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Dominant effect of increasing forest biomass on evapotranspiration: interpretations of movement in Budyko space

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Abstract. During the last 6 decades, forest biomass has increased in Sweden mainly due to forest management, with a possible increasing effect on evapotranspiration. However, increasing global CO_2 concentrations may also trigger physiological water-saving responses in broadleaf tree species, and to a lesser degree in some needleleaf conifer species, inducing an opposite effect. Additionally, changes in other forest attributes may also affect evapotranspiration. In this study, we aimed to detect the dominating effect(s) of forest change on evapotranspiration by studying changes in the ratio of actual evapotranspiration to precipitation, known as the evaporative ratio, during the period 1961–2012. We first used the Budyko framework of water and energy availability at the basin scale to study the hydroclimatic movements in Budyko space of 65 temperate and boreal basins during this period. We found that movements in Budyko space could not be explained by climatic changes in precipitation and potential evapotranspiration in 60 % of these basins, suggesting the existence of other dominant drivers of hydroclimatic change. In both the temperate and boreal basin groups studied, a negative climatic effect on the evaporative ratio was counteracted by a positive residual effect. The positive residual effect occurred along with increasing standing forest biomass in the temperate and boreal basin groups, increasing forest cover in the temperate basin group and no apparent changes in forest species composition in any group. From the three forest attributes, standing forest biomass was the one that could explain most of the variance of the residual effect in both basin groups. These results further suggest that the water-saving response to increasing CO_2 in these forests is either negligible or overridden by the opposite effect of the increasing forest biomass. Thus, we conclude that increasing standing forest biomass is the dominant driver of long-term and large-scale evapotranspiration changes in Swedish forests.

1 Introduction

Boreal and temperate forests provide important ecosystem services at local, regional and global scales. These services include water regulation, soil stabilization, biodiversity preservation and the provisioning of timber, fibre, fuel, food and cultural values for humans (Chopra, 2005). Changes to the attributes of these forests, such as forest coverage, have had important implications for the functioning of the Earth's climate and water and carbon systems (Abbott et al., 2016; Sterling et al., 2013). The return flow of water vapour from the Earth's surface to the atmosphere, known as evapotranspiration, is a key hydroclimatic variable linking these systems. Major regulators of forest evapotranspiration include forest biomass (Feng et al., 2016), leaf stomatal conductance (Lin et al., 2015), canopy leaf area index (LAI) (Mu et al., 2013), tree hydraulic traits (Gao et al., 2014) and stand surface roughness (Donohue et al., 2007). In the context of temperate and boreal Sweden, changes in forest attributes are likely to play an important role because of the higher proportion of available energy partitioned into latent heat than in other ecosystems in these regions, such as grassland, wetlands and tundra (Baldocchi et al., 2000; Kasurinen et al., 2014; van der Velde et al., 2013).

However, the dominant effects of forest change on evapotranspiration are still a matter of debate. Zeng et al. (2016) state that the increase in total canopy leaf area linked to the recent "greening" of the Earth is responsible for more than 50 % of the increase in terrestrial evapotranspiration during the last 30 years. In contrast, Betts et al. (2007) argue for a dominant global decrease of evapotranspiration induced by a water-saving response to increasing carbon dioxide (CO_2) concentrations. Recent modelling studies have found that ignoring the existence of this water-saving response may overpredict future terrestrial evapotranspiration and drought (Milly and Dunne, 2016; Prudhomme et al., 2014; Swann et al., 2016). Piao et al. (2007) argue instead that this physiological effect is cancelled by simultaneous CO_2-induced increases in plant growth and total canopy leaf area, and that changes in climate and land use are the dominant drivers of evapotranspiration changes.

Tree or plot experiments in temperate and boreal forests focusing on the effect on evapotranspiration and water yield relate generally to forest management. These experiments are generally of short duration due to the difficulty and the costs of performing long-term controlled experiments in the field. As forest clear-cutting has been found to reduce evapotranspiration and increase runoff, reforestation or regrowth has resulted in an opposite effect (Andréassian, 2004; Sørensen et al., 2009). For long-term and large-scale studies of this effect, basin-scale hydrological assessments are otherwise required (Andréassian, 2004). Long-term availability of precipitation and runoff data can be used to estimate evapotranspiration changes by water balance over long periods and to study the combined effect of climatic and forest change on forest water use (Hasper et al., 2016). However, the Budyko framework (Budyko, 1974), which links water and energy availability to basin-scale hydrology, is required to further separate this combined effect (Zhang et al., 2001). The Budyko framework has already been applied to understand impacts on forest evapotranspiration in Germany by air quality (Renner et al., 2014) and in North America to differentiate the responses of forested basins to climate and human drivers (Creed et al., 2014; Jones et al., 2012; Wang and Hejazi, 2011; Williams et al., 2012). It has also been applied in China and at the global scale to study the hydrological effects of reforestation programmes and the forest controls on water partitioning (Fang et al., 2001; Huang et al., 2003; Li et al., 2016; Xu et al., 2014; X. Zhang et al., 2008; Zhou et al., 2015).

Observation-based studies of tree water use responses to elevated CO_2 are also limited to tree- or plot-scale experiments of a few years (with the exception of a 17-year study by Tor-ngern et al., 2015). Although most of these short-term tree field experiments have found a stomatal water-saving response that reduces stomatal conductance and transpiration (Ainsworth and Rogers, 2007; Assmann, 1999; Medlyn et al., 2001), the response is often small or absent in northern tree species. In addition, stomatal conductance tends to be less sensitive to high CO_2 concentrations in gymnosperms (e.g. conifers) than in angiosperms (Hasper et al., 2017; Medlyn et al., 1999). Nordic experiments with Norway spruce showed no leaf water-saving response to elevated CO_2 (Hasper et al., 2016; Sigurdsson et al., 2013), while experiments with another conifer species, Scots pine, showed either a rather small reduction or no significant change in stomatal conductance under elevated CO_2 (Kellomäki and Wang, 1996; Sigurdsson et al., 2002, respectively). In the deciduous species silver birch, however, substantial CO_2-induced leaf water-saving responses were found (Rey and Jarvis, 1998). Stomatal water-saving responses may thus be expected to be small in conifer-dominated northern forests, but this remains to be tested at the basin level.

