Author's response for review process of "Understanding variability in root zone storage capacity in boreal regions"

by Tanja de Boer-Euser, Leo-Juhani Meriö, Hannu Marttila

Dear editor,

Please find attached the revised version of our manuscript. The comments of the reviewers have been very useful for this revised version. This document first contains a point-to-point reply to all their comments, the core of this point-to-point reply is the same as what we posted in the interactive discussion, with details included how comments were finally incorporated. The point-to-point reply is followed by a marked-up version of the revised manuscript and supplement.

The most important changes in the manuscript are:

- We have made the aim of the paper clearer by rewriting, among others, the last paragraph of the introduction and the first paragraph of the discussion.
- We have changed the structure of the paper, to make the description of the method, the presentation of the results and discussion of the results more consistent. In the revised version the Sections 'Methods', 'Results' and 'Discussion' have, among some other subsections, the subsections: 'Climate variables', 'Vegetation characteristics' and 'Vegetation types'.
- We have extended the description of the method to derive S_r from climate data.
- We have added a principal component analysis (Sections 2.4.4 and 3.1) and as a consequence we have moved the correlation matrix (Figure 8 in the first version of the manuscript) to the supplement, to prevent overlapping information.
- We have added the Spearman's correlation coefficients in the titles of the subplots of the scatter plots comparing S_r with climate variables, root biomass and vegetation types, for all catchments combined and for the individual boreal regions. The Spearman's correlation coefficients for the comparison of S_r with leaf cover and tree height are mentioned in the text.
- Due to the change in structure of the method, result and discussion sections, the order of the figures changed in the following way:

revised version	first version
Figure 1	Figure 1
Figure 2	Figure 2
Figure 3	not yet present
Figure 4	Figure 5
Figure 5	Figure 6
Figure 6	Figure 4
Figure 7	Figure 3
Figure 8	Figure 7
Figure 9	Figure 9

We would like to submit this revised version for the next step in the review process.

On behalf of all authors,

Kind regards,

Tanja de Boer-Euser

1 Reply to review of anonymous referee #1

Dear referee,

Thank you for reviewing our manuscript and your positive evaluation of the general findings. The more detailed comments you have given made us realise that especially some elements of the used method need more attention in a revised version of the manuscript. Below we have replied in more detail to all your comments.

A weakness in the analysis is that S_r is derived at the basin scale, and then assessed against vegetation type and attributes, but different vegetation types prefer different soil texture and moisture conditions. A diverse catchment likely has a diverse soil and an S_r value that may not apply very well to any of the vegetation types in the particular catchment. Conversely, I would expect stronger correlations and more valid S_r values in catchments containing a dominant vegetation type. From looking at Figure 3, I suspect that peatlands never make up enough of the catchments for the S_r value obtained to be applicable to them, and this would also be the case for many of the agricultural areas. Forest is usually the dominant vegetation type and this is shown by its close agreement with the broad boreal zone plot.

We agree with the reviewer that stronger correlation between S_r and vegetation characteristics could have been found if the catchments contain only one dominant vegetation type. We used existing small catchment data which allowed us to compare catchment attributes to S_r-values, but boreal catchments are rather heterogenic and thus suitable data from catchments with single vegetation type does not exist. However, the calculation method assumes equilibrium in the catchments: all vegetation in the catchment managed to survive there together. This means that the catchment representative root zone storage capacity is appropriate to sustain the transpiration demands of the vegetation. Although S_r is a catchment average conceptual parameter we expected that is related to different vegetation characteristics, which we have shown in the results.

Regarding the land cover types in Figure 3, we agree with the reviewer that the derived S_r values cannot fully be attributed to one of the land cover types; however, by presenting the results in this way, we think that possible influences of certain land cover types on the derived S_r-values can be explored.

We have discussed the effect of the heterogeneity of the catchments in Section 4.2 of the revised version of the manuscript.

There appear to be inconsistencies in the data that are presented in subsequent plots. These need to be corrected or explained. In Figure 3a there are two points with relatively low leaf cover and S_r values of about 230 and 110 mm. These points show up in the boreal regions plot (3d) as northern points, so they are northern forests. Based on Figures 3e and 3h, the 230 mm S_r value is also associated with a large tree length of about 210 m while the 110 mm S_r value is associated with a medium tree length of about 100 m. I'm wondering if there is something about these two basins that makes them different. Why is the leaf cover low and yet one of them has the largest observed tree length? Was there a defoliation event? When I look in Figure 4, I see no northern forests with an S_r value anywhere near 230 mm. At first I thought that perhaps it wasn't pine, spruce or deciduous, but it doesn't even appear in figure 4d. What happened to this forest that stands out in Figure 3? Figure 3 shows two northern catchments with S_r values not far from 110 mm, one is mostly forest with some peatland and the other has a bit less forest but still more forest than peatland. Figure 4 only shows *one northern catchment with S_r values close to 110 mm. What happened to the other catchment? Figure 3 shows two northern catchments with S_r of 70-80 mm and one at about 50 mm, and these appear to be forests or mostly forests, but in Figure 4 the S_r values do not fit the same distribution of two in the 70-80 mm range and one at 50 mm but instead it appears that two are at about 70 mm and one at about 85 mm. These plots appear to be derived from somewhat different datasets with respect to S_r values. The data used in the figures needs to be made internally consistent, or explanations provided for data appearing in some figures and not in others*

Thank you very much for pointing this out. In Figure 3 the data for leaf cover was slightly shifted, creating an inconsistency in the presented data. We have corrected this error, resulting in a new figure, being Figure 7 in the revised manuscript. Further, the x-axis caption is changed from tree length to tree height for more clarity and data were presented in decimeters, which is now converted to meters.

From my experience, some pine species like to grow in sandy well-drained soil, and here contribution to discharge is likely high and transpiration low. In such a catchment the estimated T should be low and there will not likely be large deficits, even though the soil can get quite dry. Spruce trees like to grow in moist soil, often in poorly drained areas. Such areas don't often dry out and contributions to discharge also likely follow precipitation quite well, except following a drought when there is recharge; again such areas may not see very large deficits. So we have pine in dry areas with small deficits and spruce in wet areas with usually small deficits.

We agree with the reviewer. Pine trees favour dry sandy soils whereas spruce favour more moist locations. However, in our data set there were also many pine trees in drained peatlands and thus we cannot fully follow this simplification in our analysis. The small expected deficits for both pine and spruce trees, is also reflected in the derived S_r-values: many catchments have S_r values below 100mm and spruce and pine are the dominant tree species. With the used method S_r values larger than 500 mm are found worldwide (e.g. Gao et al., 2014; Wang-Erlandsson et al., 2016). We have discussed the possible influence of the drainage capacity of the soil in Section 4.3 of the revised manuscript.

Deciduous trees tend to have larger transpiration demands and can grow in poorly or well drained soils. If deciduous trees exist more often in areas with larger deficits and adjust their root mass accordingly, this may explain why the best correlation is for deciduous trees in Figure 4.

Thank you for pointing this out, we have briefly discussed this aspect in Section 4.3 of the revised manuscript.

However, much of this detail would be smeared out because each basin contains multiple tree and other vegetation types and probably a combination of wet and dry areas. With this in mind, I understand why the correlations and patterns are not as strong as one might hope for.

As mentioned before, the study catchments were indeed rather heterogenic as typical boreal landscape is. However, some correlations were found between derived S_r-values and detailed catchment data. We have discussed the heterogeneity of the catchments in Sections 4.2 and 4.3 of the revised version of the manuscript.

Some of the relationships appear to be curvilinear rather than linear, so it might be more informative to try fitting some nonlinear relationships (exp, log, polynomial) to see which correlations increase and whether the *relative importance of parameters changes. Perhaps a flexible generic nonlinear model could be used.*

Thank you for the good suggestion; however we do not see need for the non-linear methods since results can be shown in linear methods. Actually, we think it is more valuable to combine the linear methods with an analysis of the possible threshold present in the data. This threshold seems to turn up at the same location for a number of the compared catchment characteristics. Significant differences between 'below' and 'above' threshold groups are presented in Section 3.5 of the revised manuscript.

More specific comments:

P4 line 4-7: Are the authors aware of the type of precipitation gauges used to measure snowfall, whether they were shielded and whether they were corrected for undercatch based on coincident wind speed measurements? Precipitation gauges always measure less than the true snowfall amount, but if properly located, shielded and adjusted using established correction factors based on wind speed, one can arrive at an accuracy that is comparable with a snow survey.

We used a spatially interpolated dataset with a resolution of 10 x 10 km^2 for the meteorological parameters (precipitation, air temperature) constructed by Finnish meteorological institute (FMI). In this data set the measurement error caused by gauges has been checked and corrected in operative quality control. For snow data (S_{SWE}), we used snow line data provided by Finnish Environment Institute and measured by standard methods. Since S_{SWE} was closest available and not always situated within the study catchment, we corrected S_{SWE} with local precipitation. We have added the following sentence to Section 2.2: 'These data have been checked for measurement errors caused by gauges and were corrected in operative quality control.'

P4 line 22-23: I am somewhat perplexed that canopy interception is included for rain but not for snow, when it is well known that boreal forests can store close to an order of magnitude more mass of snow versus water on the canopy, and interception losses on the order of 30% or more are common over a winter.

We used snow line data to provide snow water equivalent values for the S_r calculations. This data represent rather well the snow water contributing to the runoff, soil moisture and recharge, and is therefore suitable for our analysis. In addition to that, the interception included in the calculations to estimate S_r is, besides the availability of water, driven by the potential evaporation. As the latter is not measured, as it is close to zero, during winter time (so during occurrence of snow), including interception for snow would not really influence the estimated S_r values.

P5 Section 2.4: I think an explanation of the specific method used to obtain S_r is required. I looked at de Boer-Euser et al. (2016) and based on that, I think I understand what was done, but a brief overview would be helpful.

We have extended the explanation of the method in Section 2.3 of the revised manuscript, including assumptions of the method and terminology used in the remainder of the manuscript.

In Figure 3 are the values of leaf cover and tree length basin values or are they specific to each vegetation type? I see for example the two northern basins with S_r near 70-80 mm and leaf cover near 24-28% in Figure 3d, and these appear to have corresponding large forest fractions, small peatland and smaller agricultural fractions with the same leaf cover values. This suggests that these values are basin-scale and are not specific to each *vegetation type. Since most of the basins are forest-dominated, when we look at the peatlands or agricultural plots, in most cases when the fractions of these vegetation types are small, we are not looking at leaf cover or tree length values that have anything to do with the peatland vegetation or crops other than they happen to be in the same basin. This should be made more clear.*

Values in Figure 3 are basin scale and thus not specific for the vegetation types. Figure 3 illustrates the general patterns of S_r value in boreal catchments and variation with main landscape types. It cannot be used to detect vegetation type changes. We have changed the text presenting the results in this figure (Section 3.3 in the revised manuscript). The figure is now introduced with the following sentence: 'For both comparisons the data is plotted indicating the occurence of different vegetation types (forest, pristine peatlands and agriculture) in the catchments and the boreal regions in which the catchments are located'

P6 line 19: The statement "...and this correlation decreases for higher percentages of peatland..." is a bit misleading. There hasn't really been an analysis of correlation for basins with high and low peatland cover. When I look at Figure 3f, it does appear that there may be some correlation between S_r and tree length in pristine peatlands for the basins with small fractions of pristine peatlands (because the correlation is coming from the larger forest fractions) and the pattern looks more scattered (implying a lower correlation) for the larger circles or basins with a larger peatland fraction. It should be made clear that these are just visual interpretations, not a comparison of calculated correlation coefficients.

We agree that this statement is rather strong. We have changed the sentence into: 'When looking at the different vegetation types, it can be seen that catchments with a large forest cover are the ones with the widest range in leaf cover and tree length.' in the revised version of the manuscript. Further, we have added more numbers in the text and specifically mentioned if results were only visually observed from the graphs.

P6 line 20: The variability in leaf cover and tree length is small within the boreal regions but appears greater when the three regions are examined together. It appears that factors affecting tree length and leaf cover act largely but not exclusively along the latitudinal gradient such that the correlation is weak within each region. I think the strong relationship between Day of Year (date of snow-off) and S_r has more to do with the fact that the snow-off date is correlated with both maximum SWE and air temperature than a special relationship with the phase of snowmelt. For example, the timing of maximum SWE is probably determined almost exclusively by temperature, whereas the amount of maximum SWE is a combination of snowfall amount and temperature (and other factors).

We agree with you: latitudinal and climate gradient in data set affects strongly to the results, which we shortly discussed in Section 4. We have discussed this in more detail in Section 4.1 of the revised manuscript. For this point please also refer to our reply to the comment about the principal component analysis of anonymous referee #2.

Regarding the influence of snow-off date on S_r, we agree there is a strong link between max S_{SWE}, mean air temperature and snow-off date. However, from our analysis it turned out that especially the timing of the snow melt is important. Although this is strongly determined by temperature, it is not directly reflected in the mean annual air temperature. Various studies using the climate derived S_r showed that mainly two variables are important for S_r: the absolute difference between water supply (liquid precipitation or snow melt) and water demand (transpiration) and the phase difference between these two (ie. difference in timing of the majority of the supply and demand). In areas with moisture constrained evaporation the absolute difference is likely to be dominant, while in energy constraint (like boreal areas) the phase difference is likely to be dominant. So, the study areas have similar absolute differences between supply and demand on a yearly basis, while the phase difference strongly differs depending on the snow-off date and onset of potential evaporation. We have discussed this aspect in Sections 2.4.1. and 4.1 of the revised manuscript.

P7 line 22: While it is true that the clearing of land for agriculture increases soil exposure (more evaporation) and crops tend to have high transpiration demands (more transpiration), there is also the likelihood that croplands are more prevalent in the south because of the longer growing season and increased likelihood of a successful crop. So did the crops in the south cause larger S_r values because of their higher water demands or were they planted in a warmer area because it is beneficial for the crops and that just happens to coincide with larger S_r values (warmer, more evaporative demand)? I would say it works in both directions.

Thank you for pointing this out; we agree that this works in both directions. To investigate whether one of the two mechanisms is dominant, a more detailed comparison should be made between catchments in the southern region with more and less agricultural cover or between different periods of the same catchment (before and after clearing). We have discussed this in Section 4.3 of the revised manuscript.

P8 lines 1-3: Peatlands generally develop in areas where the soil does not dry out very often, either because of cold temperatures and low evaporative demand, or a combination of positive P-E and poor drainage. Since the soil does not tend to dry out, the S_r value calculated will be small because large deficits of P-T are rare.

We agree with you that S_r values will be small due to small deficits of $P - T$. We have discussed some other reasons for low S_r values in peatland areas in Section 4.3 as well.

P8 line 11-12: Maximum SWE and mean annual temperature and the snow-off date are likely highly correlated within a small region. A regression model that attempted to include all three would almost certainly show that all three are not necessary. I would be inclined to predict that mean annual temperature and maximum SWE are the most important, but maximum SWE is partially dependent on mean annual temperature based on the length of the snow period and when melt starts. Perhaps mean annual temperature and winter precipitation would do better.

In Finland and in our data set there is latitudinal and longitudinal variation in maximum S_{SWE}, mean annual temperature and snow-off date since different areas are affected by either Atlantic (Western areas), Continental (Eastern areas) or Arctic (Nordic areas) weather patterns. Thus, all of these parameters are relevant to include into the analysis, although correlation between them exists (see also our reply to the comment of anonymous referee #2 about a principal component analysis of the tested variables). And as discussed before, the timing of the water supply is very important for S_r, thus so is the snow-off date.

P9 line 6: I have read that jack pine have a tap root to access deeper water. If this is true of the pines in the Finland catchments, it may be that deeper water is accessed without a large increase in root density and this may lessen correlations between S_r and root biomass. The authors would want to find an appropriate citation before using this point as an explanation.

Scots pines have shallow rooting depth and typically have no access to deeper water. Also in our data set many mid- and south boreal catchments contained drained peatlands which might influence this negative correlation.

P9 lines 1-3: Yes, peatlands develop in places where the decomposition rates are slower than the annual increment, due to a combination of cold temperatures and/or poor drainage and anoxic conditions. Peatlands are created by the same conditions that cause the estimated S_r to be low, but I doubt that peatlands cause the small S_r values.

The climate method uses the assumption that equilibrium exists in the catchments between the existing vegetation and the develop root zone storage capacity. As the root zone storage capacity is a catchment representative value, it is 'caused' or created by the combination of all the vegetation (and thus land cover) in a catchment. So, we agree that the peatlands alone do not cause a low S_r value, but they probably contribute to it. We have clarified this in the revised version of the manuscript by extending the description of the method to derive S_r and by adding a part in the discussion about the effect of the heterogeneity of the catchments on the derived S_r values. Further we have focused more on relations between S_r and other variables and less on a causal relation between the two, as discussed in the replies to the review of anonymous referee #2 as well.

Minor comments and corrections:

S_r,20 is never defined in the text. It is stated in Section 2.3 that a drought return period of 20 years is used, but the symbol S_r,20 is not introduced here; it simply appears in figures but not in the text.

