Dear Editor,

Hereby we submit the revised version of the manuscript entitled "Global distribution of hydrological controls on forest growth". We received positive and constructive feedback during the review process leading to two major changes in the manuscript: precipitation was replaced by aridity, to include thermal control on hydrology through potential evapotranspiration (PET), as suggested by both reviewers and yourself. Secondly, we updated the methodology of calculating significance threshold slightly and compared the resulting classification with two different procedures and found the results to overlap in over 90% of the pixels. This strong overlap gave us confidence in the methodology, and we believe that the results and conclusions are robust. The reviewers seem to further agree that the manuscript is interesting and well written. We hope that the rebuttal will be positively received by the reviewers.

Best regards, on behalf of all co-authors,

Caspar Roebroek,

Utrecht, 22-6-202

Anonymous Referee #1

In this interesting work, the authors classify the land surface into patterns of dominant effects on forest growth by precipitation or water table depth (wtd) using satellite imagery of fPAR as a proxy for forest growth, modelled wtd, and measured and interpolated precipitation. The analysis is based on spatial correlations between long term averages of the high resolution data sets. They find that the relationship between precipitation and fPAR is prevalent, but the effects of wtd are still widespread and important. The authors also illustrate variations of the relationships as the result of local climate conditions and landscape characteristics. As the authors convincingly explain in a paragraph in the discussion, the results prove that in current modelling approaches of the land surface using exclusively precipitation as a hydrologic control on forest growth is not sufficient and the work is therefore timely and relevant. The paper is very well written, the analysis steps are clearly explained including underlying assumptions and the results are logically structured and interpreted.

I was wondering, however, why the authors used full correlations all the way through their analysis when the scope was to actually isolate the hydrological control/ contribution. As mentioned in the description of several ecohydrological classes and sometimes in the interpretation of the results, spatial covariates like temperature play a role and will explain some of the patterns of correlations found, especially those with precipitation. So, why not remove at least the contribution of spatial gradients in temperature as a known important control on forest growth by partial correlations to narrow down the contributions of the hydrological controls?

We agree with the importance of discussing temperature as a major contributor to determining vegetation growth. However, it should be noted that temperature effects alone cannot easily be removed due to their strong covariability with P. In order to account for the effect of temperature, we therefore took a different approach. We replaced precipitation with aridity (P/PET) in the analysis procedure to express climate driven water availability rather than only water supply. Interestingly, the results and main conclusions remained almost identical, strengthening the belief that energy and water availability are inherently intertwined and in most instances inseparable in such large-scale data analyses. By introducing temperature as a covariable, we could make the descriptions of high altitude and cold climates more straightforward, thus strengthening the conclusions.

I might pose a similar question regarding the relationship between precip and wtd, which might also be split more rigorously. However, the authors take this into account in the interpretation and explain well in the paper, so I do not pose this a major point of discussion.

We included a global map representing the correlation between P/PET and WTD (in the supplementary material) and stressed their link in the class descriptions to clarify this point better. Especially the classes on the diagonal of Figure 2 (oxygen stress, neutral, and water limited) are strongly dependent on the link between climate and landscape driven water availability, and represent the classical view of global vegetation growth assessment (such as Köppen-Geiger climate classification). One of our main results is that by separating the

gradients, most cases are not represented in this diagonal, which caused us to conclude that on global scale, landscape changes climate driven expectations on vegetation growth substantially.

Overall, the work the authors present in their paper is scientifically interesting and relevant, methodologically mostly logical (next to the one major point stated above, I pose some minor methodological questions below that need clarification or justification in my opinion), and is presented in an excellent way regarding both text and figures. I see the need for revision and minor clarifications before publication.

Minor aspects that need clarification/ discussion and potentially changes in the manuscript:

- Consistency of the long-term averages of the data sets: As shown in table 1 of the main text, the length and the periods that they represent differ by 10 years and more between individual data sets. How might this affect the consistency of the long-term averages that are the basis of the analysis?

In this study we are using data with high resolution, obtained from long term observations. The climate variables and water table depth are from an earlier period than fAPAR. We expect changes in climate to be more regional, and therefore not affect the gradient within each 15 x 15 window. Also, we do not expect WTD to have changed considerable, as the landscape forms are still the same. This will not always work, in such cases as local water extractions being implemented, but on average on the whole world these changes will be relatively minor. Therefore, the period mismatch will presumably lower the correlation values somewhat, but significance might still be tested. We believe this mismatch will not substantially influence the conclusions.

Secondly, the data availability of at least the fPAR dataset will vary seasonally due to snow or cloud effects. Has this issue been considered and taken into account in some way in order to prevent the longterm averages to be seasonally biased?

The following fPAR data source has been used: https://developers.google.com/earth-engine/datasets/catalog/MODIS_006_MCD15A3H. It uses the best value for each pixel in four consecutive days. The long-term averaging has been performed on this data directly to mostly avoid phenomena such as cloud effects.
The biases in the averaging and the seasonal cycle are addressed by the regional scale on which the correlations are calculated. Within each 15x15 grid cell window these biases are assumed homogeneous. The absolute values will shift, but the gradients would remain equal, yielding similar correlation values. We added this assumption to the methodology section to avoid ambiguity.

- Is the scope to analyse hydrological control of trees or of forests? From the title I expected only forests, but basically all results are based on any pixels having a canopy height>3m independent of any definition of a forest, eg tree density.

We are interested in all natural vegetation but applied a filter of 3 meters to exclude most farmland as the signal of the natural controls will be heavily distorted. This threshold to

classify trees seemed reasonable and is often used in literature. A pixel containing vegetation with an average height of 3 meters is consequently called forest. For clarity we will explain the use of 'forest' better in the methodology.

The assumption that the 'translation from fAPAR values to photosynthetic activity are homogeneous' (l. 91) in each moving window appears strong when only the threshold of 3m is used as a filter criterion and in reality several vegetation types might be mixed in the pixel. A slight rewording in the first and a clarification in the second case are appreciated.

This is indeed a good point. We assume not only vegetation type, but also vegetation age to be homogeneously distributed over each window (which would then make it justifiable to also assume a similar conversion function between fPAR and actual photosynthesis). Locally this assumption will not always hold, but we believe this assumption is reasonable for a global synthesis and that the errors in the assumption do not substantially alter the final observations and conclusions.

- Are only those correlations displayed and evaluated that were tested as significant? Have you tried whether the results strongly change of you apply other criteria in addition, such as a (higher) correlation threshold? A threshold of 0.11 for a significant correlation for fully available spatial windows (l.101) is quite low as to have a strong meaning for the interpretation.

We indeed only analysed and evaluated the significant correlation values. To strengthen the results and compensate for the spatial autocorrelation of the samples (see comment by reviewer #2) within windows we altered the methodology slightly and reduced the degrees of freedom used in the t-test, based on an adaptive approach which compares the t-test approach with a bootstrapping analysis and permutation test. Finally, we compared the three approaches directly by classifying South America in the ecohydrological classes. All methods show a very high degree of overlap, which makes us confident that the conclusions are robust and method independent. The results of this comparison are included in the supplementary information.

Anonymous Referee #2

General comments: In their work the authors present a method where they link forest growth patterns to precipitation and water table depth on the global scale. They use long term high resolution satellite products for fAPAR, modelled groundwater table depth and globally distributed precipitation. They have developed a classification scheme of ecohydrological classes based on the correlation between water table depth and fAPAR as well as precipitation and fAPAR. To assess the impact of climate and landscape position on the distribution of these ecohydrological classes, the authors make use of the Köppen-Geiger classification (climate) and 7 landscape classes derived from the global water table depth map. They discuss and illustrate their findings for several regions of the globe. In the end, based on their findings they develop a conceptual framework of forest growth and its link to hydrologic gradients in the landscape. Finally, the authors discuss how their findings can support a better representation of forest growth in global environmental modelling which is still a relevant question. The manuscript is well written and conceivable. It is provided with an extensive supplement which contributes to the understanding of the manuscript. There are some small points which should be clarified because they might lead to misinterpretations which, I will address in specific comments section and section for technical correction. However, I have two major points which should be discussed by the authors with more emphasis.

How have the landscape positions been validated, the map presented in Figure S6 makes sense at the global scale, but how valid are the results if you look at the landscape scale, where the authors develop their conceptual framework? I assume this can be easily done with global topography data such as SRTM. I would encourage the authors to discuss this a little bit more in detail since the landscape position is a critical part in your analysis.

The landscape classification was based on the same water table depth dataset used for the correlation calculations. This water table depth map data was produced with global topography data as one of the input datasets. The resulting classification was validated visually against some geological literature on sample regions. As with any classification some locations will be misclassified, but it does pick up on even quite small landscape features, as I will demonstrate in two examples.