Our main objective was to determine in Swedish forests the dominant forest effect(s) driving changes in the ratio of actual evapotranspiration to precipitation, known as the evaporative ratio, from a basin-scale approach. Thus, since 1900, forests in Sweden have seen important changes in forest structure and composition (Antonson and Jansson, 2011). For this purpose, we used a former application of the Budyko framework (Jaramillo and Destouni, 2014, 2015; van der Velde et al., 2014) to study movement of basins in the space comprising the aridity index and the evaporative ratio, known as the Budyko space. We separated the climatic effect on evapotranspiration that relates to changes in the aridity index from a residual effect that relates to other drivers of change. We further explored the relationships between this residual effect and the forest attributes of standing forest biomass, forest cover area or species composition. We chose the period 1961–2012 for analysing the change due to the large availability of runoff and forest attribute data across Sweden during this period.

2 Materials and methods

2.1 Hydroclimatic data

We gathered data on the daily runoff (R) for 65 unregulated Swedish basins (Fig. 1) monitored by the Swedish Hydrologic and Meteorological Institute (SMHI) and compiled by Arheimer and Lindström (2015). The daily R data

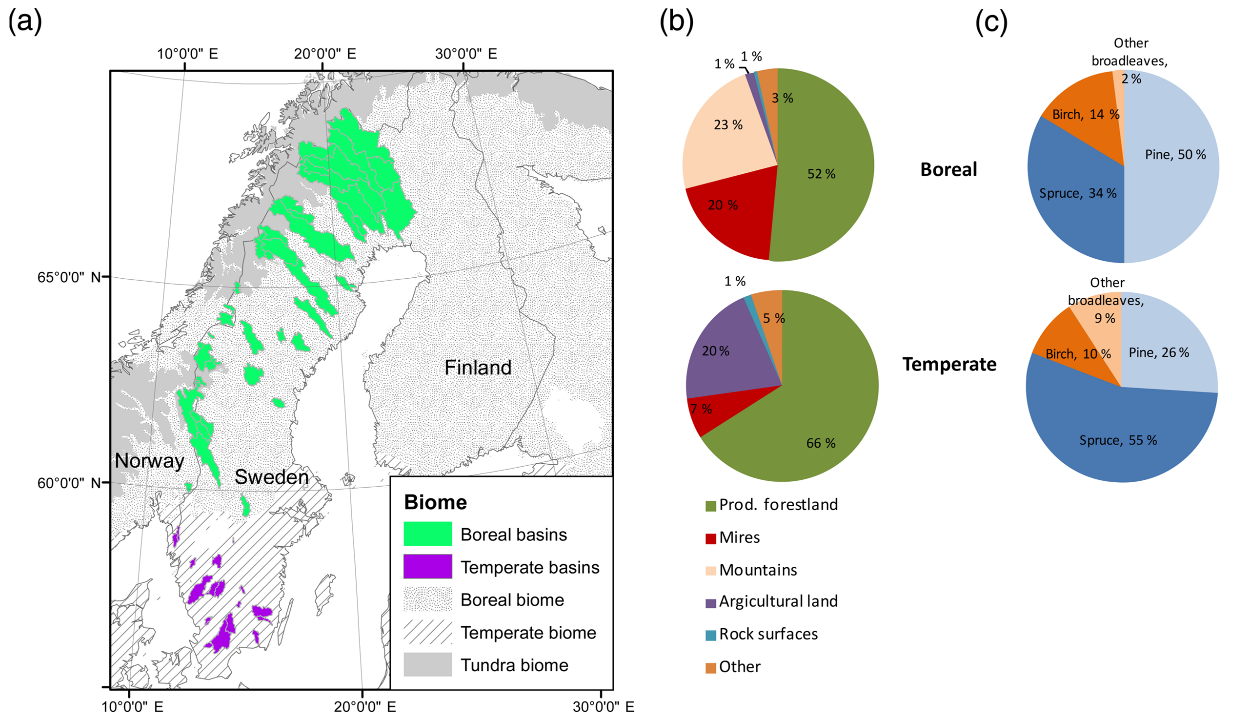

Figure 1. Location, land cover and forest change in the 65 basins used in this study. **(a)** The location of boreal (green) and temperate (purple) basins, **(b)** land cover in each basin group in terms of relative area and **(c)** composition of the forest by coniferous (blue) and deciduous (orange) species.

for the 65 basin outlets and corresponding basin boundaries were obtained from SMHI's hydrologic server (https://vattenwebb.smhi.se/station/) for the period 1961–2012. The daily R data were aggregated to annual values and we considered only complete years in the analysis, defined as years with at least 98 % data capture. We obtained the corresponding daily precipitation (P) data for the basins selected from 68 climatic stations from SMHI's online server. In order to deal with precipitation uncertainty, we also calculated daily P from the Climatic Research Unit gridded P product CRU TS3.23 (Harris et al., 2014) and an additional P product of the Luftwebb portal (http://luftwebb.smhi.se/) of SMHI. The latter is a bias-corrected gridded dataset of precipitation for Sweden during the period 1961–2014 with a 4 km × 4 km horizontal resolution and based in data collected from over 87 precipitation stations around the country (Johansson, 2000; Johansson and Chen, 2003). We made a spatial interpolation by Thiessen polygon to obtain three different estimates of mean P for each basin and used the annual P and R data to calculate actual evapotranspiration (E) as

$$E = P - R - \mathrm{d}S/\mathrm{d}t, \tag{1}$$

where $\mathrm{d}S/\mathrm{d}t$ is the change in water storage within the basin. We performed our assessments of hydroclimatic change during the period 1961–2012 by calculating the inter-annual means of the two 26-year subperiods 1961–1986 and 1987–2012 and defined all hydroclimatic and forest changes as the difference between these means. Using such long-term periods becomes an advantage since when averaged over long periods $\mathrm{d}S/\mathrm{d}t$ should be considerably smaller than P, R and E, permitting the basin-scale assumption of essentially zero long-term water storage change. These assumptions are required in order to calculate E by Eq. (1).

We also obtained mean, minimum and maximum daily temperature data (T, T_{min}, T_{max}) from the climatic stations with P data for calculations of potential evapotranspiration (E_0). Estimates of annual E_0 in the 68 stations were obtained by three models: (1) the Langbein model in terms of T (Langbein, 1949), (2) the Hargreaves model in terms of T_{min} and T_{max} (Hargreaves et al., 1985) and (3) the gridded E_0 product from the Climatic Research Unit CRU TS3.23 (Harris et al., 2014). For the first two models, the E_0 station estimates were interpolated spatially to each basin area by a trivariate spline which allows a spatially varying relationship between E_0 and elevation (Tait and Woods, 2007). We obtained a mean E_0 from the three estimates to perform an uncertainty assessment and to minimize the potential problems of relying on a single model.