We have changed '$S_{r,20}$' to 'S_r' in the figures.

P4 line 21 and elsewhere: Why is S_{SWE} used for Snow Water Equivalent instead of SWE?

Although SWE is more common in literature, we used S_{SWE} (Storage as snow water equivalent) to prevent abbreviations with multiple capital characters, as is requested in the author guidelines of the journal.

P5 line 14: "Tree length" is never defined. It is certainly not tree height, but I don't see the term in the literature.

The variable presented in figure 3 is actually tree height, but in dm and not in m. We have changed the term to tree height and the data in Figure 3 (Figure 7 in the revised manuscript) is now presented in meters.

P7 line 24-25: In Fig. 7c I might view the southern boreal region as showing a negative correlation between Drained peatland % and S_r with two outliers.

Thank you for pointing this out, we have changed the sentence as follows: 'The drained peatlands (Figure 8c) also show a negative correlation with S_r when considering all catchments and for the mid-boreal region: for the north and south boreal regions no significant correlations were found'

P9 line 24: I would change ".... for example indicates that...." to "...for example may indicate that...."

We have changed the text accordingly.

Figure 1: Add a North Arrow. Perhaps outline Finland so as to make the study area boundaries more clear.

We have added a north arrow to the map and the country boundaries are presented.

Figure 3: The letters need to be on the plots (e.g. a, b, c.... h).

The letters are added to the subplots (Figure 7 in the revised manuscript)

Figure 6: Change Julian date to Day of Year. Julian date or Julian day is not the same as Day of Year.

The label on the axes is changed to day of the year

Figure 8: What do the size of the boxes represent? There is no scale provided to interpret this.

The sizes of the boxes indicate the p values of the correlations; we have added this to the caption. Note though that we have moved this figure to the supplement, as it has a lot of overlapping info with the correlation coefficients now presented with the scatterplots and the principal component analysis (Figure 3 in the revised manuscript).

2 Reply to review of Maik Renner

Dear Maik Renner,

Thank you for the review of our manuscript and the interest in our study. Your comments made us realise that some elements are not yet explained well and that our argumentation misses some intermediate steps. Therefore they were very valuable for improving our manuscript. Below we have replied in more detail to all your comments.

The results show that S increases towards the south, increases with biomass, but decreases with area of peatlands due to high water tables. Since root biomass is used as a metric for verification, more details are required on how this was derived.

The root biomass data is based on multi-source national forest inventory data provided by Finnish Natural Resources Institute (LUKE). The data is based on field data, satellite images, digital map data and other georeferenced data sets. More information can be found from Mäkisara et al. 2016. `http://jukuri.luke.fi/handle/10024/532147`. We have added this information in Section 2.2.

The statistical analysis is presented in a way to suggest that root zone storage is independent of the climate variables (P, E_p, T, SWE), while indeed it is derived from these data. Actually the analysis of climate controls is performed like an uncontrolled sensitivity analysis of a bucket model with different inputs. The outcomes of this sensitivity analysis (Fig 6, Sect. 3.2, 4.2) are difficult to interpret since the influence of the other input parameters changes from one catchment to the next. I also wonder why there is no precipitation frequency / drought index be used to correlate with S?

We agree with you that the root zone storage capacities are dependent on climate variables. Actually, for the calculation of S_r four climate parameters are used, namely: daily precipitation, daily snow water equivalent, long term averaged discharge and long term monthly averaged potential evaporation. Although climate parameters were used in Figure 6, these are not variables that are directly used in the calculations (mean annual temperature, maximum snow water equivalent, snow off date and the ratio of precipitation and potential evaporation).

As the estimation of S_r is not one calculation, but derived from the simulated soil moisture deficit (we have made this clearer in the description of the method) the influence of different climate variables is not always straight forward. Therefore, we used these plots to see if there is any correspondence between S_r and climate variables that were not directly used in the estimation of S_r. We realise however, that we made this aim not fully clear in the discussion of the results and we have changed the text accordingly in the revised version of the manuscript. In our reply to the comment of anonymous referee #2 about a principal component analysis more details about correlations between variables are described.

With regard to the precipitation frequency/drought index: we included P/E_p in the analysis, which is a definition of the aridity index. Further, we compared S_r with runoff coefficients during the analysis, which showed a strong relation. This is logical, as it is one of the main inputs in the estimation of S_r and probably even has a stronger effect on the calculation than S_{SWE}; therefore we considered the other plots more interesting to incorporate in the manuscript.

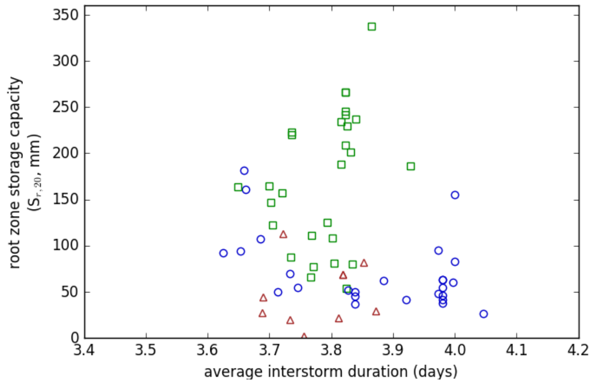

Figure 1: Average interstorm duration in relation to derived root zone storage capacities, different symbols indicate different boreal regions (green squares = south boreal; blue circles = mid boreal; red triangles = north boreal)

With respect to precipitation frequency a comparison with inter-storm duration (I_{isd}) could be made; we did not do this during the first analysis. The relation between S_r and I_{isd}, based on total precipitation and an interception capacity of 1.5 mm, can be seen in Figure 1 below. It can be seen that the variability in I_{isd} between the catchments is very limited. Therefore, we do not think that adding this plot in the revised manuscript is valuable for the analysis.

An interesting point is the influence of drainage of peatlands on S. Although the authors claim to identify an effect, I could not identify the mentioned influence of drainage in Fig 7. Unfortunately, the analysis lacks a reference to compare drainage with pristine peatlands. Here a stratification of the data could be useful means to assess this point.

From Figure 7 (Figure 8 in the revised manuscript) it can be seen that more catchments exist with larger S_r values and larger percentages covered with drained peatland than with larger S_r values and larger percentages covered with pristine peatlands. The corresponding correlation coefficients show a negative correlation between S_r and both pristine and drained peatlands; however this correlation is stronger for the pristine peatlands. Two reasons for this difference can be given. First, the drainage of peatlands for forestry probably creates larger transpiration demands and thus larger root zone storage capacities. Or, second, as most of these drained catchments are located in the south boreal region, it can also be that S_r values were already higher in these catchments before the peatlands were being drained. Unfortunately the available data series are not long enough to compare S_r values before and after drainage of some of the drained catchments. We have discussed this in Section 4.3 in the revised manuscript.

I do not understand how the method can be applied in climate or land-use change analysis. To my understanding an estimate of transpiration is required to estimate S and both are unknown for a given change scenario. Please explain.

For climate and land-use change analysis often data are available for a long period containing a change, this change is probably reflected in the corresponding S_r values as well. In case change scenarios are used, these scenarios can include a change in precipitation and/or discharge and (additionally) a (relative) change in transpiration. With respect to the land-use change analysis, this can include a hypothesised change in transpiration as well. In addition to this, it is likely that different vegetation types adjust to different return periods (Wang-Erlandsson et al., 2016), so a change in land-use can in that way have an effect on the estimated S_r-values.

In our opinion it may be worthwhile to include the estimation of (changed) S_r values in these types of analyses, as they could give more information about how the hydrology of a catchment changes under the studied climate or land-use scenarios.

We have elaborated this aspect further in Section 2.3 of the revised manuscript.

Detailed comments:

P1L17: Check the causal order of the mentioned processes "Retreating..."

We have modified the sentence as follows: 'Increasing temperatures and precipitation, shifts in precipitation from snow to rainfall and retreating seasonal snow cover are a few examples of alterations of the boreal hydrological cycle (Bring et al., 2016).'.

P2L2: add references

We have added supporting references, namely:

- Laudon et al. 2011. Consequences of More Intensive Forestry for the Sustainable Management of Forest Soils and Waters. Forests 2, 243-260.
- Nieminen et al. 2017. Impacts of forest harvesting on nutrient, sediment and dissolved organic carbon exports from drained peatlands: A literature review, synthesis and suggestions for the future. Forest ecology and management 392, 13-20.

P2L7: "but so far none have studied changes in transpiration (patterns) at the catchment scale in boreal regions." Please check (Jaramillo et al., 2018; van der Velde et al., 2013).

We have changed the sentence as follows: 'Especially under these changing conditions, a proper hydrological understanding of boreal catchments is needed (Waddington et al, 2014; Laudon et al., 2017) to understand the sensitivity and resilience of catchments (Tetzlaff et al., 2013), but also to assess the effect of possible measures. Many studies have been conducted to explore hydrological changes resulting from land use activities (Ide et al., 2013; Mannerkoski et al., 2005, Nieminen et al., 2017), and some already studied changes in transpiration (patterns) at the catchment scale in boreal regions (e.g.van der Velde et al., 2013; Jaramillo et al., 2018)'.

P2L17: "Thus, climate (or the balance between precipitation and transpiration) has a large influence on the developed S_r." Doesn't transpiration depend on the root zone storage (and not the other way around)?

Yes, we agree with you that transpiration is sustained by the root zone storage capacity and in that sense influenced by it. This is reflected in the used method by assuming that the vegetation has developed a root zone storage capacity to sustain the transpiration demand. However, to calculate this required root zone storage capacity, the long term water balance is used to estimate the transpiration demand of the vegetation. This entire approach assumes equilibrium in the catchment and therefore can be seen as working in two directions: if either the root zone storage capacity or the transpiration demand changes, the other will (probably) change as well. We have made this clearer in the extended description of the method (see also our reply to the comments of anonymous referee #1).

P4L3ff: To my knowledge there is a significant undercatch of precipitation, especially in winter. It is not clear if the undercatch was corrected for, but if not, then I disagree with the choice of the authors to correct SWE with P.

We used a spatially interpolated dataset with a resolution of 10 x 10 km2 for the meteorological parameters (precipitation, air temperature) constructed by Finnish meteorological institute (FMI). In this data set the measurement error caused by gauges has been checked and corrected in operative quality control. For snow data (S_{SWE}), we used snow line data provided by Finnish Environment Institute and measured by standard methods. Since S_{SWE} was closest available and not always situated within the study catchment, we corrected S_{SWE} with local precipitation. We have added the following sentence to Section 2.2 to clarify this: 'These data have been checked for measurement errors caused by gauges and were corrected in operative quality control.'

Sect 2.3 climate derived root zone storage capacity. Since the results show how climate variables correlate with S, I recommend to repeat the key equations to show how climate input is used in the method. Then also the choice of a return period of 20yr may become more clear.

We have included more details about the used method in the revised manuscript (see also our reply to the first reviewer). The choice of a 20 year return period follows from the analysis of Gao et al. (2014), who found that on average it is most likely that vegetation adapts it root system to a drought with a return period of 20 years.

P5L12: wording "transpiration demands" is unclear to me

Transpiration demand is used for the long term deficit between precipitation and discharge. The vegetation in the catchment should have transpired this amount of water to close the long term water balance with the given precipitation and discharge. We have made this clearer in the extended description of the method to estimate S_r.

Results / Discussion: report correlation and significance in text. For example in Sect. 3.1

The significant correlation coefficients are added as titles to the subplots. In the text it is described whether correlations were significant or not and if so, whether they were positive or negative.

P8L21: check argument: "The presented results show that climate derived root zone capacities are related to vegetation characteristics, climate variables and vegetation cover, which strongly indicates that the S_r-method can be used for boreal regions containing seasonal snow cover." Since S is computed from climate data, the relationship is not a verification of the method!

We agree with you that this statement is not well formulated; the relationship between climate data and variation of S_r values is indeed not a verification of the method. However, as discussed earlier, we think it valuable to incorporate the comparison with some climate variables. In the revised manuscript we have changed the argument into: 'The presented results show that among the compared characteristics the climate derived root zone storage capacities are strongest related to climate variables, followed by vegetation characteristics and vegetation types.'

P9L2: unclear from results "This seems to indicate that in case of low transpiration demands the plant's resources between below and above soil elements are more equally divided than for areas with higher transpiration demands."

In Figure 3a a larger range of leaf cover/tree height (above ground biomass) can be visually observed for smaller S_r-values (below ground biomass) ($S_r < 115$ mm). For larger S_r-values, the range in leaf cover/tree height is smaller. This can indicate that the vegetation uses more resources for below ground biomass in cases of larger S_r values. As the derived S_r values are strongly determined by the transpiration demands, the catchments with large S_r values also have high transpiration demand.

As this finding can only be visually observed and was not supported with numbers in this study we have removed the statement from the discussion.

P9L6f: unclear argument "However, for pine in mid- and south-boreal regions a negative correlation was observed, which means that the vegetation is able to create a larger storage capacity with fewer or thinner roots." Please calculate the significance of the correlation and possibly use a bootstrap to check the influence of outliers. Please check/report how root biomass was calculated. Also check for other influencing variables.

Although some negative correlation between pine RBM and S_r can be visually observed for the mid- and south boreal regions, this correlation is not significant. However, when the three boreal regions are considered together, the correlation is significant and negative. Which is an interesting aspect to discuss. We have changed the sentence as follows: 'However, for pine a negative correlation was observed, which means that the vegetation is able to create a larger storage capacity with fewer or thinner roots.'

P9L12: please provide references for shifting management activities

We have added the following reference in the revised manuscript: Hasper et al. 2016. Water use by Swedish boreal forests in a changing climate, Functional Ecology 30, 690-699.

There is now specific reference for shifting management activities. However, when forest resources are growing faster due to changing climate also forest management activities shifts.

P10L5: please provide references

We have added the following reference to support this statement: Menberu M, Tahvanainen T, Marttila H, Irannezhad M, Ronkanen A-K, Pentttinen J, Kløve B. 2016. Water table-dependent hydrological changes following peatland forestry drainage and restoration: Analysis of restoration success. Water Resources Research, 52(5), 3742-3760.

P10L8: "Peatland drainage for forestry changed this pattern: higher S_r values were observed in areas with larger cover of drained peatlands (Figure 7)." I could not see this effect!?

As discussed earlier, there can be two reasons for the difference between drained and pristine peatlands. We have changed this sentence as follows:'Catchments where peatland is drained for forestry show another pattern: the correlation with S_r is lower, but especially the threshold seems to be weaker. The variation between the two groups for the threshold analysis is larger for pristine peatlands than for drained ones (Mann-Whitney U-test, p=0.0008 and p=0.0135 respectively).'

Sect. 4.4: Explain how the method is applied to a change scenario when data on transpiration is required a priori?

Data on transpiration is indeed used in the analysis; however, this data is derived from the long term water balance (precipitation, discharge and S_{SWE}). When the change scenarios are constructed, the transpiration can again be estimated from the water balance or be assumed to change in a certain way. By subsequently calculating S_r values, the effect on the hydrology of the changing conditions can be further explored. We agree that this is not yet a complete analysis, but we definitely see a potential for further research.

We have added a paragraph to Section 2.3 explaining this aspect in more detail.

Figure 1: Missing y-axis labels; Add points to the boxplots. Panels of Fig1 are insightful, but hardly touched in text. Add relevant topographic info to the map.

We have added a north arrow to the map and outliers are present for the boxplots. However, adding topographical info made the figure less clear to read, so we prefer not to include it. Similarly, adding labels to the y-axes would mean the figure has to reduce in size, which decreases readability, so we prefer to keep the description in the caption only. A brief description of the panels is included in Section 2.1.

Fig 2: use white text in dark boxes

We have changed this in the revised version of the manuscript

Fig 6c, Fig 8: Julian date for snow off in Fig.6 and Julian Date for max SWE in Fig 8. Please be consistent.

We have changed all these to 'day of the year', as suggested by anonymous referee # 1.

Fig 7c,d: Peatland area per catchment? Why does the number of points change?

Figure 7c illustrates the percentage of the catchment covered with drained peatlands and Figure 7d shows the same for pristine peatlands. The number of points change since some catchments do not have pristine peatland areas and vice versa. We added a note to the caption of the figure to make this clear.

Fig 8: show correlation as text in one of the diagonals

We preferred to mention the correlation values with the scatter plots to prevent this figure from overflowing with information. Further, we have moved this figure to the supplement as it has a lot of overlapping info with the principal component analysis presented in Figure 3 in the revised manuscript.

Fig. 9: What is the ordering in y-axis? Coloring: black lines are hardly seen on dark blue background. Why is PET always the same?

The ordering on the y-axis is by increasing estimated S_r value and the figure does not show the amount of potential evaporation, but the period in which E_p is occurring/measured. We have clarified this in the figure caption and we have changed the colour of the lines to white.