Example number one is a closeup of the Netherlands (Figure 1). The bigger landscape units, the 'wetland and open water' class, defines most of the west and north of the Netherlands, the areas with extensive lowland polders (Hartemink and Sonneveld, 2013). Smaller landscape units are visible as well; the coastal dunes in the west of the Netherlands and the individual push moraines in the Veluwe complex (central Netherlands) can be distinguished (for reference see Overmeeren, 1997). Also, smaller units are visible such as the river levees of both the Meuse and Waal (the last part of the Rhine).
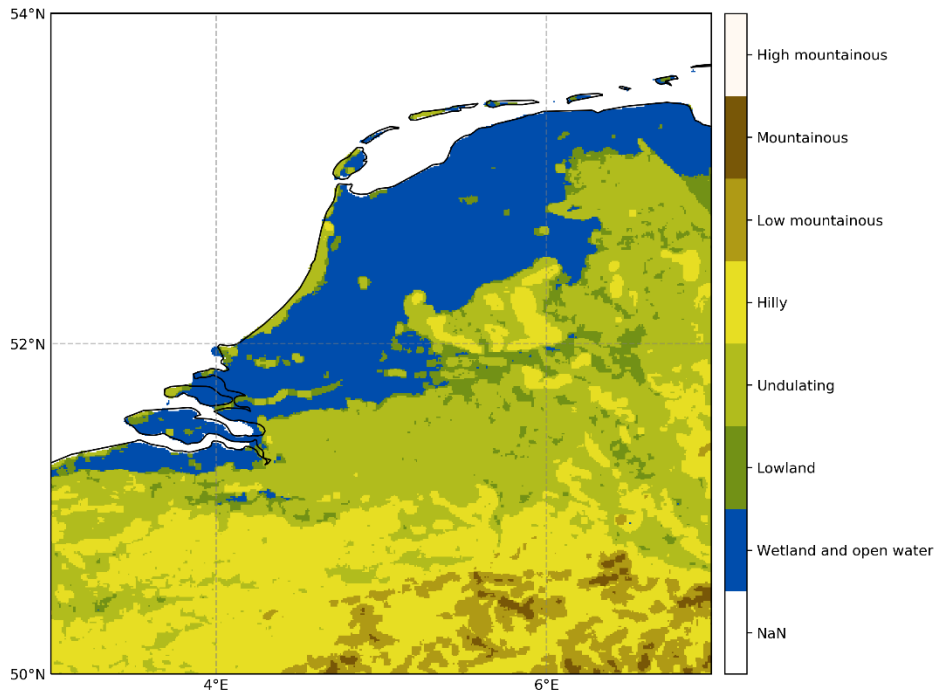
The second example shows northern Italy (Figure 2). The Alps show up as the highest locations in this example, with some detail in this mountainous area. The Apennines appear as mountainous but clearly lower than the Alps. In between, the Po valley shows up as low lying area and the delta (close to Venice) shows up as 'wetland and open water'. Smaller units are picked up as well; several lakes appear, most notably Lago di Garda, just under the Alpine region. Just below the Alps, the Euganean Hills – protrusions in the Po valley of volcanic origin – show up as well.
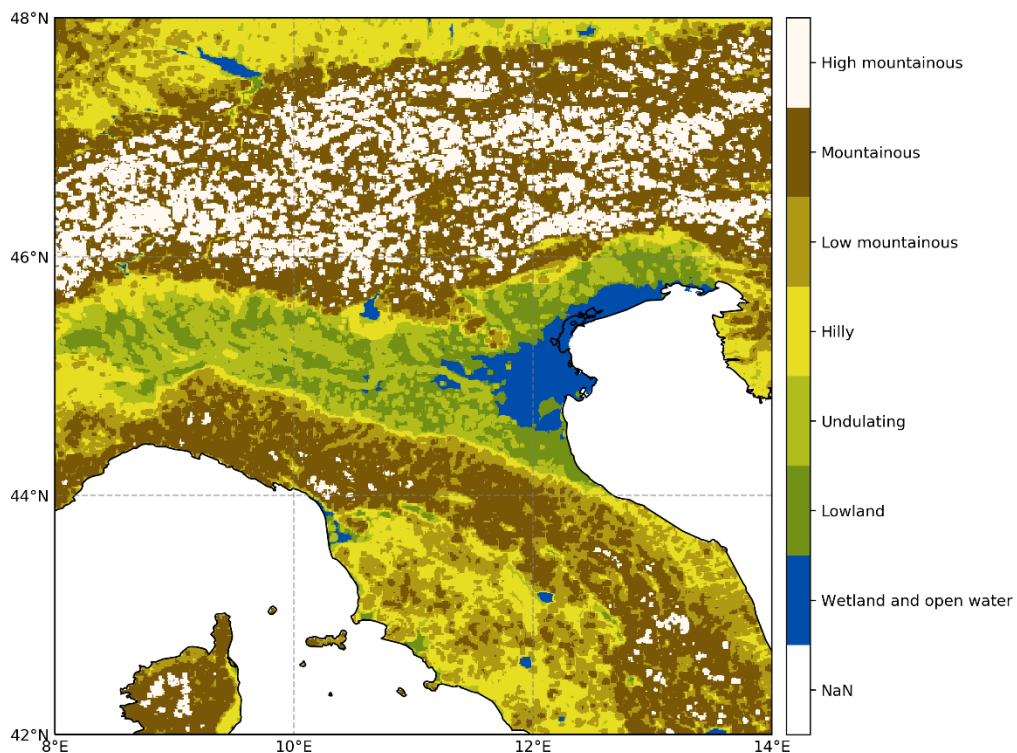
We included these examples in the supplementary material. Additionally, we will add a sentence to the main text describing that the classification has been validated based on visual inspection based on several sample regions.

In the description of the Ecohydrological classes in section 2.3 I would stronger present the effects of temperature on forest growth in the higher landscape positions to avoid misinterpretations. Since this class is mostly present in the higher landscape classes of the temperate regions.

Based on the comments of reviewer 1 and the editor we decided to more thoroughly include the effect of temperature by substituting precipitation with aridity (P/PET). For details see above and in the updated manuscript.

Specific comments

statement line 12 to 14 In my mind this statement is only true for water limited areas. For more humid, energy limited environments like the temperate and boreal zones I am not sure whether water availability determines whether vegetation grows or not especially when it comes to trees. I would argue that in the colder climates and higher mountainous areas plant growth an especially Tree growth is also limited by temperature which can be clearly also seen by the tree line distribution in the high mountain areas in the temperate regions as well as in the northern climates.

Although we definitely agree with the more nuanced picture the reviewer describes, the point we wanted to make with this sentence is that by looking globally at the vegetation distribution, water availability is key in understanding the patterns. If insufficient water is present, vegetation does not grow. On the other hand, if enough water is present it does not mean that vegetation definitely does have to grow. Besides temperature, also soil depth, stability and toxicity might be other factors preventing plants to grow at all. To avoid ambiguity, we will change the sentence to:

"Water availability is a prerequisite for vegetation growth, while plants influence the local hydrological situation through interception of precipitation and transpiration of water absorbed in the root zone."

Statement line 16 to 20 This statement might be true on large continental scale, however as experiences of the drought years 2018 and 2019 in Europe have shown that forests mainly consisting of species trees species with shallow roots such as spruces suffered serious damages during the droughts.

This is indeed a good point. This statement is meant to address the point that trees have deeper roots than other vegetation and because they are long lived species they need to be adapted to the local climate and hydrological conditions. This makes them more resilient to weather anomalies (on an ecosystem level) but extremes can still be deadly, especially for varieties (or relatively young forests) with shallower root systems. The drought of 2018 and 2019 was quite extreme for the European climate. We will change the sentence to the following:

"Because they can take up water from considerable depth with their extensive root systems, trees are highly adapted to the local climate and hydrologic regime, making them *more* resilient to weather anomalies, such as prolonged periods of drought"

Statement line 45 to 47 Rooting depth also depends soil properties like the existence of a layer of higher density in the soil profile. This is for instance very often the case in landscapes which have developed after the glaciation period or have been influenced by glaciation (e.g. in North America, Central Europa, Northern Part of Asia).

Thank you for the nuance, we will add the following statement to the manuscript:

"Exceptions can occur for various reasons, such as slope instability, insufficient soil depth and the presence of hardpans in the soil."

Figure 6: I would have expected a stronger temperature effect on forest growth also in the lower landscape classes like low mountain areas and hilly landscapes. How can this be explained?

The effect of temperature in these areas is most likely present, but the effect of increased precipitation at the highest locations seems to be dominant.

Figure 7: For the boreal and temperate regions the figure indicates a deep and unchanging rooting depth from low mountainous, mountainous and high mountainous regions. This is misleading. In fact in these areas the rooting depth decreases with elevation. In the higher elevations only shallow soils over bedrock can be found. So the development of the rooting depth should be similar as presented in the arid region.

Corrected

Technical note:

Legend Figure 1 change contrained to constrained

Corrected

Figure 7 the color codes of the arrows and lines need to be explained, either in the legend or the figure caption

Corrected

Figure S20 the figure caption mentions relationship between fAPAR and climate and landscape positions but the legend says WTD, please clarify.

Corrected
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Global distribution of hydrologic controls on forest growth

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Abstract. Vegetation provides key ecosystem services and is an important component in the hydrological cycle. Traditionally, the global distribution of vegetation is explained through ~~water availability by precipitation~~climatic water availability. Locally, however, groundwater can aid growth by providing an extra water source (e.g. oases) or hinder growth by presenting a barrier to root expansion (e.g. swamps). In this study we analysed the global correlation between ~~precipitation~~aridity (expressing
5   climate driven water availability), groundwater and forest growth, approximated by the fraction of absorbed photosynthetically active radiation, and linked this to climate and landscape position. The results show that at the continental scale, ~~precipitation~~climate is the main driver of forest productivity; ~~wetter climates~~ climates with higher water availability support higher energy absorption and consequentially more growth. ~~But within all climates,~~ Within all climate zones, however, landscape position substantially alters the growth patterns, both positively and negatively. The influence of the landscape on vegetation growth
10   varies over climate~~. The results display~~, displaying the importance of analysing vegetation growth in a climate-landscape continuum.

1   Introduction

Vegetation, key for many ecosystem services such as food production and climate stabilisation by absorbing CO_2 (Keenan and Williams, 2018), is an important component in the hydrological cycle. Water availability ~~determines whether vegetation is~~
15   ~~present at all~~is a prerequisite for vegetation growth, while plants influence the local hydrological situation through interception of precipitation and transpiration of water absorbed in the root zone. Especially trees can impact the water fluxes substantially, returning significant amounts of water back into the atmosphere ~~(Kunert et al., 2017; Brauer et al., 2018)~~(Ellison et al., 2017; Kunert et al., . As a result, large scale changes in forest cover can influence continental-scale patterns of water availability and streamflow (Teuling et al., 2019). Because they can take up water from considerable depth with their extensive root systems (Canadell
20   et al., 1996), trees are ~~therefore~~ highly adapted to the local climate and hydrologic regime (Wang-Erlandsson et al., 2016; Gao et al., 2014), making them more resilient to weather anomalies, such as prolonged periods of drought (Nepstad et al., 1994; Kleidon and Heimann, 1998; Bowman and Prior, 2005; Walther et al., 2019).