2.2 Budyko framework

We used the Budyko framework (Budyko, 1974) to characterize the observed partitioning of P into R and E during the period 1961–2012. The Budyko framework is based on the

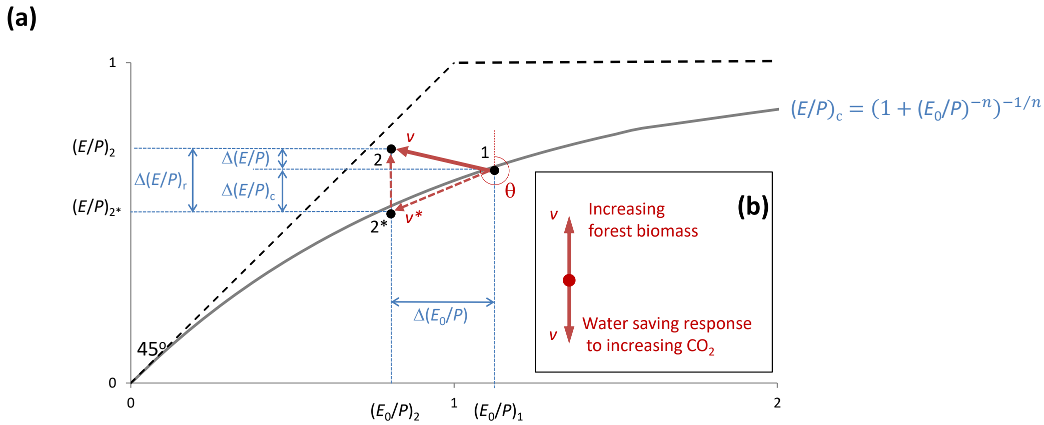

Figure 2. Schematic representation of movement in Budyko space. **(a)** Evaporative ratio (E/P) vs. aridity index (E_0/P) and the parameters describing movement in such space from period 1 (t_1) to period 2 (t_2) by a vector ($\boldsymbol{v}$). The t_1 and t_2 represent mean conditions of E/P and E_0/P during the periods 1961–1986 and 1987–2012, respectively. The change in evaporative ratio ($\Delta E/P$) is divided into an effect from changes in the aridity index, $\Delta(E/P)_c$, termed the climatic effect and represented by the vector ($\boldsymbol{v}^*$), and an effect from other drivers, termed the residual effect, $\Delta(E/P)_r$. The elliptic curve describes the Budyko-shaped curve of Choudhury's relationship between E/P and E_0/P. **(b)** The expected directions of movements in Budyko space with fixed E_0/P for increasing forest standing biomass and water-saving response to increasing atmospheric CO_2 concentrations under constant precipitation.

relationship of the partitioning of water and energy on land, and states that evapotranspiration is limited by the supply of water (i.e. P) and energy (i.e. E_0). This relationship (Fig. 2a) is often represented in the space (i.e. Budyko space) created between the ratio of actual evapotranspiration to precipitation (known as the evaporative ratio, E/P) and the ratio of potential evapotranspiration to precipitation (known as the aridity index, E_0/P).

The relationship between E/P and E_0/P is represented by Budyko-type curves expressing the first in terms of the latter: $E/P = F(E_0/P)$. The E/P is expected to increase linearly with E_0/P at low values of E_0/P, while gradually reducing its increasing rate at higher E_0/P values. Here, we use the "Budyko-type" formulation of Yang et al. (2008) which is a climatic model of the evaporative ratio, $(E/P)_c$, in terms of E_0/P and a parameter representing the effect of the contribution of catchment characteristics, such as vegetation, soils and topography for each basin (n). This formulation has the same functional form as that of Choudhury (1999) and has been synthesized by Zhang et al. (2015) as

$$(E/P)_c = \left(1 + (E_0/P)^{-n}\right)^{-1/n}. \quad (2)$$

For this study, a mean n value was calculated for each basin by solving Eq. (2) with the mean E_0/P and E/P values of the initial period 1961–1986, as done by Wang and Hejazi (2011). A basin that changes hydroclimatic conditions from a subperiod 1 (t_1) to a subperiod 2 (t_2) can be represented in Budyko space by a point moving from initial conditions (t_1: E_0/P_1, E/P_1) (Fig. 2). If the movement is only due to change in the aridity index ($\Delta(E_0/P)$), the movement will occur along the corresponding Budyko-type curve to a new point (t_{2*}: E_0/P_{2*}, E/P_{2*}), implying a change in the evaporative ratio, termed henceforth as the climatic effect ($\Delta(E/P)_c$). However, a basin will most certainly move in time due to a combination of change in the aridity index and other drivers of change (Gudmundsson et al., 2016; Jaramillo and Destouni, 2014). Under such realistic circumstances, the basin will move to a new location not falling on the initial Budyko-type curve (t_2: E_0/P_2, E/P_2), implying a corresponding observed total change in the evaporative ratio ($\Delta(E/P)$).

Regarding some possible forest-related effects on evapotranspiration, increasing forest biomass should increase E due to an increase in root depth and total canopy leaf area, which, under constant conditions of precipitation, would imply an upward movement in Budyko space (Fig. 2b). In a similar way, a tree water-saving response to increasing atmospheric CO_2 concentrations reduces stomata conductance and should decrease E, implying a downward movement in Budyko space under constant P.

Following van der Velde et al. (2014), we represented movement due to changes in the aridity index as a vector ($\boldsymbol{v}^*$) with direction of movement (θ) and magnitude (r) calculated as

$$\theta = b - \arctan\left(\frac{\Delta(E/P)_c}{\Delta(E_0/P)}\right), \quad (3)$$

$$r = \sqrt{(\Delta(E/P)_c)^2 + (\Delta(E_0/P))^2}, \quad (4)$$

where b is a constant and θ is in degrees ($0° < \theta < 360°$) starting clockwise from the upper vertical ($b = 90°$ when $\Delta(E_0/P) > 0$ and $b = 270°$ when $\Delta(E_0/P) < 0$). In a similar way, we represented the total movement vector ($\boldsymbol{v}$)

based on R and P observations by replacing $\Delta(E/P)_{\mathrm{c}}$ with $\Delta(E/P)$ in Eqs. (3) and (4).