References:

Jaramillo, F., Cory, N., Arheimer, B., Laudon, H., van der Velde, Y., Hasper, T.B., Teutschbein, C., Uddling, J., 2018. Dominant effect of increasing forest biomass on evapotranspiration: interpretations of movement in Budyko space. Hydrol Earth SystSci 22, 567–580. https://doi.org/10.5194/hess-22-567-2018

van der Velde, Y., Vercauteren, N., Jaramillo, F., Dekker, S.C., Destouni, G., Lyon, S.W., 2013. Exploring hydroclimatic change disparity via the Budyko framework. Hydrol. Process. https://doi.org/10.1002/hyp.9949

Gao, H., M. Hrachowitz, S. J. Schymanski, F. Fenicia, N. Sriwongsitanon, and H. H. G. Savenije (2014), Climate controls how ecosystems size the root zone storage capacity at catchment scale: Root zone storage capacity in catchments, Geophys. Res. Lett., 41, 7916–7923, doi:10.1002/2014GL061668.

Wang-Erlandsson, L., Bastiaanssen, W. G. M., Gao, H., Jägermeyr, J., Senay, G. B., van Dijk, A. I. J. M., Guerschman, J. P., Keys, P. W., Gordon, L. J., and Savenije, H. H. G.: Global root zone storage capacity from satellite-based evaporation, Hydrol. Earth Syst. Sci., 20, 1459-1481, https://doi.org/10.5194/hess-20-1459-2016, 2016

3 Reply to review of anonymous referee #2

Dear referee,

Thank you for reviewing our manuscript, your positive evaluation of the relevance and presentation of the results and the relevant questions you posed. The more detailed comments you have given made us realise that the aim we have in mind with the paper needs to be discussed better throughout the manuscript and that especially some elements of the used method need more attention in a revised version of the manuscript. Below we have replied in more detail to all your comments.

The study is on an important and interesting topic, as little is known about potential changes in catchment storage properties under climatic and land use change. Potential to improve our hydrological predictions under climatic and land use change is limited by lack of information and understanding, so studies in this area can be expected to be in demand by HESS audience. Another strength of this study is the dataset, which is very well described and referenced. The article is nicely structured, and the results are presented well (though I would prefer to see more numerical information to back up some claims).

My main concern about this study is about how much of the results originate from self-prediction given the high correlation between source and comparison data. S_r is derived based on climatic records, and then S_r is compared with climatic and vegetation properties which are known to be related with the source data S_r was derived from. The authors do acknowledge the relationship (e.g. p 5 l 24-25, p 6, l 2-3, p 9 l 16-17), but they still interpret results in a way where (higher) correlation implies control over S_r, which I think is questionable. The results might reflect just the closer correlation with the source climatic data for S_r, and not causal relationship with the soil storage properties. For example, it remains unclear to what extent the relationship between S_r and vegetation properties/land use are just a consequence of both being related to the climate. In this case the change in vegetation would not influence S_r as it can be expected from the results, if the vegetation is the only thing changing. This would particularly apply to cases where the results are somewhat counterintuitive (e.g. p6 l26-27 and Fig 4a, or p7 l23-25 and Fig 7b where decrease in forested area is associated with increase in S_r).

We agree with you that the variables used in the analysis are subject to internal correlations. As discussed in the reply to the review of Maik Renner, the exact variables used for the calculation of S_r are not the same as those used in the remainder of the analysis.

With respect to the influence of vegetation on S_r, this can be reflected by using a different drought return period (Wang-Erlandsson et al., 2016): different vegetation types probably have different survival strategies and therefore are likely to adjust to a different drought return period. However, for this study we only used a 20-year return period as the majority of the land cover consists of forest. So, if only the vegetation would change, a different return period can be used, which would influence the derived S_r. However, more testing would be required to see if changes can be assessed by using different return periods and how (quickly) new equilibriums would be established.

In addition to this, the catchments with a lower forest cover are generally the ones with a higher agricultural cover and a milder climate. These catchments are likely to have higher transpiration demands, leading to higher S_r values, than colder forested catchments.

Having said this, the term 'control' might be misleading, especially as our main aim with the study is to compare the calculated S_r-values with a set of catchment characteristics to explore possible relations and better understand the derived S_r-values and how the different climate variables influence the calculation. Your comments and those of the other reviewers made us realise that we did not discuss this aim consistently throughout the paper. Among others we have changed the title and the last paragraph of the introduction to make this clearer.

In this light, I think it would be more informative and would give more confidence in the results to apply some method which can account for a number of potential "controls" and assess their importance against each other, for example PCA or multimodel inference (e.g. Saft et al, 2016).

Thank you for this suggestion; we think as well that the paper would benefit from such further elaboration. Both multimodel inference (as used by Saft et al., 2016) and PCA are useful methods for this. In line with our methodology, we have worked this out further using the PCA. However, we do believe that the multimodel inference is very interesting when evaluating the possibilities to use climate derived S_r-values to assess the effects of change.

The results of the PCA are presented in Figure 3 of the revised manuscript, containing the different variables we compared with S_r in the manuscript. We have added section 2.4.4 and 3.1 describing the set-up, results and consequences of the PCA.

I am also a bit puzzled about the gap between snowmelt and onset of PET, as both are governed by exactly the same increasing energy flux (temperature/sunshine). I would assume that this gap should be very closely related to the maximum SWE (∼ more snow takes longer to melt). Anyway, it would be interesting to calculate this gap (using some threshold for snowmelt) and include it directly as yet another factor along with the other characteristics used. I wonder why it was treated separately.

E_p and snowmelt are indeed governed by the same increasing energy flux. However, the gap exists because of the measurement methods: E_p is based on pan-evaporation and can thus only be measured if temperatures are above zero. Therefore, E_p can already be slightly above zero before the pan measurements start.

With respect to treating both variables separately, this was done because in the S_r calculations one determines the water demand, the other the water supply. The balance between these variables mainly determines the calculated S_r. So, although they are governed by the same energy flux, they have a different effect on the calculation. For the aim of the paper, we think this influence is interesting to investigate and explore.

Having more insight into the combined effect of the onset of E_p and snowmelt can help to assess what can happen in case of a changing climate. For the gap between these two to change, the most important variable will indeed probably be the maximum S_{SWE}.

The gap between snow-off and the start of E_p (measurements) is incorporated in the PCA presented in Figure 3 of the revised manuscript. It can be seen this property is strongly positively correlated with the day and amount of maximum S_{SWE}. This is further discussed in Section 3.6.

On a different note, it would be good to see more numerical information (i.e. Spearman's rho, and associate p value) associated with positive/negative correlations described in the text. It is difficult to extract relevant *information from figure 8, especially since it is not numeric. Fig 8 also does not include correlation results for sub-regions which are mentioned in the text, and I could not find these results anywhere else.*

As discussed in the replies to the two other referees as well, we have included more numerical information about the correlations in the titles of the scatter plots. We preferred not to include them in Figure 8, to prevent it from overflowing with information.

Importance and implications:

What is the use of the derived S_r and discovered relationships with other characteristics? And in the context of climate change, would not it be easier to derive new S_r following the original method accounting for climate change in the source data instead of looking at the correlations?

As discussed before, our main of the paper is to explore the relations between the climate derived S_r and a set of catchment variables. We should keep in mind that S_r is a conceptual parameter, originally used as input for hydrological models. However, it is very interesting to know if and how the calculated S_r is related to other variables and if it can be wider applicable. Knowing more about the relations between S_r and catchment variables can help us to better understand the influences on the S_r calculations and therefore how we can, possibly, use it to assess the behaviour of catchment under changing conditions.

Thus, by looking at the relation between S_r and catchment variables, more confidence can be obtained in the (physical) meaning of S_r. The found relations are not directly meant to assist to assess change. To assess change indeed recalculating S_r based on new climate predictions would be the most logical approach.

We have made the division between better understanding S_r and using S_r for assessing effects of change clearer in the revised version of the manuscript, among others in the last paragraph of the introduction and the first paragraph of the discussion.

Specific comments:

p2 l 8-10 – and vegetation WUE / transpiring properties

The partitioning is indeed influenced by both water availability (in the root zone storage) and water use efficiency of the vegetation. However, with the vegetation surviving in a certain catchment, it must have had sufficient water supplies and at the same time it is not logical that it would have invested more carbon in creating storage capacity for water than it needed to survive. So, by deriving the transpiration demand from the water balance, the long term water use is estimated, making the water efficiency of the vegetation less relevant for the calculation. The balance between transpiration and runoff is of course influenced by the water use efficiency of plants.

We have acknowledged this aspect in the introduction and discussion of the revised manuscript, together with a more extensive description of the calculation method for S_r and the assumptions involved.

p2 l 17 If you talk about climate, do you mean balance between evaporation and precipitation? Transpiration is not purely climatic.

Actually we are talking about the difference between the long term average supply and demand of water to and from the active storage of the soil. These are mainly climatically driven (ie. via precipitation and potential evaporation). As processes like interception and snow melt are important as well, we decided to use the terms infiltration and transpiration (demand). Where infiltration is the total precipitation (rainfall and snow) minus interception evaporation and the transpiration (demand) is derived from the water balance ($\overline{T} = \overline{P} - \overline{E_i} - \overline{Q}$). We have clarified these terms in the extended description of the climate derived root zone storage capacity (Section 2.3) in the revised manuscript.

Section 2.1 – Just checking, is there any permafrost in northern catchments, and if so, can there be any impact (e.g. thawing permafrost → higher storage)?

Thanks for asking this clarification, but in these sites there is no permafrost. If there would be, changes in permafrost should indeed be included in the calculation of S_r, just like snow storage is.

p4 l 1 – how it was calculated?

Data of all three biomass variables (root biomass, tree height and leaf cover) are based on field data from national forest inventories, satellite images, digital map data and other georeferenced data sets. More information can be found in Mäkisara et al. 2016 (http://jukuri.luke.fi/handle/10024/532147). We have added this information to Section 2.2 of the revised manuscript.

Formula 2 – why in the middle line Pi = 1? What does 1 mean?

Thank you very much pointing this out: it should be Pi = 0. We have corrected this in the revised manuscript.

Section 4 – Can the changes in S_r be related to changes in WUE (e.g. Troch et al 2009)?

In this study we did not yet incorporate any changes in the catchments, so we suppose you mean the variations in S_r between the different catchments. The calculation of S_r is based on a daily simulation of soil moisture deficit and an extreme value distribution. The input into the simulation is effective precipitation and a transpiration demand which is estimated from the water balance. As the transpiration demand is the water that should have transpired to close the water balance, different water use efficiency probably will not really influence the derived S_r values. However, water use efficiency could influence the amount of biomass production (root biomass, leaf cover, tree height). Thank you for this suggestion; we have briefly discussed this in Section 4.4 of the revised manuscript.

p9 l 8-9 – Is it just direct numerical effect of having higher runoff from drained peatlands?

One of the assumptions underlying the climate derived root zone storage capacity is that a certain type of vegetation needs a specific amount of water to survive; independent of the climate they are located. If they are located in a drier or more seasonal climate, they will need a larger storage capacity to supply the required amount of water. This does neglect the fact that vegetation may have higher water use efficiency (Troch et al., 2009). As discussed earlier, this does not influence the calculation, as the used transpiration demand is derived from the water balance. By deriving the transpiration demand from the water balance, the runoff is already accounted for. However, differences in water use efficiency could help to explain the pattern found for the pine root biomass. We have discussed this in Section 4.2 of the revised manuscript.

p9 l 11 – suggest changing 'many affects to' to 'many effects on'

We have changed this in the revised version of the manuscript.

p9 l 15-16 – I still struggle with the idea of how S_r calculated with pan evaporation would change if only vegetation properties change (as 'or' implies independency) – see my general comment in the beginning. In any case, the argument is based on the assumption of trading space for time (Wagener et al, 2007, Singh et al, 2011), and this and associated assumptions can be acknowledged better (possibly also in introduction).

S_r is based on a daily simulation of soil moisture deficit and a drought return period the vegetation adapts to. Different vegetation types are likely to adjust to different return periods, as they have different survival strategies. In addition to that, E_p data is only used to add seasonality to the long term averaged transpiration demand, which is derived from the water balance (precipitation and runoff). So, a change in vegetation probably works in two ways: a different drought return period can be applicable and of course the balance between precipitation and runoff can change. In either way, a new equilibrium needs to be established.

In addition, the principle of trading space for time can be used as well, especially as we see shifting conditions in the study areas. However, to go into that direction in this paper would make it lose focus, but we will make the change in vegetation properties we had in mind clearer. Although we have discussed the change part in the paper, and we definitely think a thorough understanding of a climate derived S_r can help to assess hydrological change, our results do not discuss any of these elements.

Having said this, in the revised manuscript we have made clear that the aim of the paper is to better understand the climate derived S_r and its relation with certain catchment properties and we have mentioned the change as an outlook and an, in our opinion, important possible applicability.

References:

Saft, M., Peel, M. C., Western, A. W., & Zhang, L. (2016). Predicting shifts in rainfall-runoff partitioning during multiyear drought: Roles of dry period and catchment characteristics. Water Resources Research, 52(12), 9290-9305.

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4 Marked-up manuscript

The following pages contain both the manuscript and the supplement with all changes marked.

~~Controls on~~Understanding variability in root zone storage capacity in boreal regions

Tanja de Boer-Euser[1,2], Leo-Juhani Meriö[3], and Hannu Marttila[3]

[1]Water Resources Section, Faculty of Civil Engineering and Geosciences, Delft University of Technology, P.O. Box 5048, NL-2600 GA Delft, The Netherlands

[2]Department of Civil Engineering, Eduardo Mondlane University, C.P. 257 Maputo, Mozambique

[3]Water Resources and Environmental Engineering Research Unit, PO Box 4300, 90014 University of Oulu, Finland

Correspondence: Tanja de Boer-Euser (tanjaeuser@gmail.com)

Abstract. The root zone storage capacity (S_r) of ~~the~~ vegetation is an important parameter ~~for~~in the hydrological behaviour of a catchment. ~~Often this~~Traditionally, S_r is derived from soil and vegetation data~~, but a new method uses~~. However, more recently a new method has been developed that uses climate data to estimate S_r ~~under~~based on the assumption that vegetation adapts its root zone storage capacity to overcome dry periods. This method also enables ~~to account for the~~ temporal variability of derived S_r-values ~~in case of~~resulting from chang~~ing~~es in climate or land cover. Th~~is~~e current study applies th~~e~~is new method in 64 catchments in Finland to investigate the ~~controls on~~reasons for variability in S_r in boreal regions. ~~The r~~Relations were assessed between climate derived S_r-values and climate variables (precipitation-potential evaporation rate, mean annual temperature, max snow water equivalent, snow-off date), detailed vegetation characteristics (leaf cover, tree length, root biomass), ~~climate variables (precipitation-potential evaporation rate, mean annual temperature, max snow water equivalent, snow-off date)~~ and ~~land cover~~vegetation types. The results show that especially the phase difference between snow-off date and onset of potential evaporation has a large influence on the derived S_r-values~~; results even indicate~~. Further to this it is found that (non-)coincidence of snow melt and potential evaporation ~~can~~could cause a division between catchments with a high and a low S_r-value. ~~From this study, it can be~~It is concluded that the climate derived root zone storage capacity leads to plausible ~~results~~S_r-values in boreal areas and that besides from climate variables, catchment vegetation characteristics can also be directly linked to the derived S_r-values. As the climate derived S_r enables incorporating climatic and vegetation conditions in a hydrological parameter, it could be beneficial to assess the effects of changing climate and environmental conditions in boreal regions.

1 Introduction

The hydrological cycle of boreal regions is changing vastly as a result of climate change (Prowse et al., 2015) and increasing anthropogenic land use activities (Instanes et al., 2016). ~~Retreating seasonal snow cover, increasing temperatures and precipitation, and shifts in precipitation from snow to rainfall~~Increasing temperatures and precipitation, shifts in precipitation from snow to rainfall and retreating seasonal snow cover are a few examples of alterations of the boreal hydrological cycle (Bring et al., 2016). Consequences of ~~warming~~increasing temperatures are likely to be most severe in boreal systems, as slight changes in temperature can alter magnitude and timing of snow accumulation and melt (Carey et al., 2010). Predicted changes create climatic conditions at certain higher latitudes, which are similar to those at lower latitudes a few decades earlier (Intergovernmental Panel on Climate Change, 2014). These changes in climate will have an effect on different vegetation types while at the same time, land use activities have been intensified especially in European countries and are predicted to increase in near future due to a "green shift" to a bio-based economy (Golembiewski et al., 2015). The occurring land use changes consist of modifications in actual land use (increase in forest cover), but also of more intensive use of forests, including clear cutting, forest trimming, residual harvest and of increasing utilisation of peatland forests as source for biomass (e.g. Laudon et al., 2011; Nieminen et al., 2017).

