SI Appendix

Hydrologic Regulation of Plant Rooting Depth

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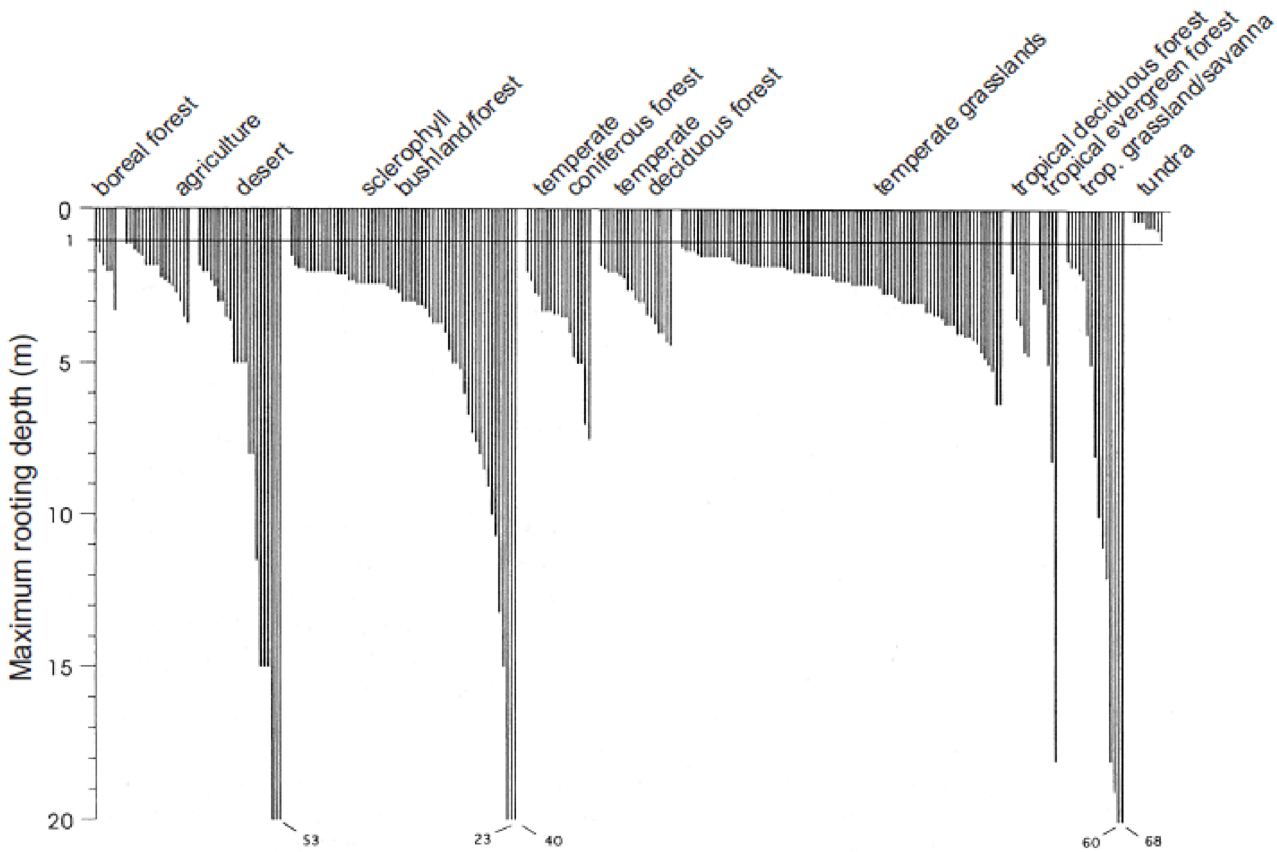

Fig. S1. Maximum rooting depth grouped by biomes (1).

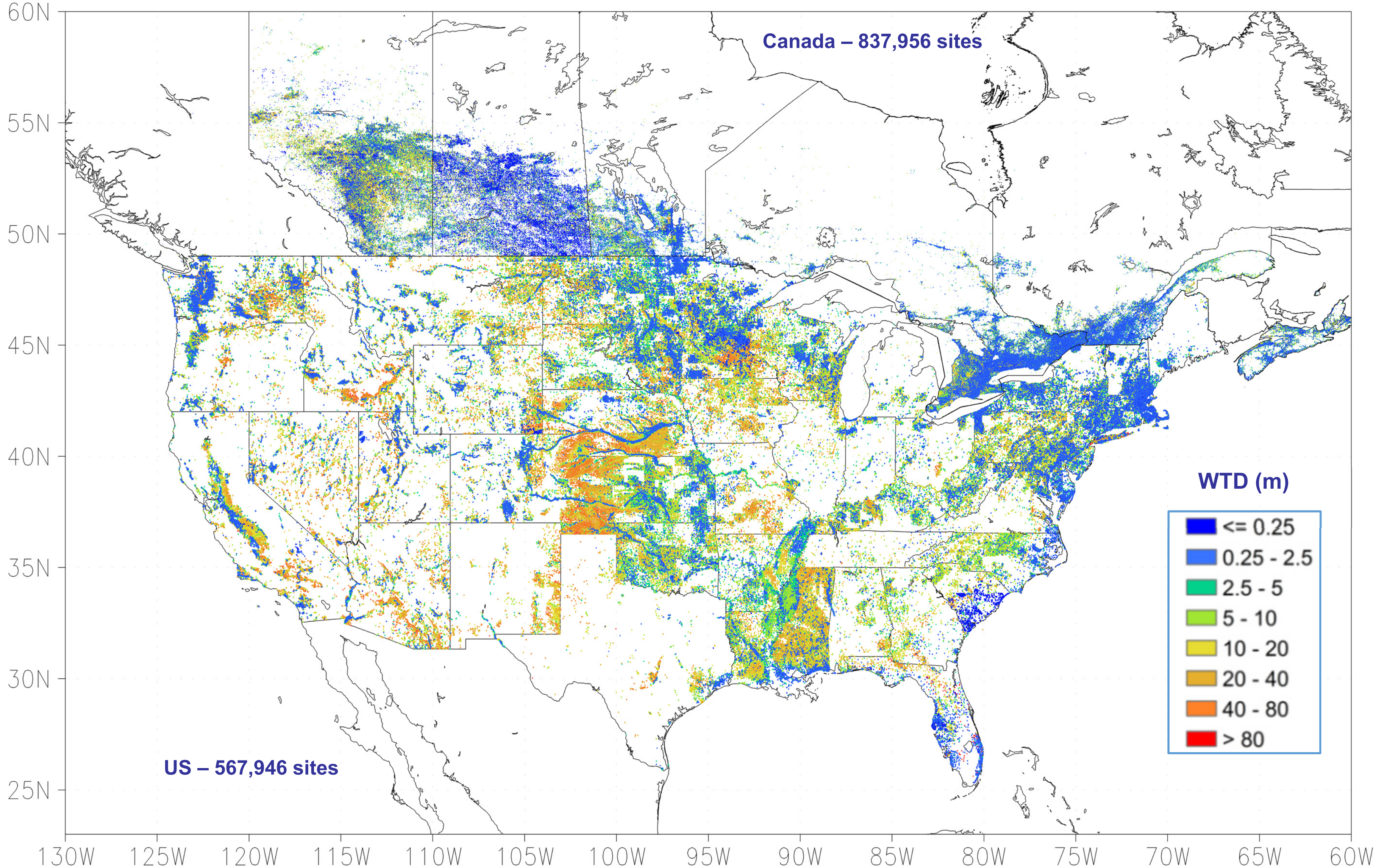

Fig. S2. Well observations of long-term mean water table depth (WTD) over North America (2).

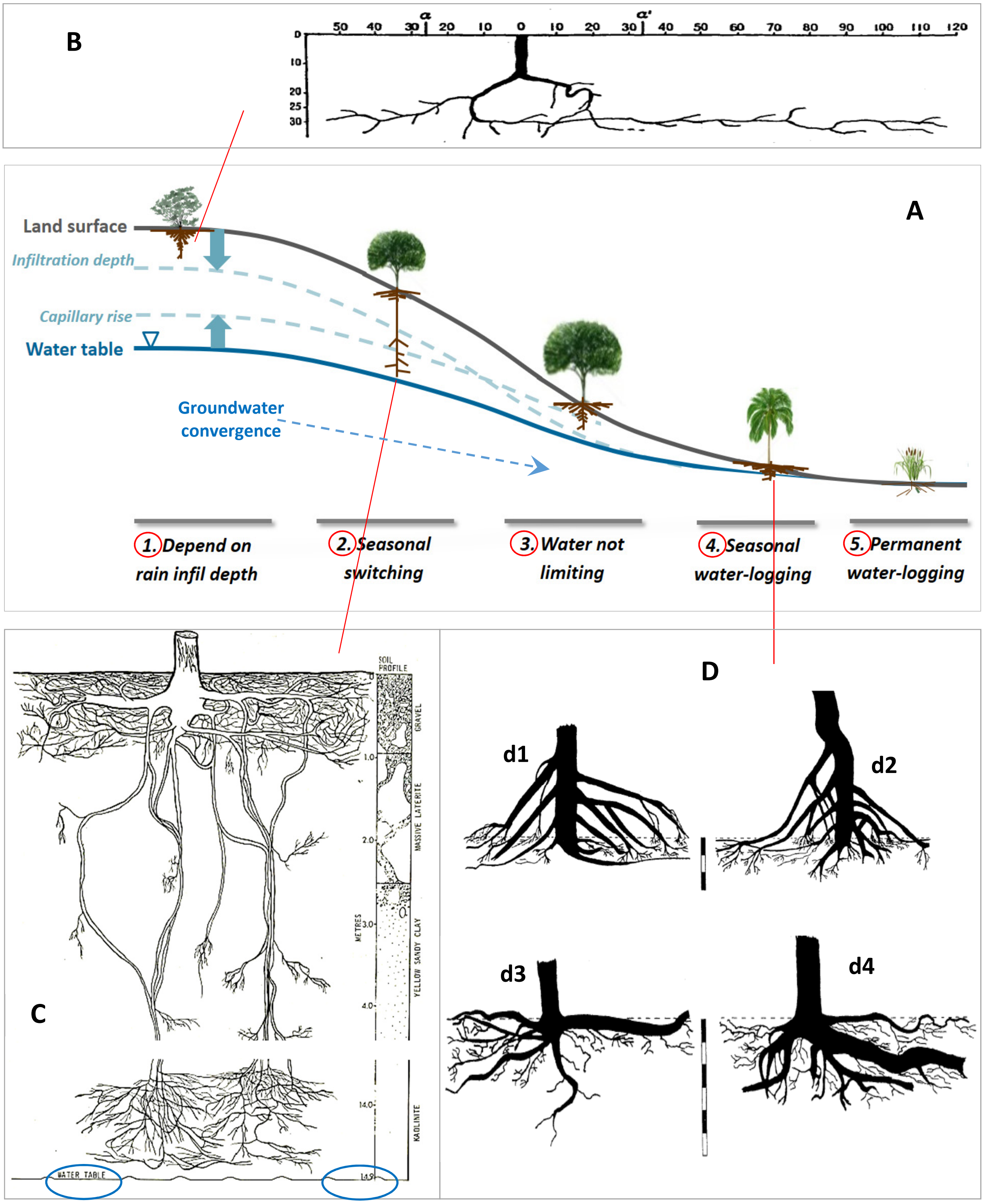

Fig. S3. (A) Schematic of root-water relations along a drainage gradient, (B) shallow and wide (cm) *Salsola rigida* roots in Israel limited by rare and shallow infiltration (3), (C) dimorphic roots of *Eucalyptus marginata* in Western Australia (4) (WTD=14.9m), and (D) aerial and shallow roots of *Cecropia distachya* (d1), *C. ficifolia* (d2), and *C. sciadophylla* (d3, d4) in Amazonia lowlands (5) (each tick mark = 10cm).

Compiling Rooting Depth Observations

We compiled rooting depth observations from published literature, government papers, and unpublished theses and reports. We searched by key words such as "root", "rooting depth", and "root system" in Web of Science database and Digital Library of JSTOR (http://about.jstor.org/), and found more reports through citations within the documents. Our compilation continues as more data come into light by incorporating international literature. The 2,020 entries of ~1100 species we have compiled so far are given in a large table at the end of this SI Appendix.