Plant available water, and with that vegetation growth, has traditionally been approximated by atmospheric states and fluxes~~such as precipitation (P) and evapotranspiration (ET). An~~. A prime example is the Köppen-Geiger climate classification, which links ecosystems to the global distribution of precipitation and temperature (Beck et al., 2018). In line with this idea, Scheffer et al. (2018) recently showed that huge trees only occur in a climate niche with extensive amounts of rainfall. Local constraints on vegetation growth have, with a similar reasoning, been approximated by the Budyko framework (Helman et al., 2017; Xu et al., 2013), which evaluates climate average precipitation, reference evapotranspiration and actual evapotranspiration to separate ecosystems into energy- or water-limited systems (Gunkel and Lange, 2017). Similarly, a recent study by Tao et al. (2016) showed a strong relation between tree growth and water yield (P $-$ ET).

The distribution of ~~atmospheric fluxes and states~~ climatic drivers alone, however, can not fully explain vegetation growth worldwide (Fan, 2015). For example, oases appear as green islands in the middle of extensive arid regions, and gallery forests exist along the rivers in otherwise dry grassland areas under seasonally arid climates. In both cases lush vegetation can grow because the plant roots can tap into the groundwater to complement their water availability from local precipitation. The water table in these ecosystems is shallow in comparison with its surroundings due to topographic redistribution of precipitation surplus. Groundwater converges towards these niches, yielding relatively high water availability, decoupled from the local precipitation (Fan, 2015). If the water table is shallow, precipitation can even become a hindrance for plant growth because it causes root-zone water-logging, limiting root oxygen uptake and hence limiting growth (Bartholomeus et al., 2008; Nosetto et al., 2009; Rodríguez-González et al., 2010; Florio et al., 2014). As such, land drainage conditions can alter the relation between precipitation and plant growth substantially, both positively and negatively.
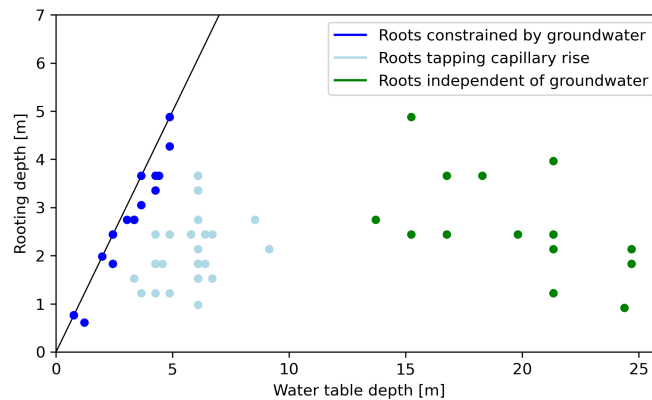

Figure 1. Illustration of the effect of water table depth on plant water uptake strategies, showing the rooting depth of 47 trees in Eastern Nebraska plotted against water table depth measured at their specific sites. Soil ~~properties~~ and ~~precipitation~~ climate properties are ~~both~~ relatively constant in the region. The roots can be divided in three distinct categories: (1) root growth is restricted by the groundwater, (2) roots are tapping the capillary rise, (3) roots are independent of the groundwater. Data from Sprackling and Read (1979) and interpretation adapted from Fan et al. (2017).

At the local scale, the effect of the water table on plant growth has been studied extensively. In an ~~extensive~~ large case study, in an area with similar soil ~~properties and precipitation~~ and climate properties (Sprackling and Read, 1979), roots were found to fall in three categories (see Figure 1): (1) roots terminating at or constrained by the groundwater, (2) roots tapping capillary rise and/or the groundwater in the wet periods and (3) roots completely detached from the groundwater (Fan et al., 2017). At the farm scale, these patterns were also observed (Zipper et al., 2015), with the conclusion that optimal plant growth occurs at the interface between the groundwater limiting root respiration and roots being completely decoupled from the groundwater. In other words: the local optimum in vegetation growth lies where the best balance between water availability and (thermally controlled) evaporative demand is found.

Site-based studies suggest that, at the landscape scale, rooting depth depends on the climate in the uplands, but on the water table depth in the lowlands ~~,~~ (exceptions occur for various reasons, such as slope instability, insufficient soil depth and the presence of hardpans in the soil), presenting an optimal position where growth is aided by the groundwater while not suffering from rooting space limitation (Zipper et al., 2015; Fan et al., 2017). ~~At the global scale , Koirala et al. (2017) examined the~~ In global scale analyses a similar picture arises, with vegetation growth being energy limited in high altitude (Körner and Paulsen, 2004), and high latitude regions (Keenan and Riley, 2018). Koirala et al. (2017) recently presented the first global study on the influence of the water table depth on vegetation growth. They found that both mechanisms, plant growth aided by groundwater in water limited areas and plant growth hindered by groundwater due to oxygen stress, were reflected in the global satellite imagery analysis. The questions that remain are what the interplay is between ~~precipitation and~~ climate-driven water- and energy availability and groundwater for vegetation growth, how landscape position determines this interplay over different climates, and how extensive the area is in which vegetation growth is influenced by the groundwater.

Therefore, the purpose of this study is to understand and evaluate the global distribution of the effect of both ~~precipitation and~~ climate-driven water- and energy availability (reflected by aridity) and land drainage (reflected by water table depth) on vegetation growth, and to assess the control of climate and landscape on these processes. To do this, we make use of global high-resolution (30 arc-seconds) datasets of water table depth, precipitation, potential evapotranspiration and tree growth, approximated by the fraction of absorbed photosynthetically active radiation (fAPAR). The relatively high resolution for a global study allows us to account for landscape-scale features within computational limits (Fan et al., 2017). We focus on trees, rather than vegetation in general, because they better represent the long term local hydrologic regime. At the same time this lets us avoid confounding signals such as irrigation of annual crops, the response of annual vegetation to seasonal availability of soil water and inter-annual variation. In this way we aim to evaluate plant productivity over a climate gradient at the global scale, and quantify the global extent of vegetation growth influenced by the water table.

2 Materials and Methods

2.1 Input data

To approximate tree growth we used two different datasets. The first one is the MODIS fAPAR product, which is used as an approximation of plant primary production (Wu et al., 2010). The data has a 15 arc-second spatial and an 8-day temporal reso-

lution (Myneni et al., 2015). For this study, we averaged the data over the period 2003 to 2018 and subsequently downsampled it to a spatial resolution of 30 arc-seconds using bilinear interpolation (see Figure S1). The second dataset is a global map of tree height, created from space-borne LIDAR images and validated against field measurements at different FLUXNET sites (see Figure S2) (Simard et al., 2011). To solely focus on trees (to largely avoid the distorted signal of irrigated croplands), the fAPAR dataset was filtered with the tree height data, using a height threshold of 3 meters. The resulting pixels are subsequently referred to as forest, but might not in all regions be consistent with the classical understanding of forested ecosystems. For water table depth (WTD), the dataset by Fan et al. (2017) is used (updated version of the original dataset in Fan et al. 2013). This dataset was produced by an integrated groundwater, soil water and plant root uptake model at 30 arc-second resolution and at hourly time steps (see Figure S3). The precipitation data (WorldClim V2) was created by interpolating station observations using ancillary information, under which MODIS land surface temperature and a digital elevation model (Fick and Hijmans, 2017) (see Figure S4). A summary of the datasets is provided in Table 1. The time period column describes the time frame of the input data of the specific studies to generate the datasets used here As described in the introduction, temperature plays a major role in vegetation growth, both through reducing plant available water with evaporative demand as well as by direct thermal control on growth. Here we focus on the hydrologic control on growth and account for the effect of temperature on water availability by normalising precipitation by (Penman-Monteith) potential evapotranspiration (PET), often referred to as aridity. The data on potential evapotranspiration was produced from the data available in the WorldClim V2 database (see Figure S5 and S6 for a global representation of PET and P/PET respectively) (Zomer et al., 2008; Trabucco and Zomer, 2018). Although we focus on the hydrologic drives, the direct control on growth exerted by temperature will be implicitly represented in one of the ecohydrological classes presented below. A summary of the datasets is provided in Table 1. It should be noted that both the WTD and fAPAR datasets were created using the MODIS MCD15A2H data and are therefore not completely independent. The MODIS data was used in the WTD model to describe the vegetation characteristics and to calculate the evapotranspiration and groundwater recharge fluxes. We believe this dependence to reflect the natural relation between vegetation and groundwater. Also, the impact on pixel-to-pixel correlations (between the fAPAR and WTD data) will be limited because of spatial exchange of information in the WTD dataset, which causes the WTD to mainly reflect topography rather than local vegetation conditions.

2.2 Analysis procedure

To understand and visualise the relation between the hydrologic gradients and forest growth, the local Pearson correlation was calculated between (1) WTD and fAPAR and between (2) P/PET and fAPAR. This was done by applying a moving window (15×15 grid cells) to both datasets and correlating the values within that window. Windows containing less than 25 percent of the data were discarded. This approach was chosen over catchment binning, as used in previous studies (Koirala et al., 2017), to minimise compensation of contrasting relations (rooting space limitation in lowlands and groundwater convergence driven vegetation growth in uplands both occurring in a single catchment resulting in a net neutral relation between the water table and vegetation growth). Finally, each pixel contains a correlation value between the hydrologic gradient (WTD, P/PET) and vegetation growth. With this approach it is assumed that within each window, ecosystems (e.g. forest age), soils (e.g. nutrient

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Table 1. Summary of the datasets used in this study. The time period column describes the time frame of the input data of the specific studies to generate the datasets used here.