We used the approach of Jaramillo and Destouni (2014) to synthesize climate-driven and total movements for the 65 basins as typical wind roses of direction and magnitude. The roses illustrate in the same plot the combination of changes in the aridity index and evaporative ratios for all basins. It is worth noting that since the magnitude and direction of change in Budyko space depends on the specific hydroclimatic conditions of each basin (Greve et al., 2016; Gudmundsson et al., 2016; Jaramillo and Destouni, 2014) and on the definition of the space in which such movement occurs, such wind roses oversimplify the variability of movements in Budyko space. However, using these wind roses is a simple way to synthesize general tendencies of movement in large sets of basins and enables a first-order identification of the importance of drivers of change different from the aridity index. For instance, directions of movement that go beyond the range of slopes of any Budyko-type curve (i.e. $45° < \theta < 90°$ and $225° < \theta < 270°$) imply that drivers different from long-term changes in the aridity index dominate the observed changes in the evaporative ratio. This when the n parameter in Eq. (2) is held constant in time.

2.3 Forest attributes

According to recent data from the Swedish National Inventory (NFI; www.slu.se/en/Collaborative-Centres-and-Projects/the-swedish-national-forest-inventory/), productive forestland now accounts for 57 % of the Swedish land surface after constantly expanding throughout the 20th century (Nilsson et al., 2016). The productive forest standing volume has increased by 85 % since the first NFI took place in 1923 (KSLA, 2015). In Sweden, forest management is responsible for most changes in the abundance of coniferous and deciduous species (Elmhagen et al., 2015; Laudon et al., 2011). The forest data from the NFI here used quantifies the surface area of all types of land use (i.e. productive forestland, mires, mountainous regions, agricultural land, rock surfaces and urban areas); however, the most comprehensive data are collected for forestland. The NFI utilizes a stratified systematic sample based upon clustered sample plots designed to deliver statistics at the county level and as of today accounts for changes in methodology across time. The standing forest volume is differentiated into several categories (i.e. species, diameter and age composition, forest management stage). The species differentiated are Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris* L.), silver birch (*Betula pendula*) and other deciduous broadleaf species. The strata of the NFI are the Swedish counties; the sample plots have been distributed within each stratum. A single sample distribution is completed every 5 years – however, as each year (representing a fifth of the sample) is evenly distributed over the country, any consecutive 5-year period can be used. A detailed description of the inventory design and methods was provided by Fridman et al. (2014).

The main forest attributes studied here were forest cover area and standing volume of productive forest, extracted for the period 1961–2012 from the plots falling within the 65 basins. The sample plots are not restricted to provide only county-wise estimates – every sample plot has an upscaling factor that can be used to create estimates of forest attributes for a given area after grouping the sample plots falling in it. However, a larger area will result in more sample plots being used and a lower standard error. Many of the original 65 basins contained too few sample plots to provide meaningful estimates and therefore the basins were aggregated into larger groups. We thus aggregated the 65 basins into two main basin groups (i.e. temperate and boreal) according to a terrestrial ecoregion classification (Olson et al., 2001) to show the change in forest statistics within the 65 basins and reduce the sampling standard error.

For the analysis, forest cover and standing forest volume (i.e. biomass) were divided by the area of each of the two basin groups to obtain relative values of area (A in $\mathrm{km^2\,km^{-2}}$) and volume (V in $\mathrm{km^3\,km^{-2}}$), respectively. According to the NFI data, in both basin groups more than 50 % of the area is covered by forests (Fig. 1b), and these forests consist mainly of coniferous species (Fig. 1c). Although both the boreal and temperate basin groups have a similar proportion of coniferous and deciduous species – species distribution varies between them in terms of standing volume. In the boreal group, Scots pine accounts for 50 % of all trees whereas in the temperate group Norway spruce is the dominating species (55 % of all trees). Furthermore, as a proxy for species composition, we studied the ratio of the deciduous standing forest volume, V_{d}, to the total standing volume ($Q_{\mathrm{v}} = V_{\mathrm{d}}/V$). We assumed a conservative sampling standard error of A (2.7 %), V (5 %) following (Fridman et al., 2014) and a corresponding propagated error for Q_{v} (10 %) (Taylor, 1996).

2.4 Calculation of the residual effect on the evaporative ratio

In order to identify possible forest-related effects on the evaporative ratio, we separated the non-climatic residual effect from the climatic effect. The residual effect on the evaporative ratio from 1961–1986 to 1987–2012 ($\Delta(E/P)_{\mathrm{r}}$) was calculated as

$$\Delta(E/P)_{\mathrm{r}} = \Delta(E/P) - \Delta(E/P)_{\mathrm{c}}. \tag{5}$$

The combination of three P products with the three E_0 products resulted in nine possible combinations of P and E_0 for each basin. This is important since the evaporative ratio estimates depend on the sources of P and E_0 and the models being used (Greve et al., 2015; Wang et al., 2015). For each basin, we built the corresponding uncertainty ranges for n, $(E/P)_{\mathrm{c}}$, E/P, $\Delta(E/P)$ and the components $\Delta(E/P)_{\mathrm{c}}$ and

$\Delta(E/P)_r$. The arithmetic and the area-weighted (i.e. based on basin areas) means of $\Delta(E/P)$, $\Delta(E/P)_c$ and $\Delta(E/P)_r$ for each basin group, temperate and boreal, were calculated by averaging the values of all basins within that group that represent the largest area – that is, excluding any nested basins. In a similar way, the uncertainty ranges of each basin were also aggregated into basin group uncertainty ranges.

2.5 Regression analysis of the residual effect and forest attributes

In order to determine which of the forest attributes (A, V, Q_v) could better explain the changes in the residual effect on the evaporative ratio, we performed for each basin group linear regressions between all annual values (52 values) of the residual of the evaporative ratio, $(E/P)_r = E/P - (E/P)_c$, and each of the attributes A, V, Q_v. A bootstrapping procedure was performed to account for the sampling standard errors of the forest attribute data in the regression analysis. We constructed a normal distribution of 20 data points for each annual value of each forest attribute with the given mean and sampling standard error of each attribute data point. The coefficient of determination (R^2) and the statistical significance of the linear regression ($p < 0.05$) were calculated for each of 1000 random samples of the annual time series 1961–2012. We finally obtained the mean of the 1000 combinations of R^2 and p values to determine the attributes that could best explain the residual effect.