Especially under these changing conditions, a proper hydrological understanding of boreal catchments is needed (Waddington et al., 2015; Laudon et al., 2017) to understand the sensitivity and resilience of catchments (Tetzlaff et al., 2013), but also to assess the effect of possible measures. Many studies have been conducted to explore hydrological changes resulting from land use activities (Ide et al., 2013; Mannerkoski et al., 2005; Nieminen et al., 2017), ~~but so far none have~~and some already studied changes in transpiration (patterns) at the catchment scale in boreal regions (e.g.van der Velde et al., 2013; Jaramillo et al., 2018). The partitioning between transpiration and runoff is largely determined by the water use efficiency of vegetation (e.g. Troch et al., 2009) and the available root zone storage capacity (S_r) of the vegetation (e.g., Zhang et al., 2001): the water use efficiency determines the amount of water the vegetation needs and the root zone storage capacity ensure sufficient storage to supply this water. ~~t~~Thus, detailed knowledge about ~~this parameter~~these variables can increase the hydrological understanding of catchments under different conditions.

Traditionally, S_r is estimated from soil and vegetation data or calibrated in a hydrological model. Following the analysis that S_r is strongly related to climate variables (e.g., Kleidon and Heimann, 1998; Gentine et al., 2012; Gimbel et al., 2016), Gao et al. (2014) developed a new method to estimate S_r from climate data. Subsequently, several studies have been carried out in which this method was used. For example, Wang-Erlandsson et al. (2016) used earth observation data to estimate S_r globally; de Boer-Euser et al. (2016) did a comparison between the influence of soil and climate on S_r; Nijzink et al. (2016) investigated the change in S_r after deforestation and Zhao et al. (2016) introduced a snow component to the method and carried out a sensitivity analysis.

Thus, climate (or the balance between precipitation and transpiration) has a large influence on the developed S_r. However, it is very likely that root development is affected by other factors, including nutrients (e.g., Shahzad and Amtmann, 2017), the survival mechanism of the vegetation (e.g., Christina et al., 2017), or reduced space for root development due to shallow soil layer or high ground water tables (e.g., Soylu et al., 2014). S_r is expected to change if any of these factors changes, which has consequences for the hydrology of the area (e.g., Saft et al., 2015). Assessing the (future) hydrology of boreal catchments could benefit from a better understanding of the relation between S_r and ~~(changing)~~ climatic and vegetation conditions.

~~At this moment, a climate derived root zone storage capacity has not yet been specifically tested for boreal areas. Applying the method in these areas requires adding a snow component to the method. Earlier studies showed that climate has a strong influence on S_r, but other controls have not yet been studied in combination with a climate derived S_r. Therefore, this paper assesses the relation between the root zone storage capacity and vegetation and climate variables, in order to better understand what mainly controls the root zone storage capacity in boreal regions. The aim of the study is to determine S_r values for different boreal catchments and expectations are to find variation resulting from climate conditions, vegetation type and proportion of peatlands. Furthermore, it is expected that the influence of anthropogenic activities can be seen, especially with respect to intensive use and drainage of peatlands.~~The method to derive S_r from climate data was originally developed to estimate an important parameter in conceptual hydrological models (e.g. Gao et al., 2014). So, influences on the derivation and wider applicability of the climate derived S_r need to be investigated before it can be used to further assess the hydrology of boreal areas and to assist in assessing the hydrological effects of climate and land use change. Therefore, this study aims at better understanding the influences of different climate variables on the climate derived S_r-values and its wider applicability by comparing it with various catchment and vegetation characteristics.

2 Methods

2.1 Characteristics of study catchments

A total of 64 headwater catchments were used for this study, spread over Finland. The catchments are located in different boreal regions (south, mid- and north boreal; Ahti et al., 1968) and thus have different climate conditions and vegetation patterns (Figure 1). All sites belong to National network of small catchments (Seuna and Linjama, 2004) and have been used in various studies (e.g., Kortelainen et al., 2006; Sarkkola et al., 2012, 2013b). The catchments used in this study were selected based on the availability of long-term runoff records, snow line records and meteorological data from the catchments.

The climate of the region is humid, with annual average air temperatures varying from 5 °C in the south to -2 °C in the north and average precipitation of 600-700 mm/y in the south and 450-550 mm/y in the north. Average maximum snow depth by the end of March is 50-400 mm in the south and 600-800 mm in the north.

The principal land cover in the study catchments is forest (with a median of 81% coverage of evergreen, deciduous and mixed forest), followed by shrubs and herbaceous vegetation, inland waters and wetlands. Agricultural activities were present in some of the ~~southern~~ sites in the south and mid-boreal regions. Total root biomass, as well as root biomass for spruce and deciduous trees decreases towards the north, while pine root biomass is more or less constant (Figure 1The surface area of the catchments ranges from 0.07 km^2 to 122 km^2 (median 6.15 km^2).

The soil type in the southern sites is dominated by clay layers whereas basal till and peatland cover is increasing when moving towards east and north. The catchments have relatively flat topography with a mean difference in elevation of approximately 70 m. The selected catchments do not contain any urban settlements.

Tables 1 and 2 in the supplementary material give an overview of available vegetation and climate characteristics of the study catchments.

2.2 Data use and correction

Two sets of data were used in the study: one for the calculation of the climate derived root zone storage capacity and one to investigate the ~~different controls on~~variation of S_r. For the S_r calculations daily precipitation, daily snow water equivalent, monthly potential evaporation and yearly discharge data were used. For investigating ~~different controls~~the variability and relations with catchment characteristics additional data were used about leaf cover, tree length, root biomass, temperature, snow-off date and land cover.

Daily discharge was measured with water stage recorders and weirs were routinely checked for errors by the Finnish Environment Institute. Precipitation (P) and temperature data were taken from the national 10 km x 10 km interpolated grid produced by Finnish Meteorological Institute (FMI) (Paituli database[c11]). These data have been checked for measurement errors caused by gauges and were corrected in operative quality control. The snow line data for snow water equivalent (S_{SWE}), potential evaporation (E_p), using pan measurements, and runoff data used were obtained from Finnish Environmental Institute's open database (Hertta). Note that because E_p is derived from pan measurements, it is not measured when temperatures are below zero. However, it can be assumed that if it would be measured, amounts would be very low. The snow line measurement points used in the study were either located inside or in close proximity of the study catchments.

The snow line measurement points were either located inside or in close proximity of the study catchments; however, for some catchments the increase in S_{SWE} during a season was higher than the total measured precipitation for the same period. As the precipitation data was assumed to be more reliable and less spatially variable, the S_{SWE} data was adjusted on a daily basis to make it consistent with the precipitation data.

Corine Land Cover 2012 data (Paituli database) was used for determining the land cover of the study catchments. The surface lithology and geology data are based on the Surface Geology Map of Finland (Hakku database[c1]). The national forest inventory database (LUKE open data[c2]) was used to calculate root biomass, tree length and leaf cover of the sites.Data for root biomass, tree length and leaf cover are based on multi-source national forest inventory data provided by Natural Resources Institute Finland (LUKE open data[c2]). Data is based on field inventory data, satellite images, digital map data and other georeferenced data sets. Tree data was available for Pine, Spruce and Deciduous forest types. Drained and pristine peatlands masks were obtained from Finnish Environmental Institute (SYKE).

Although the snow line measurement points were either located inside or in close proximity of the study catchments, for some catchments the increase in S_{SWE} during a season was higher than the total measured precipitation for the same period. As the precipitation data was assumed to be more reliable and less spatially variable, the S_{SWE} data was adjusted on a daily basis to make it consistent with the precipitation data.

2.3 Climate derived root zone storage capacity

To test the controls oninvestigate the variability in root zone storage capacity, a climate derived root zone storage capacity (S_r) was used. The derivation of this S_r is based on the principle that vegetation will create a buffer with its root system just sufficient to overcome a drought with a certain return period. Investing less in a root system would lead to the vegetation dying in case of a severer drought and investing more is not efficient in terms of carbon use. This method results in a catchment representative storage capacity, which reflects the root zone storage capacity for all vegetation combined in a catchment.It is further assumed that the amount of required storage depends on the amount of water that should have transpired to close the water balance. In this study the same base calculation was used as in de Boer-Euser et al. (2016), but as snow accumulation cannot be neglected in Finland, an additional snow module was added (Figure 2). For the calculation of S_r the daily balance between infiltration

[c11] https://avaa.tdata.fi/web/paituli/latauspalvelu
[c1] https://hakku.gtk.fi/en/locations/search
[c2] http://kartta.metla.fi/opendata/valinta.html
[c2] http://kartta.metla.fi/opendata/valinta.html

(I) and transpiration demand (T) is used to simulate the amount of storage the vegetation would need to cover the infiltration deficit.

The transpiration demand used in this method is the amount of water that should, in the long term, transpire to close the water balance. For the calculation $\overline{T}$ was thus derived from the long term water balance ($\overline{T} = \overline{P} - \overline{E_i} - \overline{Q}$); following monthly averaged potential evaporation was used to add seasonality to T. In this study the same base calculation was used as in de Boer-Euser et al. (2016), but as snow accumulation cannot be neglected in Finland, an additional snow module was added (Figure 2). Due to the high forest cover, for all analyses a S_r was used corresponding to a drought with a return period of 20 years. In the original S_r calculations (e.g. Gao et al., 2014; de Boer-Euser et al., 2016)it is assumed that a part of the precipitation is intercepted and the remaining infiltrates immediately, unless the soil moisture deficit is zero.Infiltration was assumed to be the result of precipitation minus interception evaporation in the original calculations (e.g. Gao et al., 2014; de Boer-Euser et al., 2016) . However, in case of solid precipitation, the precipitation is stored on the soil surface for days to months and only infiltrates during the snow melt period. As this is a relevant process in most of the study catchments, a snow component (Equations 1-4) was added to the calculation method used by de Boer-Euser et al (2016). The change in S_{SWE} was used to determine the amount of precipitation stored on and infiltrating into the soil daily. Interception was only taken into account in case of liquid precipitation and an interception threshold of 1.5 mm was assumed for all catchments. Sublimation was not taken into account, as potential evaporation is generally (very) low when snow cover is present.

The estimates for infiltration and transpiration demand were used in a daily simulation of the root zone storage. Infiltration forms the inflow of water and transpiration the extraction; any excess water is assumed to runoff directly. This simulation results in annual required maximum storage capacities, which were used in a Gumbel (Gumbel, 1935) distribution to obtain the required storage capacity to overcome a drougth with 20-year return period. A 20-year return period was selected based on the results of Gao et al. (2014) and Wang-Erlandsson et al. (2016) and based on the high percentage of forest cover in the study catchments.

The method described above estimates S_r for a current situation based on historical drought occurences. However, the same principle and calculation method can be used to estimate S_r under changing conditions. These can be derived from observed data (e.g. Nijzink et al., 2016), but also consist of scenarios of changing climate variables or land use characteristics. The latter one could be represented by using a different drought return period (e.g. Wang-Erlandsson et al., 2016).

For estimating S_r in this study, data from 1 January 1990 to 31 December 2012 were used. For precipitation and snow water equivalent daily values were used, while for discharge and potential evaporation data, long term yearly and monthly average were used respectively. For some of the catchments discharge data was limitedly available for the study period; for these catchments older discharge data was taken into account as well to obtain a long term average.

$$P_{rz} = P_i + P_m \tag{1}$$

[1 is replaced by 0 in the second line of the equation below]

$$P_i = \begin{cases} 0, & \text{if } S_{SWE} > 0 \text{ and } \Delta S_{SWE} < 0 \\ 0, & \text{if } S_{SWE} > 0 \text{ and } \Delta S_{SWE} > 0 \\ P_t, & \text{if } S_{SWE} = 0 \end{cases} \tag{2}$$

$$P_m = \begin{cases} P_t - \Delta S_{SWE}, & \text{if } S_{SWE} > 0 \text{ and } \Delta S_{SWE} < 0 \\ 0, & \text{if } S_{SWE} > 0 \text{ and } \Delta S_{SWE} > 0 \\ 0, & \text{if } S_{SWE} = 0 \end{cases} \tag{3}$$

$$\Delta S_{SWE} = S_{SWE,t=i} - S_{SWE,t=i-1} \tag{4}$$

with, P_{rz} = infiltration, P_t total precipitation, P_i effective precipitation, P_m snow melt, S_{SWE} snow water equivalent.

2.4 ~~Assumptions for estimating root zone storage capacity~~Relations between S_r and catchment characteristics

To further explore the physical meaning and applicability of the climate derived root zone storage capacity, S_r-values were compared with climate variables, vegetation characteristics and coverage of vegetation types.

2.4.1 Climate variables

[text originates from section 2.4 in first version of manuscript] ~~First, the relation with climate was investigated; t~~The method used to derive S_r is based on climate data, so it is expected that climate has a strong ~~control~~influence on the derived S_r-values. However, the derived S_r-values are not a linear combination of the used variables (i.e. daily P, daily S_{SWE}, yearly Q, monthly E_p) and thus the influence of different climate variables is not straight forward. Therefore, ~~by comparing the spatial patterns of climate variables and~~ derived S_r-values are compared with four other climate variables (P/E_p-ratio, mean annual temperature, snow-off date and maximum S_{SWE}) ~~and their mutual correlation, it can be analysed.~~ to analyse which ~~climate variables~~ones have the strongest ~~influence on~~relation with the S_r-values. These variables were selected as they are expected to reflect the absolute and phase difference between water supply (precipitation and snow melt) and water demand (transpiration), which is assumed to have the largest influence on the derived S_r-values.

The relations between the estimated S_r-values and ~~catchment characteristics~~climate variables were assessed in two ways; by analysing spatial patterns and scatterplots. ~~First, scatterplots between S_r and the various characteristics were analysed; second, correlation statistics were calculated.~~ To assess the correlation between the different variables, the non-parametric Spearman's correlation coefficient was used. ~~For analysis of the threshold behaviour in S_r (presented in Section 3.3), the catchments were divided into two groups separated by a S_r of 115 mm. For both groups the significant differences between catchment characteristics were investigated.~~

2.4.2 Vegetation characteristics

~~The calculation of the climate derived root zone storage capacity involves sevaral assumptions, as also discussed by de Boer-Euser et al. (2016) and Wang-Erlandsson et al. (2016). The data available for the study catchments can be used to explore the relations between S_r and other vegetation properties and thus the plausibility of two of these assumptions.~~

[The order of root biomass and leaf cover/tree length changed with respect to the first version of the manuscript] The climate derived S_r is originally a parameter for conceptual hydrological models and for that purpose it is expected to reflect a representative storage capacity in a catchment. In that sense it cannot be attributed to a single type of vegetation or be directly measured in the field; despite this, it is expected that it is related to actual vegetation characteristics. When this correlation indeed exists, the climate derived S_r will be more useful to use for other purposes than modelling.

~~Second~~First, ~~the climate derived S_r is a conceptual parameter and is expected to represent a representative storage capacity in a catchment. In that sense it cannot be directly measured in the field; despite this,~~ it is expected that vegetation actually has to increase its root biomass in order to increase the root zone storage capacity. Therefore, the derived S_r is compared with data about root biomass for three different tree types. ~~First~~Second, an essential part of the S_r calculation is the estimation of the transpiration demand. The average transpiration for the calculations is derived from the water balance (difference between precipitation and discharge), and is reflected in the derived S_r-values. As the precipitation is relatively similar for the study catchments (mean of 1.65 mm/d, with a standard deviation of 0.14 mm/d), higher transpiration demands will lead to higher S_r-values. Similarly, higher transpiration demands indicate that the vegetation can use more (solar) energy for their development and thus, establishing more above ground biomass as well. So, it is expected that the derived S_r-values are related to vegetation properties like leaf cover and tree ~~length~~height as well.

2.4.3 Vegetation types

[text originates from section 2.4 in first version of manuscript] Different vegetation types and their corresponding land covers occur in different climates and ecosystems and can have different survival mechanisms. And, a change of vegetation or land cover type is likely to change the transpiration and thus the hydrology of a catchment ~~Second~~Therefore, the relation ~~of~~between S_r ~~with~~and land cover and vegetation types was investigated. ~~Different vegetation types occur in different climates and ecosystems and can have different survival mechanisms. Therefore, the vegetation types and their transpiration needs can have a strong control on the derived S_r.~~ The vegetation types included in th~~e~~is analysis are forest, pristine peatlands, drained peatlands and agricultural area. The relations between the estimated S_r-values and ~~catchment characteristics~~these vegetation types were assessed using ~~in two ways. First,~~ scatterplots between S_r and the ~~various characteristics~~vegetation types ~~were analysed; second, correlation statistics were calculated.~~ ~~To assess the correlation between the different variables, t~~The non-parametric Spearman's correlation coefficient was used to assess the correlation between the different variables. ~~For analysis of the threshold behaviour in S_r (presented in Section 3.3, the catchments were divided into two groups separated by a S_r of 115 mm. For both groups the significant differences between catchment characteristics were investigated.~~

2.4.4 Dependencies

The catchment characteristics that were compared with the climate derived S_r are very likely to be correlated, making it difficult to assess their individual relation with S_r. A principal component analysis (PCA) was used to explore the dependencies between the used characteristics. A PCA is a statistical tool which can be used to reduce the dimensions of a problem and explore correlations between variables.

