (g-i) Northwestern America over the three investigated periods in the 1970s, 1990s, and 2010s; blue areas indicate water, snow, and ice; brownish areas are nonvegetated areas; the darker the green of the areas the denser is the vegetation [Colour figure can be viewed at wileyonlinelibrary.com]

Norway and the lowest increase (10.1 mm/decade) in Alaska and Canada. These results agree with data in the IPCC report for 2013, which indicates an increase in precipitation of between 0.63–5.82 mm per year (6.3–58.2 mm/decade) from 1951 to 2008 in areas between 60°N and 90°N (Hartmann et al., 2013). However, in five of the six study areas, the increase in precipitation was higher from the 1970s to the 1990s (1989–1998) than from the 1990s to the 2010s. The overall increase in precipitation during the past four decades is most likely connected with the observed increase in temperature, due to more abundant water vapor in the atmosphere and increasing moisture transport from lower latitudes (Dyurgerov, Bring, & Destouni, 2010; Zhang et al., 2013). However, it should be noted that the

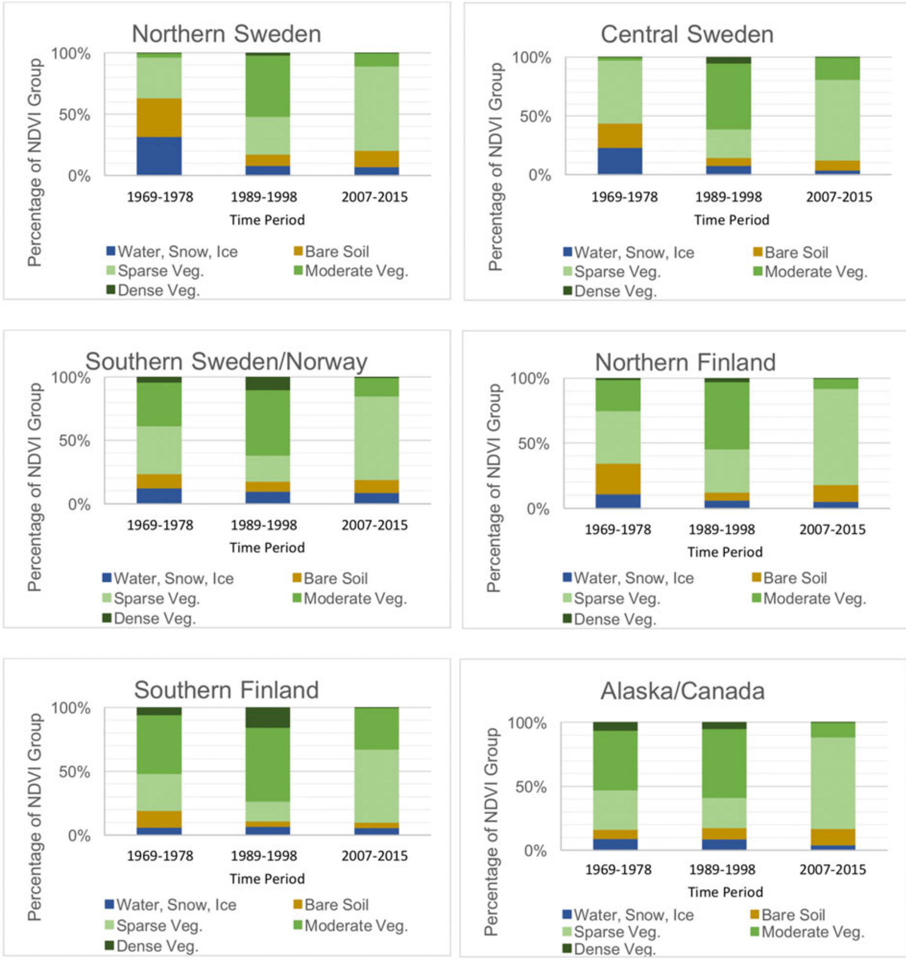

FIGURE 4 Changes in the percentage of the NDVI groups water, snow, ice, bare soil, sparse vegetation moderate vegetation, and dense vegetation over the three investigated periods in the 1970s, 1990s, and 2010s [Colour figure can be viewed at wileyonlinelibrary.com]

relationship between increasing temperature and increasing precipitation varies between seasons (Francis et al., 2009), an aspect we did not take into consideration here.

