Do plant responses to increased atmospheric CO_2 affect river runoff?

-A study of Swedish rivers

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Sammanfattning

Det har under det senaste århundradet skett en ökning i global vattenavrinning. Denna har tillskrivits flera orsaker såsom (i) förändrat klimat (i.e. ökad nederbörd och temperatur) (ii) förändrad markanvändning(i.e avskogning och dikning) och (iii) stomatas respons på ökad CO_2-halt i atmosfären. Stomata förväntas stänga partiellt i högre CO_2-halter för att spara vatten och därmed minskar trädens vattenupptag. Således förväntas vattenavrinningen öka. Fältstudier har visat att denna respons finns hos grödor men inte för t. ex. gran. Det pågår en diskussion kring vilken av ovanstående faktorer som globalt är viktigast för avrinningen och det har föreslagits att boreala ekosystem är förbisedda i nuvarande modeller. Denna studie har försökt kartlägga avrinningen i svenska älvar och vattendrag i ovanstående sammanhang. Studien försöker svara på tre forskningsfrågor.

1. Minskar evaportanspirationen som ett resultat av CO_2-påverkan på stomata?
2. Är evapotranspiration i Sverige begränsad av vatten och/eller temperatur?
3. Ökar evapotranspirationen, och därmed dess effekter på avrinningen, över en nord-sydlig-gradient?

Med hjälp av långa tidsserier med mätdata för avrinning, nederbörd, temperatur och markanvändning från SMHIs öppna databas kunde ingen signifikant ökning i avrinning ses generellt i landet. Däremot kunde en signifikant ökning av evapotranspirationen ses under år med högre nederbörd för samtliga avrinningsområden, vilket skulle kunna tyda på en vattenbegränsning. En tydlig ökning av evapotranspirationen över en nord-sydlig gradient kunde också ses.

Abstract

There has been an observed increase in river runoff during the twentieth century. This increase has been attributed different reasons (i) climate change (i.e., increased temperatures and precipitation) (ii) land-use change (i.e., deforestation and ditching) and (iii) the partial closure of stomata in higher atmospheric CO_2-levels. Stomata are expected to close in higher CO_2-levels as a means of water savings and optimisation of water use efficiency, thus runoff would increase. Contrary, field studies have shown that this is true for crops but not for some trees, such as Norway spruce. There is an ongoing discussion about what factor(s) are the most important for runoff and it has been suggested that boreal ecosystems are overlooked in current land surface models. This study has investigated patterns and trends in historical runoff for eleven Swedish rivers in the above-mentioned context. Three research questions were asked.

1. Does evapotranspiration decline over time as a result of CO_2 induced stomatal closure?
2. Is evapotranspiration in Sweden limited by water and/or temperature?
3. Does evapotranspiration, and thus its effect on runoff, increase across a north to south gradient?

Using observational data for runoff, precipitation, temperature and land-use from the Swedish Meteorological and Hydrological Institutes (SMHI) open source database the study could not find any general increase in runoff for the time studied. Instead an increase in evapotranspiration was detected, especially for years with high precipitation. This suggests that plants, especially in southern Sweden, are water limited. There was a significant increase in evapotranspiration across the north-south gradient.

Introduction

River runoff is an important part of the hydrological cycle. It has direct impact on water quality (Dai et al., 2009; Wisser et al., 2010) and thus indirect effects on biodiversity (Jackson et al., 2001) and human water resources (Jackson et al., 2001; Wisser et al., 2010; Haddeland et al., 2006). There is an ongoing discussion about changes in global surface water runoff during the last century (e.g., Labat et al., 2004; Gedney et al, 2006; Betts et al., 2007; Dai et al., 2009; Alkama et al., 2011) where an increased runoff has been observed in the worlds largest rivers, despite increases in human water abstraction.

In a global study Labat et al. (2004) found a significant increase in global river runoff with the exceptions of Europe where runoff were stable and Africa, where runoff were decreasing. Observed and reconstructed monthly values were used from datasets ranging between 4-182 years. They suggested an intensification of the hydrological cycle with increasing temperatures. As a consequence of increasing evaporation over sea a 4% increase in runoff for every 1°C increase in temperature was estimated. Using the same dataset, Gedney et al. (2006) later attributed the globally increased runoff to rising CO_2-levels in the atmosphere through the partial closure of stomata in elevated CO_2. This process is referred to as the physiological forcing of CO_2 on stomata. In gas exchange between the leaf and the atmosphere through the stomata, water vapour is also lost (transpiration). Thus, it is hypothesised that stomata of plants close partially in elevated CO_2-levels as a means of water savings. The combined effect of transpiration and evaporation (e.g., from lakes and soils) is called evapotranspiration (ET).