We recorded the following information:

(A) Reference of data source (all included in the reference list at the end of this document)

(B) Geographic Location (nearest city, state or province, country or region, continent)

(C) Biome (if not given by the author, it is based on the map of major world biomes from Wikipedia: http://commons.wikimedia.org/wiki/File:Biomes.jpg); inconstancies in terminology are to be expected

(D) Observation Site (for those investigations that include multiple sites)

(E) Vegetation Phenology / Leaf Form (evergreen vs. deciduous, broad-leaf vs. needle-leaf, perennial vs. annual for herbaceous plants, succulents, geophytes etc.); some are not given and thus based on information found on the USDA Plant Database (https://plants.usda.gov/java/), and if not listed, Wikipedia

(F) Vegetation Growth Form or Stature (large or small tree, woody shrub, vines, grass, and herbs); where not specified by the author, information is found on the internet (such as Wikipedia and USDA Plant Database)

(G) Common Name of plants in English (where available)

(H) Scientific Name, recording dominant species if roots are not distinguished among species; no entry if not given by the investigators, as is often the case when terms such as "tropical rainforest" or "shrub land" are used only

(I) Maximum Rooting Depth (m)

Although the focus of the data compilation, the absolute maximum rooting depth is difficult to ascertain because most excavations, soil trenches, coring, or rhizotron/mini-rhizotron tubes terminated at arbitrary depths without knowing or following the deepest roots to the end. In most cases, the maximum rooting depth recorded is the depth of the investigation, such as the depth of the trench or the soil core, and they are clearly under-estimates of the true maximum rooting depths. In other cases where chemical tracers are used to infer the depths of root "water-uptake", the maximum rooting depth can be over-estimated if capillary rise transported the tracer upward toward the shallower roots, or under-estimated if tracer injection depth is above the maximum rooting depth and taken up by the shallower portion of the root system. The recorded maximum rooting depth can be that of a single plant (e.g. through excavation of individuals), the mean of several plants of the same species (e.g., in monoculture stands), or that of many species/individuals intercepted by the soil trench, monoliths, or cores.

(J) Method of making root observations, including excavation of the whole or partial root system, soil trench walls and root counting using a grid overlay, soil monoliths, road cuts or quarry exposures, stream bank erosion exposures, soil coring or block sampling, rhizotron or mini-rhizotron imaging, and natural or injected isotopes or other chemical tracers found in plant tissues. We avoided the latter if there are direct measurements of rooting depths in the area, but included it in regions with few data such as the Kalahari Desert.

(K) Profile Data availability: some provide quantitative information on root mass or length distribution with depth, while others are in the form of scaled drawings and photographs

(L) Mean Annual Precipitation (Ppt) (mm) as reported by the investigators based on site or nearest rain gage (no attempt was made to fill in the data gaps)

(M) Precipitation Seasonality as reported by the investigators

(N) Potential Evapotranspiration (PET) (mm) as reported by the investigators

(O) Topographic Position of the site, e.g., hilltop or ridge, mid-slope vs. valley, floodplain vs. upland, slope aspect, scree slope, good vs. poor drainage etc., as reported by the investigators

(P) Water Table Depth Range (m) at the site as reported by the investigators (where available) over the period of investigation

(Q) Mean Water Table (WT) Depth (m) at the site as reported by the investigators

In some cases, water table position is inferred from authors' remarks, such as deeper excavation below a certain depth is prevented by the water table, or site is poorly drained with frequent soil mottling at a certain depth, or hydric soil at a certain depth, or roots were restricted by water-logging at a certain depth.

(R) Soil Texture or Type as reported by the investigators, with vertical sequence in some cases; no entry where no soil information is given

(S) Nature of soil hardpans or concretions, as reported by the investigators

(T) Depth at which hardpans / concretions are encountered, as reported by the investigators

(U) Bedrock types and degree of fracturing, as reported by the investigators

(V) Depth of bedrock, as reported by the investigators

(W) Human Alterations (such as croplands/plantations/coppices, plowed, recently burned, fertilized, drained, or irrigated), as reported by the investigators

(X-Y) Latitude and Longitude (in decimal degree)

Precise geographic locations are often not provided, or roughly provided to the degree and minutes, particularly in the older literature before GPS is widely used in the field. In these cases, GoogleEarth is used to estimate a location that best fits the information provided by the investigators (e.g. 35km SE of a particular city, in a forest surrounded by croplands, on a NE facing slope, etc.). If the authors indicate that heavy equipment is used for excavation, the site is assumed to be near roads. If hydraulic excavation is used and a pond/river is mentioned as the water source, the site is assumed to be near these water features. If the site elevation is given, the site location is further constrained by roaming on GoogleEarth. In some cases detailed maps of the research forests or experimental stations can be found with a Google Search independently, which often have names of research tracks and plots, further constraining the locations. But many of the site locations cannot be constrained and are left undefined.

(Z) Elevation of the site (m)

Where not reported, elevation is found from GoogleEarth based on reported or estimated latitude-longitude, or the best fit based on authors' descriptions.

(AA) Author Notes, direct quotes from the authors regarding root characteristics not reflected by rooting depth information, such as lateral extent, depth of structural vs. absorbing roots, dimorphic roots, seasonal root demographics, etc., as well as remarks on the site conditions.

(AB) Notes on data compilation (e.g., estimating site locations, rooting depth extrapolations etc.), including some comments and notes by us; sometimes direct quotes from authors are placed here in quotation marks when space in AA is limited.

The greatest disappointment in the course of this data compilation effort is that many, many studies only examined the shallow roots down to a few tens of centimeters (e.g., 30cm is very common for fine root biomass and turn-over studies, the standard IPCC sampling depth for soil organic carbon). These data are not recorded here, which unfortunately excluded many studies with otherwise excellent and detailed observations.

A spreadsheet containing observed rooting depths can be accessed with the online Supporting Information. It contains the complete references organized alphabetically by authors: A(6–18), B(19–40), C(41–67), D(68–92), E(93–99), F(100–112), G(113–125), H(126–143), I(144), J(145–157), K(4, 158–174), L(175–191), M(192–212), N(213–225), O(226–229), P(5, 230–238), Q(239), R(240–261), S(3, 262–297), T(298–303), V(304–307), W(308–322), X(323, 324), Y(325–327), Z(328–334)

Rooting Depth Analyses

Rooting depth is plotted in Fig. 3 of the main text against (A) mean annual precipitation, (B) soil texture class (Table S1A), (C) depth of soil physical barriers (hardpan, bedrock), (D) sorted by plant growth form (Table S1B), (E) sorted by genus for the 30 most observed genera (Table S1C), and (F) water table depth. Most investigations lack information on one or more of the factors considered here, and only the available pairs are used. Thus each plot has a different sample size with only partial overlap. The sample size is given in the plots, out of a total of 2,020 root observations.

For rooting depth, mean annual precipitation, water table depth, and depth of soil physical barriers, sometimes a range of values are given by the investigators, and the mid-point is used in the plot.

For plotting rooting depth against soil texture class, numerical value of 1 to 7 is assigned to soils of increasingly coarser texture, with 1=clay, and 7=coarse sand and gravel (Table S1A). Sites with shallow bedrocks or soil hardpans are not included in this plot.

For plotting rooting depth against growth forms, the mean rooting depth for each class is used to rank them from 1 to 11, with 1=succulents, and 11=evergreen broadleaf trees (Table S1B).

In plotting rooting depth vs. the 30 most observed genera in this dataset, the mean rooting depth for each is used to rank them from 1 to 30, with 1=*Carex* (sedge) and 30=*Acacia* (Table S1C). Also included here are *Opuntia* (prickly pear), *Fagus* (beech), *Salix* (willow) and *Banksia* (banksia), which although have fewer observations than others are nonetheless representative of characteristic environments such as the desert and the boreal region.

Unfortunately, there is practically no report on precipitation or snowmelt infiltration depth at the sites where rooting depths are investigated.

Table S1. Rooting depths sorted by soil texture classes (A), growth forms (B), and the 30 most observed genera in this dataset (C). In (C) the genera marked in green are the six best observed, and they are plotted in Fig. S6 along precipitation and water table gradients

(A) Soil Texture	Soil Type		Mean Rooting Depth (m)	Std Dev (m)	Sample Size
1	clay		2.27	1.31	13
2	clay-loam, clay-silt, silty-clay		1.34	1.77	95
3	silt, peat, deeply weathered tropical clay		2.30	3.27	207
4	silty-loam, silty-sand, sandy-clay, clay-sand		1.59	1.43	339
5	sandy-loam, sandy-silt		3.54	8.30	427
6	fine-medium sand		2.36	4.79	287
7	coarse sand, gravel, rock fragments		4.09	9.33	58
(B) Growth Form	**Growth Form / Phenology**		**Mean Rooting Depth (m)**	**Standard Deviation (m)**	**Sample Size**
1	succulent/storage herb		0.72	1.17	41
2	deciduous needle-leaf tree		0.78	0.57	12
3	annual herb		0.90	0.76	29
4	perennial grass		1.04	0.73	254
5	annual grass		1.06	0.98	36
6	perennial herb		1.20	1.10	290
7	deciduous shrubs		1.76	2.78	118
8	evergreen needle-leaf tree		1.79	2.79	351
9	evergreen shrubs		2.07	2.29	235
10	deciduous broad-leaf tree		3.71	6.99	409
11	evergreen broad-leaf tree		6.30	10.17	245
(C) Genus	**Genera**	**Common Name**	**Mean Rooting Depth (m)**	**Standard Deviation (m)**	**Sample Size**
1	*Carex*	Sedge	0.59	0.37	23
2	*Opuntia*	Prickly Pear	0.68	0.51	6
3	***Picea***	**Spruce**	**0.74**	**0.47**	**82**
4	*Fagus*	Beech	0.83	0.46	8
5	*Bouteloua*	Grama Grass	0.84	0.40	18
6	*Larix*	Larch	0.90	0.67	14
7	*Zea mays*	Maize	0.91	0.36	15
8	*Stipa*	Feather grass	1.01	0.48	25
9	*Pseudotsuga*	Douglas fir	1.03	0.37	15
10	*Bromus*	Brome grass	1.19	0.51	12
11	*Festuca*	Fescue	1.23	0.84	23
12	*Abies*	Fir	1.30	0.67	28
13	*Combretum*	Bushwillow	1.32	0.70	13
14	*Agropyron*	Wheatgrass	1.34	0.41	22
15	*Atriplex*	Saltbush	1.35	1.13	13

16	*Salix*	Willow	1.35	1.53	8
17	*Artemisia*	incl. sagebrush	1.48	0.77	31
18	*Andropogon*	Beard Grass	1.60	0.78	13
19	*Acer*	Maple	1.75	1.26	18
20	*Juniperus*	Juniper	2.41	2.40	22
21	***Pinus***	**Pine**	**2.45**	**3.92**	**152**
22	*Brachystegia*	Miombo	2.68	1.16	32
23	***Populus***	**Poplar**	**3.00**	**4.75**	**33**
24	*Ulmus*	Elm	4.83	2.83	11
25	***Quercus***	**Oak**	**5.23**	**5.79**	**60**
26	*Tamarix*	Tamarisk	5.33	6.71	12
27	*Banksia*	Banksia	5.56	2.38	7
28	*Prosopis*	Mesquites	6.08	10.41	23
29	***Eucalyptus***	**Eucalyptus**	**8.71**	**8.75**	**45**
30	***Acacia***	**Acacia**	**12.85**	**17.99**	**34**