In terms of runoff, we observed an increase for all study areas from the 1970s to the 2010s. Similar to precipitation, the increase in runoff from the 1970s to the 1990s was higher than the increase from the 1990s to the 2010s. An increase in precipitation should generally lead to an increase in river discharge (Hartmann et al., 2013), and we

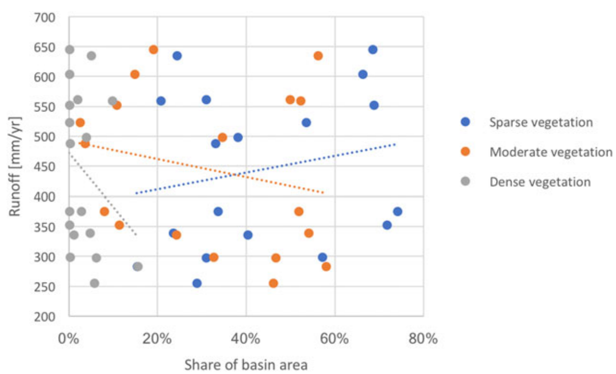

FIGURE 5 The share of vegetation in three density classes and the corresponding values of average runoff for all six regions and three time periods [Colour figure can be viewed at wileyonlinelibrary.com]

found that the two variables were in fact strongly connected when considering all regions and periods. In this study, we did not consider human influences such as dam construction and land use changes, which can have strong impacts on the streamflow (Hartmann et al., 2013; Kalantari et al., 2014; Kalantari, Ferreira, Walsh, Ferreira, & Destouni, 2017), in addition to climate change. However, this influence is generally much stronger on seasonal than on annual scales, as dams and reservoirs primarily redistribute water between seasons rather than years (Di Baldassarre, Martinez, Kalantari, & Viglione, 2017). Furthermore, the periods investigated here did not overlap with the years of the most intense hydropower development schemes in the study regions, and therefore, we expect that the effect of dam construction during or between the observed periods to be limited.

Overall, the observed changes in hydroclimate were as expected in terms of drivers, both when we considered changes between periods and when we investigated the long-term trend over the entire length of record. This was particularly the case for temperature, which increased steadily between all three periods and for all study areas. Precipitation also increased in general, but the change was more variable over time and less pronounced from the second period to the third. Also, some study areas did not show significant changes over the entire period. The runoff response of the basins studied was also largely as expected when considering precipitation, although an effect of vegetation is possible, as we discuss below.

4.2 | Vegetation changes

Our second question concerned the observed patterns in vegetation density, and whether they agree with a general expected greening, or increase in density. Overall, we found that changes in vegetation were quite different between the 1970s to 1990s and the 1990s to the 2010s, and there was no consistent pattern of increasing vegetation density when considering all three periods.

From the 1970s to the 1990s, moderate vegetation increased and sparse vegetation decreased in all study areas. In areas where bare soil and water, snow, or ice was extensive in the 1970s, the increase in moderate vegetation was sharp. However, the low area coverage of moderate vegetation and high area coverage of nonvegetated areas in northern Finland, northern Sweden, and central Sweden in the 1970s is an indication of possible cloud cover in the satellite data in these areas, even though we set a limit for maximum cloud cover in satellite images to 10%. This means that areas actually covered with moderate vegetation may have been erroneously identified as nonvegetated areas in satellite images. In turn, this shows the challenge in finding satellite images with low cloud cover in the northern regions, especially for the 1970s. For areas where the coverage of nonvegetated land was small (Alaska/Canada, southern Finland, southern Sweden), a significant increase in moderate vegetation was noted from the 1970s to the 1990s. Moreover, the coverage of dense vegetation increased (from 1970s to 1990s) in all study areas except Alaska/Canada. It is difficult to estimate the magnitude of any errors in classification due to cloud cover, but if moderate vegetation was underestimated in the 1970s, it could imply that the vegetation density increase was lower than the results indicate, at least for northern and central Sweden where nonvegetated areas were the most prevalent during the 1970s.