The assumption of steady-state conditions ($\mathrm{d}S/\mathrm{d}t \approx 0$) of the Budyko framework required to maintain the constant water supply limit may also become a potential source of uncertainty for calculations of $(E/P)_r$ (Chen et al., 2013; Greve et al., 2016; Wang and Tang, 2014; L. Zhang et al., 2008). It is possible that a time interval of 1 year may not guarantee stationary conditions (i.e. $\mathrm{d}S/\mathrm{d}t \neq 0$) in these basins, affecting the calculations of E (Eq. 1) (Bring et al., 2015; Budyko, 1974; Moussa and Lhomme, 2016). We therefore applied the same bootstrapping and regression analysis to the 17 values and 10 mean values resulting from averaging the annual data of the period 1961–2012 into 3- and 5-year means, respectively. The 3- and 5-year means were also applied on the original moving 5-year consecutive average periods of the NFI data (see Sect. 2.3).

Additionally, recent findings have shown that changes in the ratio of precipitation in the form of snow to total precipitation (f_s) might affect E/P (Berghuijs et al., 2014). We therefore additionally calculated f_s per year and for each basin based on the mentioned collected daily P and T data; we assumed that in days with mean temperatures below 1 °C precipitation fell as snow and above 1 °C as rain, following Berghuijs et al. (2014). Finally, we spatially aggregated these values to the basin group level and incorporated f_s into the regression analysis previously described.

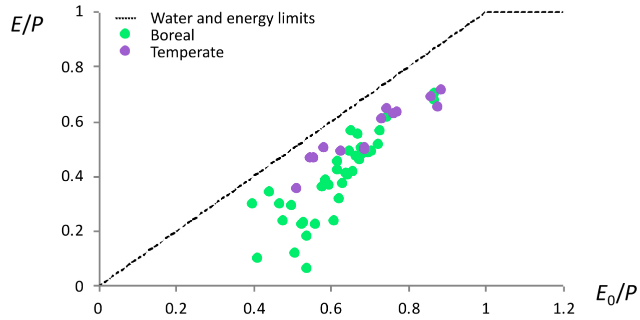

Figure 3. Hydroclimatic conditions in Budyko space. **(a)** Mean hydroclimatic conditions of the 65 basins during the period 1961–2012 illustrated in Budyko space, in terms of the aridity index (E_0/P; x axis) and evaporative ratio (E/P; y axis) for temperate (purple) and boreal (green) basins.

3 Results

3.1 Movement in Budyko space and separation of effects

Most of the 65 basins presented energy-limited conditions since their aridity index E_0/P fell below 1 (Fig. 3). This means that evapotranspiration in these basins was more limited by energy than by water availability. The mean E_0/P and E/P values of the boreal basins were generally lower than those of the temperate basins due to their northerly and cool location. Some basins plotted low in Budyko space, i.e. evaporative ratio E/P near zero, possibly due to underestimates of precipitation due to precipitation undercatch in rain gauges because of falling snow and/or wind, unrealistic measurements of runoff or significant groundwater flux across the basin boundary.

The roses of movements in Budyko space (Fig. 4) show the direction and magnitude of movement of each basin from the period 1961–1986 to the period 1987–2012, in the same way that a typical wind rose shows wind direction and wind speed. The roses show that from the period 1961–1986 to the period 1987–2012, all basins in temperate and boreal biomes experienced a decrease in the aridity index ($180° < \theta < 360°$; Fig. 4a, c). The roses also evidence an increase in the evaporative ratio in most basins in both the temperate (60 %) and boreal (61 %) groups, moving them upwards in Budyko space (Fig. 4a, c), with the direction of movement in both biomes being similar. Furthermore, the movements of highest magnitude occurred in upward directions, with increasing E/P. However, in the absence of other drivers of change, a decrease in the E_0/P can only result in a decrease in the E/P (Fig. 4b, d). Hence, the occurrence of the upward movements ($270° < \theta < 360°$) suggests the influence of other drivers of that movement different from long-term changes in E_0/P. As such, changes in the aridity index are not the only or the most important drivers in these basins.