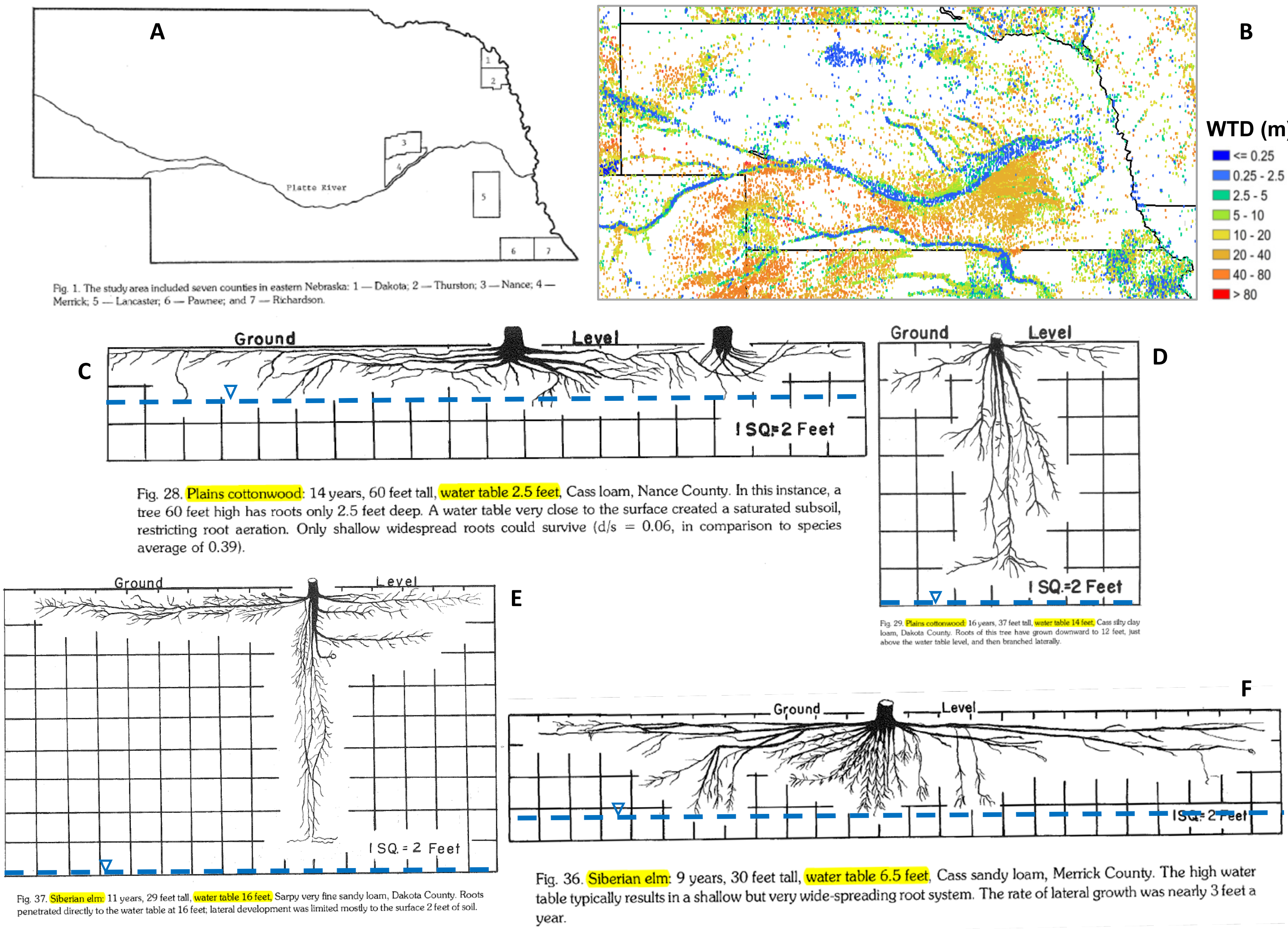

Fig. S4. Tree roots of Eastern Nebraska (288): (A) counties of roots excavation, (B) observed water table depth from groundwater wells (2), (C) and (D) roots of two plains-cottonwood specimens, and (E) and (F) roots of two Siberian-elm specimens.

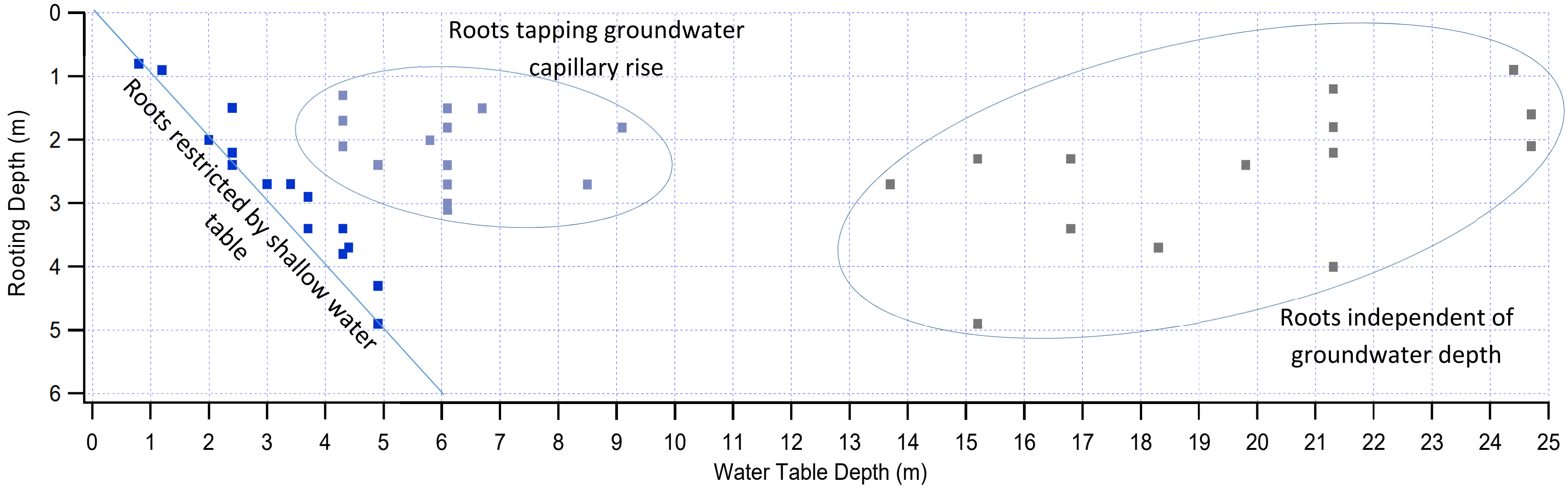

Fig. S5. Rooting depth vs. WTD for 46 trees (37 species) in Eastern Nebraska (288) indicating three types of root-WTD relations.

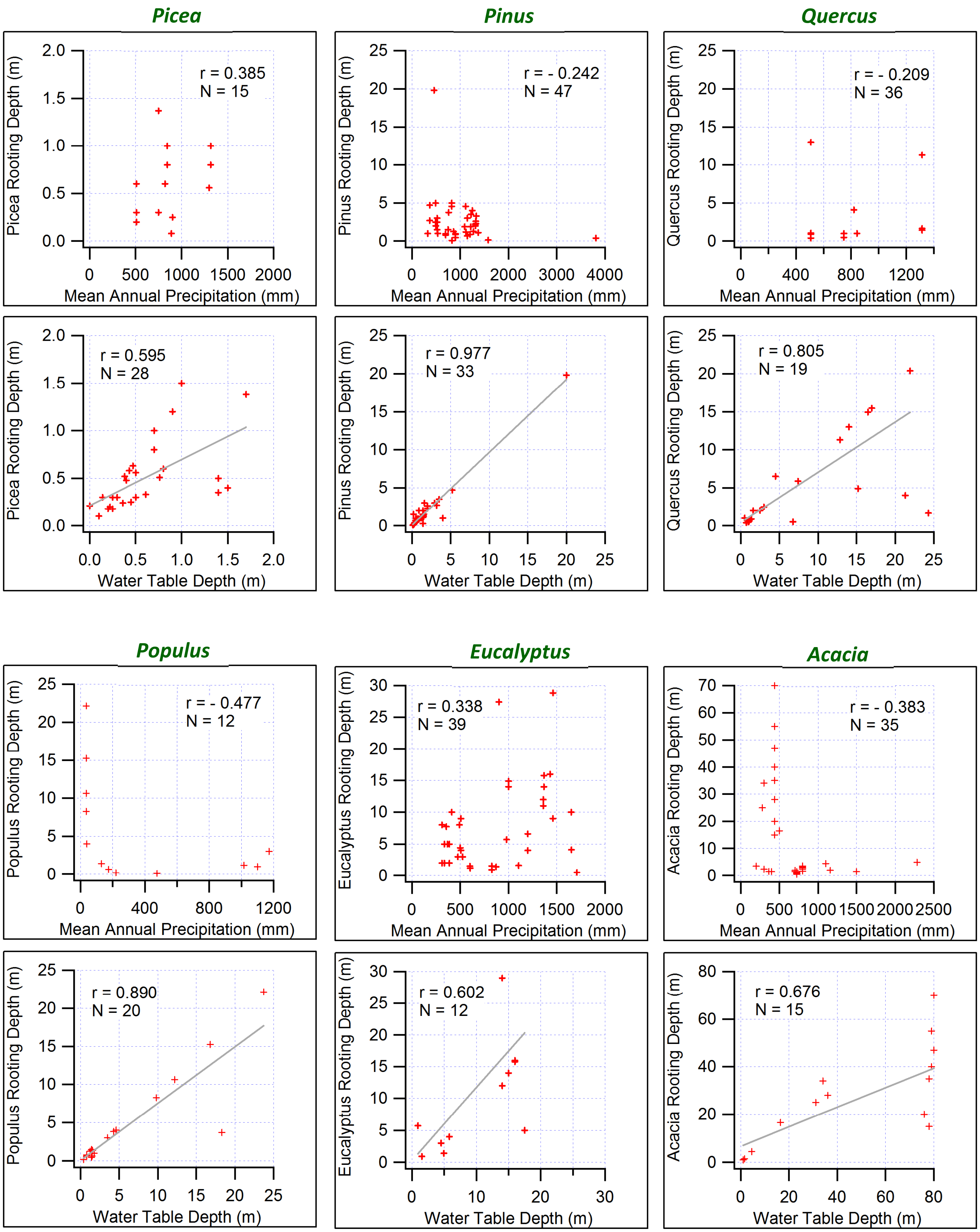

Fig. S6. Rooting depth vs. precipitation (top) and WTD (bottom) for the six best observed genera (marked in green in Fig. 4e and Table S1C), with Pearson correlation coefficient ***r*** and the sample size ***N***. Note vertical scale difference. Not all sites have both precipitation and water table data.

Inverse Modeling of Root Water Uptake Profiles

The inverse model has three parts. First, we simulate the soil water profile at each grid and time step, driven by observed climate, soil properties and topography, at 30 arc-second global grids (<1km) and hourly steps. The results are the *soil water supply profile* at any grid/time, wetted by infiltration from the top and groundwater from below. Second, we calculate plant transpiration from observed/reanalysis atmosphere and leaf area index. The results are the *actual plant water demand*. Third, we use Ohm's law to allocate the demand as root water uptake from different soil depths. The root uptake alters the soil water profile, infiltration and water table recharge, and subsequent uptake. Thereby the inverse model captures the 2-way plant-water relations. The three parts are computed at each time step, as described below.

1. Estimating Soil Water Profile

We use a continental-scale hydrology model designed to resolve 1km-scale processes globally, at hourly steps over decades, run offline forced by satellite-observed leaf area index (LAI) and observed or reanalysis atmospheric conditions. The model is described in detail elsewhere (335, 336); its basic structure is illustrated in Fig. S7 and briefly outlined here.

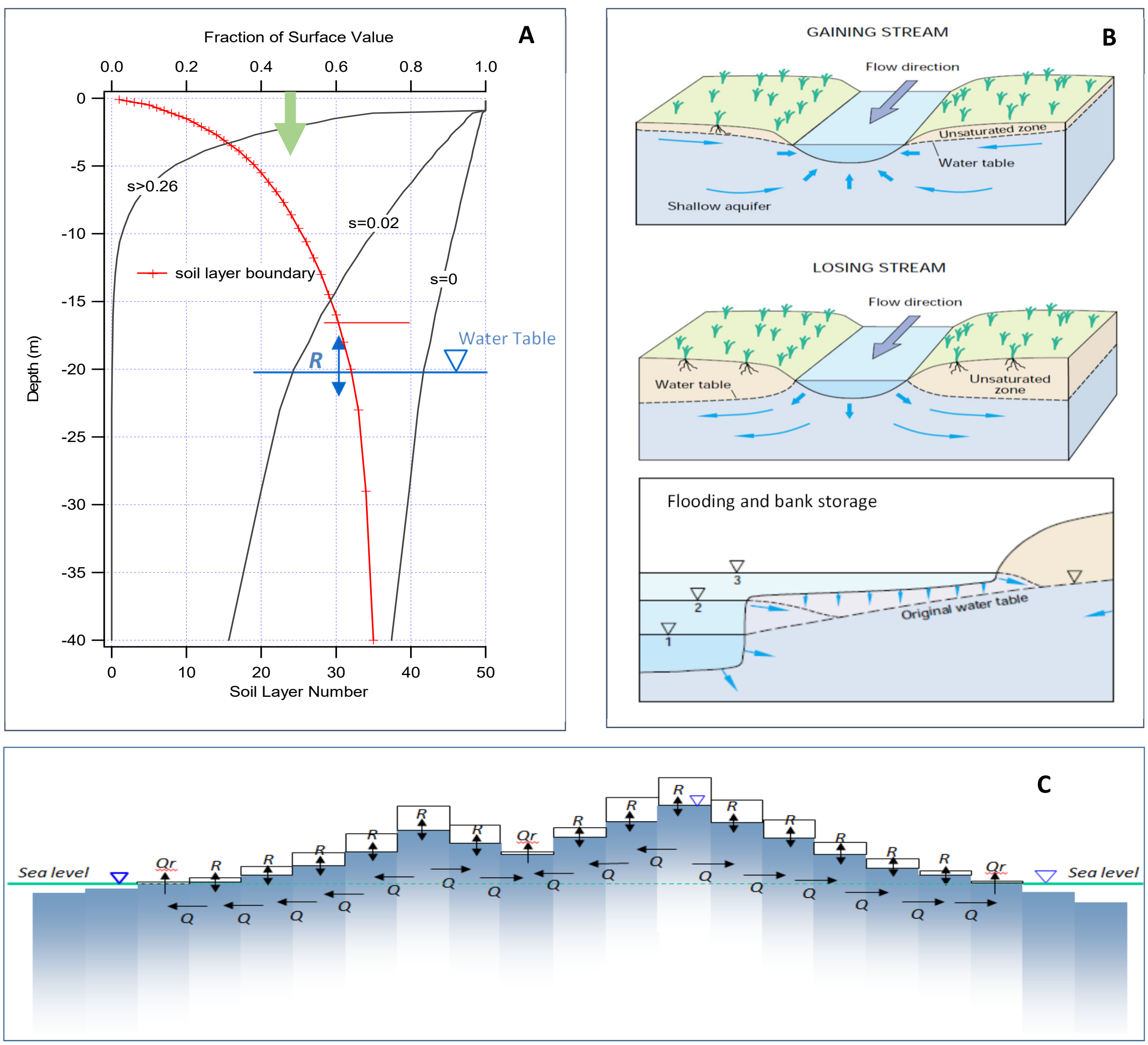

Fig. S7. Structure of the hydrology model: (A) soil layer thickness increases with depth (to 1km), porosity/permeability decrease with depth depending on land slope *s* (3 examples shown), and a dynamic water table that rises and falls depending on recharge *R*, 2-way exchange with rivers and floodplains (B), and lateral groundwater convergence among grid columns (C).