Dataset	Spatial resolution $[arc-seconds]$	Time period	Version	Reference	
fAPAR	15	2003 - 2018	MCD15A2H V6	Myneni et al. (2015)	
Tree height	30	2005	-	Simard et al. (2011)	
Water table depth	30	~~1961~~2003 - ~~1990~~2014	V2	Fan et al. (2017)	
Precipitation	30	1970 - 2000	WorldClim V2	Fick and Hijmans (2017)	
Potential evapotranspiration	30	1970 - 2000	WorldClim V2	Trabucco and Zomer (2018)	
Climate zones	30	1980 - 2016	V1 (present)	Beck et al. (2018)	S
Landscape classes	30	1961 - 1990	-	Text S1	S

availability), management parameters (e.g. fertilisation), ~~error~~ uncertainty in the input data and translation from fAPAR values to photosynthetic activity are homogeneous. The resulting correlation values are subsequently tested for significance, resulting in a negative, neutral or positive category in each pixel. The threshold of significance was calculated by casting the correlation values into the t-distribution with Equation 1, in which r corresponds to the correlation, t to the t-value and ~~n to the number of samples~~df to the degrees of freedom.

$$t = r\sqrt{\frac{n-2}{1-r^2}} \sqrt{\frac{df}{1-r^2}} \tag{1}$$

This can be rewritten to calculate the critical correlation value based on the t-value.

$$r = \frac{t}{\sqrt{df + t^2}} \tag{2}$$

The degrees of freedom are determined with the following formula, in which n represents the number of samples:

$$\underset{\sim}{r}df = \frac{t}{\sqrt{n-2+t^2}}(1-df_{offset})n-2 \tag{3}$$

~~Using the~~ The df_{offset} parameter is introduced to compensate for the spatial dependence of the samples due to the spatial organisation of the landscape. If the data were not auto-correlated, the df_{offset} parameter would be 0, in which case the traditional formula for calculating the confidence boundaries for correlation values appears. This additional parameter is determined by matching the significance boundaries of the t-test with boundaries determined by applying a permutation test and a bootstrap analysis (as described in Rahman and Zhang, 2016) to all windows with exactly 225 data points. The exact procedure and results, including a visual comparison of all three methods is presented in supplementary text S1 (see Figures S7 and S8 for the results of the permutation test and bootstrapping analysis, and the effect of the chosen metric on the final

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125 classification as described below). Subsequently, using the percent point function of the t-distribution with a significance level of $p < 0.05$ ~~and~~ (using a one-tailed approach), the significant t-value can be calculated. Feeding this value into Equation 2, the t-value can be translated into the threshold correlation value. With 225 sample points (15×15 pixel moving window approach, assuming all pixels contain values) this yields ~~that the threshold for considering correlation significant is 0.11~~significant correlation values above 0.121 for the correlations between P/PET and fAPAR and 0.130 for the correlations between WTD

130 and fAPAR (see Figure S7). In windows containing fewer data points, this threshold increases accordingly. If an absolute correlation value exceeds the respective threshold, it is interpreted as significantly positive or negative, depending on the the sign of the value.

To investigate the interplay between P/PET and WTD on forest growth, we combined the two significance maps, yielding nine distinctive classes (see Figure 2), henceforth called ecohydrological classes. This combination is visualised using a

135 bivariate colour scheme ~~(Teuling et al., 2011)~~(Teuling et al., 2011; Speich et al., 2015). For the interpretation of the classes it needs to be considered that WTD is defined negatively; a higher value (less negative) corresponds with a shallower water table. Consequently a positive correlation between WTD and fAPAR means higher plant productivity with a shallower water table. A negative correlation signifies an increase in productivity for a deeper water table. A positive correlation between P/PET and fAPAR means higher plant productivity with higher ~~precipitation~~climate driven water availability. To interpret the different

140 classes, the key shown in Figure 2 is proposed, which is discussed in the next section. The classes have been interpreted and named a priori, based on a review of literature (see Introduction) and the current state of understanding.

The effect of landscape and climate on the hydrologic controls of vegetation growth was characterised by analysing the obtained ecohydrological classes in different climate zones and landscape positions. A recent, high resolution Köppen-Geiger climate classification was used, based on the same precipitation data as used for this study (Beck et al., 2018)(Figure ~~S5~~S9).

145 To asses landscape positions, we used a landscape classification based on the moving window mean and standard deviation of WTD (5×5 pixels). Subsequently, the result was binned into 7 landscape classes: wetland and open water, lowland, undulating, hilly, low mountainous, mountainous, high mountainous (see Text ~~S1~~S2 in the supplementary information). The classification scheme is depicted in Figure ~~S7~~S10 and the resulting map is presented in Figure ~~S6.~~S13. The resulting classification has been visually validated against several sample regions (Figure S11 and S12).

150 All maps are downsampled to a resolution of 5 arc-minutes by applying a majority kernel on categorical and a mean kernel on continuous data. This was done to ease calculation and to be able to focus on the global patters. Some figures are displayed at their full resolution to discern finer patterns in the maps, in which case it is stated in the caption.

2.3 Ecohydrological classes

Based on the significance of the correlation analysis between WTD and fAPAR, and between P/PET and fAPAR, we distinguish

155 9 ecohydrological classes. These are depicted in Figure 2. Below we provide a description of each class, discussing processes that might play a role in the vegetation - hydrologic gradient relation, starting from the bottom left.

[*Oxygen stress*]; In this class, negative correlations with both hydrologic gradients suggests that plant growth is limited by higher precipitation and shallower groundwater, indicating an excess of water with poor drainage conditions. This combina-
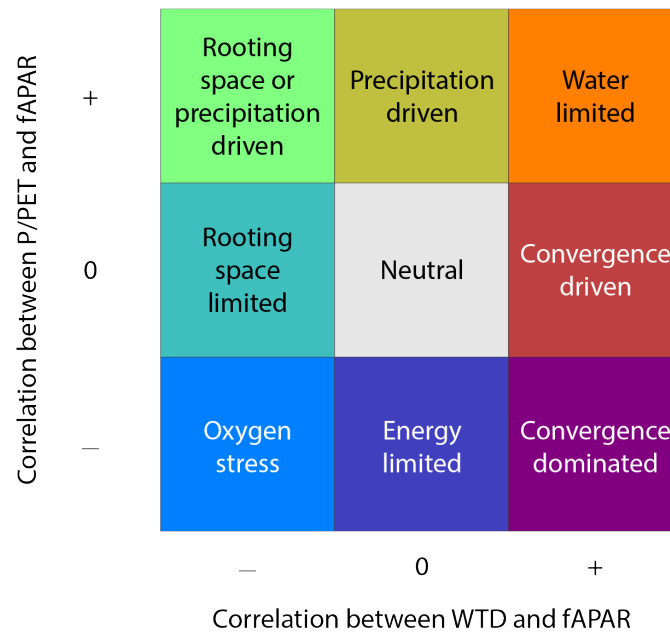
6

Figure 2. Ecohydrological classes and their interpretation of the combined spatial correlation maps between respectively WTD, P/PET and fAPAR. The figure is used as the legend of Figures 3, 4, 5, 6 and 7

tion causes root-zone water-logging, which limits root respiration (oxygen stress) and hence growth (Nosetto et al., 2009;

160 Rodríguez-González et al., 2010; Florio et al., 2014; Zipper et al., 2015).

[*Rooting space limited*]; Here, plant growth is limited by shallower groundwater. In humid climates this indicates an excess of water in combination with poor drainage conditions. This class is largely similar to *Oxygen stress* except that there is no clear relation between precipitation and vegetation growth, which might be caused by the absence of a clear precipitation gradient. In arid and seasonally arid climates, the negative influence of the vicinity of the water table might be explained by high salt

165 concentrations of the water in low landscape positions. Due to groundwater convergence, salts are transported to the lowest positions in the landscape and high evapotranspiration increases the salt concentration dramatically, hindering plant growth (Jolly et al., 2008).

[*Rooting space or precipitation driven*]; This class is a transitional class between *Rooting space limited* and *Precipitation driven*. Either the negative correlation between WTD and fAPAR (rooting space limitation) or the positive correlation between

170 ~~precipitation~~ P/PET and fAPAR (water limitation) explains the local tree growth gradients while the other correlation is caused by a negative relation between WTD and precipitation. Often this negative relation can be explained by orography. Since WTD is roughly the inverse of altitude, locations with orographic precipitation (Fick and Hijmans, 2017) have a clear negative gradient between WTD and P. This negative correlation can sometimes also be explained by micro-climatic phenomena. This class can be interpreted as *Rooting space limited* if roots reach the groundwater and *Precipitation driven* if roots do not reach

175 the groundwater. Alternatively, in the dryer parts of the world, this class can also be interpreted directly as forests growing on

the edges of basins where both a deeper water table and higher (orographic) precipitation help to counter growth limitation by high salt concentrations. In the centre of these basins the salt concentration is very high due to groundwater convergence transporting the salts and strong evapotranspiration. Higher rainfall in combination with well drained soils can flush away the salt, creating more favourable conditions. This explains both the negative correlation between WTD and fAPAR and the

180   positive correlation between P/PET and fAPAR.

[*Precipitation driven*]; Plant growth is enhanced by increasing precipitation and is decoupled from the groundwater table. This likely occurs in well-drained, upland positions, where roots cannot reach the groundwater, under climatic conditions where plant growth is slightly to severely limited by water availability. Here, precipitation is the main driver for productivity.