The reduced ET as an effect of the physiological forcing on runoff found by Gedney et al. (2006) was later implemented into land surface modelling by Betts et al. (2007). However, they also discussed the possibility of a CO_2-fertilisation of the photosynthesis, as found in some previous Free Air Carbondioxide Enrichment (FACE) experiments (see for example Schäfer et al. 2002). This would lead to an increase in the leaf area index (LAI) and thus enhance transpiration. The LAI is the relation between the total surface area of the leaf and the land area under the plant. This offset between fertilisation and stomatal closure was also found by Piao et al. (2007).

In conclusion, an increased amount of CO_2 has two effects on plants with opposite direction. The first is the partial closure of stomata, that would lead to a decrease in ET and the second as a fertiliser that increases LAI and thus ET. However, field studies have shown that stomata of some gymnosperms (e.g., Norway spruce, *Picea abies*) lack this response (Uddling & Wallin, 2012). In low CO_2-levels (100 ppm) all terrestrial plants seem to increase their stomatal conductance by a larger stomatal opening. However, in elevated CO_2 (600 ppm) only angiosperms seem to close their stomata and thus optimising their water use efficiency (Brodribb et al., 2009).

In contrast to the results of Gedney et al. (2006), Piao et al. (2007), using a land surface model that incorporated land use, climate factors and CO_2 effects, found an increase in runoff as a result of land use changes, in particular agricultural land expansions. The CO_2 fertilisation effect was expected to decrease runoff as a result of increased LAI.

Land-use impacts on river runoff

It is important to consider land-use effects as a part of the hydrological cycle (Everard & Powell, 2002). The impact of land cover changes on river runoff is likely to have affected the water cycle during the last century. Trees generally have a larger LAI compared to grasses and crops, and thus a higher transpiration. Studies have shown that tree plantations can dramatically decrease runoff (Jackson et al. 2005). The four main drivers that affect change in ET is the available water, available energy, surface roughness and LAI

(Sterling et al., 2013). Croplands have higher ET than grasslands (e.g., graze land and pastures) as crops have been bred for fast growth and thus higher rate of photosynthesis (Bonan, 2008). On a global basis irrigation of croplands and other types of water withdrawal affect the amount of water ending up in the oceans (Haddeland et al., 2006).

In Sweden, ditching is used as a way of draining agricultural land and forests, thus reducing water stress in plants. It is also used to extend the time when it is possible to grow crops as ditched agricultural land dries up earlier in spring, when soils are water logged. With a more intensive forestry ditching of wet forests and wetlands has been done during the last century to increase production. The intensification of the forestry has also led to denser forest stands (i.e., more trees per unit area) , and as an effect, higher transpiration. Dams and hydropower plants also affect the water cycle, but more on a local basis than on the whole catchment (Wisser et al., 2010). The damming of streams and rivers also affect the temporal patterns of the flow and even out peaks in the water flow (Haddeland et al., 2006).

Changed climate

Humans also affect the water cycle indirect through a changed climate. As mentioned above, Labat et al. (2004) proposed an intensification of the water cycle with increasing temperatures. Warmer air can contain a higher amount of water and may thus transport larger amounts of water over land where it can precipitate. The assumption is that increased precipitation lead to increased runoff. Globally, a change in water distribution is also expected. Dry areas are predicted to become drier and wet areas wetter (IPCC, 2013). Increasing temperatures also drives soil evaporation.

In summary there are three major explantations for the increased runoff that has been observed during the twentieth century.

1. Climate change, i.e., increasing temperatures and precipitation over land.
2. Changed land use, i.e., the expansion of agricultural land, deforestation, and ditching
3. The physiological forcing of CO_2 on stomata, i.e., the partial closure of stomata in higher CO_2-levels.

The discussion is complex. Many studies work with datasets that to a large extent have been restored and reconstructed (for example Labat et al., 2004; Gedney et al., 2006; Dai et al., 2009) which give an uncairtanity in the data (Alkama et al., 2011). Alkama et al., (2011) suggested that runoff trends are a regional-scale issue rather than a global-scale. In their study they also found the largest difference between observed and modelled results of runoff in boreal regions. As a conclusion it was also suggested that current land surface models do not account for ”cold processes”(e.g, changes in permafrost) in the boreal ecosystems. Also, current land surface models assume that stomata for all species respond equally to increased CO_2 and thereby predict decreased ET in future CO_2-levels (Luo et al., 2008). This is not true in all cases, as discussed above for gymnosperms.

Aim and hypothesis

The aim of this study was thus to investigate the historic datasets for runoff, temperature, precipitation, and ET for Swedish rivers along with land-use impacts. Three research questions were asked in this study.

1. Does ET decline over time as a result of CO_2 induced stomatal closure?
2. Is ET in Sweden limited by water and/or temperature?
3. Does ET, and thus its effect on runoff, increase across a north to south gradient?