Each continent is represented by discrete land columns of 30 arc-second horizontal resolution (<1km). Each land column is 1km-deep, and has 40 layers (Table S2, Fig. S7A red symbol/line, showing only top 40m). Lacking global 3D porosity/permeability data, we assume that both parameters decrease with depth exponentially, the rate depending on local land slope (2) so that porosity drops quickly with depth in steep uplands with shallow bedrocks (Fig. S8). The three black lines in Fig. S7A give examples of three slopes, i.e., how the permeability/porosity values drop with depth, shown as fractions of the top 1m known values from global soil datasets.

Table S2. Model soil layer thickness and depth (m)

Layer Number	Thickness (m)	Cumulative depth (m)	Layer Number	Thickness (m)	Cumulative depth (m)
1	0.1	0.1	21	0.7	6.2
2	0.1	0.2	22	0.7	6.9
3	0.1	0.3	23	0.8	7.7
4	0.1	0.4	24	0.9	8.6
5	0.1	0.5	25	1.0	9.6
6	0.2	0.7	26	1.0	10.6
7	0.2	0.9	27	1.2	11.8
8	0.2	1.1	28	1.2	13.0
9	0.2	1.3	29	1.5	14.5
10	0.2	1.5	30	1.5	16
11	0.3	1.8	31	2.0	18
12	0.3	2.1	32	2.0	20
13	0.3	2.4	33	3.0	23
14	0.3	2.7	34	6.0	29
15	0.4	3.1	35	11	40
16	0.4	3.5	36	20	60
17	0.4	3.9	37	50	110
18	0.5	4.4	38	100	210
19	0.5	4.9	39	250	460
20	0.6	5.5	40	540	1000

The model does not explicitly represent the depth to the bedrock. However, the regolith-bedrock transition is in reality blurred by saprolites and bedrock fractures that store and transmit water, and the frequency and connectivity of fractures tend to decrease with depth in a gradual manner. Some of the fractures can be very deep, and roots are known to penetrate into them to obtain water and nutrients, particularly in water stressed seasons and settings such as rocky terrain covered with only a thin soil/regolith mantle (25, 27, 28, 33, 87, 99, 131, 145, 165, 182, 221, 239, 246, 253, 258, 259, 337–342). There is further evidence of this in Fig. 3C where roots have penetrated into the bedrocks (points below 1:1 line). Thus a gradual transition in the model is deemed more realistic than a sharp no-flow boundary.

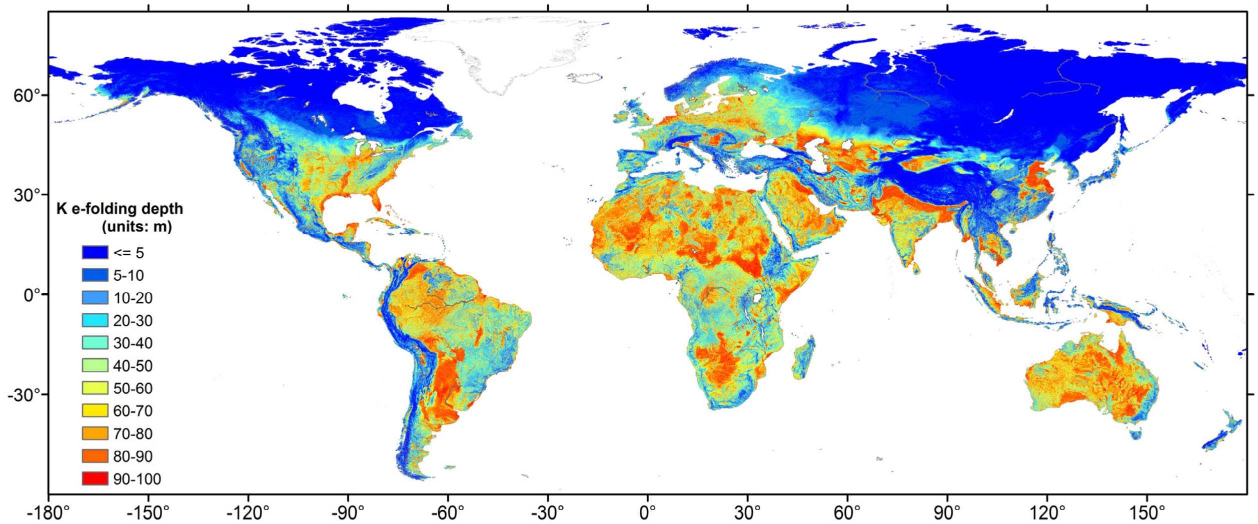

Fig. S8. The e-folding depth of exponential decrease with depth in permeability and porosity, obtained from local terrain slope and winter temperature (defining permafrost depth).

In regions with seasonal frost or permafrost, the shallow frost table prevents drainage, thus the decrease in porosity and permeability is faster than in unfrozen soils. This fact is accounted for by an empirical formula relating frost table depth to January temperature, as fully described elsewhere (2). This leads to the shallow e-folding depth (f values) in Fig. S8 in cold regions.

In each model grid column, the canopy water balance determines the interception, with the remaining water reaching the soil. Infiltration is determined by solving the 1D Richards equation of soil water movement in partially saturated media. The infiltration pulses (green arrow, Fig. S7A) wet the top soil and may or may not reach the water table, the latter being the lower boundary condition (saturation). The water table position is dynamic in time and variable in space, driven by recharge or discharge (R) from/to the soil above (blue arrow, Fig. S7A), the 2-way exchange with local (within-grid) rivers and floodplains/wetlands (Fig. S7B), and lateral drainage from higher to lower grid cells (groundwater convergence, Fig. S7C) constrained by the sea level (the ultimate boundary condition for continental drainage). The 2-way exchange with rivers and floodplains within a grid cell (Fig. S7B) is calculated using USGS MODFLOW river conductance formula (343) (Chapter 6, River Package), so that rivers receive base-flow if the water table in the cell is higher than the river surface elevation, and infiltrate into stream beds if the water table is lower. Floodwater can infiltrate into the sediments (bank storage) and seep out later (344). Lateral groundwater convergence (Fig. S7C) is calculated using the Darcy's law driven by the water table gradient, using the Dupuit-Forchheimer formula (345), which calculates the vertically-integrated lateral fluxes. This approach is necessitated by lacking the depth-structure in soil/regolith/bedrock permeability. It also reduced computation greatly, making it feasible to run the model dynamically at sub-kilometer grids over the globe. The model has been tested and applied to investigate the role of groundwater in regulating river flow, flooding, wetlands, soil moisture, and evapotranspiration over N. America (346–348) and the Amazon Basin (335, 336, 349, 350).

Input data on the land side include soil texture (as sand and clay fractions) and land surface topography (Table S3). A well-known issue in modeling soil hydrology is the poorly constrained soil hydraulic parameters based on empirical "pedo-transfer functions" that relate a limited number of soil texture classes to porosity, saturated hydraulic conductivity, field capacity, wilting point, and water content - metric potential, and water content - hydraulic conductivity relations. These empirical functions had been derived from soil samples in the temperate northern latitudes and are inadequate for tropical soils such as deeply weathered clays; tropical clays behave fundamentally differently, "draining like sand but holding on to moisture like clay" due to the formation of clay aggregates (351). This is a primary cause of the low infiltration rate in the earlier model studies of the Amazon (335, 336), and needs to be addressed. We thus introduce a new soil class, termed "tropical clay", to the 12 existing classes in the Clapp-Hornberger (352) pedo-transfer function, the latter widely applied in large-scale land models. The new soil class has a saturated hydraulic conductivity of 0.5m/day similar to that of a sandy clay loam (i.e., drains like sand), but a wilting point at a volumetric water content of 0.235 similar to that of a clay loam (i.e., hold onto water like clay). We assigned soils classified as Ultisols or Oxisols into this new category.

The model is run at 30-arc second grid resolution, continent by continent with sea-level as the lateral boundary condition, at 1-hour time steps, and over 11-years (2003-2013) to capture the event to inter-annual time-scales of variability. Model output is saved at monthly steps for later analyses, due to the enormous of amount of data and physical limits on data output/storage. The initial water table depth is the climatologic equilibrium water table obtained earlier (2) at the same global grid. To spin up the model to the new ECMWF-Interim climate forcing and the new root water uptake, and its feedback to soil hydrology, we run the model for 11 years, and then use the end water table and soil moisture profile to repeat the run, starting roots again from the top. This is repeated until long-term drifts are eliminated. The final water table is deeper in drier climates than before (2) largely due to groundwater use by adaptive and deep root uptake in the current model run.

Table S3. Model forcing data

Data Type	Source	Coverage	Resolution
Atmosphere	ECMWF-Interim (http://www.ecmwf.int/en/research/climate-reanalysis/era-interim), and precipitation from MSWEP (http://www.gloh2o.org)	Global Jan 1979 - present	0.25° lat-lon (~25 km) 3 hourly
Leaf Area Index (LAI)	MODIS Mod15A3 (https://lpdaac.usgs.gov/products/modis_products_table/mcd15a3) NCAR Seasonal Cycle http://www2.mmm.ucar.edu/wrf/users/download/get_sources_wps_geog.html	Global July 4 2002 - present	30" 4 days
Vegetation Types	MODIS land use (http://www2.mmm.ucar.edu/wrf/users/download/get_sources_wps_geog.html)	Global For the year 2000	~1km at Equator (32 arc-sec)
Maximum Leaf Conductance	NASA Land Data Assimilation System (http://ldas.gsfc.nasa.gov/nldas/web/web.veg.table.html)	Lookup table	By vegetation type
Vegetation Height	ORNL DAAC Global Forest Canopy Height (http://webmap.ornl.gov/wcsdown/dataset.jsp?ds_id=10023)	Global	1km
Soil Texture	FAO Global Harmonized Soil Data Base (http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/)	Global	~1km at Equator (30 arc-sec)

Land Surface Topography	SRTM (HydroSHEDS) below 60 ° N (http://hydrosheds.cr.usgs.gov/index.php)	Global	~1km at Equator (30 arc-sec)

2. Estimating Plant Water Demand

Plant transpiration is calculated using the Penman-Monteith equation modified by Shuttleworth-Wallace (S-W) (353, 354) to separate evaporation from transpiration in areas of partial vegetation cover. Input to the S-W equation includes atmosphere and vegetation variables as summarized in Table S3.

The atmospheric variables, including temperature, air humidity, pressure, wind, surface downward short-wave and net radiation, and soil temperatures, are directly derived from the ECMWF-Interim Reanalysis products. Atmospheric reanalyses assimilate multitudes of observations into models of atmospheric dynamics to produce regularly gridded (in space and time) atmospheric fields over continents or the globe. ECMWF-Interim Reanalysis offers ~0.7° latitude-longitude grid resolution and 3-hourly global products from 1979 to present. Wind and radiation fields are interpolated to our 30" grids; temperature, surface pressure and humidity are adjusted for elevation difference. Precipitation is obtained from the Multi-Source Weighted-Ensemble Precipitation (MSWEP) version 1.1 dataset, a 3-hourly 0.25° global gridded product merging gauge, satellite, and ECMWF-Interim Reanalysis. The precipitation corrections applied to the reanalysis product removed the early biases (e.g., in the Amazon where it rained too much in the dry season, as discussed in our earlier work) (335, 336, 349). If the grid cell has snow, we apply snowmelt (instead of precipitation) from an off-line Interim-Land (355) simulation from the ECMWF land model, forced by exactly the same atmosphere (including MSWEP precipitation) as in our experiments.