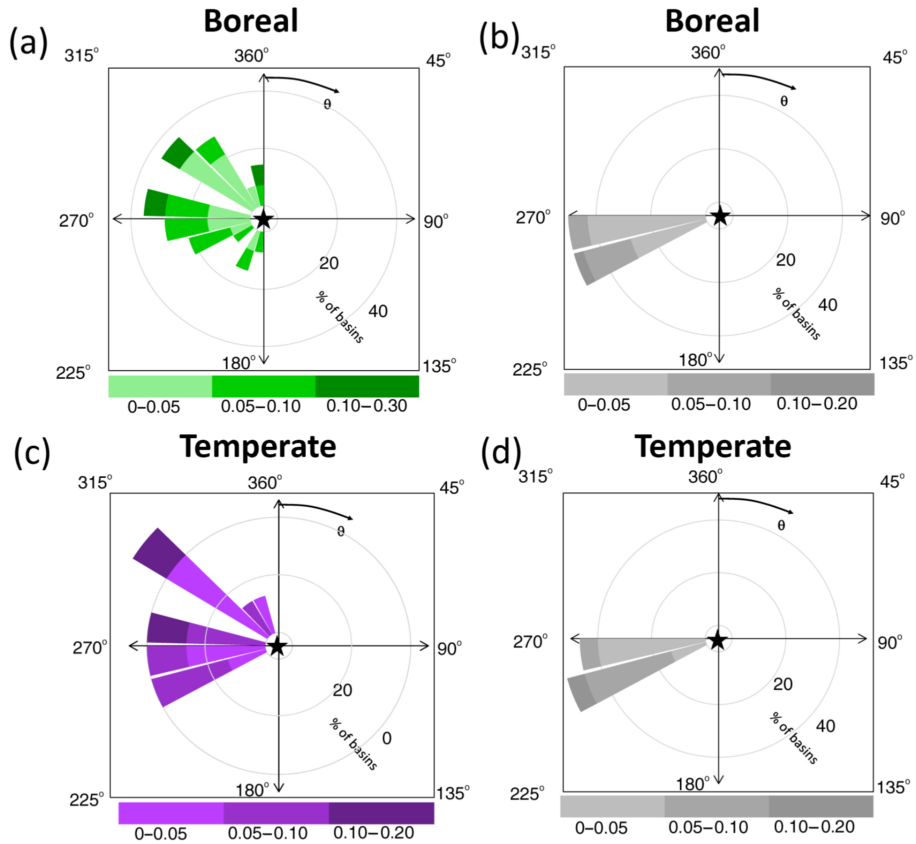

Figure 4. Hydroclimatic movement in Budyko space for the 65 basins due to changes in aridity index (E_0/P) and evaporative ratio (E/P) between the two comparative periods 1961–1986 and 1987–2012. Wind roses of individual basin movements of the boreal basin-group according to **(a)** the combined effect (green) of all drivers of change by calculating E/P from runoff observations (i.e. E/P by Eq. 2) and **(b)** the effect (grey) of only change in the aridity index by calculating E/P from modelled data (i.e. $(E/P)_c$ by Eq. 4), with fixed n and varying E_0/P). **(c–d)** Similar wind roses for temperate basins (purple and grey, respectively). The range of directions of movement ($0 < \theta < 360°$) is divided into 15° interval paddles that group all basins moving in each direction interval, with directions θ starting from the upper vertical and clockwise. We chose this 15° value arbitrarily, to provide sufficient detail of direction. Intensity of colour intervals represent the magnitude of the movement (r) in Budyko space in given direction θ. As an example, 37 % of all boreal basins (Fig. 4a) moved in the range of directions $270° < \theta < 295°$. Colour intensity describes the range of magnitude (r: –) of those movements in Budyko space. As an example, of those boreal basins moving in the range of direction previously described (37 % of the boreal basins), 14 % have moved with magnitudes between 0 and 0.05 (light green), 14 % with magnitudes between 0.05 and 0.10 (medium green) and 9 % with magnitudes between 0.10 and 0.30 (dark green). In contrast, no boreal basin moved in this range of direction ($270° < \theta < 295°$) when using the Choudhury equation (Fig. 4b).

The general decreases in the E_0/P appeared to be the result of an increase in P between the two time periods that was considerably larger than an increase in E_0 (Fig. 5). The increase in P occurred mostly around winter (January and February) and late spring–summer (May–August), and was larger in the temperate than in the boreal group of basins. For instance, the maximum increase of P in the boreal group occurred in June and reached 25 mm yr^{-1}. In contrast, although the increase in E_0 was larger in the temperate basin group, it was rather small with the highest value occurring in April in both biomes (7 mm yr^{-1} across biomes).

3.2 The residual effect on the evaporative ratio

The separation of the climatic and residual effects on the evaporative ratio at the basin group scale shows that the evaporative ratios in the temperate and boreal basin groups have experienced a decreasing climatic effect driven by less arid conditions, $\Delta(E/P)_c < 0$, between the periods 1961–1986 and 1987–2012 (Fig. 6). They have also experienced an increasing residual effect due to other drivers of change, $\Delta(E/P)_r > 0$. Note that the distribution of change for all basins shows that these counteracting effect applies to the median, arithmetic and area-weighted means and interquartile ranges of both basin groups. The uncertainty assessment of the arithmetic and area-weighted means of $\Delta(E/P)_c$ and

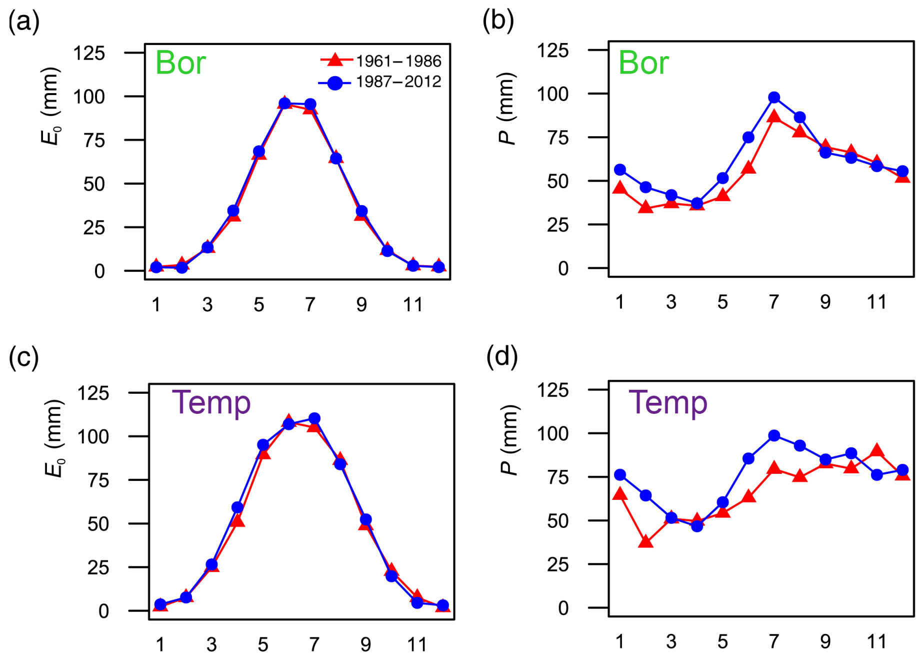

Figure 5. Intra-annual change in precipitation (P) and potential evapotranspiration (E_0). Changes in the mean of P and E_0 between the periods 1961–1986 and 1987–2012 in the boreal **(a–b)** and temperate **(c–d)** basin groups for each month – January (1) to December (12).

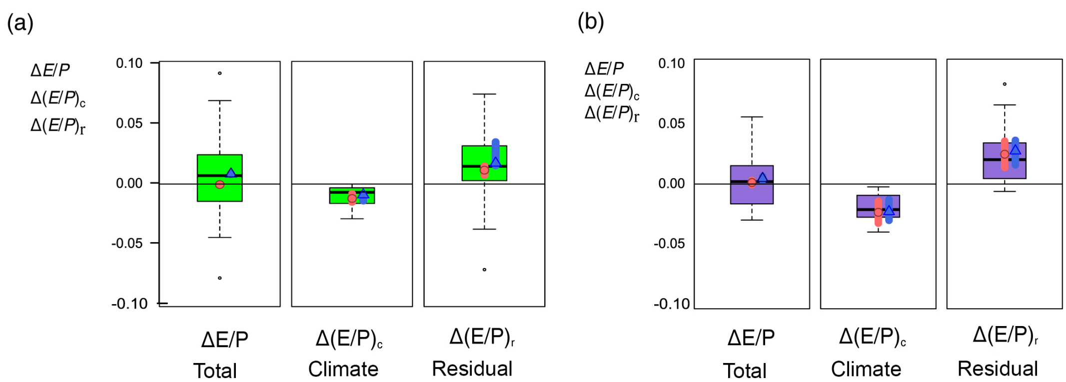

Figure 6. Climate and residual effects on the evaporative ratio. Distribution of changes from 1961–1986 to 1987–2012 in the evaporative ratio, $\Delta E/P$, and its climatic, $\Delta(E/P)_c$, and residual, $\Delta(E/P)_r$, effect components in the **(a)** boreal and **(b)** temperate groups of basins. Boxplot statistics include arithmetic mean (blue triangles), area-weighted mean (pink circles), median (thick horizontal black line), interquartile range (IQR) (boxes), whiskers (confidence interval of $\pm 1.58 \times \mathrm{IQR}\sqrt{N}$, where N is the number of basins in each biome group) and outliers (small black circles). Corresponding uncertainty ranges of the calculated arithmetic and area-weighted means of $\Delta E/P$, $\Delta(E/P)_c$ and $\Delta(E/P)_r$ for each basin group are shown as blue and pink vertical ranges of uncertainty, respectively. These uncertainty ranges arise from the use of three different precipitation and potential evapotranspiration data products.