In contrast to the observed changes between the 1970s and 1990s, a strong decline in moderate vegetation and a substantial increase in sparse vegetation was observed between the 1990s and the 2010s across all study areas. In four of the six study areas, no dense vegetation was observed in the 2010s. Therefore, the three periods differed quite markedly, with changes between the first two showing a general greening or increasing vegetation density, whereas change between the second and third period showed an opposed tendency. In the next section, we discuss possible explanations for these overall patterns when considering hydroclimate change, but first, we address here two other factors that could have influenced our vegetation observations.

In addition to the cloud cover and resolution limitations discussed above, the vegetation observations could have been affected by timing, as vegetation density increases during the growing season. We attempted to select images from the same time of season, but tested this effect by comparing the date of satellite image acquisition for all study areas and periods with the corresponding vegetation density. For the proportions of sparse, moderate, and dense vegetation, the correlations with acquisition dates were next to zero, ranging from −0.12 to −0.02 ($p > 0.6$ in all cases). For water/snow/ice and bare soil, the correlations were higher (0.26 and 0.23, respectively) but still not significant ($p = 0.29$ and $p = 0.35$, respectively). Thus, although we cannot rule out an effect of seasonal differences between periods, we consider it unlikely that differences in image acquisition times during the growing season were responsible for the observed differences in vegetation density patterns.

Finally, there could be other nonhydroclimate factors affecting the observations. For instance, we did not consider forestry practices, logging, or other human influences that could alter vegetation density, nor other natural disturbances such as wildfires. In Canada, a decline in forest area of about 0.33% was noted from 1990 to 2010, mostly due to conversion from forest to agricultural or urban land. However, this is a very small value in relation to the observed changes. Similarly, the forest area in Europe did not decrease but rather increase between 1990 and 2015 (Barreiro, Schelhaas, McRoberts, & Kändler, 2017), and for both the Nordic countries and most of Alaska, an increase in biomass was observed during the 1980s and 1990s (Myneni et al., 2001). Therefore, although land use and forestry practices can certainly have an effect, they are unlikely to have contributed substantially to the observed results.

4.3 | Links between hydroclimate and vegetation changes

Our final question concerned the links between hydroclimate and vegetation changes and whether the observed patterns support a possible landscape-scale NBS.

Considering the change between the first two periods, when both temperature and precipitation increased in step with vegetation density, we observed an expected pattern whereby increases in temperature and precipitation may have supported an increase in biomass. This also aligns with general observations of increased vegetation cover and plant biomass (greening), with the treeline moving upward in altitude and northward in latitude, and forest biomass increasing (Finstad et al., 2016). However, for the change between the second and third periods, the hydroclimate observations did not support the expected process, as vegetation density decreased while temperature increased and precipitation also increased or was mostly unchanged.

In general, our observations indicate that changes in precipitation had a substantially higher influence on river discharge than changes in vegetation, as there was a strong relationship between precipitation and runoff (Figure S1). Regarding the relationship between vegetation and runoff, we observed an increase in runoff with reduced vegetation density (more sparse vegetation) and a decrease in runoff with increasing vegetation density (more moderate and dense vegetation), which is compatible with the expected effect landscape-scale NBS. However, compared with the influence of precipitation, this relationship was much weaker and not statistically significant (Figure 5). We note, however, that the relationship was substantially stronger when considering all individual basins instead of groups of basins, although it was still not significant.

We selected the time periods primarily on the basis of data availability, and hence, we do not know whether other time periods would have led to different results. Similarly, there are uncertainties in the classification and interpretation of satellite data and in the measurement of hydrological and climatological parameters, which could all influence the results. We have addressed the sensitivity and robustness of results by a number of additional investigations, such as a complementary trend analysis of the entire period next to the analysis of differences between discrete periods.

Taken all together, our results do not support a landscape-scale NBS of vegetation changes driven by hydroclimate. In particular, the observed changes between the two last periods indicate that future greening cannot be counted on to moderate the runoff from increasing precipitation, as there is no evidence for overall ongoing greening. This conclusion is strengthened by the fact that the satellite observations that underlie results for the two latter periods were more reliable than those supporting the opposing greening tendency between the earlier two periods.

We also note that investigating the data in different ways support this interpretation: Both on the study area level and individual basin level, there was no significant statistical relationship between the share of vegetation in the sparse, moderate, and dense categories and the runoff during the corresponding period. Similarly, the hydroclimatic patterns we observe were also salient when investigated as changes between periods and when investigated as long-term trends.