River		Measure station		
	Years	Precipitation	Temperature	Runoff
Kalixälven	1962 - 2011	Pajala, Katterjåkk, Överkalix	Pajala	Räktfors
Luleälven	1973 - 2011	Jokkmokk, Kvikkjokk-Årrenjarka	Jokkmokk	Bodens kraftverk
Umeälven	1962 - 2011	Gunnarn, Hällnäs-Lund	Gunnarn	Stornorrfors kraftverk
Dalälven	1976 - 2011	Malung, Särna, Falun-Lugnet	Malung	Älvkarleby kraftverk
Klarälven	1962 - 2011	Gustafsfors, Malung	Gustafsfors	Edseforsens kraftverk
Svartälven	1962 - 2011	Ställdalen, Gustafsfors	Ställdalen	Gullspångs kraftverk
Tidan	1973 - 2011	Skara	Skara	Moholm
Emån	1962 - 2011	Målilla	Målilla	Emsefors
Lagan	1985 - 2011	Osby	Osby	Laholms kraftverk
Mörrumsån	1962 - 2011	Växjö	Växjö	Mörrum
Helge river	1962 - 2011	Osby	Osby	Torsebro kraftverk

Table 1: The eleven rivers in the study with relevant measure stations from which data has been derived for each catchment and between what years the data has been collected. Note that the datasets are nog complete and that missing values can occur in the data records.

Methods

Runoff (Q) is dependent on the precipitation (P), evapotranspiration (ET) and the change in water storage over the year (ΔV) in the following relationship:

$$Q = P - ET + \Delta V \approx P - ET \qquad [1]$$

The amount of water stored in soils is changing during the year with a peak in autumn when the water magazines are filled from the autumn rains and ET is very low. The date when the variation in ΔV is considered as small as possible is on the 1 October and is referred to as the hydrological new year. In this study the hydrological year was used for calculations of P, Q and ET. This is the approximation of Q showed in the last part of formula [1]. During winter P is generally stored as ice in the boreal biome. This is true for the largest part of Sweden with the exception of the most southern parts of the country. The water storages are successively drained during the vegetation period due to the transpiration of plants. The long term change in the water holding capacity of the soil, such as ditching of wetlands and forests, were disregarded in this study. Yearly mean values for temperature (T) measurements were made from T within the vegetation period, that was approximated to occur from April to September for catchments south of Dalälven and from May to September for northern catchments.

Data collection and processing

For this study 11 Swedish streams and rivers were selected across a North-South gradient (see Table 1). Data were collected from the Swedish Meteorological and Hydrological Institute's (SMHI) open source database. For Q data, flow measures were collected from the measurement station (mostly hydropower plants and dams) closest to the stream or river outflow. For P data the measurement station within or closest to the stream or river catchment were chosen for southern Sweden. For large catchment areas (predominantly in northern Sweden) a mean of P records within the catchment was made. For T one measurement site was selected in the middle of the catchment area. Only observed data were used and measurement stations with long data records were used above stations with shorter data records. Mainly datasets ranging from 1961-2011 were selected. However, datasets this long were not always available, no datasets shorter than 1085-2011 were used. Missing data were regarded as gaps in the datasets and no attempt to fill in these was made.

Q is measured in $m^3 s^{-1}$ and were converted to mm yr^{-1} to be comparable with the P and ET. In this conversion the area specific Q is calculated and the area effect of the catchment is thus disregarded. The assumption of the calculations are that P, ET and Q occur evenly throughout the whole catchment area. This assumption is also made for calculations of T. Calculations for ET were made indirectly as the difference between P and Q for the yearly values. This relationship was derived from formula [1].

Land use data were also collected from SMHI and is the data used for the S-HYPE model. This data is compiled from SVAR (Swedish water archive) SJV (Statens Jordbruksverk) Blockdatabase and Corine land cover. For this study five classes were used, forest; agricultural land; lake, wetland and others. The "others" land use class include mountains with shallow soils, glaciers, grasslands and urban areas. The northern catchment areas has a large fraction of mountains in their catchment (see Table 2) while mainly urban areas constitute the class "others" in southern Sweden. Land use was assumed to be

Catchment	Total area (km	Forest	Agriculture	Lake	Wetland	Other
Kalixälven	27 419	53,76 %	0,10 %	5,40 %	15,73 %	25,00 %
Luleälven	24 514	44,30 %	0,14 %	9,59 %	8,12 %	37,84 %
Umeälven	26 658	62,95 %	0,64 %	7,79 %	8,07 %	20,55 %
Dalälven	28 954	76,84 %	3,20 %	6,78 %	7,49 %	5,70 %
Klarälven	8 587	57,69 %	3,77 %	10,54 %	7,07 %	20,93 %
Svartälven	5 044	78,33 %	4,18 %	12,88 %	3,22 %	1,39 %
Tidan	2 190	58,21 %	34,92 %	2,31 %	1,52 %	3,04 %
Emån	4 472	79,66 %	12,47 %	5,76 %	0,57 %	1,54 %
Lagan	6 452	73,35 %	11,81 %	8,53 %	4,40 %	1,91 %
Mörrumsån	3 369	73,24 %	11,21 %	12,60 %	0,78 %	2,18 %
Helge river	3 898	58,53 %	32,73 %	3,16 %	1,06 %	4,52 %