[*Water limited*]; Plant growth is stimulated by a shallower water table and higher precipitation, indicating a general lack

185   of water. This likely occurs on mountain slopes where the water table is within root reach and in (semi-)arid climates where plants depend on deeper ground water. ~~In mountainous regions this class can, however, have another possible explanation. If the highest landscape positions receive less precipitation than the associated valleys, the relation between water table depth and precipitation will be positive. This can, for example, occur when the higher positions are above the zone of maximum precipitation (Miller, 1961; Junquas et al., 2016). Together, this means that higher vegetation growth can be expected in valley~~

190   ~~positions (higher vegetation growth with a shallower water table) with higher precipitation. In this case the class can be linked to growth limitation at higher altitudes, like lower temperatures and a shorter growing season (Fan et al., 2009).~~

[*Convergence driven*]; Plant growth is stimulated by a shallower water table. This represents areas that receive water from surrounding, higher areas by lateral redistribution of the groundwater, as described in Fan (2015). This likely occurs in arid or seasonally arid climates where precipitation is low and irregular, but where the groundwater is within the reach of roots.

195   These circumstances occur, for example, in desert oases and gallery forests (Fan, 2015). In mountainous regions this class can also be related to different processes that are linked to higher altitudes (further from the water table generally means higher in the landscape), like lower temperatures (Leal et al., 2007), a shorter growing season (Fan et al., 2009) and lower nutrient availability (Leuschner et al., 2007), that hamper tree growth.

[*Convergence dominated*]; Plant growth is stimulated by a shallower water table but is limited by an increase in precipitation.

200   This class is a transition between *Convergence driven* and *Energy limited*. In water limited climates this corresponds to similar environments as described in *Convergence driven*: vegetation growth is mainly determined by the gradient in water table depth. In energy limited environments this class expresses higher vegetation growth in lower landscape positions (thus a positive correlation between WTD and fAPAR) as the energy availability is higher and the growing season longer. In both cases the negative correlation between precipitation and fAPAR mainly occurs because of the orographic link between the water table

205   depth and precipitation. ~~The negative correlation between precipitation and fAPARlikely occurs in the following scenarios. Firstly, the orographic effect causes higher precipitation in regions with higher altitudes. In arid or seasonally arid regions this increase in precipitation is present but cannot provide vegetation with as much water as the groundwater can in the lower positions, leading to an apparent negative correlation . Secondly, higher precipitation comes with higher cloud cover and lower temperatures, which in turn can limit plant growth. Here, vegetation growth mainly happens during the dry period, during~~

210   ~~which groundwater access is a major advantage for plant growth.~~

[~~Composite~~*Energy limited*] This class displays no significant relation between the proximity of the groundwater and plant growth while plant growth is negatively influenced by ~~precipitation. This can mean different things in different landscape positions. Firstly, in lowland regions it can be linked to oxygen stress (as in class~~ aridity. The negative correlation with aridity indicates that vegetation growth is constrained by energy availability, which is traditionally described as energy limited systems. In lowland positions, this is caused by an imbalance in water availability and evaporative demand. A relative excess in plant available water, as explained in *Oxygen stress*~~). If the water table is flat enough, no correlation is expected to be found but the negative correlation between precipitation and plant growth can still be present. Secondly, in mountainous regions absence of a correlation between water table depth~~, limits root respiration and hence growth. In mountainous regions the negative relation between aridity and growth is directly caused by the temperature gradient as the highest landscape positions are colder, and have a shorter growing season, reducing the growth potential. As the highest positions generally receive more precipitation and have lower potential evapotranspiration the correlation between aridity and fAPAR is negative. The neutral correlation between WTD and fAPAR can be ~~linked to ecosystems~~ explained by vegetation being completely detached from the groundwater ~~. A negative influence of precipitation could be explained in different ways; (1) precipitation in convex positions in the landscape can lead to local over-saturation causing water-logging, decreasing plant growth, or (2) precipitation increases with altitude, and factors linked to a higher position in the landscape (as described in *Convergence driven*) are limiting plant growth~~in mountainous areas and by the absence of a gradient in the water table in lowland positions.

[*Neutral*]; This class contains the locations that show no significant correlation between either water table depth or precipitation and fAPAR.

Overall, there can be several process drivers in each ecohydrological class, dependent on climate and landscape position. In the next section, we will explore the global spatial distribution of the discussed ecoyhdrological classes.

3 Results

3.1 Global distribution of ecohydrological classes

Figure 3 displays the global distribution of the ecohydrological classes that were described in the previous section. In more than half of the pixels, forest growth is significantly influenced by the water table depth, and in more than ~~80 percent by~~ 75 percent by (normalised) precipitation, confirming the hypothesis that ~~P~~ climate is an important but not the only driver of forest growth. All different classes are present in this global analysis; to a varying degree on all continents and in all climate zones. Clear cases of water limitation (both correlations positive) are relatively under-represented as most water limited areas were filtered out by applying a tree height threshold of 3 meters. The results show that the water table depth plays a major role in determining forest growth, even in regions that are traditionally seen as energy limited environments. WTD clearly shows a different signal than P/PET, since the correlation between the two gradients can both be strongly positive (more precipitation with a shallower water table) or negative (more precipitation with a deeper water table, likely caused by orography) (see Figure ~~S10~~S16).
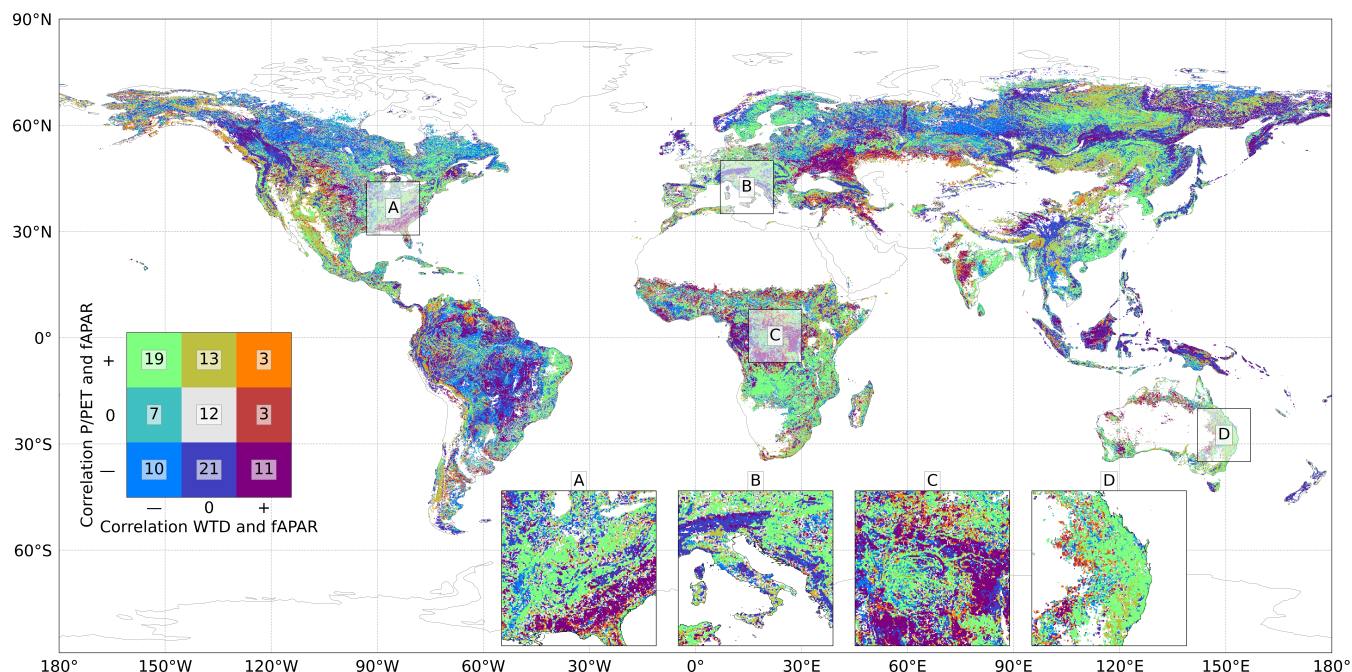
9

Figure 3. Global distribution of ecohydrological classes. The legend indicates the percentage of grid cells in the different classes. The map is downsampled to a resolution of 5 arc-minutes. For a bigger version of the map see Figure ~~S11 and for the version at original resolution of 30 arc-seconds see Figure S12~~S17. Note that the percentages add up to ~~101~~99, which is caused by rounding.

Four insets (15 degrees) are displayed in Figure 3. The same insets are displayed in Figure ~~S13 to Figure S16~~ S18 to Figure S21 together with the input and individual correlation data. Inset *A* (Figure ~~S13~~S18) shows the Mississippi river valley on the
245 left and the southern part of the American East Coast on the right. The river valley itself shows a neutral or negative correlation between both WTD and P~~/PET~~ with fAPAR, representing an environment where too much water leads to over-saturation and water-logging which hampers tree growth. This corresponds to the ecohydrological classes *Oxygen stress* and *Rooting space limited*. Further away from the river, the relation between ~~P~~ aridity and fAPAR changes to positive, leading to a classification of *Rooting space or precipitation driven*, which links a higher position in the landscape to more precipitation and more vegetation
250 growth. Towards the coast, on the interface between Georgia, Alabama and Florida, forest growth is *Convergence dominated* and in some places *Water limited* and *Convergence driven*.

Inset *B* (Figure ~~S14~~S19) shows South-Eastern Europe with the Alps. In this mountainous region, plant growth is predominantly detached from groundwater influences (hardly any significant correlations between WTD and fAPAR). In the southern part of the Alps, forest growth is precipitation driven while the northern part falls in the ~~Composite~~*Energy limited* class, featur-
255 ing a negative correlation between P~~/PET~~ and fAPAR. In mountainous regions this class corresponds to an ecosystem that is detached from the groundwater and grows best in the lower or mid landscape positions. Higher up in the mountains, vegetation growth is disturbed by factors such as low temperatures, shallow soils and a reduced growing season. The hilly regions around

the Alps are predominantly classified as *Rooting space or precipitation driven*, as in inset *A*. This corresponds to enhanced tree growth in the higher locations, associated with more rain and more rooting space. Another interesting feature in this inset is the Pannonian Basin (north-east in the inset), showing a similar pattern as the Mississippi valley of *Rooting space limited* vegetation growth. Groundwater convergence from the surrounding higher regions causes very shallow water table depths in this area, hampering forest growth.