-Before carrying out the PCA, the end products were standardised to have zero mean and unit variance on the covariance matrix. The final number of principal components (PCs) was determined using the broken-stick model (Jackson, 1993) , in which eigenvalues from a PCA are compared with the broken-stick distribution. Since each eigenvalue of a PCA represents a measure of a component's variance, a component was retained if its eigenvalue was larger than the value given by the broken-stick model.

2.5 Controls on root zone storage capacity

In addition to these assumptions, also the relation between the derived root zone storage and a set of catchment characteristics was investigated. It is expected that these relations can be informative for the variables that control the development of the root zone storage capacity.

First, the relation with climate was investigated; the method used to derive S_r is based on climate data, so it is expected that climate has a strong control on the derived S_r-values. However, by comparing the spatial patterns of climate variables and derived S_r-values and their mutual correlation, it can be analysed which climate variables have the strongest influence on S_r. Second, the relation of S_r with land cover and vegetation type was investigated. Different vegetation types occur in different climates and ecosystems and can have different survival mechanisms. Therefore, the vegetation types and their transpiration needs can have a strong control on the derived S_r. The vegetation types included in the analysis are forest, pristine peatlands, drained peatlands and agricultural area.

The relations between the estimated S_r-values and catchment characteristics were assessed in two ways. First, scatterplots between S_r and the various characteristics were analysed; second, correlation statistics were calculated. To assess the correlation between the different variables, the non-parametric Spearman's correlation coefficient was used. For analysis of the threshold behaviour in S_r (presented in Section xxx), the catchments were divided into two groups separated by a S_r of 115 mm. For both groups the significant differences between catchment characteristics were investigated.

3 Results

3.1 Dependencies

The variables that were compared with S_r are very likely to be correlated. Therefore, Figure 3 shows a principal component analysis based on the catchment characteristics used in the analysis. Figure 3a shows the individual catchments with their loadings on PC1 and PC2; Figure 3b shows the same for the catchment charactersitics used in the comparison. The plotted catchments (top plot) indicate that the eco-regions mainly differ in climate characteristics and that especially in the mid- and south boreal regions a large range of vegetation characteristics and vegetation types occur.

Figure 3b shows that the majority of the climate variables (shown in blue) are positively correlated to each other and negatively correlated to the mean annual temperature and transpiration demand. What can also be seen is the limited correlation between the majority of the climate variables and (summer) precipitation. With respect to vegetation characteristics (shown in green), these are strongly correlated with forest and agricultural land covers, but limitedly correlated to the majority of the climate variables. Only peatland covers are positively correlated with the majority of the climate variables.

-Especially, the relative independence of the vegetation characteristics and vegetation types with respect to the climate variables is important to keep in mind for the remainder of the analysis. This means that relations between S_r-values and vegetation characteristics are not likely to be strongly influenced by the climate variables.

3.2 Climate variables

[text originates from section 3.2 in the first version of the manuscript]

Two types of controls on root zone storage capacity were investigated: the influence of different climate variables and the influence of land cover. The first one can be split into the precipitation and evaporation on one hand and snow cover and melt on the other.Derived S_r-values were compared with a set of climate variables reflecting the absolute and phase difference between water supply and demand. Focussing first on the relation between S_r and precipitation and potential evaporationthe absolute difference, Figure 4 shows the spatial patterns of S_r and P/E_p (a definition of the aridity index). S_r-values generally decrease from south to north and especially for the mid-boreal region a large difference exists between the eastern and western side of the country. For the catchments in the north and mid-boreal regions larger S_r-values generally coincide with smaller P/E_p ratios, but for the south boreal region this pattern is less clear. The same can be observed from Figure 5a: the catchments in the north and mid-boreal regions show a negative correlation between S_r and P/E_p, while in the south boreal region no significant correlation exists: the range in S_r-values is large, although the variability in P/E_p is small (see Figure 8 for significant correlations).

The differences in S_r between catchments can partly be explained by mean annual temperature (T_{AM}) andSecond, snow cover (expressed in snow water equivalent, S_{SWE}) is important when focussing on the phase difference between water supply and demand. With more precipitation being stored for longer periods the supply of water will be delayed. Figure 4 shows for the majority of the catchments higher derived S_r-values (a) in case of lower maximum S_{SWE} (b). However, for some catchments in the mid-boreal region very small S_r-values are derived while max S_{SWE} is not very high. Figure 6b shows that T_{AM} clearly distinguishes between boreal regions and that T_{AM} and S_r are positively correlated, which weakens for higher temperatures. Figure 5 further shows that the differences within the mid-boreal region largely coincide with the differences in S_{SWE}. A closer look into the correlations between S_{SWE} and S_r, shows that a higher maximum S_{SWE} leads to smaller S_r-values (Figure 6 d). Unsurprisingly,As already shown in Figure 3 P/E_p and S_{SWE} are correlated. Especially, both E_p and snow storage and melt are driven by temperature. Figure 5 shows the strongest correlation between mean annual temperature (T_{MA}) and S_r, followed by snow-off date, max S_{SWE} and P/E_p. This indicates that for the studied catchments the phase difference as well as the absolute difference between water supply and demand are important, with the first one probably having a larger influence the catchments with a higher maximum S_{SWE} are also the ones with a higher P/E_p ratio (Figure 6 a). In addition to this, the snow-off date (Figure 6 c) is even stronger correlated with S_r than the maximum observed S_{SWE}.

3.3 Assumptions for estimating root zone storage capacityVegetation characteristics

[Presentation of the comparison of S_r with root biomass and with leaf cover/tree height changed order with respect to the first version of the manuscript.]

Estimated root zone storage capacities were compared with vegetation characteristics in the study catchments. In Figure 6 the relation is shown between the climate derived S_r andis compared with the observed root biomass in the catchments. A distinction is made between three tree types of trees: pine, spruce and deciduous trees. Root biomass of spruce and deciduous trees mainly has a positive correlation,is positively correlated with S_r when considering all catchments; with an increasing spread in the data for the more southern catchments. One exemption is the root biomass of spruce in the mid-boreal region; here no clear correlation with S_r can be observedwhen considering the individual boreal regions, only a significant correlation exists for deciduous trees in the north boreal region. The correlation between S_r and root biomass of pine is very interesting: the northern region shows a slight positive correlation, but for the middle and southern region a negative correlation is showna negative correlation exists between S_r and root biomass when considering all catchments. For the individual regions no significant correlation exists: this indicates that more storage is created with less or thinner roots. Figure 6d combines the results for all tree types and shows indeed a mixture of the results observed for the individual tree types. In general, a positive correlation exists between S_r and root biomass, which seems to weaken for catchments in the south boreal region, where S_r-values are higherin general higher S_r-values for higher densities of root biomass, but this correlation is not significant.

Figure 7 shows the relation between S_r and average leaf cover (top row) and tree lengthheight (bottom row). For both comparisons a distinction is made between different land cover (forest, peatlands, agriculture) and the boreal regionsthe data is plotted indicating the occurence of different vegetation types (forest, pristine peatlands and agriculture) in the catchments and the boreal regions in which the catchments are located. S_r is positively correlated with both leaf cover and tree height (Spearman's coefficients of 0.33 and 0.32 respectively), but no significant correlation exists for the individual boreal regions. Some correlation can be observed between S_r and leaf cover for the catchments with forest (a) and peatland (b) cover (see Figure 8 for significant correlations). On the other hand, for catchments with more agricultural cover (c) a wide spread in S_r-values can be seen, while the variation in leaf cover is relatively small. The relation between S_r and tree length shows more or less the same pattern: some correlation can be seen for catchments with a high forest cover (e) and this correlation decreases for higher percentages of peatland (f) and agriculture (g). When looking at the different boreal regions (d, h), the correlation between S_r and leaf cover or tree height is mainly present for catchments in the mid-boreal region.When looking at the different vegetation types, it can be seen that catchments with a large forest cover are the ones with the widest range in leaf cover and tree length. Especially for catchments with a large agricultural cover this range is smaller. More details about the relation between vegetation type and S_r are discussed in Section 3.4 and Figure 8.

3.4 Vegetation types

[this text originates from section 3.2 in first version of the manuscript] BesidesIn addition to climate and vegetation characteristics, also land covervegetation types can have an influence on the derived S_r, mainly because different vegetation types have different transpiration patterns and survival strategies. Before analysing correlations between S_r and land covervegetation type, it should be noted though that land cover isthese are (partly) correlated with climate as well (Figure 13). This is especially relevant for the correlations between S_r and (pristine) peatlands and agriculture and forest cover.

The strongest correlation between S_r and vegetation types can be found for agricultural cover; here not only a significant positive correlation is present when considering all catchments, but also for the three individual regions (Figure 8). Figure 7a shows that with an increase in agricultural area, S_r increases as well. Although the spread in data increases when moving from north to south, the correlation increases for the individual regions as well. Further, a decrease in forested area coincides in general with an increasewith a larger range in S_r, but thisno significant correlation is not present for the individual regionsfound, neither for all catchments and for the individual regions (Figure 8b). The drained peatlands (Figure 8c) on the other hand show a slight positive correlation with S_r for the north and south boreal regions, while theyalso show a clear negative correlation with S_r when considering all catchments and for the mid-boreal region: for the north and south boreal regions no significant correlations were found. While for the former three land covervegetation types showed a stronger or weaker gradual relation with S_r can visually be observed, the pristine peatlands show strong threshold behaviour. For catchments covered forwith more than 20% with pristine peatlands, S_r-values are below 115 mm. It should be noted though, that catchments with high pristine peatland cover do not occur in the south boreal region.

Figure 8shows the correlations between S_r and the various catchment characteristics. From this figure it follows that the strongest positive correlation was found between S_r and the mean annual temperature and the strongest negative correlation was found for S_r and the (timing of) maximum S_{SWE}. Further, it can be seen that a strong correlation exits between the different vegetation characteristics and between the different climate variables. In addition, the land cover (except for drained peatlands) also shows a strong correlation with the climate variables.

3.5 Controls on root zone storage capacity

Two types of controls on root zone storage capacity were investigated: the influence of different climate variables and the influence of land cover. The first one can be split into the precipitation and evaporation on one hand and snow cover and melt on the other. Focussing first on the relation between S_r and precipitation and potential evaporation, Figure 5shows the spatial patterns of S_r and P/E_p. S_r-values generally decrease from south to north and especially for the mid-boreal region a large difference exists between the eastern and western side of the country. For the catchments in the north and mid-boreal regions larger S_r-values generally coincide with smaller P/E_p ratios, but for the south boreal region this pattern is less clear. The same can be observed from Figure 6a: the catchments in the north and mid-boreal regions show a negative correlation between S_r and P/E_p, while in the south boreal region the range in S_r-values is large, although the variability in P/E_p is small (see Figure 8for significant correlations).

The differences in S_r between catchments can partly be explained by mean annual temperature (T_{AM}) and snow cover (expressed in snow water equivalent, S_{SWE}). Figure 6b shows that T_{AM} clearly distinguishes between boreal regions and that T_{AM} and S_r are positively correlated, which weakens for higher temperatures. Figure 5further shows that the differences within the mid-boreal region largely coincide with the differences in S_{SWE}. A closer look into the correlations between S_{SWE} and S_r, shows that a higher maximum S_{SWE} leads to smaller S_r-values (Figure 6 d). Unsurprisingly, the catchments with a higher maximum S_{SWE} are also the ones with a higher P/E_p ratio (Figure 6 a). In addition to this, the snow-off date (Figure 6 c) is even stronger correlated with S_r than the maximum observed S_{SWE}.

Besides climate, also land cover can have an influence on the S_r, mainly because different vegetation types have different transpiration patterns and survival strategies. Before analysing correlations between S_r and land cover, it should be noted though that land cover is correlated with climate as well (Figure 1). This is especially relevant for the correlations between S_r and agriculture and forest cover.

Figure 7a shows that with an increase in agricultural area, S_r increases as well. Although the spread in data increases when moving from north to south, the correlation increases for the individual regions as well. Further, a decrease in forested area coincides in general with an increase in S_r, but this correlation is not present for the individual regions (Figure 7b). The drained peatlands (Figure 7c) on the other hand show a slight positive correlation with S_r for the north and south boreal regions, while they show a clear negative correlation for the mid-boreal region. While the former three land cover types showed a stronger or weaker gradual relation with S_r, the pristine peatlands show strong threshold behaviour. For catchments with more than 20% pristine peatlands, S_r-values are below 115 mm. It should be noted though, that catchments with high pristine peatland cover do not occur in the south boreal region.

Figure 8shows the correlations between S_r and the various catchment characteristics. From this figure it follows that the strongest positive correlation was found between S_r and the mean annual temperature and the strongest negative correlation was found for S_r and the (timing of) maximum S_{SWE}. Further,

~~it can be seen that a strong correlation exits between the different vegetation characteristics and between the different climate variables. In addition, the land cover (except for drained peatlands) also shows a strong correlation with the climate variables.~~

3.6 Threshold behaviour

The results ~~discussed~~presented before show to a variable extent a threshold in the relation between the derived S_r-values and ~~other variables~~the catchment characteristics. This threshold is mainly visible in Figures 5 and 8d and seems to be the strongest for snow characteristics (Figure 5c,d) and pristine peatlands (Figure 8d). For all variables the threshold is located at a S_r of approximately 115 mm. To further investigate the origin and position of the threshold the catchments were divided into two groups separated by a S_r of 115 mm. Within the groups statistically significant variations exist in both vegetation, specifically in tree root biomass (pine RBM: Mann-Whitney U-test, p=0.0131; spruce RBM: U-test, p=0.0363) and proportion of pristine (U-test, p=0.0008) and drained (U-test, p=0.0135) peatlands ~~in the catchments (U-test, p=0.0013)~~. At the same time also climatic parameters changed: ~~snow fraction (U-test, p=0.0443)~~P/E_p (U-test, p=0.0264), ~~maximum snow water equivalent~~max S_{SWE} (~~max S_{SWE}:~~U-test, p=0.0000), snow-off date (U-test, p=0.0000) and mean annual temperature (T_{AM}: U-test, p=0.0000) showed a significant difference between the groups.

As not only the maximum S_{SWE} and T_{AM} are important, but also the snow-off date (Figure 5), it is possible that the threshold is related to the phase difference between water input and demand in the catchments. Therefore, Figure 9 shows the period with snow cover (colour plot) and the period in which potential evaporation is above zero (white lines) for each catchment. In general, for catchments with a S_r smaller than 115 mm (bottom part of the plot), the snow melt and onset of potential evaporation overlap. On the other hand, for catchments with a S_r larger than 115 mm the snow has already melted at the onset of the potential evaporation measurements. In the first case the phase difference between input and demand is decreased, while in the second case it is increased, thus requiring a larger storage capacity. The phase difference between snow-off and onset of E_p was calculated and included in Figure 3; it is positively correlated with the majority of the other climate variables. It is therefore likely to show the combined effect of the different climatic influences. This phase difference ~~explains~~gives an explanation for the origin of the threshold, but not for the location at 115mm. A clear reason for the threshold being located at 115 mm could not be found and it might be an artifact of this specific data set.

4 Discussion

The presented results show that among the compared characteristics the climate derived root zone storage capacities are strongest related to climate variables, followed by vegetation characteristics~~, climate variables~~ and vegetation ~~cover~~types~~, which strongly indicates that the S_r-method can be used for boreal regions containing seasonal snow cover~~. These results gain better understanding the influence of the different climate variables on the calculation of S_r in snow dominated regions. Moreover, they can be used to explore the physical meaning and wider application of S_r from land and water management purposes. ~~According to the results, the correlation between S_r and the tested climate and vegetation variables varies and is not always straight forward. In addition, many of the presented compar-~~

isons showed a threshold around a S_r-value of 115mm. PBelow, possible reasons for this threshold and for differences in correlation and for the found threshold are discussed below, together with implications of the findings.

4.1 Climate variables

[Text originates from section 4.2 in the first version of the manuscript]

As the root zone storage capacity is derived from climate data, logically a correlation exists between the derived S_r-values and various climate variables. The strongest correlations between S_r and the catchment characteristics are found when all three boreal are considered together and to a lesser extend when the boreal regions are considered individually; these boreal regions mainly differ in climate characteristics (Figure 3). Together with the results presented in Figure 5 this shows that the relation between climate and S_r is stronger than the relations between S_r and other catchment characteristics.

However, it is interesting to see that not all climate variables have the same amount of influence (Figure 5) on the derived S_r-values. More specifically, the phase difference between the snow-off date (water supply) and onset of potential evaporation (water demand) turns out to be very important (Figure 9). Further, the different analyses show that for the colder regions, the influence of individual climate variables (P/E_p, T_{AM}, snow-off date) is more important. This larger influence of climate variables in colder regions can also influence or partly cause the observed threshold behaviour.