Table 2: Land use results for the catchments. Forests constitute the largest part for all catchments. Agrigultural land expands drastically to the south with the largest parts for the Tidan catchment and Helge å. The class "others" has its largest part in the north where mountains with shallow soils is the largest component, in the south urban areas almost exclusively constitute the land use class.

unchanged during the observed time. However, both agricultural land and forests are human influenced and dynamic landscapes. Agricultural land changes between grasslands and crop fields over the years and forests are cut, dramatically decreasing ET for a short time and give room for pioneering broad leaved trees such as birch (*Betula sp.*). However, in the large perspective land cover can be considered unaltered.

The coefficients for the time series made for P, Q and ET were analysed with the land use data to investigate if the rate of change in the water cycle variables was related to land cover.

Statistical analysis

All time-trends (i.e., P, Q, ET and T) and functional correlations (i.e., inter annual variation and land use-analysis) were analysed with regression analyses. Results were considered significant if p<0,05 and near significant if 0,1>p<0,05. The statistical software used was IBM SPSS statistics 22.0.

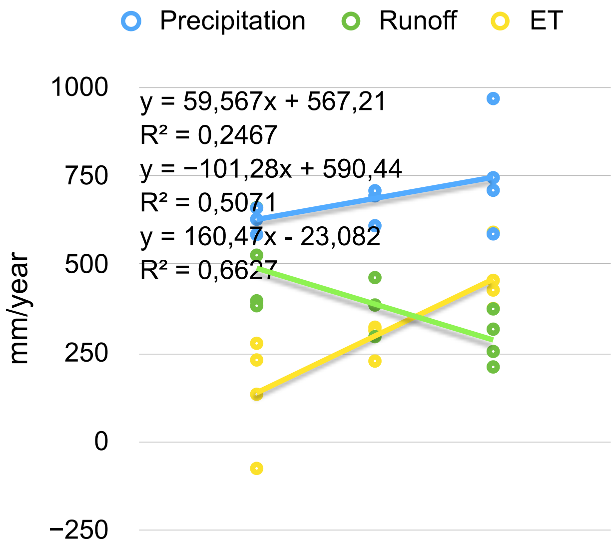

Fig. 3: Mean values (mm/year) of precipitation, runoff and evapotranspiration for all catchments during the time observed in this study. ET increases significantly (p=0,002) to the south as runoff decreases (p=0,014) and become larger than runoff for the most southern catchments. The trend seen for precipitation is non-significant (p=0,12).