$\Delta(E/P)_r$ demonstrates that, regardless of the data sources and models of P, T, E_0 used, $\Delta(E/P)_c$ and $\Delta(E/P)_r$ always show these counteracting effects in both basins groups.

3.3 Forest change and effects on the evaporative ratio $(E/P)_r$

The positive residual effect $\Delta(E/P)_r$ in both biomes might be the result of increasing E due to increasing standing forest volume or surface cover. Indeed, between the two 26-year periods, the forest cover area A and the standing forest biomass V increased beyond the standard sampling error in the group of temperate basins (Fig. 7a–b). In the group of boreal basins, V also increased more than the standard sampling error but A remained stable. There was no statistically significant change in the overall forest composition in any of the basin groups; the change in Q_v was considerably smaller than the propagated sampling standard error (Fig. 7c).

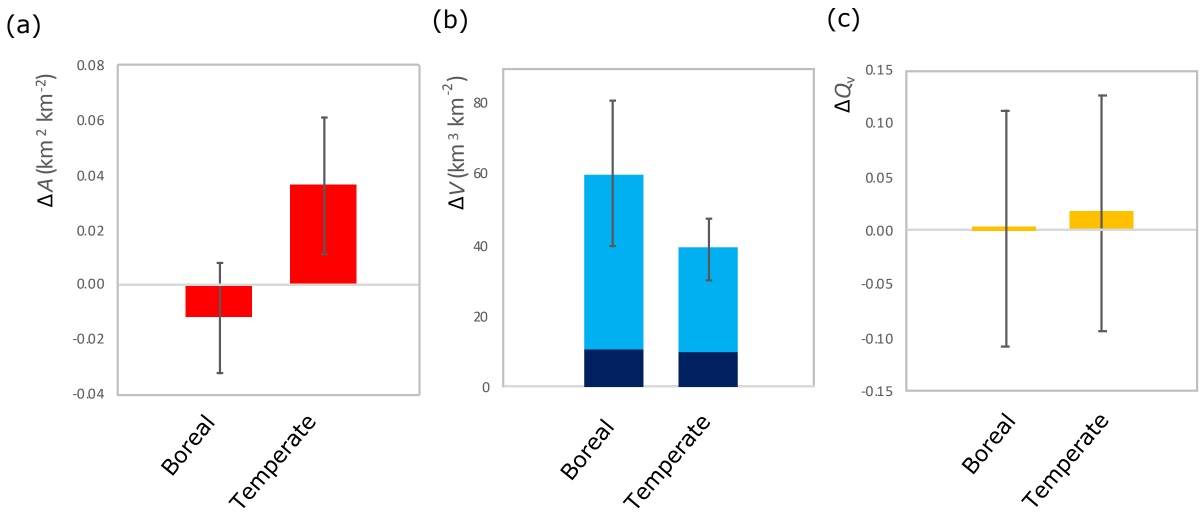

Figure 7. Changes in forest attributes per biome. Changes in both basin groups between the comparative 26-year periods 1961–1986 and 1987–2012, in **(a)** forest cover (ΔA), **(b)** standing forest volume (ΔV) and **(c)** forest composition represented as the ratio of the standing deciduous-forest volume to total standing forest volume (ΔQ_v). The whiskers represent the uncertainty range of ΔA, ΔV and ΔQ_v corresponding to the sampling standard errors for A (2.7 %), V (5 %) and propagated Q_v (10 %). For **(b)**, the dark blue represents ΔV of deciduous trees and light blue of coniferous trees.

The regression analysis between the annual $(E/P)_\mathrm{r}$ and V in the period 1961–2012 presented a significant ($p < 0.05$) positive relationship in the boreal basin group when using any of the 1-year, 3-year and 5-year mean options used to divide the period 1961–2012 (Fig. 8 and Table S1 of the Supplement). Hence, V was the attribute that could best explain the residual effect on the evaporative ratio in this basin group. The A, Q_v and f_s could not explain significantly ($p > 0.05$) the variance of $(E/P)_\mathrm{r}$ in any case, although f_s was close to be significant ($p = 0.06$) based on data with a 3-year time step. The V was also the only attribute that could significantly ($p < 0.05$) explain the variance of $(E/P)_\mathrm{r}$ in the temperate basin group, but only when using annual data. The relationship of $(E/P)_\mathrm{r}$ and V was almost significant ($p = 0.07$) for 3-year mean data and that of $(E/P)_\mathrm{r}$ and A when using annual data ($p = 0.08$). Hence, among the four parameters studied, V was the attribute that could best explain the residual effect on the evaporative ratio also in the temperate group.

4 Discussion

4.1 Dominant forest-related effects on the evaporative ratio

Our results show that the increase in the residual effect on the evaporative ratio $\Delta(E/P)_\mathrm{r}$ during the period 1961–2012 was best explained by an increase in standing forest biomass. Under a hypothetical situation with no changes in climate and stomatal conductance, increasing standing forest biomass should increase transpiration if the canopy LAI and root biomass increased. At least in the case of LAI, an increase in Sweden has been indicated by remote sensing and modelled data (Zhu et al., 2016), and LAI and standing forest biomass are typically strongly correlated in Scandinavian forests (Heiskanen, 2006). Studies in many forest ecosystems across the world have found with reforestation a similar increase in evapotranspiration and/or decrease in runoff at the plot scale (Andréassian, 2004; Bosch and Hewlett, 1982; Sørensen et al., 2009) and basin scale (Fang et al., 2001; Huang et al., 2003; Li et al., 2016; Xu et al., 2014; X. Zhang et al., 2008).