Combining the predicted change of all these climate variables in the near future in boreal regions (Prows et al., 2015)with their possible influence on the observed threshold, could indicate a remarkable effect on the hydrological behaviour of northern catchments. This finding for example indicates that earlier snow melt decreases soil moisture during summer, resulting in larger root zone storage capacities. A possible increase in root zone storage capacity with increasing annual temperature and declining snow cover may cause also substantial changes to biogeochemical cycles (Wrona et al., 2016)and generated stream flows (Bring et al., 2016). It would therefore be interesting to extend this research to other boreal and temperate regions. In such a study it can be investigated if this threshold occurs in many areas with energy constrained evaporation or that it is mainly linked to the (non-)existence of snow cover.

4.2 Vegetation characteristics

[Text originates from section 4.1 in the first version of the manuscript] Figure 3 shows that the vegetation characteristics are not strongly correlated with the majority of the climate variables, which makes it interesting to compare their patterns with those of S_r. However, the result of this comparison did not show patterns as strong as expected. One of the reasons of this could be the heterogeneity in vegetation types in the study catchments. Another reason could be that the S_r parameter does not have a very strong physical meaning in boreal regions. The derived root zone storage capacities mainly follow the south-north gradient, along which clear vegetation variations occur as well.

[The order of discussing root biomass and leaf cover/tree height changed with respect to the first version of the manuscript.] Despite the conceptual character of the climate derived root zone storage capacity, it can bewas expected that it is positively correlated with root density or root biomass; this study is the first to show thissuch a connection exists for spruce and decideous trees (Figure 6). However, for pine in mid- and south-boreal regions a negative correlation was observed, which means that the vegetation is able to create a larger storage capacity with fewer or thinner roots. This can have multiple reasons, among which, the survival strategies of the trees (e.g., that in these areas the pine trees have other methods to access water or water use efficiency), or the combined effect with other catchment characteristics (e.g., ~~that the~~a low density of pine trees ~~is very low~~ in these catchments, thus their influence on the overall transpiration and storage in the catchments or influence of the drained peatlands in which pine trees often occur). ~~Interestingly, also the most northern catchment in our data set, with tundra vegetation, verified our calculations by having both a small S_r and minor root biomass.~~

By using a climate derived root zone storage capacity, it is assumed that the S_r developed by the vegetation is in balance with the transpiration demands. Not necessarily one causes the other, but ~~develops~~ a larger S_r coincides ~~in case it has to deal~~ with higher or more variable transpiration demands. When the transpiration demand in boreal areas is higher, it is likely that vegetation has higher potential to develop as well (ie. more leaf cover, larger trees). Figure 7 shows indeed a positive ~~some~~ correlation between S_r and leaf cover or tree ~~length~~height.~~, but this correlation is mainly present below the threshold of 115 mm and hardly present for catchments with more agriculture cover. This seems to indicate that in case of low transpiration demands the plant's resources between below and above soil elements are more equally divided than for areas with higher transpiration demands~~

4.3 ~~Influence of peatlands~~Vegetation types

Although not as strong as for the climate variables and the vegetation characteristics, relations between S_r and vegetation types were found as well, especially for agriculture and pristine peatlands. A lack of strong patterns could, similarly as for the vegetation characteristics, for example be caused by the heterogeneity of the study catchments. The combined effect of different variables is another option that should especially be considered when looking at vegetation types. For example when looking at the interaction between transpiration demand and vegetation type: does the existence of agriculture or deciduous forest increase transpiration rates and thus derived S_r-values, or are these vegetation types more likely to occur in areas with larger differences between water supply and demand? Or what is the role of soil: the used method assumes that soils are not important for the derived S_r, but they probably influence which vegatation will develop, which again influences the transpiration demands. Or how do the development of vegetation type and climate exactly coincide: especially peatland showed to be strongly correlated to climate (Figure 3), but to smaller extends agriculture and deciduous forest as well. To answer these questions, more detailed analysis of specific catchments would be required.

When ~~considering different land cover types, it can be seen that especially a higher occurrence of~~looking especially at pristine peatlands it can be seen that they have ~~has~~ a strong ~~influence on~~relation with the derived root zone storage capacity. In case of more than 20% pristine peatland cover, S_r does not exceed the ~~(again same)~~earlier found threshold of 115 mm. ~~The threshold behaviour is even strongest for the relation between pristine peatland cover and S_r.~~ This may indicate that the "below threshold" conditions are ideal for the development of peat lands, which makes sense as peatlands develop in areas where precipitation exceeds evaporation and thus moisture conditions favour creation of peatland vegetation. In the developed peatlands generally~~Interestingly,~~ the available space for root development ~~in these peatlands~~ is small, due to high groundwater tables and fully saturated soil moisture conditions (e.g. Menberu et al., 2016). However, this is not explicitly accounted for in the S_r calculations. This indicates that the pristine peatlands do not have a high transpiration demand and that evaporation is not excessively increased by high ground water tables. Typically evaporation from peat surfaces is small, especially if the water levels are below the growing sphagnum vegetation (Wu et al., 2010). Catchments where ~~P~~peatland is drain~~age~~ed for forestry ~~changed this~~show another pattern: the correlation with

S_r is lower, but especially the threshold seems to be weaker. The variation between the two groups for the threshold analysis is larger for pristine peatlands than for drained ones (Mann-Whitney U-test, p=0.0008 and p=0.0135 respectively).higher S_r values were observed in areas with larger cover of drained peatlands (Figure 7). This wasAn effect could be expected since the motivation for artificial drainage is to create suitable soil moisture conditions for trees and increase forest growth (Sarkkola et al., 2013a). Peatland drainage has shown to have many affects toeffects on hydrological processes (ie. low flows, peak flows), which cancould be partly be explained by the change in S_r.

[The following paragraph originates from Section 4.1 in the first version of the manuscript] Overall, the used data shows a variable relation between vegetation characteristics and vegetation types and S_r-values in boreal landscapes. This is especially interesting as forestry actions together with shifting vegetation regions towards the north (e.g. Hasper et al., 2016), may thus result in different outcomes for root zone properties. Therefore it would make sense for future catchment scale studies focusing on the effects of changes in land use or climate on hydrological patterns, shouldto take into account possible changes in S_r as well.

4.4 Usefulness of a climate derived S_r

As shown in earlier studies, climate derived root zone storage capacities can be very useful in a modelling study. However, this study compared derived S_r-values with a set of catchment characterisicsdifferent effects on this root zone storage capacity, which is a first step in analysing how transpiration influences catchment scale runoffexploring the wider application of S_r. The comparison with vegetation characteristics and types showed that the climate derived S_r indeed also has some physical meaning. In addition, the comparison with climate variables showed that the (non-)coincides of snow melt and the onset of potential evaporation has a large influence on the derived S_r-values. Combining these two findings it can be expected that if the timing of either of them changes, this can have a remarkable effect on the hydrological behaviour of northern catchments. This finding for example may indicate that earlier snow melt decreases soil moisture during summer, resulting in larger root zone storage capacities. A possible increase in root zone storage capacity with increasing annual temperature and declining snow cover may cause also substantial changes to biogeochemical cycles (Wrona et al., 2016) and generated stream flows (Bring et al., 2016). It would therefore be interesting to extend this research to other boreal and temperate regions. In such a study it can be investigated if the found threshold occurs in many areas with energy constrained evaporation or that it is mainly linked to the (non-)existence of snow cover.

In this contextWith this in mind a climate derived S_r is especially valuable, as it will probably change when the climatic conditions (ie. amount of precipitation, snow-off date) or vegetation properties (ie. transpiration pattern) change. Before S_r-values can be used in this way, more analyses should be carried out to investigate how (quickly) new equilibria are established and whether vegetation does change their survival mechanisms. However, when eExtending this line of thought, a climate derived S_r can possibly be used to assess the hydrological effect of future changes in climatic and land cover conditions and the consequences for biogeochemical processes. This is essential in a global perspective, but especially in boreal regions which are facing drastic changes in near future resulting from joint pressures of intensified land use and climate change.

5 Conclusions

This paper showed that the climate based method to derive root zone storage capacities, with a snow component included, can be well applied to a range of boreal catchments. Subsequently, this paper tested the influence of different controls oninvestigated the relations between a set of catchment and vegetation characteristics and the developedderived root zone storage capacity to further understand the possibilities and physical meaning of this parameter. A climate derived S_r was compared with vegetation characteristics, climate variables, vegetation characteristics and land covervegetation types. A comparison between S_r and the vegetation characteristics showed in general a positive correlation between S_r and leaf cover, tree length and root biomass. This comparison had not been carried out before and further supports the plausibility of the climate-based method; additionally, it confirms the suitability of the method to determine S_r values for boreal regions. Another important finding is that especially the (non-)coincidence of the snow-off and the onset of potential evaporation has a large effect on the derived S_r. In the studied regions, where evaporation is energy constrained, these two are the main variables determining the supply and demand and supply of water. Further, it was observed that catchments with a large pristine peatland cover have small S_r-values and that for colder regions the influence of individual climate variables on S_r is larger. A climate derived S_r, as used in this study, enables reflecting (changes in) climatic and vegetation conditions in a hydrological parameter. Therefore it gives additional information about the hydrological characteristics of an area and it could be beneficial to assess the effects of changing conditions.

Data availability. All data used for this study originates from open access databases which are listed in the data use subsection

Competing interests. The authors declare that no competing interests exist.

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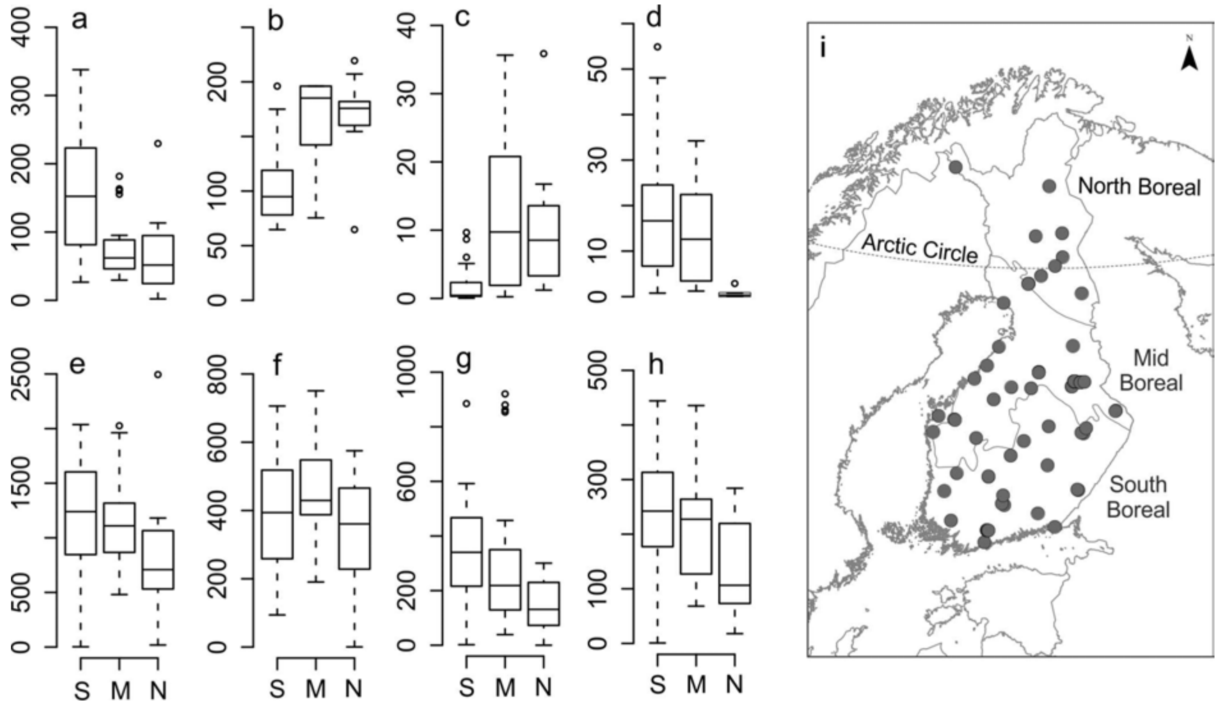

Figure 1. a) Root zone storage capacity (mm), b) maximum snow water equivalent (S_{SWE}, mm), c) percentage of pristine peatlands (%), d) percentage of agricultural areas (%), e) total tree root biomass (10 kg/ha), f) pine root biomass (10 kg/ha), g) spruce root biomass (10 kg/ha), h) deciduous root biomass (10 kg/ha) at different ecoregions (S is south boreal, M is mid-boreal and N is north boreal).

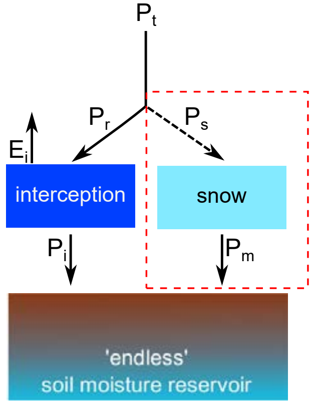

Figure 2. [The font colour of this figure is changed] Schematisation of the method to calculate S_r, including snow module; the part in the red square is added for this research, the 'endless' soil moisture reservoir is similarly to the one in de Boer-Euser et al. (2016). The arrow for P_s is dashed as this flux is not actually calculated, but P_m is derived from the change in S_{SWE}.

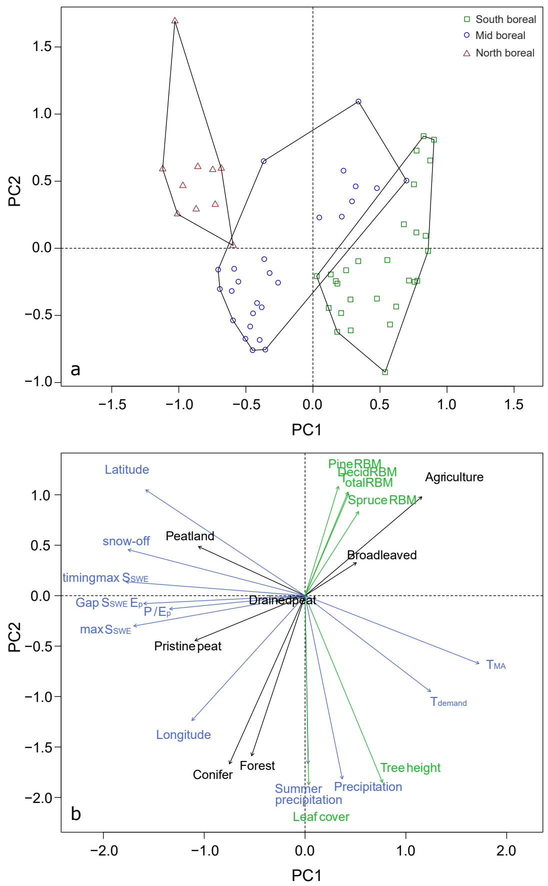

Figure 3. [This figure was newly added] Principal component analysis with the catchment characteristics that are being compared with S_r in the study. a) Catchments plotted on PC1 and PC2, with boreal regions indicated. Note that for readability the axis of the two plots are not the same. b) Catchment characteristics with their loadings on PC1 and PC2; catchment characteristics are divided into three categories: climate (blue), vegetation characteristics (green) and land use types (black).

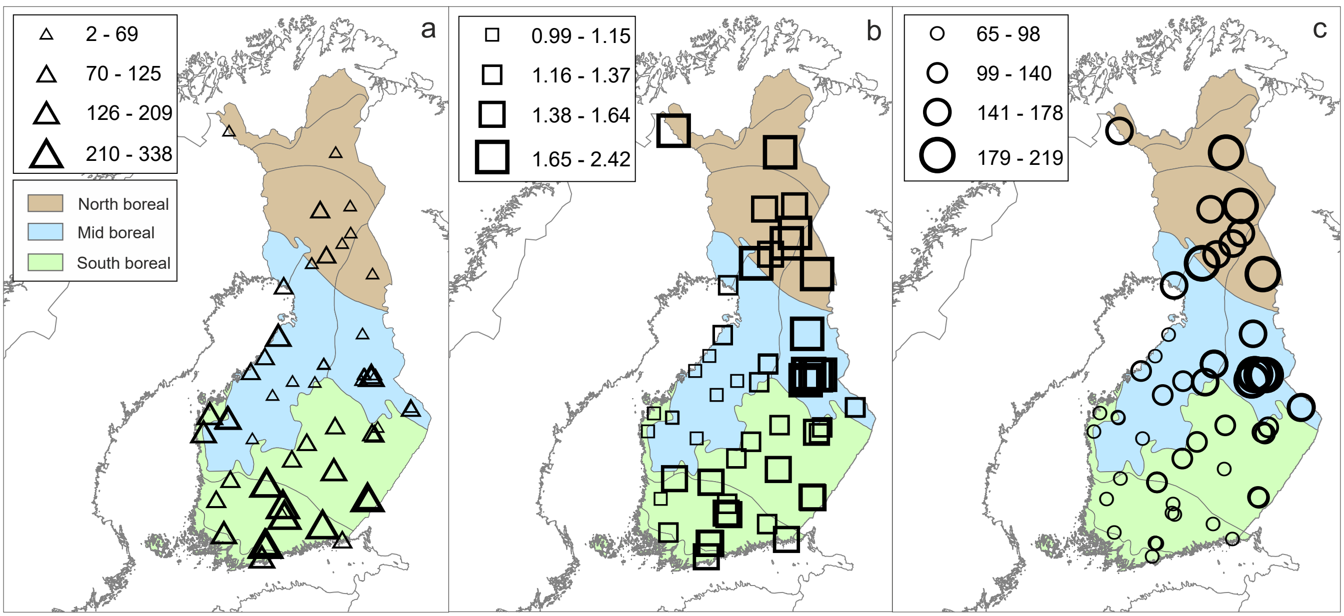

Figure 4. [This was Figure 5 in the original manuscript] Map with study ~~site location~~catchments and a) calculated root zone storage values (~~$S_{r,20}$~~S_r, mm), b) ratio of precipitation and potential evaporation, and c) maximum snow water equivalent (S_{SWE}, mm). Different boreal ecoregions (south boreal, mid-boreal and north boreal) are shown in colors and subdivision of ecoregions is marked with gray lines.