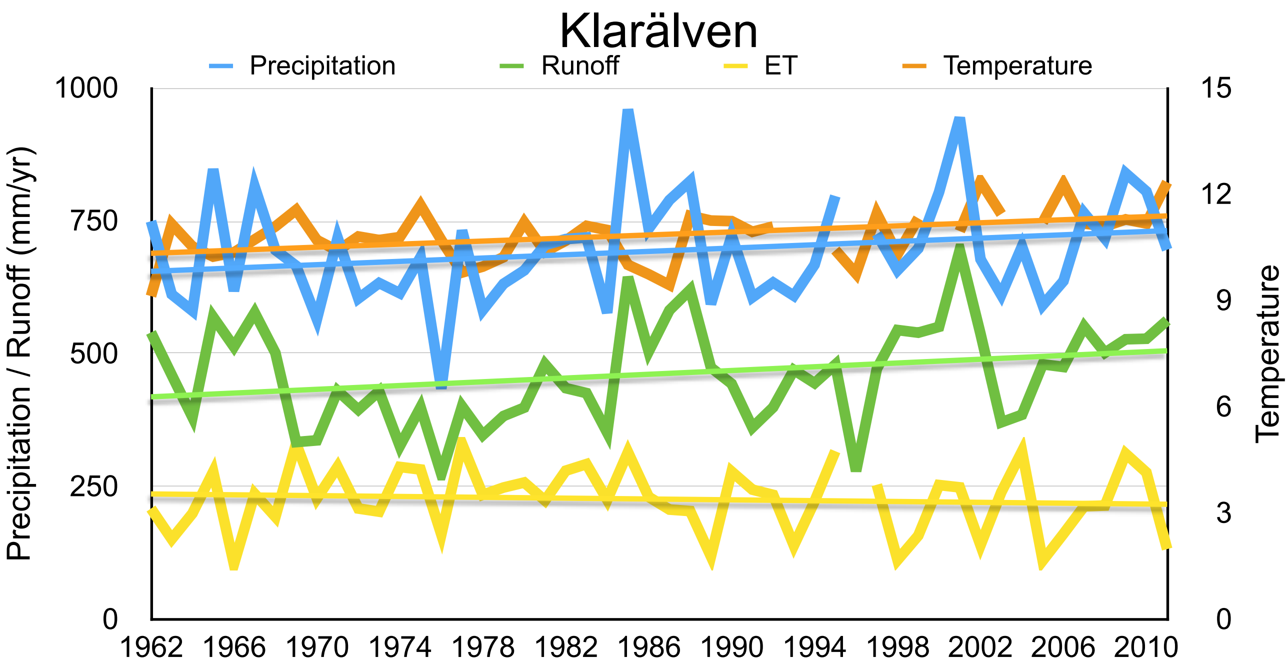

Fig. 1: Trends for Klarälven with yearly data from 1962-2010. There is a significant trend for increased runoff (p=0,038) with a variation that corresponds well with the precipitation. However, the trend in precipitation is not significant (p=0,125). There is a slight but non-significant decrease in evapotranspiration.

Para-meter	Variable	Stream										
		Kalix älven	Lule älven	Ume älven	Dal älven	Klar älven	Svart älven	Tidan	Emån	Mörru msån	Lag an	Helg e å
P	n	49	38	49	35	48	49	38	49	49	25	49
	missing values	1	1	0	0	2	0	0	0	0	1	0
	R	0,23	0,01	0,28	0,06	0,05	0,06	0,31	0,11	0,18	0,01	0,09
	coefficient	2,84	0,95	3,64	2,07	1,56	1,73	6,61	2,06	2,39	2,16	2,52
	y-intercept	554,9	564,3	566,6	622,2	654,0	663,8	477,0	533,6	648,1	937,6	680,3
	sign.	0,000	0,293	0,000	0,292	0,125	0,14	0,004	0,041	0,001	0,795	0,043
Q	n	49	38	49	35	49	49	38	49	49	26	49
	missing values	1	1	0	0	1	0	0	0	0	0	0
	R	0,05	0,04	0,06	0,03	0,08	0,00	0,16	0,02	0,07	0,02	0,03
	coefficient	0,95	1,48	1,49	1,49	1,77	0,46	2,95	0,66	1,39	0,77	1,12
	y-intercept	373,0	629,0	487,8	355,7	417,7	373,6	237,0	193,6	218,9	363,6	288,4
	sign.	0,108	0,145	0,063	0,31	0,038	0,46	0,068	0,691	0,123	0,405	0,619
ET	n	49	38	49	35	48	49	38	49	49	25	49
	missing values	1	1	0	0	2	0	0	0	0	1	0
	R	0,13	0,00	0,22	0,01	0,00	0,06	0,16	0,06	0,03	0,00	0,02
	coefficient	1,89	−0,53	2,14	0,58	−0,39	1,27	3,66	1,39	1,01	1,50	1,40
	y-intercept	181,9	−64,8	78,9	266,5	237,0	290,2	240,1	340,0	429,2	569,7	391,9
	sign.	0,007	0,797	0,003	0,993	0,611	0,317	0,066	0,048	0,108	0,930	0,205
T	n	49	33	49	35	45	48	35	45	48	25	38
	missing values	1	6	0	0	5	1	3	4	1	1	11
	R	0,19	0,00	0,22	0,02	0,20	0,13	0,27	0,29	0,21	0,47	0,40
	coefficient	0,03	0,00	0,03	0,01	0,02	0,02	0,04	0,03	0,02	0,08	0,03
	y-intercept	9,4	10,1	9,9	11,1	10,3	10,3	11,6	11,4	11,9	11,3	11,6
	sign.	0,004	0,475	0,002	0,131	0,003	0,033	0,003	0,000	0,002	0,000	0,000

Table 3: Results for time-trends for precipitation(P), runoff(Q), evapotranspiration (ET) and temperature(T). Significant results (p<0,05) are shown in green, time-series without detectable trends (p>0,1) are shown in red and near-significances (0,1> p <0,05) in orange. 9 out if 11 measurement sites showed a significant increase in temperature. Six catchments showed a significant increase in precipitation. Three catchments had significant increases in ET and only one river showed an increase in runoff.