The land variables needed for the S-W formula include canopy water storage capacity and canopy-level stomata resistance, which are functions of the leaf area index (LAI) as observed by the MODIS satellites at 4-day intervals and 1km grids. The MODIS product, however, is plagued with frequent cloud cover in the tropics. The frequently missing data, and the spuriously rapid fluctuations in LAI within a matter of days, prevent us from using the product directly. We thus resort to the seasonal cycle in LAI derived from MODIS product by NCAR (Table S3). This unfortunately eliminated the large inter-annual variations in plant productivity, which can be lower in drought years, thus reducing water demand and preventing deep roots. Other land variables include the vegetation type and the associated maximum leaf-level stomata conductance, vegetation height required to calculate the roughness height and friction wind velocity for turbulent transfer.

This gives the actual (not potential) plant water needs, because the transpiration here is inferred from the actual LAI and observed/reanalysis atmosphere. This actual water need is to be met by taking water from the soil layers/depths as deemed necessary, discussed next.

3. Determining Root Water Uptake Profile

There is a fast growing literature on modeling plant root dynamics (59, 356–374). Our goal here is not to develop another model, but to ask one simple question using inverse modeling: what would be the global patterns in root water-uptake depth, if indeed roots respond to local soil water profiles as revealed here by observations? This question is similar to those addressed by several investigators using global model inversions, that is, to back-calculate the necessary uptake depth to meet the observed plant productivity. These earlier inverse models assumed that root-water uptake reflects the plants' tendency to maximize primary production (356, 357), or to minimize energy expenditure while meeting water demands (362), and other ecological principles with carbon/nutrient constraints (367). Our inverse model differs from these earlier model inversions, because it is based on the conceptual model proposed here; that is, root water uptake profile depends on the soil water profile, which depends on both infiltration from above (accounted for in earlier inverse models) and drainage from below (neglected in earlier models). The latter is influenced by the spatial patterns and temporal dynamics of the groundwater, which depends strongly on the fine-scaled topographic structure.

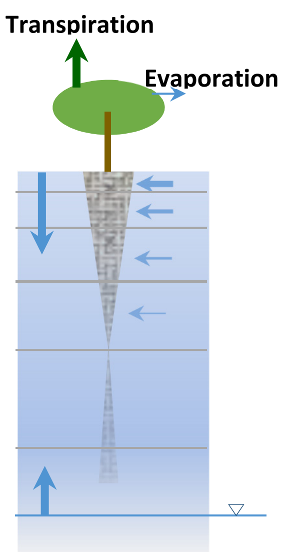

Fig. S9. Root water-uptake from "parallel-connected" soil layers.

We follow the Ohm's law of potential-driven flow through parallel-connected electronic resistors, here the resistors being the multiple soil layers simultaneous conducting water to roots (Fig. S9). This way, uptake occurs preferentially in low-resistance layers, but also in high-resistance layers, resulting in an overall least resistance path for the whole soil column-plant system. We calculate a dimensionless "ease function" (e) for each soil layer (j) given its water potential and depth below the surface:

$$e_j = \left(\frac{\psi_{lmin} - \psi_j}{\frac{2}{3}h_{veg} + d_j}\right) \qquad (1)$$

where ψ_{lmin} is the minimum leaf water potential set here as a constant of -2MPa for simplicity, ψ_j is the soil water potential in layer j, h_{veg} is the vegetation height, and d_j is the depth of soil layer j. The numerator is the driving force for soil-root-leaf water flux, and the denominator is the resistance to that flux (lifting height or flow path length of soil water, assuming mean canopy height being 2/3 of vegetation height) (data source in Table-S3). Thus the model makes it easier for roots to take up water from wetter (higher soil-to-leaf water potential difference and soil hydraulic conductivity) and shallower (shorter lifting height and flow path, reducing resistance) soil layers. The fractional contribution from each soil layer (r_j) is then based on the relative value of e and layer thickness (soil water store):

$$r_j = \frac{e_j \Delta z_j}{\sum e_j \Delta z_j} \qquad (2)$$

where Δz_j is the thickness of soil layer j. As an example, Fig. S10 illustrates a typical soil column in the dry season that is wetted from the top by the shallow and infrequent dry-season infiltration events, and from below by a water table. The soil water potential (blue dashed line) is high near the surface, decreasing with depth due to the shallow infiltration, but increases again in the capillary fringe. Accordingly, the easy function (green solid line) decreases with depth as a result of *both* decreasing soil water potential (ψ_j) *and* increasing soil depth (d_j). It would increase again in the capillary fringe, but

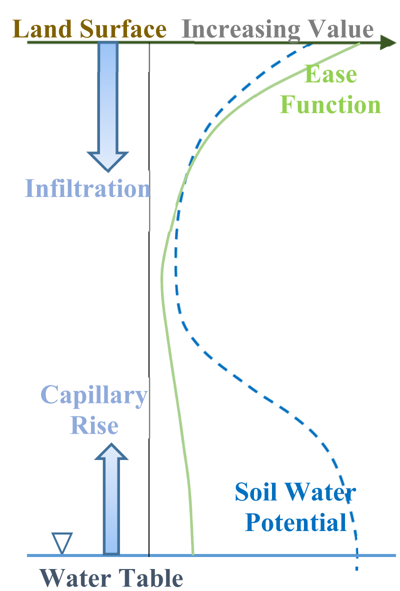

Fig. S10. Schematic profiles of the soil water potential (blue dashed line) and the ease function (green solid line).

only slightly due to the greater lifting depths. The result is that plants must balance water availability and the cost of procuring that water, but will pay the cost only if necessary to meet transpiration demand. Where the leaf area index is low, uptake will only use the top-wetted zone, but where it is high, uptake will cross the dry zone to reach the bottom-wetted zone maintained by groundwater capillary rise.

For a soil column with a very deep water table, the root zone soils are only wetted from the top by infiltration events, and both the soil water potential and the ease function would decrease monotonically with depth, leading to the widely reported deceasing root presence with depth in well-drained upland environments.

Thus in this model, root water uptake favors wetter and shallower soil layers, but roots also tap into drier and deeper layers if it is demanded by the transpiration calculated in the previous section. We further apply the following rules. (a) Uptake starts from the top, activating the deeper layer only when the ease function in the deeper layer is greater than in all the layers above. (b) If a layer does not contribute water for over a year, it is flagged inactive and can only be re-actived when condition (a) is met. (c) There is no root water uptake below the water table, and where/when the water table rises above the top soil layer, uptake is assumed to be from the top layer only (10cm thick). (d) Soil water content in each layer cannot fall below the wilting point, and if roots demand more water, the result is a deficit not met and recorded in the model output, as in the case of high leaf area index sustained by irrigation. We note that our hydrology model does not represent crop irrigation, and where this happens the artificially high LAI will lead to either a large deficit, or a much deeper root uptake if the water table is accessible. Therefore our inverse model gives the root-uptake depths as if all vegetation depends on the natural hydrologic cycle, and caution should be used in interpreting results in regions of heavily irrigated croplands.

Maximum root water uptake depth from the inverse model (Fig. S11-15) can be viewed interactively and downloaded as NetCDF files by continent at the European Union eartH2Observ Water Cycle Integrator (WCI), a public data portal (https://wci.earth2observe.eu/).

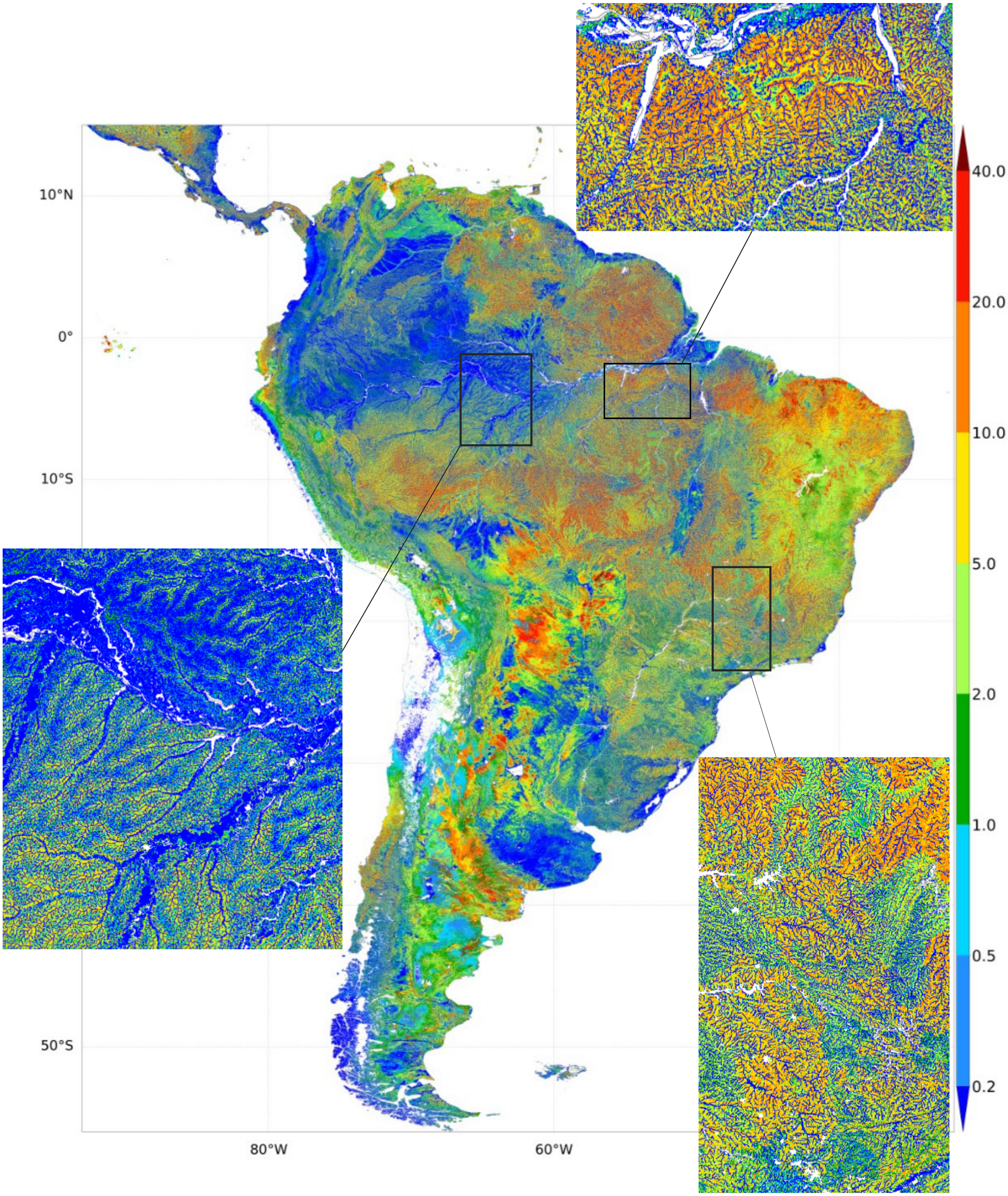

Fig. S11. Maximum depth of root water uptake (m) in S. America, averaged over 10yrs, with details over three regions. White grid cells have leaf area index (LAI) not detectable by MODIS and hence are not modeled.