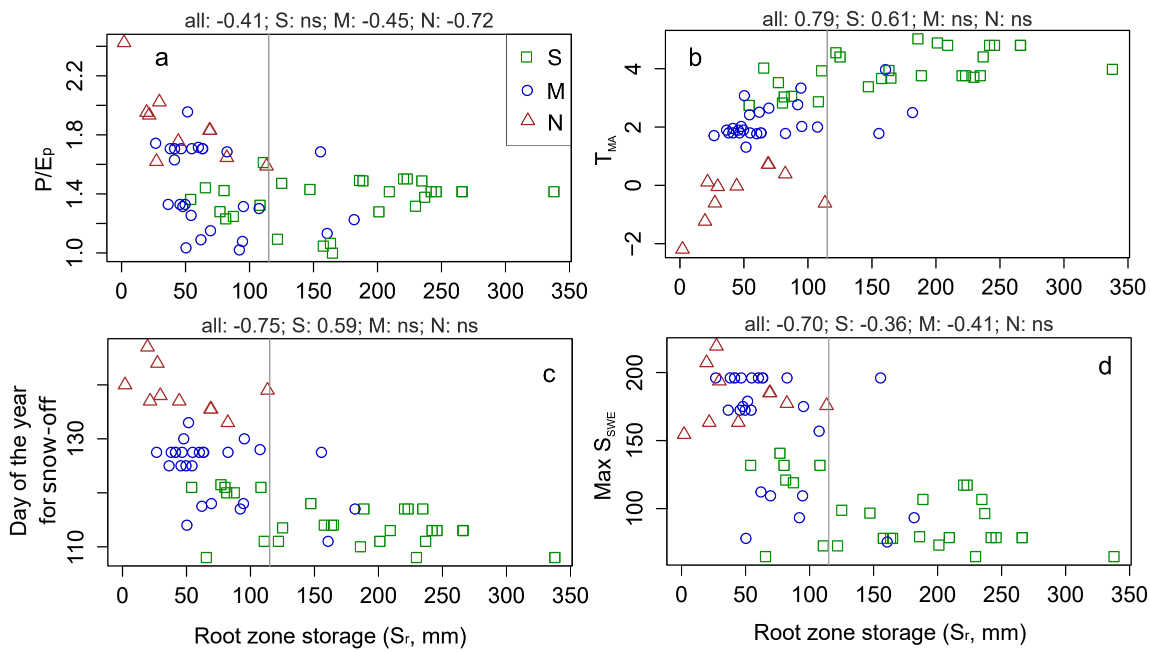

Figure 5. [This was Figure 6 in the original manuscript] Root zone storage capacities and a) ratio of average precipitation and potential evaporation (P/E_p), b) mean annual temperature (T_{AM}), c) day of the year for snow-off, and d) maximum snow water equivalent (S_{SWE}) in the catchment at different ecoregions (S is south boreal, M is mid-boreal and N is north boreal). The titles of the subplots show the Spearman's correlation coefficients (significant correlation for p<0.05). The line at 115 mm illustrates the discussed threshold.

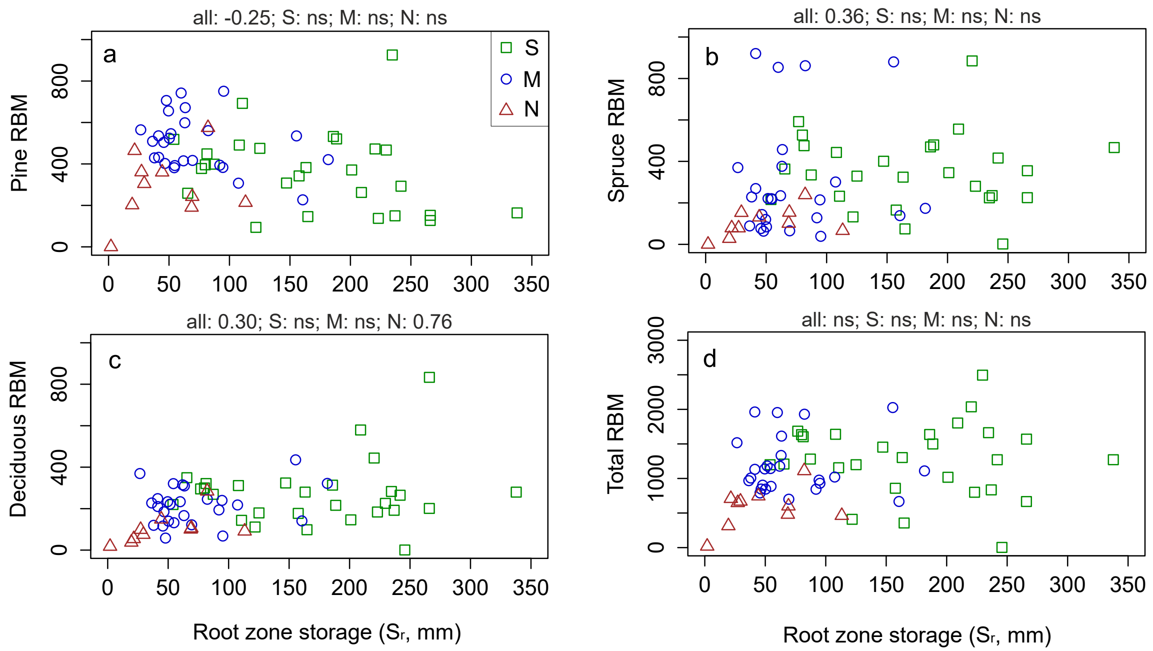

Figure 6. [This was Figure 4 in the original manuscript] Root zone storage capacities and a) pine root biomass (RBM), b) spruce RBM, c) deciduous ~~trees~~ RBM and d) total RBM in the catchment at different ecoregions (S is south boreal, M is mid-boreal and N is north boreal). The titles of the subplots show the Spearman's correlation coefficients (significant correlation for $p<0.05$).

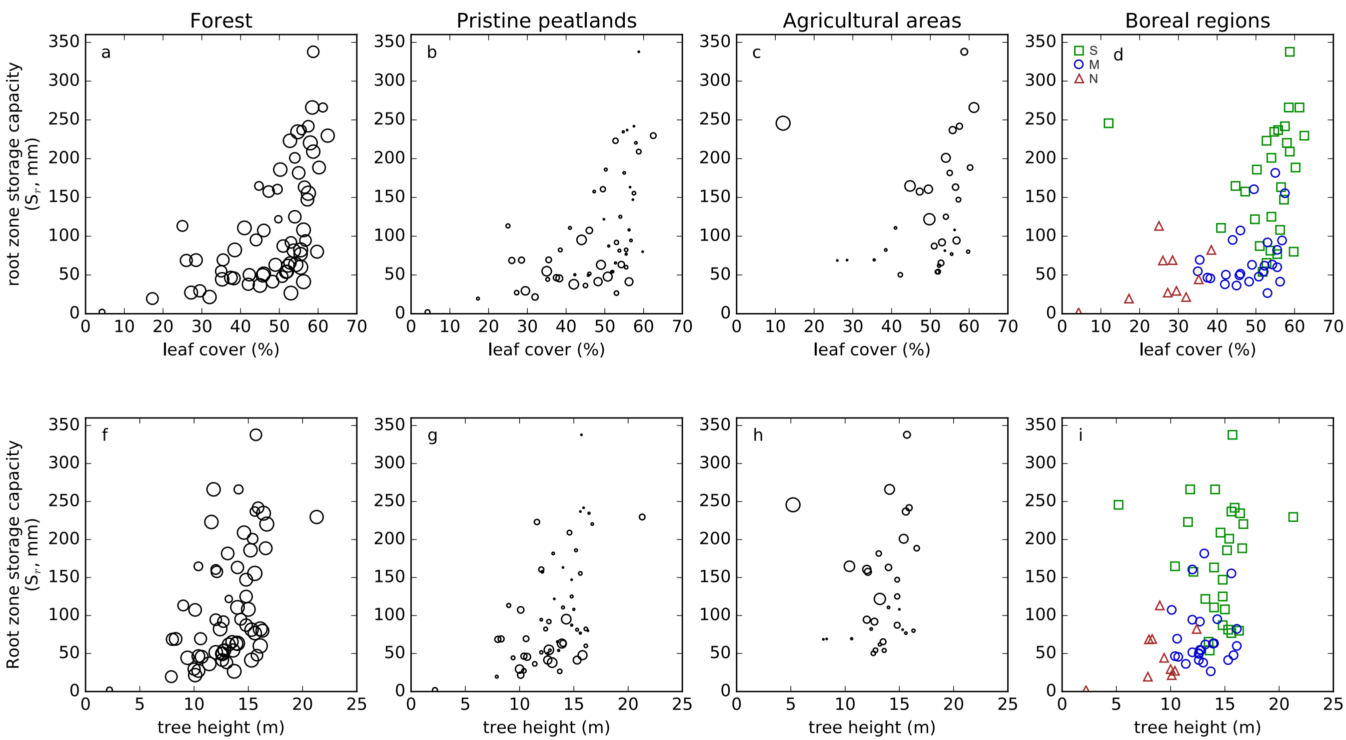

Figure 7. [This figure is updated with correct data and was Figure 3 in the original manuscript] Calculated root zone storage capacity versus average leaf cover (top) and tree ~~length~~height (bottom) of four years. Larger circles indicate higher percentage of ~~land cover~~vegetation type for a&e) forest, b&f) pristine peatlands, c&g) agriculture; d&h) are colour coded by boreal region. S_r has statistically significant Spearman's correlation with leaf cover ($r = 0.33$) and tree height ($r = 0.32$). Different boreal regions did not resulted in statistically significant correlations when considered individually.

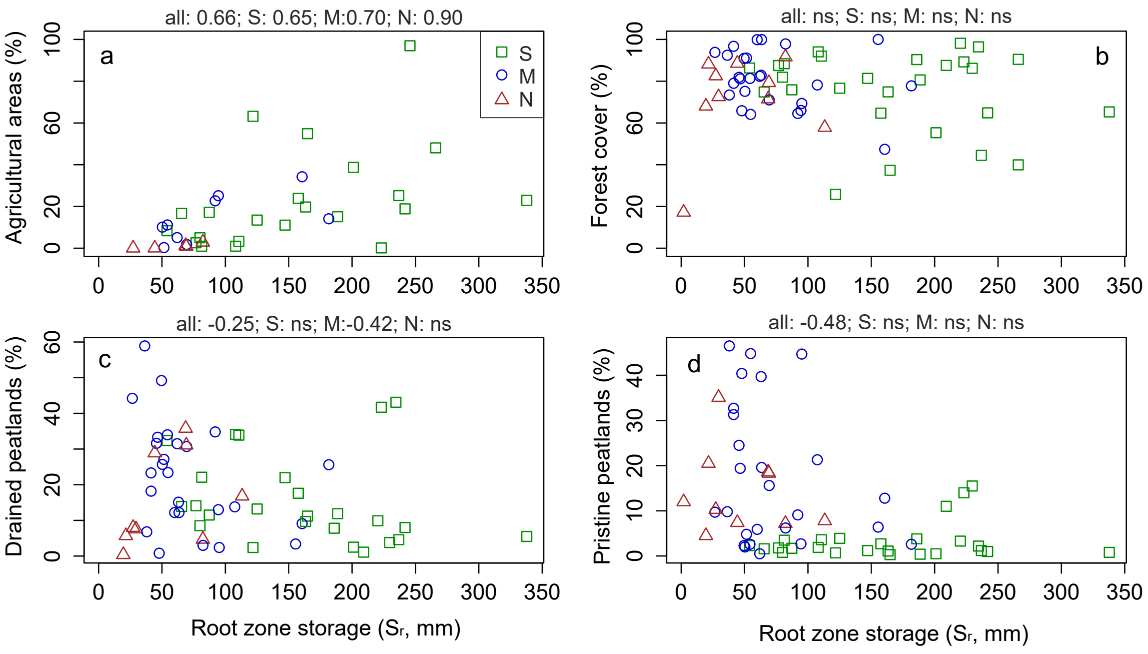

Figure 8. [This was Figure 7 in the original manuscript] Root zone storage capacities ($S_{r,20}$ S_r, mm) and proportion of a) agricultural areas (%), b) forest cover (%), c) drained peatlands (%) and d) undrained peatlands (%) in the catchment at different ecoregions (S is south boreal, M is mid-boreal and N is north boreal). The titles of the subplots show the Spearman's correlation coefficients (significant correlation for p<0.05). Note that not all vegetation types are present in each catchment, thus the number of catchments per subplot may differ.

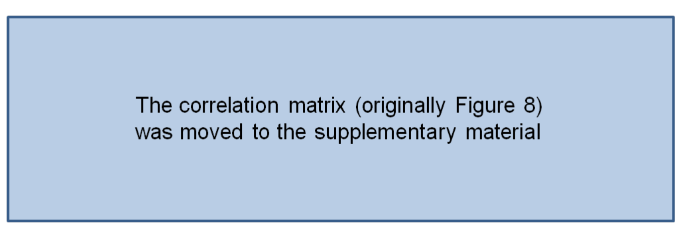

Figure 8. Correlation matrix for calculated root zone storage capacity (20 year return period), calculated transpiration demands (used in the S_r calculation) and catchment characteristics. The asterisks indicates a significant correlation (p<0.05).

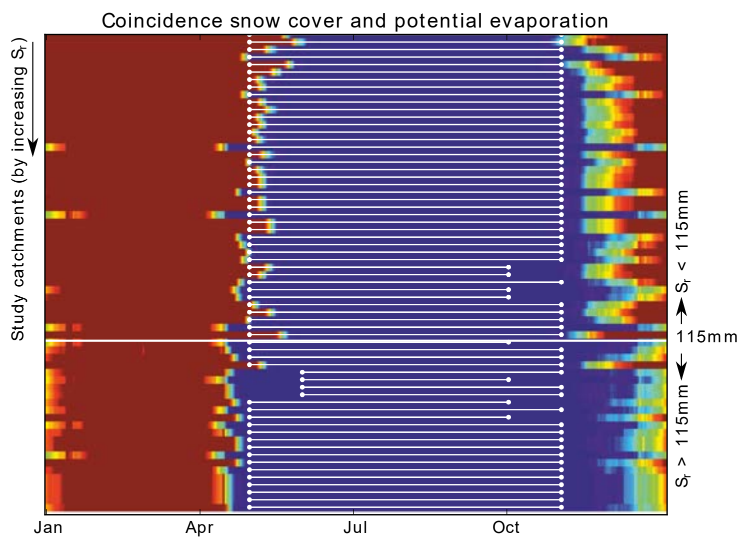

Figure 9. [this figure has been changed: black lines are replaced by white lines and labels on y-axes have been adjusted] Coincidence of sSnow cover is presented by the colour plot (red: $S_{SWE} > 15$ mm, blue: $S_{SWE} = 0$)(colour plot) and oOccurrence of potential evaporation ($E_p > 0$) is presented by (blackwhite lines); note that the actual amount of E_p is not presented. pPresented data are long term daily averages. Catchments are ordered by increasing S_r-values. S_{SWE} is cut off at 15 mm to better visualise the changes in S_{SWE} during snow melt and accumulation.

Supplement belonging to "~~Controls on~~ Understanding variability in root zone storage capacity in boreal regions"

by Tanja de Boer-Euser, Leo-Juhani Meriö, Hannu Marttila

1 Background on study catchments

Tables 1 and 2 give an overview of available vegetation and climate characteristics of the study catchments.