Inset *C* (Figure ~~S15~~S20) depicts the Congo river basin. The Congo river and its side-channels show similar patterns of increased vegetation growth on levees, leading to a *Rooting space or precipitation driven* classification. The regions to the south and east of the Congo river basin are dominated by savannas. These savannas receive a substantial amount of precipitation yearly, but rainfall is not evenly distributed over the year and makes water relatively scarce in comparison with the energy input at these latitudes (Verhegghen et al., 2012), leading to a classification of *Convergence dominated*. Areas at high altitude in this closeup shows ~~a~~ an *~~Composite~~Energy limited* class; most forest growth occurs at the foot of mountains or on the slopes, while higher locations are less suitable due to lower temperatures and a shorter growing season.

Inset *D* (Figure ~~S16~~S21) shows an orographic region in Eastern Australia, where vegetation growth is driven by the precipitation gradient. The lowland, west of the mountain range (Great Dividing Range), is classified as ~~vegetation limited by~~ *Rooting space limited* and *Rooting space or precipitation driven*. Converging water from the mountain range causes a shallow water table depth in this region, hampering forest growth. The most western part of this inset that still contains trees receives between 250 and 500 mm precipitation per year. This region is *Convergence driven*, ~~also receiving~~ where vegetation depends on water from the higher areas.

All four insets display a high spatial variability in ecohydrological classes, demonstrating that the local interplay in climate and landscape position highly influence which hydrologic driver stimulates or hampers forest growth.

3.2 Local examples at high resolution

To better visualise and understand the patterns of ecohydrological classes, detailed maps of the input, correlation and output maps are displayed in Figure 4 and Figure 5. Landscape position is approximated and displayed based on the standard deviation of the WTD map (which is the main constituent of the landscape classification procedure). This representation was chosen over the landscape classes, used throughout the rest of the paper, to obtained a more detailed visualisation.

The presented patterns in Figure 4, displaying the western Amazon, show a clear overlap with ecosystem functioning as described in Ferreira-Ferreira et al. (2014). The river and its major contributing streams display the *Rooting space or precipitation driven* class. Considering the (slightly) negative correlation between WTD and P/PET, this can be attributed to rooting space limited growth: the vegetation on the natural levees next to the channels are known for the highest and most diverse forests of the Amazon (High Varzea in Ferreira-Ferreira et al. (2014)). On these levees the trees have more rooting space, receive more precipitation and suffer comparatively little from the inundation that characterises these rivers, leading to optimal growth conditions. In the depressions between streams (especially on the eastern side of these maps), forest growth is classified as
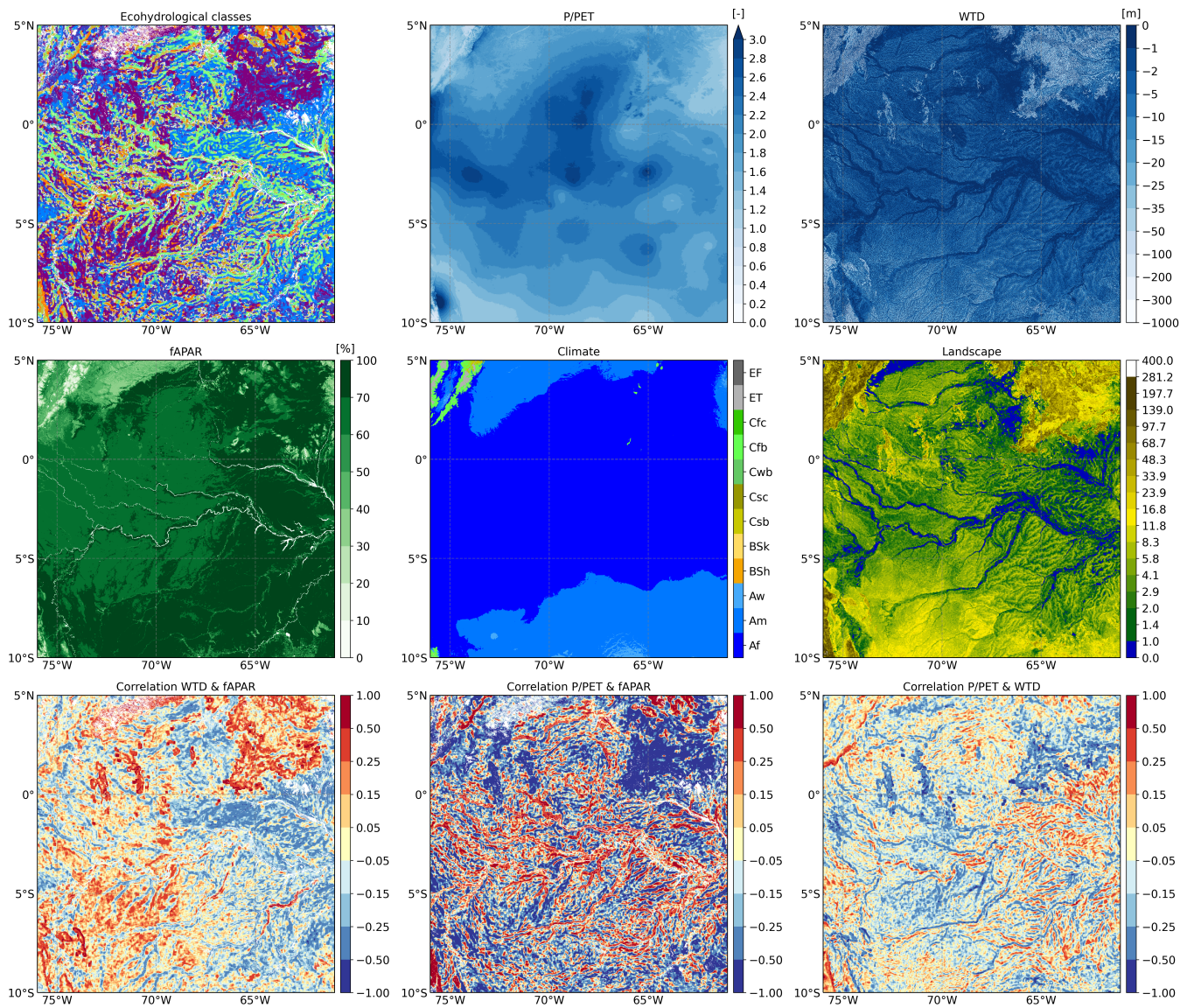
Figure 4. High-resolution illustration of ecohydrological classification in the Amazon. Input and correlation maps are shown at full resolution of 30 arc-seconds. ~~Note that the~~ The white pixels in the upper left map (ecohydrological classes) represent the locations where the correlations were not calculated due to the tree height falling below the threshold value of 3 meters.

Oxygen stress. Here forests suffer from the very frequent inundations that hampers their respiration. These same areas feature a positive relation between P/PET and WTD, linking precipitation to percolation and a higher groundwater table.

The western part of the maps show *Convergence dominated* forest growth. This area is higher than the eastern part, presenting fewer streams, and has a (slightly) higher relief, making inundation much more rare. This area agrees with the mapping of the White-sand Ecosystems as published by Adeney et al. (2016). These ecosystems have sandy, very well draining soils. Even slightly elevated surfaces know temporary periods of draught with lower vegetation growth. Tree growth at the lowest positions in these landscapes is higher, causing the *Convergence dominated* classification. In the hilly, north-eastern part of maps forest growth is also classified as *Convergence dominated* as well as *Water limited* which is in stark contrast with the general perception of water abundance for vegetation growth in the Amazon region. This can be explained by the high amount of available energy, even with respect to such extensive amounts of rainfall. At the foot of these hilly regions vegetation can reach the groundwater, and consequentially grow faster, thus causing a *Convergence dominated* classification. If the vegetation in a whole window cannot reach the groundwater anymore this turns into the *Water limited* class.

The second high resolution example (Figure 5) shows ~~India~~the Indian Peninsula. The western part of India features a mountain range (Western Ghats), which is a strong orographic zone, receiving moisture from the Arabian Sea (especially during the monsoon season). This zone is predominantly classified as *Rooting space or precipitation driven*. In contrast with the Amazon example, this class is caused here by the precipitation driven vegetation (positive correlation P/PET and fAPAR), as the groundwater is too deep to be reached by the vegetation. The negative correlation between the WTD and fAPAR is caused by the strong orographic gradient, with higher precipitation in higher areas (with a lower water table). This negative gradient can be seen in the lower right subplot of Figure 5.