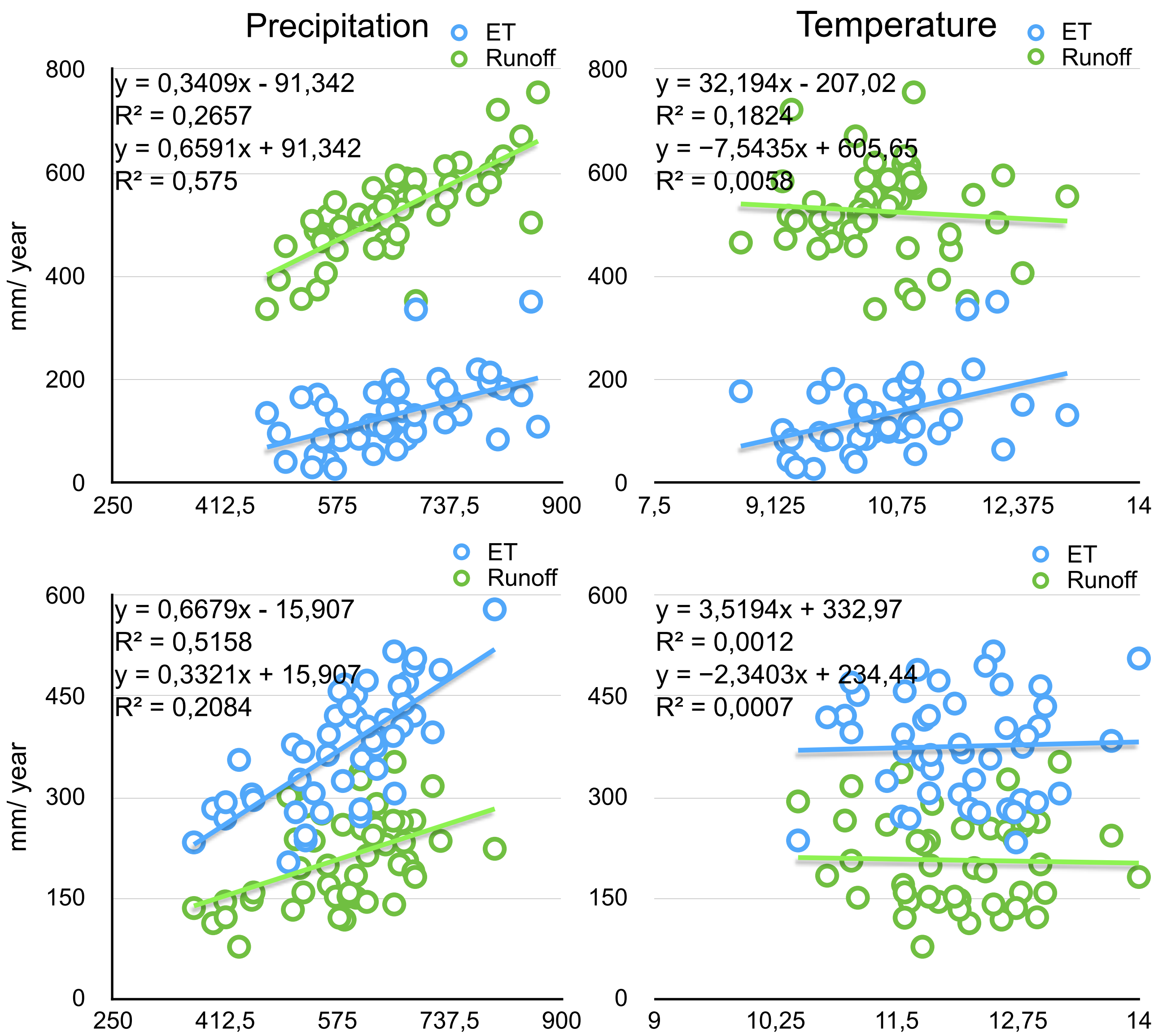

Fig. 2: Inter annual variation in precipitation and temperature in one northern (top row) and one southern (bottom row) catchment. Umeälven (top row) represents a northern catchment whereas Emån (bottom row) represents one southern catchment. For years with high precipitation there is an increase in both runoff and ET($p<0,000$) over the whole north-south gradient. For the three most northern rivers (i.e., Kalixälven, Luleälven and Umeälven) temperature also had an effect on ET ($p<0,05$). ET is small in the north but larger than the runoff in the south of Sweden.

Results

All catchments except Luleälven and Dalälven showed a highly significant increase ($p <0.01$) in T (see Table 3). Six of the eleven catchments showed an increase in P over the time measured. This increase in P was however not represented in increased Q for any of the observed rivers. The only stream that showed a significant increase ($p=0,038$) in Q was Klarälven. This increase did however not correspond to a significant increase in P ($p=0,125$) for the same catchment, possibly as a result of higher inter annual variation in P as the trends for both series are similar (Fig. 1 and Table 3). Umeälven and Tidan showed a near significance ($p=0,063$ and $p=0,068$, respectively) in Q. There was no significant decrease in ET for any of the rivers. The catchments that showed significant ($p<0,05$) time trends for ET were Kalixälven, Umeälven and Emån. Tidan showed a near significant ($p=0,066$) trend towards increased ET. The coefficients of the trends, that were all increasing, were larger for the two northern rivers, Kalixälven (b=0,380) and Umeån (b=0,419), than for Emån (b=0,297).