4.2 No evidence of effect from the water-saving response or intra-annual climatic changes

If the water-saving response caused by reduced stomatal conductance under rising atmospheric CO_2 concentrations was a dominant driver of changes in evapotranspiration in the Swedish forests, a decrease in $(E/P)_\mathrm{r}$ should have been observed in our study. However, our results show that in both basin groups $(E/P)_\mathrm{r}$ rather increased. Hence, the increase in $(E/P)_\mathrm{r}$ found in the two basin groups between the two periods implies that this water-saving response is either negligible or overridden by the positive effect from increasing standing forest biomass. The trees in both the temperate and boreal basin groups are dominated (> 80 %) by coniferous tree species and we found no statistically significant change in forest composition in the two basin groups towards more deciduous trees that could have affected $(E/P)_\mathrm{r}$ by increasing the CO_2-induced water-saving response. This response has been found to be less pronounced in coniferous when com-

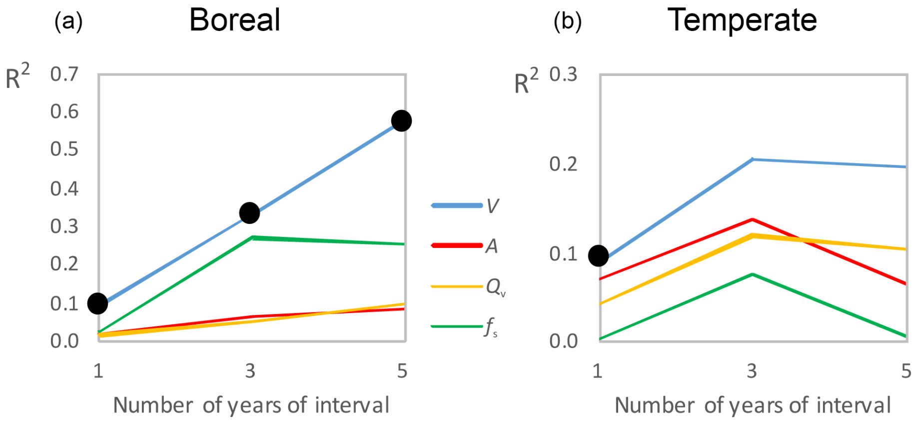

Figure 8. Performance of forest attributes as predictors of the residual of the evaporative ratio. Coefficients of determination (R^2) of the linear regressions between the residual of the evaporative ratio, $(E/P)_r$, and the forest attributes of forest biomass (V), forest cover (A), forest composition (Q_V) and fraction of precipitation falling as snow (f_s), in the boreal and temperate basin groups. The Pearson coefficient of determination (R^2) is shown for the regressions using annual ($N = 52$), 3-year ($N = 17$) and 5-year means ($N = 10$) during the period 1961–2012, with N being the number of values available for each regression with each interval selection. The significance ($p < 0.05$) of the R^2 of each linear regression is shown with a black dot. See Table S1 in the Supplement for values.

pared to deciduous tree species (Hasper et al., 2017; Medlyn et al., 1999).

Intra-annual or seasonal changes of precipitation and temperature with no corresponding change in the annual absolute values of these variables may also affect $(E/P)_r$ (Chen et al., 2013; Milly, 1993; Zanardo et al., 2012). However, the general seasonality pattern of potential evapotranspiration and precipitation in northern latitudes is persistent in time (Fig. 5). Furthermore, although the fraction of precipitation falling as snow f_s decreased from the period 1961–1986 to the period 1987–2012 from 0.20 to 0.14 in the temperate basin group and from 0.45 to 0.43 in the boreal basin group, there was no consistent or significant relationship between f_s and $(E/P)_r$ (Fig. 8 and Table S1).

4.3 Uncertainty on other possible drivers of change on the evaporative ratio

Apart from the inherent uncertainty in the hydroclimatic and forest-attribute data, are there any other factors that may explain the increase in $(E/P)_r$ in both basin groups? The areal extent of forest fires and wind throws in Sweden is small, and such effects should thus have minor influences on large-scale evapotranspiration. Drainage practices used in forestry and agriculture may have played a role in the partitioning of water in Swedish landscapes, although the magnitude of this effect is uncertain and differs between different drainage techniques (Wesström et al., 2003). Farmers implemented open ditches in forests throughout the 20th century, mainly during the 1930s, before the present study period, and the extent of functioning drainage in Sweden today is about 5 % of the total land area (Berglund et al., 2009).

Flow regulation and hydropower development have been shown to increase the evaporative ratio at local to global scales (Destouni et al., 2013; Jaramillo and Destouni, 2015; Levi et al., 2015). However, all the basins used in this study are unregulated (Arheimer and Lindström, 2015). Technological improvements over time in rain gauges to reduce losses of water due to wind, evaporation and snow undercatch may also lead to a false increase in precipitation and corresponding increase evapotranspiration. Nevertheless, in Sweden, these improvements occurred before the period of the present study; windshields were introduced in Sweden in 1853, and the last installations were reported in 1935. Even the replacement of the old cans made out of galvanized iron for new aluminium ones occurred around 1958 (Sofokleous, 2016).

5 Conclusion

We used the Budyko framework to study movements in Budyko space of 65 unregulated Swedish basins, aiming to detect the dominating effect(s) of forest. In all basins, the aridity index decreased due to an increase in precipitation larger than a corresponding increase in potential evapotranspiration. In 60 % of the basins, this decrease was accompanied by an increase in the evaporative ratio, which, as the Budyko framework of water and energy availability implies, cannot be explained by changes in precipitation or potential evapotranspiration. In both the temperate and boreal basin groups studied, a positive residual effect on the evaporative ratio counteracted the negative climatic effect, maintaining the evaporative ratio relatively stable over time. The positive residual effect occurred along with increasing standing forest biomass in both the temperate and boreal basin groups, increasing forest cover in the temperate basin group, and with no apparent changes in forest species composition.

In general, standing forest biomass was the forest attribute that best explained the variance of the residual effect on the evaporative ratio across basin groups. These results further suggest that the water-saving response to increasing CO_2 in these forests or any other negative effect is either negligible or overridden by the opposite effect of the increasing forest biomass. We conclude that forest expansion is the dominant driver of long-term and large-scale evapotranspiration changes in Swedish forests.

Data availability. All data required to conduct this study are available at the Bolin Centre Database, Stockholm University; https://bolin.su.se/data/Jaramillo-2018.

The Supplement related to this article is available online at https://doi.org/10.5194/hess-22-567-2018-supplement.

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