~~Behind the mountain range lies a vast rain shadow, receiving very little precipitation~~ The mountain range taps most of the precipitable water from the atmosphere, creating a vast rainshadow to the East (Climate classes BWh and BSh). This area can be subdivided in two different zones; a southern and northern zone. Although they receive similar yearly amounts of precipitation the northern zone contains much more forests than the southern zone (which is mainly filtered out in this analysis since vegetation height is mostly under the threshold value of 3 meters). This stark difference can be attributed to the distance of the water table to the surface. As can be seen in the upper right subplot of Figures 5, the southern zone has much deeper groundwater than the northern zone. The forest growth classification in the northern zone, following the same rational, is *Convergence driven*, *Convergence dominated* and *Water limited*; forest growth is highest in the lowest landscape positions with the easiest access to the groundwater as additional water source. Further east the amount of precipitation rises again (around 81°E and 18°N). This area features higher topography but a relatively shallow water table (plateau). This combination causes tree roots to be constrained, leading to the *Oxygen stress* classification. In contrast, the Eastern Ghats (first mountain range of India seen from the Bay of Bengal) show ecohydrological classes *Rooting space or precipitation driven* and ~~*Composite*~~*Energy limited*, which are linked to the orographic effect and decrease in temperature and growing season at higher altitudes.
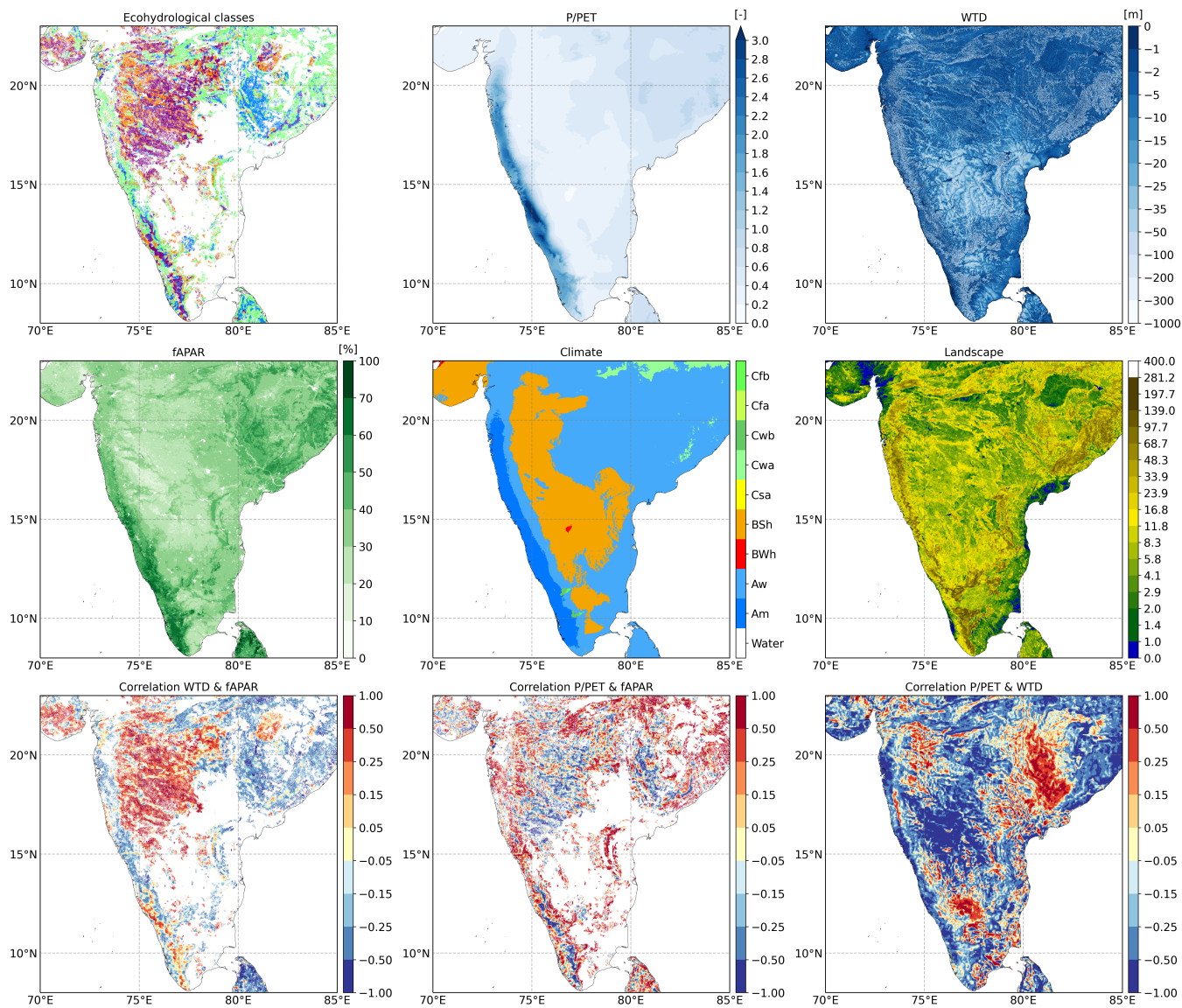
Figure 5. High-resolution illustration of ecohydrological classification over ~~India~~the Indian Peninsula. Input and correlation maps are shown at full resolution of 30 arc-seconds. ~~Note that the~~ The white pixels in the upper left map (ecohydrological classes) represent the locations where the correlations were not calculated due to the tree height falling below the threshold value of 3 meters.

325   When zooming in even further on the Amazon basin (~~see Figure S17~~Figure S22) and India (~~see Figure S18~~Figure S23), the potential of this high resolution analysis becomes apparent. In Figure ~~S17~~ S22 individual levees and gullies can be identified based on the ecohydrological classes, demonstrating local differences in water availability for forest growth. In Figure ~~S18~~ S23 the strong gradients of the orographic effect and the driving effect of groundwater proximity as alternative water source can be observed.

330   **3.3   Landscape and climate as drivers of the hydrological controls**

Figure 6. Distribution of average ecohydrological ~~functioning~~ class as a function of landscape position and climate. This Figure shows a subset of the Köppen-Geiger climates for clarity; namely arid (BWh), ~~boreal~~ temperate (~~Dfb~~Cfa), ~~temperate~~ continental (~~Cfa~~Dfa), and tropical (Af). For an extended version containing all the climates see Figures ~~S19~~S24, ~~S20~~ S25 and ~~S21~~ S26 in the supplementary material. (a) mean fAPAR, (b) mean water table depth and (c) prevalent ecohydrological class (after removing the cells in the neutral class). In Figure S27 the full distribution of the ecohydrological classes within the selected climates is presented.

    To characterize the influence of landscape and climate on the governing processes, the data have been segregated on Köppen-Geiger climate classes and landscape position classes. The results for four major climates are shown in Figure 6. Figure 6a shows clear patterns in both landscape positions and climates. The arid climate (BWh) has much lower fAPAR values than the tropical climate (Af) and the intermediate temperate (Cfa) and ~~boreal (Dfb~~continental (Dfa) climate fall in between, confirming
335   the hypothesis that tree growth, at climate scale, follows the gradient of precipitation. Both extremes in the landscape (High mountainous and Wetland) display lower fAPAR, except for the arid climate in which the lowest position in the landscape corresponds to the highest fAPAR. The highest fAPAR in the other climates falls in the intermediate landscape positions. Figure 6b shows mean water table depth in the different climate and landscape positions. As expected, the water table is generally deeper in arid climates compared to wetter climates in similar landscape positions, except for the lowest landscape
340   position.
    The ecohydrological classes (Figure 6c) show ~~a consistent pattern~~some interesting patterns. In the lowest positions in the landscape, vegetation growth is limited by rooting space ~~. This is followed by a region that~~ (in the arid class this becomes

apparent in the full distribution of classes as can be seen in Figure S27 and can be linked to oases). Higher in the landscape we find a region where vegetation growth is driven by the precipitation gradient (*Rooting space or precipitation driven* and

345 *Precipitation driven*). *Rooting space or precipitation driven* displays a negative correlation between WTD and fAPAR here, as a consequence of more (orographic) precipitation at higher locations in the landscape. This process is similar in most climate zones (see Figure 6c and Figure ~~S21~~S26), but the threshold within the landscape is lower in arid environments, following a general lower water table depth at similar landscape positions (Figure 6b). Exceptions are the tropical climates (Af and Am), in which vegetation growth in mid-landscape positions is driven by groundwater convergence, hinting at a relative scarcity of

350 water in comparison to the energy availability.

In the temperate, continental and tropical climates, where precipitation is generally high, limited rooting space in the lowest landscape positions suppresses growth. Consequentially, the optimum in fAPAR occurs higher up in the landscape, where rooting space is no longer a limitation. In the arid ~~and boreal climates~~ regions the lowest position in the landscape is favourable~~(higher fAPAR than adjacent landscape positions). In arid climates this~~. This is associated to groundwater con-

355 vergence from large areas, as water availability from precipitation is generally low. ~~In a boreal climate this optimum might instead be caused by higher temperatures at lower landscape positions.~~ The highest landscape positions are ~~decoupled from the groundwater and are therefore classified as *Composite*,~~ classified as *Energy limited* in all but the arid climate, reflecting a strong thermal control on growth in mountainous regions. In the arid climate the mountainous regions are classified as *Precipitation driven* and *Water limited*. ~~The *Composite* class is in this context associated with a growth optimum on the slopes, while valleys

360 and ridges show a reduction in plant primary production,~~ as water is scarce and vegetation is completely decoupled from the groundwater. Not surprisingly, the highest positions in the arid climate has the lowest fAPAR of all ~~positions and is classified as~~ landscape positions and climate regions. The continental climate (and even more strongly the boreal and arctic climates Dfc, Dsc and ET as can be seen in Figure S26) is predominantly energy limited as reflected by the ~~Water~~ *Energy* limited. classification. In the low landscape positions this is linked to an excess in water availability in respect to the thermally controlled

365 evaporative demand while in the highest landscape positions vegetation growth is reduced by a low energy availability and a shorter growing season.

3.4 A novel framework to link forest growth to the hydrologic gradients in a climate-landscape continuum

Based on our results, we propose a framework for tree growth in different landscape positions and climates, displayed in Figure 7. In arid regions the vegetation is concentrated in the lowest landscape positions, where roots can access the groundwater,

370 which correspond to the notion that vegetation in deserts predominantly thrives in oases, which are driven by groundwater convergence of extended areas. Another optimum, though with lower tree growth, exists higher up in the landscape, where the mountains are wetter, cooler and greener than the surrounding desert basins (better visible in Figure 6a).