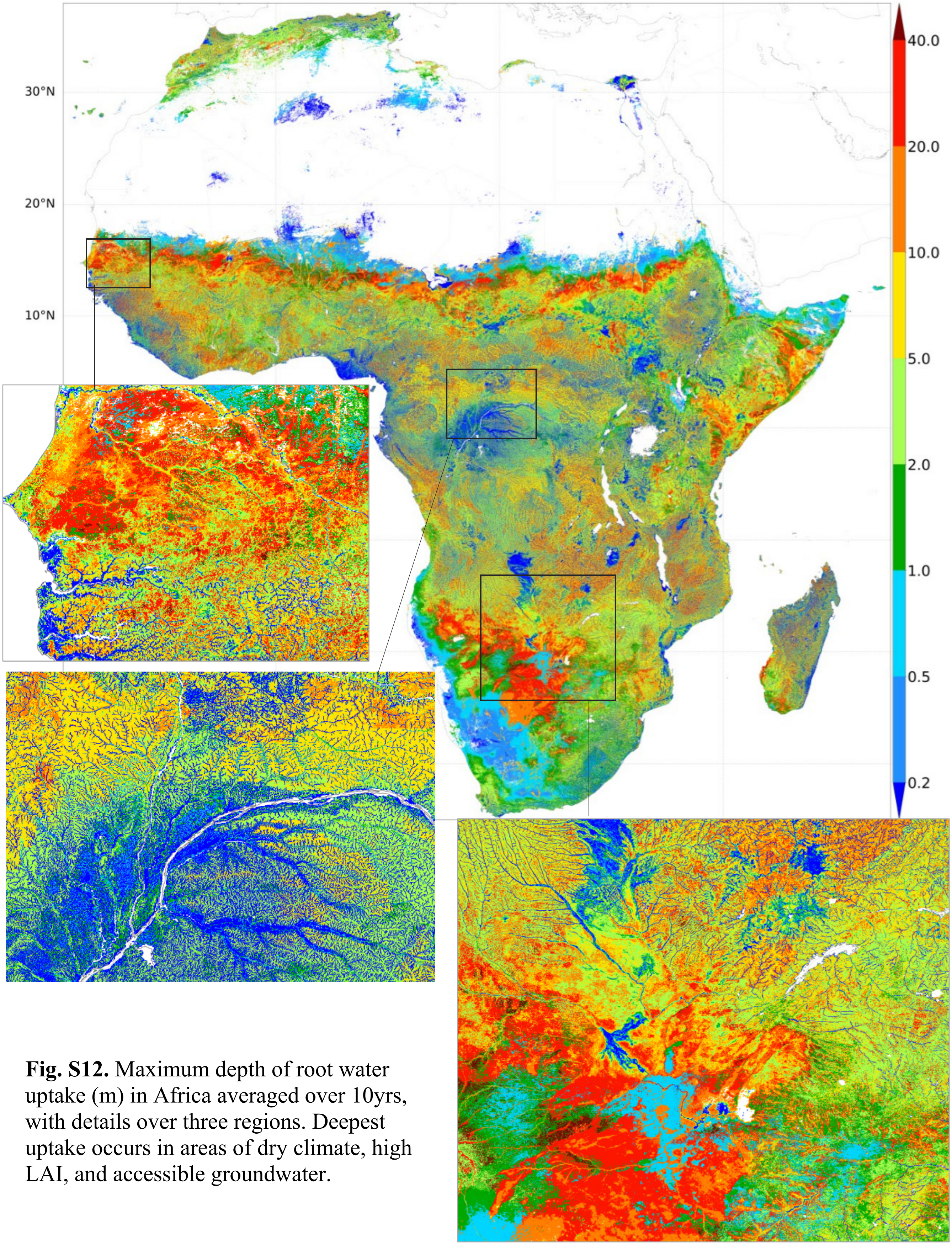

Fig. S12. Maximum depth of root water uptake (m) in Africa averaged over 10yrs, with details over three regions. Deepest uptake occurs in areas of dry climate, high LAI, and accessible groundwater.

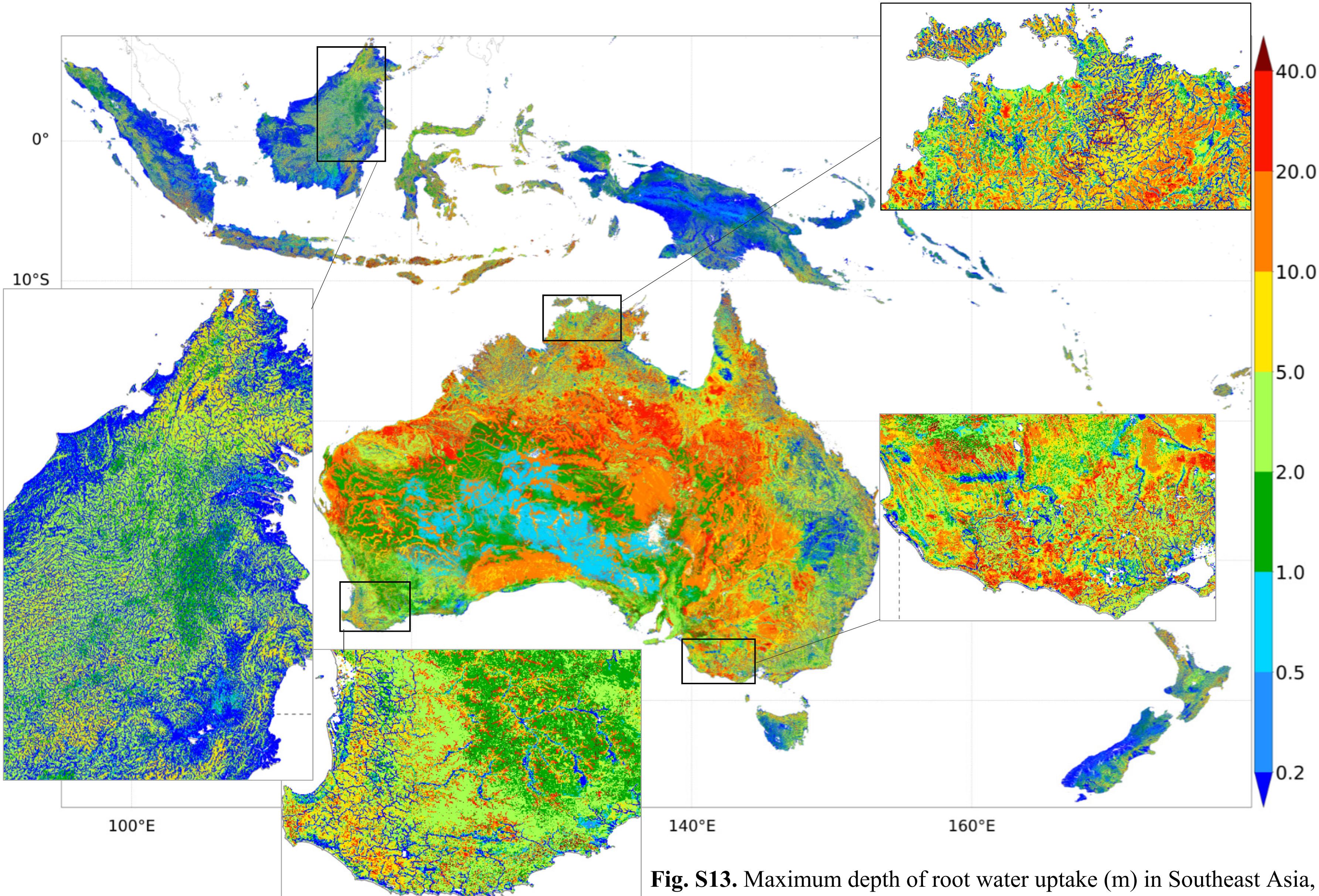

Fig. S13. Maximum depth of root water uptake (m) in Southeast Asia, Australia, and New Zealand. Uptake is shallow in per-humid tropics and deep in arid regions with high LAI and accessible water table.

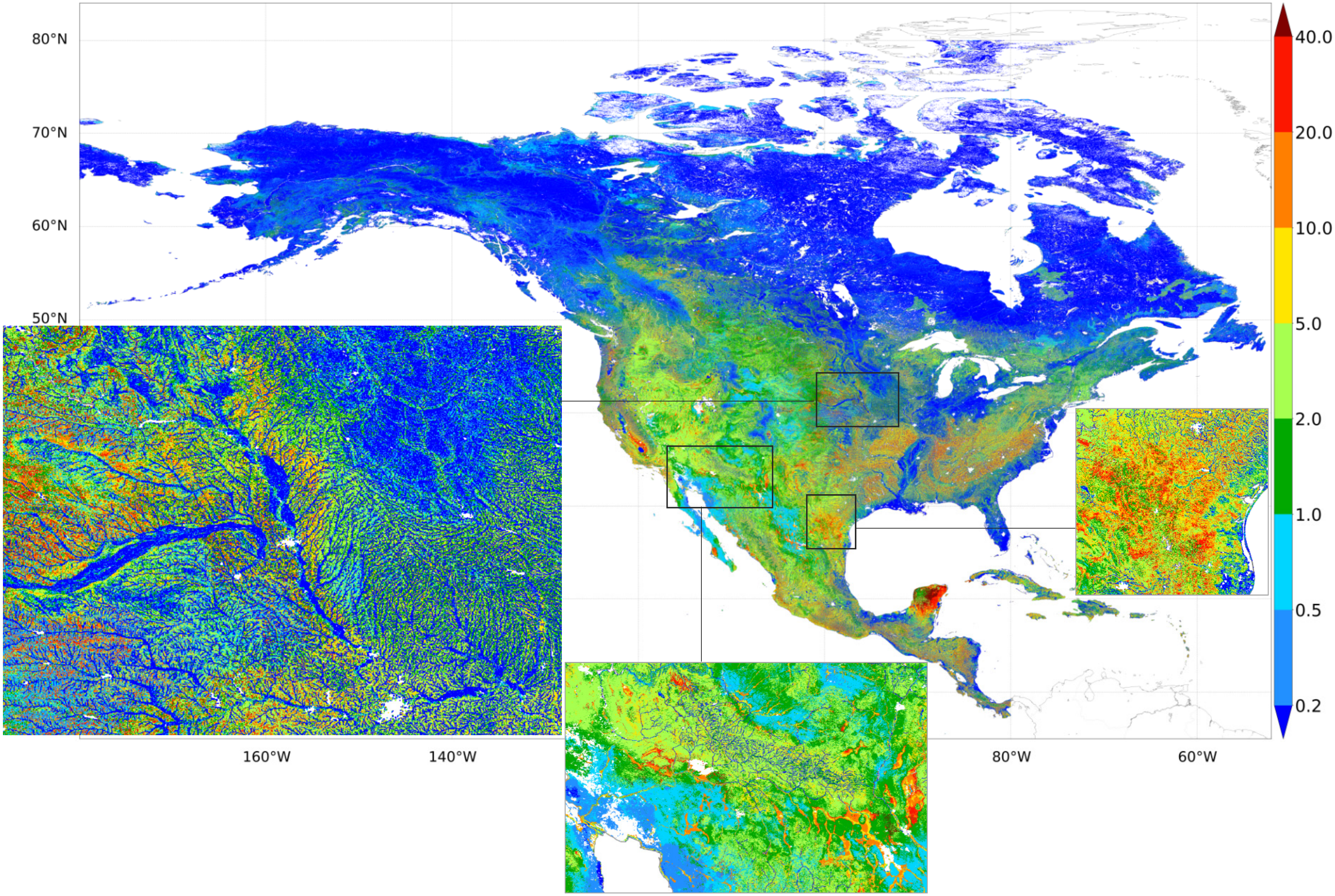

Fig. S14. Maximum depth of root water uptake (m) in North-Central America (details over E Nebraska and areas of known deep roots).

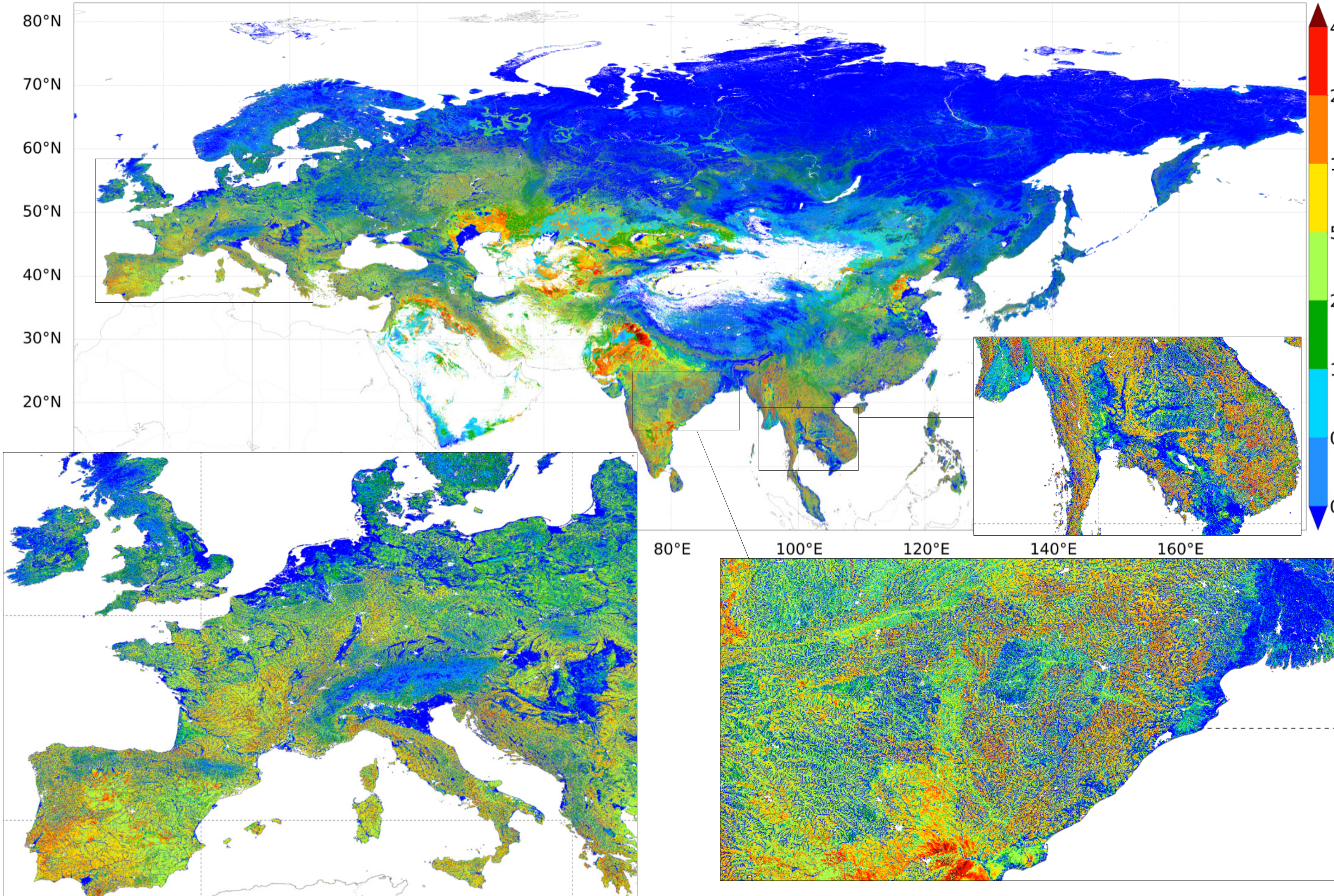

Fig. S15. Maximum depth of root water uptake (m) in Eurasia.