As shown in Fig. 2 ET increased in years with high P. This was true for all the catchments observed (see Table 5). P also affected Q for all catchments except Luleälven and Helge river. Lagan, having a shorter time record (n=25), showed a near significance (p=0,063) for the P-Q relationship. In the three most northern rivers there was also an effect of increased T on ET. Svartälven in the south of Sweden, showed a near significance (p=0,074). T did not have an effect on Q for any of the catchments. Helge river stood out from the other south catchments as it showed a relationship between ET and P, but not Q, for years with large P (see Fig. 4). This suggested that all the extra P in those years go into increased ET. Helge river was also the catchment where the largest extent of broad leaved trees could be expected.

The proportion of P that ended up as ET also increased along the north to south gradient, which was expected as the vegetation period is longer and T larger. As can be seen in both Fig. 2 and 3, ET is low in north of Sweden but increases towards southern catchments where it becomes larger than Q.

There was no significant relationship (p<0,05) between land-use and rate of change in Q. However, there are trends in the land cover classes. The rate of change in Q decrease with increasing forest cover, while ET is unaffected (see Fig. 5). This indicating that forests may have a mitigating effect on Q by increased P. Agricultural land and lakes show two trends with opposite direction, where the rate of change in ET is larger for catchments with high contents of agricultural land. For catchments with a larger proportion of lakes ET seemed to be more stable over time. However, these trends are highly insecure and may be confounded by the large proportion of forests.

Discussion

In this study a rough picture of the climatic factors (i.e., precipitation and temperature) and runoff patterns has been drawn along the whole north to south gradient in Sweden for

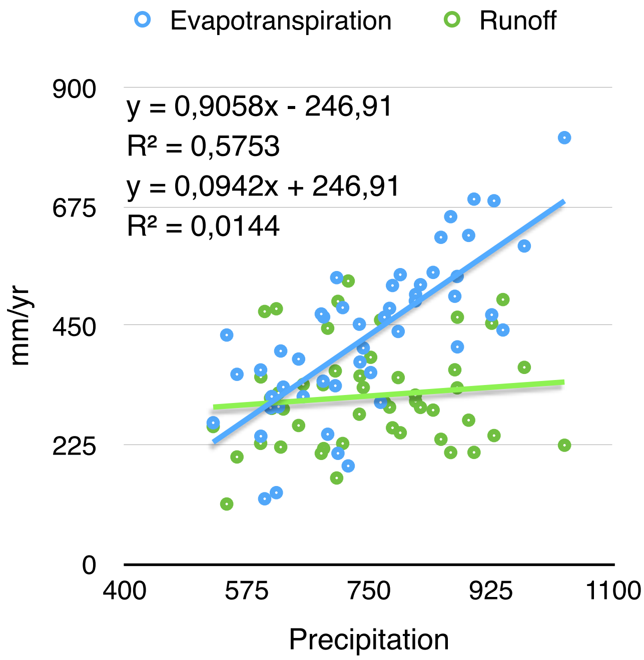

Fig 4: Inter annual variations for Helge river. Evapotranspiration increases significantly with increased precipitation. Runoff does not correlate with precipitation. This suggests that most of the extra precipitation goes into evapotranspiration.

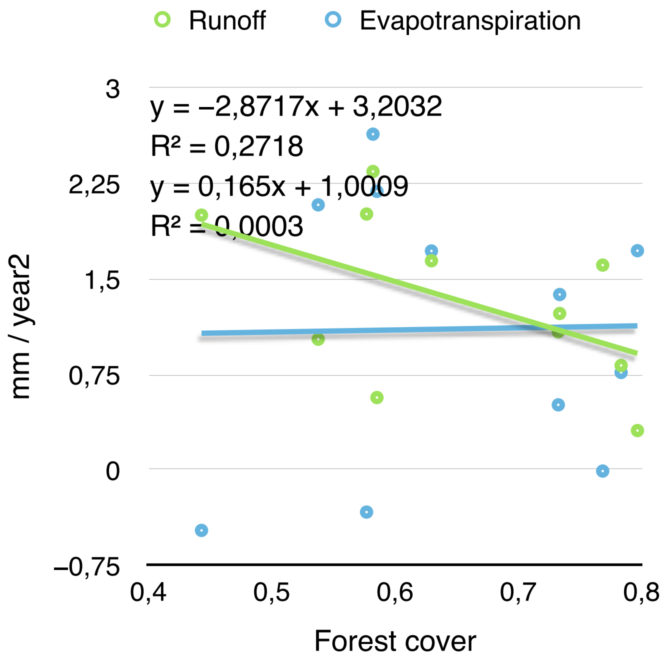

Fig. 5: The rate of change (mm/year^2) in runoff and evapotranpiration with forest cover. The two trends are non-significant with p=0,103 for runoff and p=0,961 for evapotranspiration.