Table 1: Vegetation and land use characteristics of study catchments

ID	Catchment name	Size (km^2)	Pine RBM (10 kg/ha)	Spruce RBM (10 kg/ha)	Decid RBM (10 kg/ha)	Total RBM (10 kg/ha)	Forest (%)	Conifer (%)	Broad-leaved (%)	Agri-cul-ture (%)	Drained peat-land (%)	Pris-tine peat-land (%)	Leaf cover (%)	Tree length (dm)
7	Rudbäcken1	1.42	532	470	313	1636	90	53	4	0	8	4	50	152
11	Hovi	0.12	0	2	1	2	0	0	0	97	0	0	12	52
12	Ali-Knuuttila	0.25	127	225	201	666	40	18	6	48	0	0	61	141
13	Yli-Knuuttila	0.07	152	355	833	1569	90	11	29	0	0	0	59	118
14	Teeressuonoja	0.69	262	556	579	1802	88	30	13	0	1	11	59	146
15	Kylmänoja	4.04	293	416	265	1271	65	36	6	19	8	1	58	159
17	Koppelonoja	7.81	164	467	280	1271	65	33	5	23	6	1	59	157
18	Löyttynoja	8.2	259	363	349	1209	75	38	5	17	14	2	53	135
21	Löytäneenoja	5.64	94	132	111	409	26	13	1	63	2	1	50	132
22	Savijoki	15.4	371	346	146	1017	55	37	1	39	3	1	54	154
31	Paunulanpuro	1.5	472	885	444	2037	98	66	1	0	10	3	58	167
32	Siukolanpuro	1.86	138	280	184	800	89	58	2	0	42	14	53	116
33	Katajaluoma	11.2	692	232	144	1155	92	66	0	3	34	4	41	140
41	Niittyjoki	29.7	150	235	192	835	44	24	3	25	5	1	56	156

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Table 1 – *Continued from previous page*

ID	Catchment name	Size (km^2)	Pine RBM (10 kg/ha)	Spruce RBM (10 kg/ha)	Decid RBM (10 kg/ha)	Total RBM (10 kg/ha)	Forest (%)	Conifer (%)	Broadleaved (%)	Agri-culture (%)	Drained peat-land (%)	Pris-tine peat-land (%)	Leaf cover (%)	Tree length (dm)
42	Ravijoki	56.9	475	329	179	1199	77	51	4	13	13	4	54	148
43	Latosuonoja	5.34	521	480	216	1499	81	60	2	15	12	0	60	166
44	Huhtisuonoja	5.03	926	225	283	1663	96	80	0	0	43	2	55	164
45	Juonistonoja	13	308	401	324	1454	81	42	5	11	22	1	57	148
51	Kesselinpuro	21.7	491	443	311	1639	94	59	2	1	34	2	56	150
52	Kuokkalanoja	2.67	396	527	300	1634	82	51	6	5	9	1	60	163
53	Mustapuro	11.2	518	216	220	1199	86	55	3	8	32	2	52	136
54	Murtopuro	4.94	565	370	369	1517	94	47	1	0	44	10	53	137
55	Liuhapuro	1.65	536	920	248	1962	97	75	0	0	23	31	56	153
56	Suopuro	1.13	392	219	132	886	64	50	0	0	23	45	35	127
57	Välipuro	0.86	599	376	166	1333	83	75	0	0	15	40	49	139
58	Kivipuro	0.54	672	457	309	1613	100	83	0	0	12	20	54	140
59	Koivupuro	1.18	402	144	185	847	81	53	0	0	33	19	38	104
61	Korpijoki	122	382	220	321	1143	81	43	5	11	34	3	52	128

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Table 1 – *Continued from previous page*

ID	Catchment name	Size (km^2)	Pine RBM (10 kg/ha)	Spruce RBM (10 kg/ha)	Decid RBM (10 kg/ha)	Total RBM (10 kg/ha)	Forest (%)	Conifer (%)	Broadleaved (%)	Agri-culture (%)	Drained peat-land (%)	Pris-tine peat-land (%)	Leaf cover (%)	Tree length (dm)
62	Kohisevanpuro	10.65	449	476	321	1604	88	53	4	1	22	4	54	153
71	Ruunapuro	5.39	399	335	269	1281	76	48	5	17	12	2	51	148
72	Heinäjoki	9.4	378	592	295	1684	88	58	3	3	14	2	56	156
81	Haapajyrä	6.09	146	74	98	356	37	18	2	55	11	0	45	104
82	Kainastonlu-oma	79.2	342	165	177	858	65	35	2	24	18	3	47	121
83	Kaidesluoma	45.5	524	84	140	846	75	54	1	10	26	2	42	126
84	Norrskogsdiket	11.6	227	138	141	667	47	29	1	34	9	13	50	120
85	Sulvanjoki	26.85	383	324	280	1302	75	48	2	20	10	1	57	140
91	Tuuraoja	23.5	394	128	194	844	65	39	1	23	35	9	53	127
92	Tujuoja	20.5	415	235	315	1178	82	48	4	5	32	1	52	132
93	Pahkaoja	23.3	417	65	122	700	71	50	0	2	31	16	36	106
94	Kuikkisenoja	8.05	383	215	240	975	66	36	3	25	13	3	57	120
101	Huopakinoja	19.7	421	174	322	1110	78	40	4	14	26	3	55	131

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Table 1 – *Continued from previous page*

ID	Catchment name	Size (km^2)	Pine RBM (10 kg/ha)	Spruce RBM (10 kg/ha)	Decid RBM (10 kg/ha)	Total RBM (10 kg/ha)	Forest (%)	Conifer (%)	Broadleaved (%)	Agri-cul-ture (%)	Drained peat-land (%)	Pris-tine peat-land (%)	Leaf cover (%)	Tree length (dm)
102	Vääräjoki	19.3	305	153	75	670	73	51	0	0	8	35	30	100
103	Myllypuro	9.86	546	221	221	1181	91	61	0	0	27	5	46	120
104	Murronoja	4.38	509	89	227	968	92	57	1	0	59	10	45	114
105	Koppamäenoja	6.15	504	76	116	791	82	52	1	0	32	25	38	107
106	Kaukolanpuro	4.84	656	120	233	1138	91	63	1	0	49	2	46	126
111	Kuusivaaran-puro	27.6	361	131	149	745	89	50	0	0	29	7	35	94
112	Lismanoja	2.77	214	66	91	463	58	43	0	0	17	8	25	90
113	Korintteenoja	6.13	575	239	284	1111	92	75	0	3	5	7	39	124
114	Vähä-Askanjoki	16.4	464	79	55	709	88	67	0	0	6	21	32	101
116	Myllyoja	28.5	362	79	99	649	83	50	1	0	8	10	27	104
117	Iittovuoma	11.6	0	0	18	19	17	0	17	0	0	12	4	22
118	Kirnuoja	6.79	307	301	218	1020	78	25	3	0	14	21	46	101
119	Ylijoki	56.27	191	101	101	480	72	39	1	1	36	19	26	80

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Table 1 – *Continued from previous page*

ID	Catchment name	Size (km^2)	Pine RBM (10 kg/ha)	Spruce RBM (10 kg/ha)	Decid RBM (10 kg/ha)	Total RBM (10 kg/ha)	Forest (%)	Conifer (%)	Broadleaved (%)	Agri-cul-ture (%)	Drained peat-land (%)	Pris-tine peat-land (%)	Leaf cover (%)	Tree length (dm)
120	Kotioja	18.11	243	154	106	600	79	48	1	1	31	18	29	83
121	Laanioja	13.62	203	28	38	314	68	57	0	0	0	5	17	79
200	Valkea-Kotinen	0.34	467	1656	226	2495	86	86	0	0	4	16	63	213
201	Iso Hietajärvi	4.64	706	63	58	903	66	58	0	0	1	40	51	158
202	Pieni Hietajärvi	0.67	751	39	68	930	69	58	0	0	2	45	44	143
501	Kauheanpuro	1.76	432	269	210	1132	79	51	1	0	18	33	48	126
502	Korsukorven-puro	0.72	429	229	120	1007	73	60	0	0	7	47	42	130
503	Kangasvaaran-puro	0.56	561	862	245	1930	98	78	2	0	3	6	56	161
504	Kangaslammen-puro	0.3	535	880	436	2026	100	78	0	0	3	6	58	156
505	Porkkasalon-puro	0.72	742	854	233	1954	100	90	0	0	12	6	56	161

Table 2: Climate characteristics of study catchments

ID	Catchment name	Mean annual temperature (°C)	Mean annual precipitation (mm)	Max annual SWE (mm)	P/E_P (-)	Snow-off (Julian date)
7	Rudbäcken1	5	682	79	1.49	110
11	Hovi	4.8	652	79	1.42	113
12	Ali-Knuuttila	4.8	652	79	1.42	113
13	Yli-Knuuttila	4.8	652	79	1.42	113
14	Teeressuonoja	4.8	652	79	1.42	113
15	Kylmänoja	4.8	652	79	1.42	113
17	Koppelonoja	4	616	65	1.41	108
18	Löyttynoja	4	614	65	1.44	108
21	Löytäneenoja	4.5	566	73	1.09	111
22	Savijoki	4.9	664	73	1.28	111
31	Paunulanpuro	3.8	624	117	1.5	117
32	Siukolanpuro	3.8	624	117	1.5	117
33	Katajaluoma	3.9	678	73	1.61	111
41	Niittyjoki	4.4	646	96	1.38	111
42	Ravijoki	4.4	695	99	1.47	113.5
43	Latosuonoja	3.8	623	107	1.49	117
44	Huhtisuonoja	3.8	623	107	1.49	117
45	Juonistonoja	3.4	584	97	1.43	118
51	Kesselinpuro	2.9	605	132	1.32	121
52	Kuokkalanoja	2.8	645	132	1.42	121

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Table 2 – *Continued from previous page*

ID	Catchment name	Mean annual temperature (°C)	Mean annual precipitation (mm)	Max annual S_{SWE} (mm)	P/E_P (-)	Snow-off (Julian date)
53	Mustapuro	2.7	620	132	1.36	121
54	Murtopuro	1.7	658	196	1.74	127.5
55	Liuhapuro	2	624	196	1.63	127.5
56	Suopuro	1.8	642	196	1.71	127.5
57	Välipuro	1.8	642	196	1.71	127.5
58	Kivipuro	1.8	642	196	1.71	127.5
59	Koivupuro	1.8	642	196	1.71	127.5
61	Korpijoki	2.4	574	172	1.25	125
62	Kohisevanpuro	3	593	121	1.23	120
71	Ruunapuro	3.1	605	119	1.25	120
72	Heinäjoki	3.5	659	141	1.28	121.5
81	Haapajyrä	3.7	533	78	1	114
82	Kainastonluoma	3.7	547	78	1.05	114
83	Kaidesluoma	3.1	545	78	1.03	114
84	Norrskogsdiket	4	572	75	1.13	111
85	Sulvanjoki	3.9	535	78	1.06	114
91	Tuuraoja	2.8	478	93	1.02	117
92	Tujuoja	2.5	533	112	1.09	117.5
93	Pahkaoja	2.6	575	109	1.15	118
94	Kuikkisenoja	3.3	512	109	1.08	118
101	Huopakinoja	2.5	514	93	1.23	117

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ID	Catchment name	Mean annual temperature (°C)	Mean annual precipitation (mm)	Max annual S_{SWE} (mm)	P/E_P (-)	Snow-off (Julian date)
102	Vääräjoki	0	581	194	2.02	138
103	Myllypuro	1.3	600	179	1.96	133
104	Murronoja	1.9	607	172	1.33	125
105	Koppamäenoja	1.9	607	172	1.33	125
106	Kaukolanpuro	1.9	607	172	1.33	125
111	Kuusivaaranpuro	0	498	163	1.76	137
112	Lismanoja	-0.6	541	176	1.59	139
113	Korintteenoja	0.4	552	177	1.65	133
114	Vähä-Askanjoki	0.1	546	163	1.93	137
116	Myllyoja	-0.6	550	219	1.62	144
117	Iittovuoma	-2.2	434	154	2.42	140
118	Kirnuoja	2	494	157	1.3	128
119	Ylijoki	0.7	614	185	1.83	135.5
120	Kotioja	0.7	614	185	1.83	135.5
121	Laanioja	-1.2	541	207	1.95	147
200	Valkea-Kotinen	3.7	632	65	1.32	108
201	Iso Hietajärvi	2	652	175	1.31	130
202	Pieni Hietajärvi	2	652	175	1.31	130
501	Kauheanpuro	1.8	642	196	1.71	127.5
502	Korsukorvenpuro	1.8	642	196	1.71	127.5
503	Kangasvaaranpuro	1.8	640	196	1.68	127.5

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ID	Catchment name	Mean annual temperature (°C)	Mean annual precipitation (mm)	Max annual S_{SWE} (mm)	P/E_P (-)	Snow-off (Julian date)
504	Kangaslammenpuro	1.8	640	196	1.68	127.5
505	Porkkasalonpuro	1.8	653	196	1.72	127.5

2 Background on correlations between catchment characteristics

Figure 1 shows the correlations between S_r and the various catchment characteristics. From this figure it follows that the strongest positive correlation was found between S_r and the mean annual temperature and the strongest negative correlation was found for S_r and the (timing of) maximum S_{SWE}. Further, it can be seen that a strong correlation exits between the different vegetation characteristics and between the different climate variables. In addition, the different land covers (except for drained peatlands) also show a significant correlation with the climate variables.

[This figure was moved from the manuscript to the supplement]

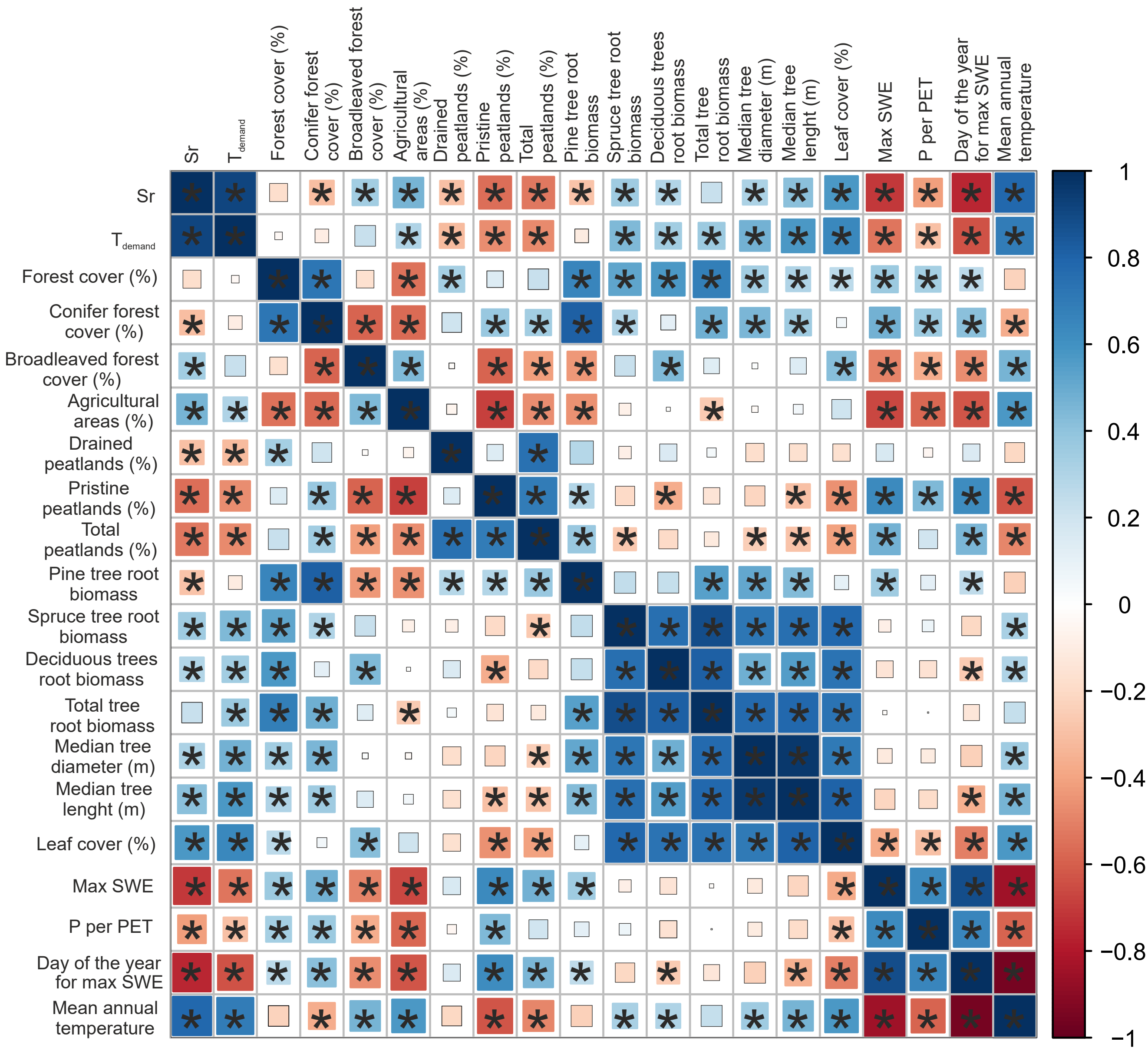

Figure 1: Correlation matrix for calculated root zone storage capacity (20 year return period), calculated transpiration demands (used in the S_r calculation) and catchment characteristics. The sizes of the boxes indicate the p-values; the asterisks indicates a significant correlation (p<0.05).