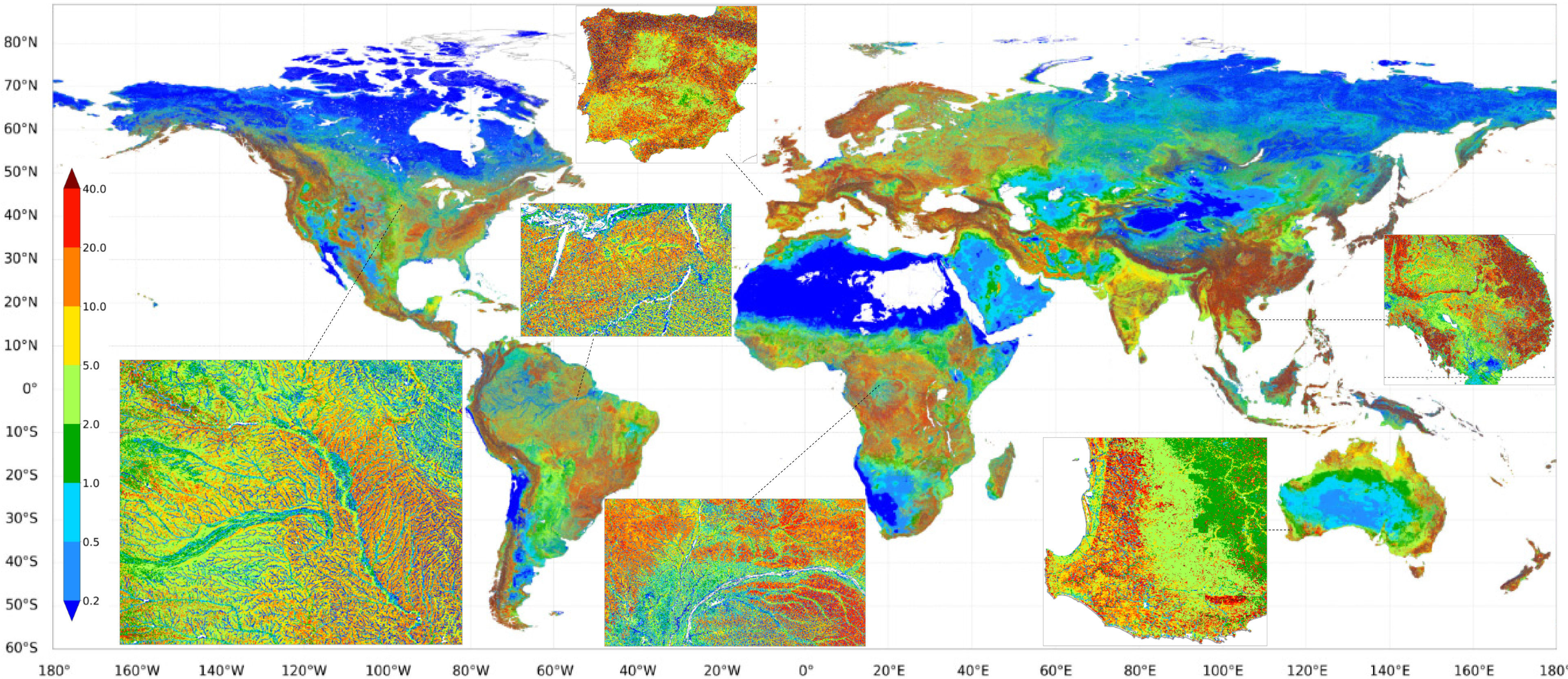

Fig. S16. Inverse-modeled 10yr-mean precipitation infiltration depth (m) with details over the same regions as in Fig. 6 of the main text. It reflects the climate (precipitation amount and frequency), soil texture giving it a patchy appearance, and the water table depth (Fig. S17), the latter sets the maximum depth of infiltration, although on arid uplands it rarely reaches the water table. This is why the infiltration depth reflects the topographic structure, because the water table surface is known to mimic the topography, esp. near the river valleys.

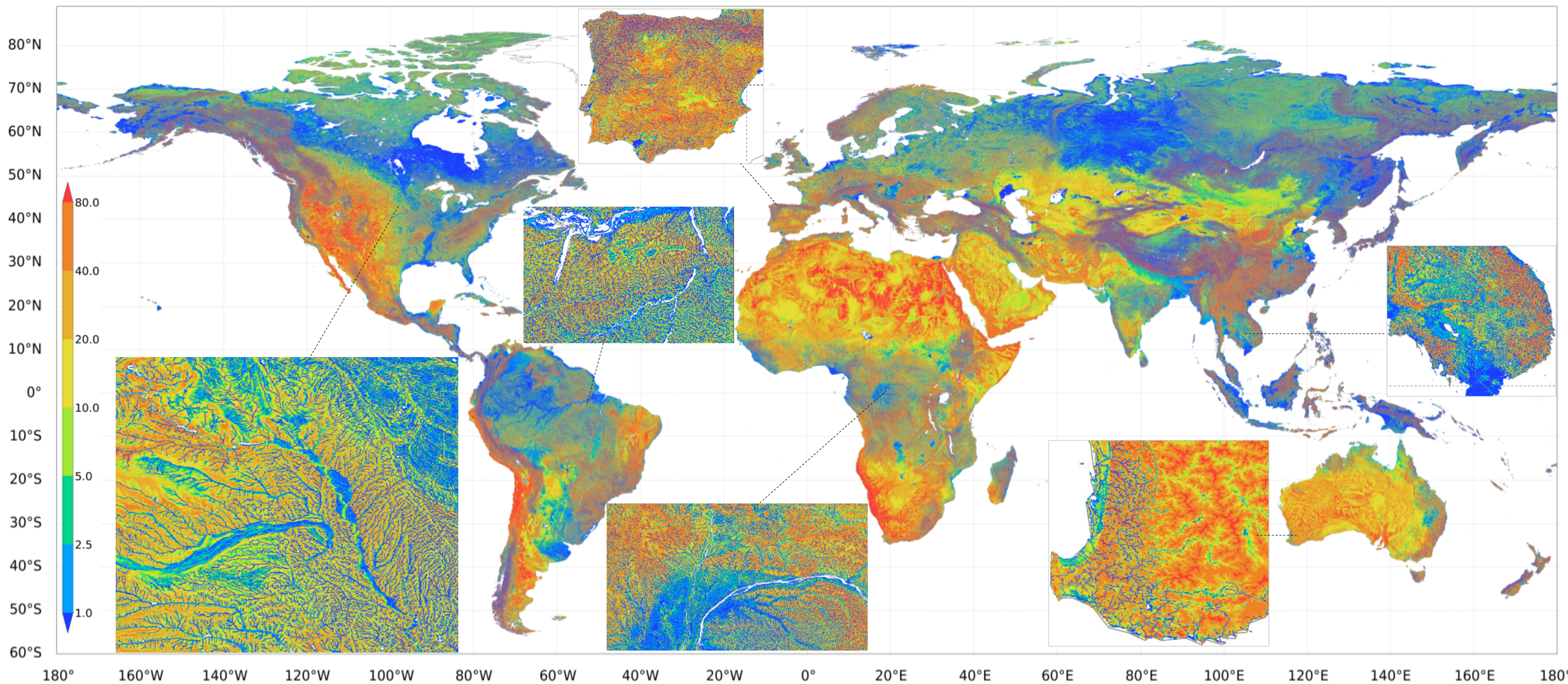

Fig. S17. Inverse-modeled 10yr-mean water table depth (m) with details over the same regions as in Fig. 6 of the main text. The color-scale is different from that of root uptake depth (Fig. 6, Fig. S11-15) and precipitation infiltration depth (Fig. S16) in order to display the very large range of water table depth. Note that compared to our early model estimates (2), the water table is now deeper in the lowlands, because here plant roots can use shallow groundwater, drawing down the water table.

References

1. Canadell J, et al. (1996) Maximum rooting depth of vegetation types at the global scale. *Oecologia* 108(4):583–595.
2. Fan Y, Li H, Miguez-Macho G (2013) Global patterns of groundwater table depth. *Science* 339(6122):940–943.
3. Schwarz M (1938) Root conditions of certain plants of the Wilderness of Judaea. *The journal of the Linnean Society Botany* 51(340):383–388.
4. Kimber PC (1974) The root system of Jarrah (Eucalyptus marginata). *Research Papers No 10, Forests Department of Western Australia*.
5. Pavlis J, Jenik J (2000) Roots of pioneer trees in Amazonian rain forest. *Trees - Structure and Function* 14(8):442–455.
6. Aaltonen VT (1920) *ACTA Forestrallia Fennica 14. Abreiten Der Forstwissenschaftlichen Gesellschaft In Finnland* (Heilsingforsiae) doi:10.1017/CBO9781107415324.004.
7. Abbott M, Fraley Jr L, Reynolds T (1991) Root profiles of selected cold desert shrubs and grasses in disturbed and undisturbed soils. *Environ Exp Bot* 31(2):165–178.
8. Abdelkrim L, Noria S, Gradziel T (2014) Root architecture of Atlas pistachio in relation to underlying soil properties under arid conditions. *African Journal of Agricultural Research* 9(6):620–626.
9. Abdi E, Majnounian B, Genet M, Rahimi H (2010) Quantifying the effects of root reinforcement of Persian Ironwood (Parrotia persica) on slope stability; a case study: Hillslope of Hyrcanian forests, northern Iran. *Ecological Engineering* 36(10):1409–1416.
10. Addington RN, et al. (2006) Adjustments in hydraulic architecture of Pinus palustris maintain similar stomatal conductance in xeric and mesic habitats. *Plant, Cell and Environment* 29(4):535–545.
11. Albaugh TJ, Allen HL, Kress LW (2006) Root and stem partitioning of Pinus taeda. *Trees - Structure and Function* 20(2):176–185.
12. Alexandre DY, Ouédraogo SJ (1992) *Variations in Root Morphology of Faidherbia albida in Relation to Soil and Agronomic Effects* (World Agroforestry Centre).
13. Angadi S V, Entz MH (2002) Root system and water use patterns of different height sunflower cultivars. *Agron J* 94:136–145.
14. Antos JA (1988) Underground morphology and habitat relationships of three pairs of forest herbs. *American Journal of Botany* 75(1):106–113.
15. Archer N a. L, Quinton JN, Hess TM (2002) Below-ground relationships of soil texture, roots and hydraulic conductivity in two-phase mosaic vegetation in South-east Spain. *Journal of Arid Environments* 52:535–553.
16. Armas C, Padilla FM, Pugnaire FI, Jackson RB (2010) Hydraulic lift and tolerance to salinity of semiarid species: Consequences for species interactions. *Oecologia* 162(1):11–21.
17. Arndt SK, Kahmen A, Arampatsis C, Popp M, Adams M (2004) Nitrogen fixation and metabolism by groundwater-dependent perennial plants in a hyperarid desert. *Oecologia* 141(3):385–394.
18. Ash AN, Gross HD, Noggle GR (1975) Root growth and distribution in Festuca arundinacea. *Bulletin of the Torrey Botanical Club* 102(5):238–243.
19. Badia D, Marti C, Poch RM (2011) A soil toposequence characterization in the irrigable lands - protected area contact zone of El Basal , NE-Spain. *Arid land research and Management* 25(1):1532–4982.
20. Baitulin IO (1996) Root research in natural plant communities of Kazakhstan. *Acta*

Phytogeogr Suec 81:7–10.