In the temperate and tropical climate, only one growth optimum is discernible. In the tropical climate this optimum corresponds with the region driven by local groundwater convergence (see Figure 6a and c). This optimum lies exactly on the

375 point where the correlation between water table depth and fAPAR switches from ~~positive~~ neutral/positive (see Figure S27) to negative, implying the existence of a distance to the groundwater that is shallow enough to be accessible for roots and deep
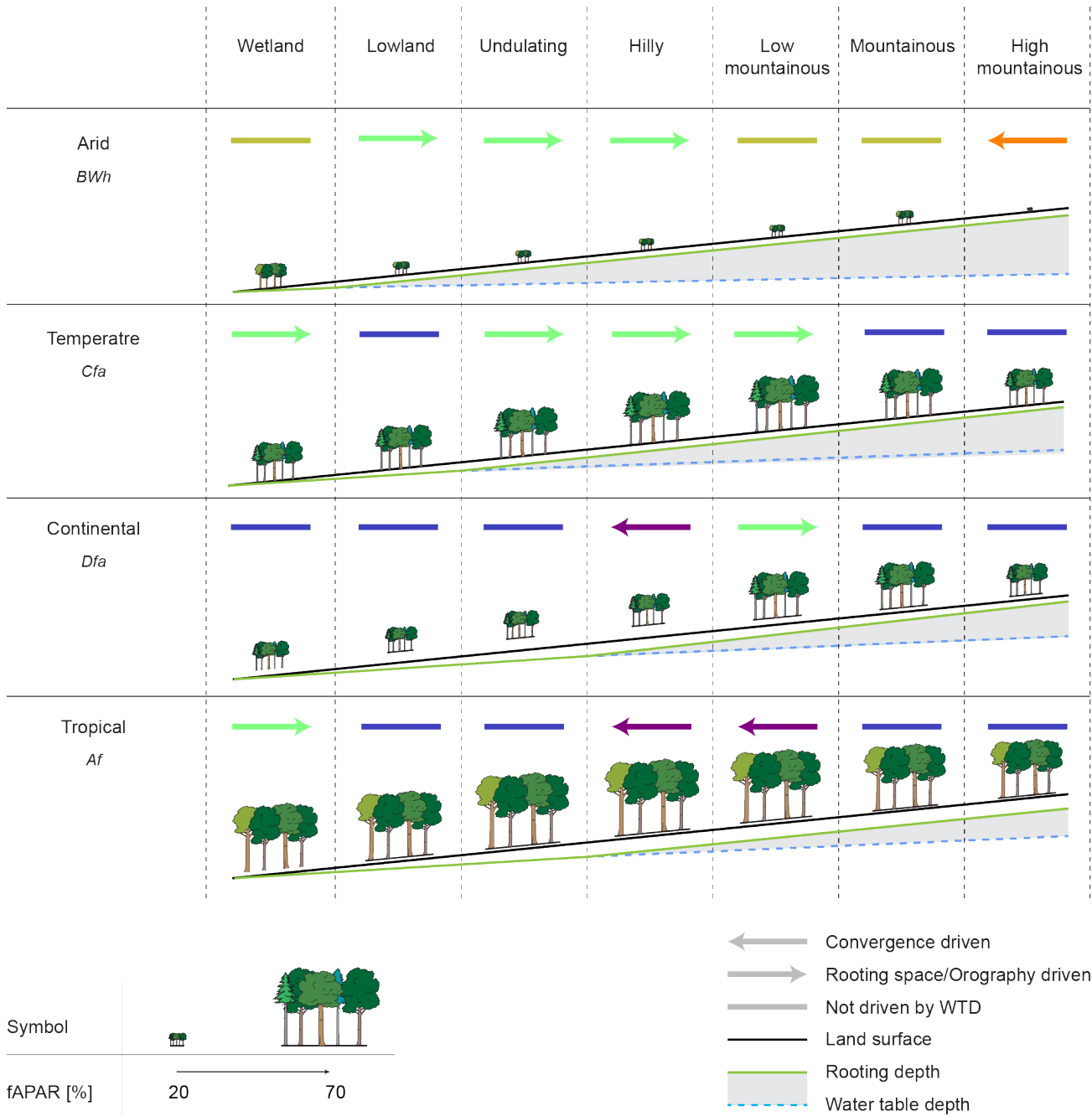
Figure 7. Conceptual framework summarizing the links between fAPAR, water table depth, the correlations and implications for the patterns of rooting depth across climate and landscape classes. Different percentages of fAPAR are depicted as tree symbols, the ecohydrological classes are shown as arrows, where the colors represent the classes and the point of the arrow indicates the sign of the correlation between WTD and fAPAR.

enough for it not to negatively influence root growth. In the temperate climate the optimum of vegetation growth lies in the zone classified as *Rooting space or precipitation driven*, with a negative correlation between WTD and fAPAR. In ~~comparison~~ contrast with lower positions in the landscape, this zone displays a positive correlation with ~~precipitation~~aridity, hinting at

380 precipitation driven vegetation, only displaying a negative correlation between WTD and fAPAR because higher precipitation falls at higher locations. This suggests that vegetation is detached from the groundwater in these mid-landscape positions, with vegetation growth being limited by water availability. In the lowest landscape positions even more water is available but, because the shallow groundwater confines the root zone, plants can not take optimal advantage of the resource.

The ~~boreal~~ continental climate shows a very similar pattern as the temperate ~~climate~~and tropical climates, although fAPAR

385 values are lower. This climate does show a second optimum in fAPAR in the lowest landscape position (better visible in Figure 6a), similar to the arid climate. In most landscape positions in the continental climate vegetation *Energy limited*, indicating a relative excess in plant available water in the lowlands and thermally controlled growth in the highlands.

4 Discussion

4.1 Correlation in hydrologic gradients

390 The presented results show that global gradients of ~~P and WTD~~ aridity and water table depth have a substantial effect on forest growth. These gradients, however, are not independent, which needs to be considered when interpreting the results. The correlation between ~~precipitation~~ P/PET and WTD is shown in Figure ~~S10~~ S16 and shows clear spatial patterns of both positive and negative values. A negative correlation corresponds to higher precipitation with a deeper water table while a positive correlation indicates lower precipitation with a deeper water table. In terms of processes, these relations can best be explained

395 when considering that water table depth is roughly the inverse of altitude (especially in hilly and mountainous terrain). A negative correlation between WTD and P/PET would correspond to more precipitation higher in the landscape, which is linked to orographic precipitation. Positive correlation values between WTD and P seem to often occur in either low-lying areas, where more precipitation yields more percolation and a shallower water table, or in mountainous areas, which could correspond to a decrease in precipitation with altitude due to a loss of atmospheric moisture due to orographic precipitation in lower lying

400 areas. These processes are clearly present in the class *Rooting space or precipitation driven*, but a correlation between P/PET and WTD should be considered in all other classes as well. ~~For example, Borneo is partly classified as *Water limited*. As a tropical mountainous island, *Precipitation driven* would be expected. Considering the a positive correlation between WTD and P (higher precipitation at lower locations in the landscape), the term *Water limited* that was assigned to this class does not correctly describe all processes in this region.~~

405 ### 4.2 Variation over time

In this study we analysed forest growth under long term average gradients of water table depth and normalised precipitation, even though both hydrologic gradients can show considerable seasonality. We acknowledge that seasonality in precipitation

and water table depth can influence the local vegetation type, but we believe that by focusing on forests only, long term averages in hydrologic gradients can provide useful insights. It can be assumed that forests are strongly adapted to the local hydrological regime and therefore mainly respond to long term changes in these regimes. This approach was chosen to understand the global patterns of long term ecosystem behaviour and water resources. By using the long term average gradients we focus on the question if, and where forests are driven by the groundwater, precipitation, or both.

4.3 A start for a more sophisticated forest growth representation in global modelling studies

Many global Earth system modelling studies do not account for water table depth as a driver of forest growth. Our results suggest that landscape-scale interaction between vegetation and groundwater, including lateral convergence, moisture and oxygen stress, is important in most parts of the world and should be better represented in these Earth system models. Groundwater can either be an extra water source for vegetation growth, but also a constraint on root growth and with that vegetation growth. The presented framework can serve as a first approach to account for both forest growth stimulation and growth limitation based on precipitation and water table depth in a climate-landscape continuum. Local examples, such as the the Amazon river and the mainland of India, show a consistent overlap between the presented patterns and expected tree growth, based on the understanding of the ecosystems. It needs to be considered that seasonality and inter-annual variability of both precipitation and the water table can change the presented patterns substantially, but the understanding of average ecosystem behaviour on a climate-landscape continuum can be used as a baseline in further studies. The global importance of the landscape-scale water table variability on forest growth proves that it needs to be considered in global environmental modelling.

5 Conclusions

The goal of this study was to relate ~~two hydrologic gradients (precipitation and water table depth)~~ climate and groundwater driven water availability to forest growth on a global scale. The presented results show that across most of Earth's surface, water is an important control on plant productivity, determining the presence of vegetation and constraining it's growth. Water table depth, an often ignored parameter in global Earth system modelling, displays a significant influence on vegetation growth in more than 50 percent in the forested pixels, both positively (e.g. tree growth stimulation in oases) and negatively (e.g. tree growth hindrance in swamps). In a substantial part of the globe, this influence does not overlap with an influence of precipitation, although both gradients generally show ~~strongly~~ a strong spatial correlation.

Inter-climate analysis demonstrates that, at the continental scale, vegetation growth is strongly driven by precipitation; vegetation in wetter climates shows higher energy absorption. Within these climate zones, vegetation growth can substantially change over the landscape gradient. The effect of landscape is, however, not constant in all climate zones. As hypothesised, vegetation growth in arid regions is mainly driven by groundwater convergence, showing the highest energy absorption in the lowest landscape positions. In more humid climate zones, tree growth presents an optimum in mid-landscape positions. Below this optimum a shallow ground water table limits root growth and vegetation development, while at and above this optimum vegetation is detached from the groundwater and tree growth mainly follows the precipitation gradient. At high altitude and

440 in colder climates vegetation is mainly driven by energy availability. The proposed framework illustrates the importance of coupling landscape and climate together to describe vegetation patterns world wide, tying root growth and water availability from precipitation and groundwater together. In the light of global changes in hydrologic gradients and land use, the water cycle will substantially change in the future. To predict the changes and mitigate the effects, water availability and root growth should be considered in global environmental modelling.

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