However, despite these indications, there are also some arguments that support further research to provide a definitive answer. In this study, we have selected study areas on the basis of hydrological data availability and found that there is relatively weak evidence of a landscape-scale NBS moderating runoff across these basins. Thus, our starting point, in terms of the study areas, was based on the possibility to evaluate patterns on the basis of solid hydrological data. Another approach that could possibly be helpful in improving our understanding of hydrology and vegetation interactions on landscape scales could be to start from satellite data and carefully select periods and areas to achieve a contrast in vegetation patterns—for instance, isolating a number of cases with clear increases or decreases in vegetation. Then these study areas could be evaluated in terms of hydrological data availability, and an investigation of the NBS effect could be carried out from that end.

In addition to this alternative approach, observing vegetation and evapotranspiration on the ground could also be explored. Although there have been large improvements in remote sensing in recent decades, the technology cannot fully replace surface-based investigations. In the context of NBS, such surface-based approaches could, for example, involve water balance and vegetation analyses on catchment scales. For instance, Williams et al. (2012) used ground measurements for 167 sites to analyze how vegetation and evapotranspiration are related to runoff across various basin types around the world. Similarly, Goulden and Bales (2014) used ground observations of evapotranspiration, in conjunction with remotely sensed NDVI, to investigate vegetation controls on runoff across a climate gradient. Thus, future work could involve water balance analysis for regions where there is available ground truthing data, to support and complement remote sensing investigations.

Finally, there are also some limitations in our study that could have influenced the results and that could motivate further investigation. For example, we found large changes in vegetation density in several cases, which cannot fully be explained neither by hydroclimate drivers nor possible confounding factors. Although we attempted to select image dates during the same time of the season, we cannot rule out the possibility that seasonal differences had some other effects that were not possible to detect here. Furthermore, the increase in precipitation and runoff was smaller from the 1990s to the 2010s than from the 1970s to the 1990s, which could have affected vegetation growth negatively over these periods and thus contributed to the result of decreasing vegetation density. Additionally, climate warming can ultimately have negative effects on vegetation even in northern climates under certain conditions. Increasing temperature and increasing vegetation lead to higher evapotranspiration rates that can cause drying of soils. Drier summer months further increase the risk of forests fires (ACIA, 2004). A decrease in vegetation could also be caused by an increasing number of extreme events and autumn and winter warming, as warmer autumns can trigger a reduction in winter hardening and rain-on-snow events can lead to plant ice encasement (Phoenix & Bjerke, 2016). In summary, although we consider a runoff moderating effect unlikely for these basins, other aspects of the large vegetation density changes observed in this study could merit further investigation, in order to identify and understand their drivers.

5 | CONCLUSIONS

We investigated whether vegetation density has increased in six different study areas in the Nordic region and northwest America and whether hydroclimate changes support the notion of climate-driven vegetation change as a landscape-scale NBS for these regions. With increasing temperatures at northern high latitudes, we expected an overall increase in precipitation and an increase in vegetation density (disregarding other factors such as anthropogenic landscape change). We observed changes that are compatible with this expected pattern, from the 1970s to the 1990s. In contrast, from the 1990s to the 2010s, changes in precipitation were smaller and more variable, and patterns of vegetation change generally shifted direction, giving an overall vegetation density decrease. Considering these results and the general pattern of runoff response to vegetation density in the study areas, there was some evidence of a runoff moderating effect of vegetation density, but this effect was relatively weak and not consistent across all study areas and periods. Thus, we concluded that any overall landscape-scale NBS arising from climate-driven vegetation change in the northern and Arctic regions studied here is unlikely. However, there are complex interactions between vegetation and hydroclimate that remain to be fully explored. We note a couple of directions for future research: First, a targeted investigation of areas where there are evident vegetation changes, instead of considering a broad set of areas based on hydrological data availability, could reveal more detail about vegetation–hydrology interactions, as long as there are hydrological data also for those areas and periods. Second, investigations could also consider the more dynamic effect of vegetation on runoff response on daily or even hourly time scales, particularly for regions where risks from increasing precipitation and runoff rates are more pronounced. This is especially important in northern high-latitude regions, where the rate of climate change will remain high over the coming decades.

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SUPPORTING INFORMATION

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