	Temperature		Precipitation	
River	**Runoff**	**Evapotranspiration**	**Runoff**	**Evapotranspiration**
Kalixälven	0,246	0,023	0,000	0,000
Luleälven	0,149	0,042	0,126	0,000
Umeälven	0,599	0,002	0,000	0,000
Dalälven	0,936	0,143	0,000	0,073
Klarälven	0,851	0,165	0,000	0,001
Svartälven	0,335	0,074	0,000	0,014
Tidan	0,953	0,587	0,000	0,000
Emån	0,865	0,822	0,001	0,000
Mörrumsån	0,132	0,161	0,002	0,000
Lagan	0,807	0,633	0,063	0,000
Helge river	0,492	0,876	0,406	0,000

Table 5: Significance-levels for the relationships in the inter-annual variation of P and T with Q and ET. Significant ($p<0,05$) results are marked in green and near-significances ($0,1> p < 0,05$) are marked in orange. There was a significant increase in evapotranspiration (ET) with temperature for the three most northern rivers. ET increased with precipitation for all rivers. Runoff also increased with precipitation for all catchments except Luleälven and Helge å.

the time 1961-2011. The general pattern is an increase in T and P over the whole country. The increased P is not reflected in increased Q, which were without significant trend for all rivers except Klarälven. This pattern is the opposite the expected from the results of Gedney et al. (2006) where Q is expected to increase from CO_2 forcing on stomata. Contrary, ET was found to significantly increase over the time studied for three of the eleven catchments. Looking at the inter annual variation, all catchments showed an increase in ET for all catchments in years with larger P. ET also showed a positive correlation with T for the three most northern catchments. This may suggest that plant water-use in the whole of Sweden is limited, and that plants in northern Sweden is also limited by T. The water limitation would not be unlikely in the south, but is surprising for the northern catchments where water otherwise is abundant.

The amount of water that is available for plant uptake and what excess water that goes into Q will be strongly dependent on the rainfall distribution patterns (Leuzinger & Körner, 2010). During longer rain periods soil water storages will be logged and Q will increase. A study of Volga´s upper catchment (Olchtev et al., 2002) showed similar results for the water limitation. In years with small P, ET in *P. abies* was limited by low soil moisture. Olchtev et al. (2002) also discussed the potential change in rainfall distribution pattern in a changed climate. A change towards increased P during winter and decreased P in summer would lead to higher water limitations during the vegetation period. The amount of yearly P that falls during winter is also important since the larger part of it will run off during the spring flood.

For this study however, the uncertainty is large for ET, as it is only calculated as a residual of P and Q. This uncertainty is particularly large where ET is low and has a low variation, as in the northern catchments. Since P is also calculated as a mean of within-catchment measurement stations a bias in the magnitude is possible. The method is however robust when P is considerably larger than Q.

Even though experiments on the leaf level reveals trends in CO_2 forcing (i.e., stomatal closure and increase in LAI) these effects may be confounded on the ecosystem level by processes such as soil evaporation (Lenka & Lal, 2012). To investigate the climatic drivers for the increased ET more mechanistically, modelled Potential Evapotranspiration (PET) should also be included in studies. This will quantify the influences of abiotic factors such as T and global irradiance in the discussion.

Helge river stands out as a catchment as it shows no increase in Q due to high levels of P. This catchment is situated where the largest extent of broad leafed trees could be expected. Olchtev et al. (2002) found a 10%-20% higher transpiration in broad leafed trees (e.g., *Betula sp.* and *Populus tremula*) compared to the coniferous forest (i.e., *P. abies* and *P. sylvestris*). Some broad leaved trees also have deep roots. A hypothesis is that a larger rhizosphere drains deeper soil layers of water and thus decreases ground water outflow, causing a decreased Q. However, the catchment also contains a large amount of planted *P.abies.* In this study, no analysis of tree species composition was made, and land-use was considered to be unaltered for the time observed. Future studies should also aim at including these factors.

Conclusions

In this study there was no evidence of decreased ET as a result of CO_2 forcing on plants for the observed time as first suggested by Gedney et al. (2006). Contrary, ET was increasing in years with larger P, suggesting that plant water-use is limited. ET was also found to increase in a north to south gradient, supposedly as an effect of increased T. For the three most northern rivers (i.e. Kalixälven, Luleälven and Umeälven) ET was also significantly higher for years with larger T during the vegetation period, suggesting plants in northern catchments to be limited by T. There is also a clear trend of increasing ET in a north-south gradient. Future studies should also aim at incorporating models of PET to investigate the climatic drivers of the increased ET. Better land-use data is also required to analyse the importance of land-use for river runoff.

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