21. Bakker MR, Augusto L, Achat DL (2006) Fine root distribution of trees and understory in mature stands of maritime pine (Pinus pinaster) on dry and humid sites. *Plant and Soil* 286(1–2):37–51.
22. Bannan MW (1940) The root systems of northern Ontario conifers growing in sand. *American Journal of Botany,* 27(2):108–114.
23. Becker P, Sharbini N, Yahya R (1999) Root architecture and root : shoot allocation of shrubs and saplings in two lowland tropical forests : Implications for life-form composition. *Biotropica* 31(1):93–101.
24. Berish CW (1982) Root biomass and surface area in three successional tropical forests. *Canadian Journal of Forest Research* 12:699–704.
25. Berndt HW, Gibbons RD (1958) *Root distribution of some native trees and understory plants growing on three sites within Ponderosa pine watersheds in Colorado* (USDA Forest Service) doi:10.1017/CBO9781107415324.004.
26. Bhattachan A, et al. (2012) Evaluating ecohydrological theories of woody root distribution in the kalahari. *PLoS ONE* 7(3). doi:10.1371/journal.pone.0033996.
27. Bishop DM (1962) Lodgepole Pine rooting habits in the Blue Mountains of northeastern Oregon. *Ecology* 43(1):140–142.
28. Bleby TM, Mcelrone AJ, Jackson RB (2010) Water uptake and hydraulic redistribution across large woody root systems to 20 m depth. *Plant, Cell and Environment* 33(12):2132–2148.
29. Bobich E, Huxman T (2009) Dry mass partitioning and gas exchange for young ocotillos (Fouquieria splendens) in the Sonoran Desert. *International journal of plant sciences* 170(3):283–289.
30. Boggie R (1977) Water-table depth and oxygen content of deep peat in relation to root growth of pinus contorta. *Plant and Soil* 48:447–454.
31. Bonal D, et al. (2000) Water acquisition patterns of two wet tropical canopy tree species of French Guiana as inferred from (H2O)-O-18 extraction profiles. *Annals of Forest Science* 57(7):717–724.
32. Bornman TG, Adams JB, Bate GC (2004) The influence of floodplain geohydrology on the distribution of Sarcocornia pillansii in the Olifants Estuary on the West Coast, South Africa. *Journal of Arid Environments* 56(4):603–625.
33. Bornyasz MA, Graham RC, Allen MF (2005) Ectomycorrhizae in a soil-weathered granitic bedrock regolith: Linking matrix resources to plants. *Geoderma* 126(1–2 SPEC. ISS.):141–160.
34. Bouillet J-P, et al. (2002) Changes with age in the spatial distribution of roots of Eucalyptus clone in Congo: Impact on water and nutrient uptake. *Forest Ecology and Management* 171:43–57.
35. Bréda N, Granier A, Barataud F, Moyne C (1995) Soil water dynamics in an oak stand. I.Soil moisture, water potentials and water uptake by roots. *Plant and Soil* 172(1):17–27.
36. Briones O, Montana C, Ezcurra E (1996) Competition between three Chihuahuan desert species: Evidence from plant size-distance relations and root distribution. *Journal of Vegetation Science* 7(3):453–460.
37. Brunel J-P (2009) Sources of water used by natural mesquite vegetation in a semi-arid region of northern Mexico. *Hydrological Sciences Journal* 54(January 2015):375–381.
38. Bucci SJ, Scholz FG, Goldstein G, Meinzer FC, Arce ME (2009) Soil water availability and rooting depth as determinants of hydraulic architecture of Patagonian woody species. *Oecologia* 160(4):631–641.

39. Bunger MT, Thomson HJ (1938) Root development as a factor in the success or failure of windbreak trees in the Southern high plains. *Journal of Forestry*:790–803.
40. Buettner V (1994) Spatial and temporal patterns of fine root abundance in a mixed oak-beech forest. *Forest ecology and management* 70:11–21.
41. Canham CA, Froend RH, Stock WD, Davies M (2012) Dynamics of phreatophyte root growth relative to a seasonally fluctuating water table in a Mediterranean-type environment. *Oecologia* 170(4):909–916.
42. Cannon WA (1911) *The Root Habits of Desert Plants* (Carnegie Institution of Washington) doi:10.5962/bhl.title.32210.
43. Cannon WA (1913) *Botanical Features of the Algerian Sahara* (Carnegie Institution of Washington, Washington, D.C.).
44. Cannon WA (1913) Some relations between root characters, ground water and species distribution. *Science* 37(950):420–423.
45. Cannon HL, Starrett WH (1956) *Botanical Prospecting for Uranium on La Ventana Mesa , Sandoval County New Mexico, USGS Bulletin 1009-M* (USGS).
46. Cardinael R, et al. (2015) Competition with winter crops induces deeper rooting of walnut trees in a Mediterranean alley cropping agroforestry system. *Plant and Soil* 391(1–2):219–235.
47. Carrick PJ (2003) Competitive and facilitative relationships among three shrub species , and the role of browsing intensity and rooting depth in the Succulent Karoo, South Africa. *Journal of Vegetation Science* 14(5):761–772.
48. Carter MR, Gregorich EG (2010) Carbon and nitrogen storage by deep-rooted tall fescue (Lolium arundinaceum) in the surface and subsurface soil of a fine sandy loam in eastern Canada. *Agriculture, Ecosystems and Environment* 136(1–2):125–132.
49. Castellanos J, Maass M, Kummerow J (1991) Root biomass of a dry deciduous tropical forest in Mexico. *Plant and Soil* 131(2):225–228.
50. Castelli RM, Chambers JC, Tausch RJ (2000) Soil-plant relations along a soil-water gradient in great basin riparian meadows. *Wetlands* 20(2):251–266.
51. Cattanio JH, Anderson AB, Rombold JS, Nepstad DC (2004) Phenology, litterfall, growt , and root biomass in a tidal floodplain forest in the Amazon estuary. *Revista Brasil Bot* 27(4):703–712.
52. Ceballos DS, Frangi J, Jobbágy EG (2013) Soil volume and carbon storage shifts in drained and afforested wetlands of the Paraná River Delta. *Biogeochemistry* 112(1–3):359–372.
53. Cerri CC, Volkoff B (1987) Carbon content in a yellow Latosol of central Amazon rain forest. *Acta Oecologica* 8(1):29–42.
54. Chapman SB (1970) The nutrient content of the soil and root system of a dry heath ecosystem. *Journal of Ecology* 58(2):445–452.
55. Chapman SB (1979) Some interrelationships between soil and root respiration in lowland Calluna Heathland in southern England. *Journal of Ecology* 67(1):1–20.
56. Cheyney EG (1929) *A study of the roots in a square yard of jack pine forest*.
57. Cheyney EG (1932) The roots of a jack pine tree. *Journal of Forestry* 30(8):929–932.
58. Christina M, et al. (2011) Almost symmetrical vertical growth rates above and below ground in one of the world's most productive forests. *Ecosphere* 2(3):art27.
59. Christina M, et al. (2016) Importance of deep water uptake in tropical eucalypt forest. *Functional Ecology*:1–11.
60. Claus A, George E (2005) Effect of stand age on fine-root biomass and biomass distribution in three European forest chronosequences. *Canadian Journal of Forest Research* 35(7):1617–1625.

61. Cline JF, Uresk DW, Rickard WH (1977) Comparison of soil water used by a sagebrush-bunchgrass and a cheatgrass community. *J Range Manage* 30(May):199–201.
62. Coile TS (1937) Distribution of forest tree roots in North Carolina piedmont soils. *Journal of Frestry* 35:4–39.
63. Comino E, Druetta A (2010) The effect of Poaceae roots on the shear strength of soils in the Italian alpine environment. *Soil and Tillage Research* 106(2):194–201.
64. Coughenour MB, Ellis JE, Popp RG (1990) Morphometric relationships and developmental patterns of Acacia tortilis and Acacia reficiens in southern Turkana, Kenya. *Bulletin of the Torrey Botanical Club* 117(1):8–17.
65. Coupland RT, Johnson RE (1965) Rooting characteristics of native grassland species in Saskatchwan. *Journal of Ecology* 53(2):475–507.
66. Cuevas E, Brown S, Lugo AE (1991) Above- and belowground organic matter storage and production in a tropical pine plantation and a paired broadleaf secondary forest. *Plant and Soil* 135(2):257–268.
67. Curt T, Lucot E, Bouchaud M (2001) Douglas-fir root biomass and rooting profile in relation to soils in a mid-elevation area (Beaujolais Mounts, France). *Plant and Soil* 233:109–125.
68. Dai Y, Zheng XJ, Tang LS, Li Y (2015) Stable oxygen isotopes reveal distinct water use patterns of two Haloxylon species in the Gurbantonggut Desert. *Plant and Soil* 389(1–2):73–87.
69. Danjon F, Fourcaud T, Bert D (2005) Root architecture and wind- firmness of mature Pinus pinaster. *New Phytologist* 168(1):387–400.
70. Da Silva F, et al. (2015) Allometric equations for estimating biomass of euterpe precatoria, the most abundant palm species in the Amazon. *Forests* 6(2):450–463.
71. Das DK, Chaturvedi OP (2008) Root phytomass recovery and rooting characteristics of five agroforestry tree species in eastern India. *Journal of Tropical Forest Science* 20(3):156–166.
72. Daubenmire RF (1941) Some ecologic features of the subterranean organs of alpine plants. *Ecology* 22(4):370–378.
73. David TS, Ferreira MI, Cohen S, Pereira JS, David JS (2004) Constraints on transpiration from an evergreen oak tree in southern Portugal. *Agricultural and Forest Meteorology* 122(3–4):193–205.
74. David TS, et al. (2013) Root functioning, tree water use and hydraulic redistribution in Quercus suber trees: A modeling approach based on root sap flow. *Forest Ecology and Management* 307:136–146.
75. Davidson E, et al. (2011) Carbon inputs and water uptake in deep soils of an eastern amazon forest. *Forest Science* 57(1):51–58.
76. Davis G, Neilsen W, Mcdavitt J (1983) Root distribution of Pinus radiata related to soil characteristics in five Tasmanian soils. *Australian Journal of Soil Research* 21(2):165.
77. Dawson T (1993) Hydraulic lift and water use by plants: Implications for water balance, performance and plant-plant interactions. *Oecologia* 95(4):565–574.
78. Dawson TE, Pate JS (1996) Seasonal water uptake and movement in root systems of Australian phraeatophytic plants of dimorphic root morphology: a stable isotope investigation. *Oecologia* 107(1):13–20.
79. Day MW (1941) The root system of red pine saplings. *Journal of Forestry*:468–472.
80. Dell B, Bartle J, Tacey W (1983) Root occupation and root channels of Jarrah forest subsoils. *Australian Journal of Botany* 31(6):615.
81. Derbel S, Chaieb M (2012) Growth establishment and phenology of four woody Saharan species. *African Journal of Ecology* 51(2):307–318.
82. Dittmer HJ (1959) A study of the root system of certain sand dune plants in New Mexico.

Ecology 40(2):265–273.
83. Do FC, et al. (2008) Stable annual pattern of water use by Acacia tortilis in Sahelian Africa. *Tree physiology* 28(1):95–104.
84. Donovan LA, Richards JH, Muller MW (1996) Water relations and leaf chemistry of Chrysothamnus nauseosus ssp. consimilis (Asteraceae) and Sarcobatus vermiculatus (Chenopodiaceae). *American Journal of Botany* 83(12):1637–1646.
85. Dorji T, et al. (2013) Plant functional traits mediate reproductive phenology and success in response to experimental warming and snow addition in Tibet. *Global Change Biology* 19(2):459–472.
86. Douglas DA (1989) Clonal growth of Salix setchelliana on glacial river gravel bars in Alaska. *Journal of Ecology* 77(1):112–126.
87. Drexhage M, Gruber F (1998) Architecture of the skeletal root system of 40-year-old Picea abies on strongly acidified soils in the Harz Mountains (Germany). *Canadian Journal of Forest Research* 28(1):13–22.
88. Dumortier M (1991) Below-ground dynamics in a wet grassland ecosystem. *Plant Root Growth, an Ecological Perspective*, ed Atkinson D (Blackwell Scientific Publications, Oxford).
89. Du J, et al. (2010) Clonal integration increases performance of ramets of the fern Diplopterygium glaucum in an evergreen forest in southeastern China. *Flora: Morphology, Distribution, Functional Ecology of Plants* 205(6):399–403.
90. Duncan WH (1935) Root systems of woody plants of old fields of Indiana. *Ecology* 16(4):554–567.
91. Dupuy NC, Dreyfus BL (1992) Bradyrhizobium populations occur in deep soil under the leguminous tree Acacia albida. *Applied and Environmental Microbiology* 58(8):2415–2419.
92. Dye PJ (1996) Response of Eucalyptus grandis trees to soil water deficits. *Tree physiology* 16:233–238.
93. Eamus D, Chen X, Kelley G, Hutley LB (2002) Root biomass and root fractal analyses of an open Eucalyptus forest in a savanna of north Australia. *Australian Journal of Botany* 50:31–41.
94. Eis S (1974) Root system morphology of western hemlock, western red cedar, and Douglas fir. *Canadian Journal of Forest Research* 4(1):28–38.
95. Eis S (1987) Root systems of older immature hemlock, cedar, and Douglas-fir. *Canadian Journal of Forest Research* 17(11):1348–1354.
96. Elliott GRB (1924) Relation between the downward penetration of corn roots and water level in peat soil. *Ecology* 5(2):175–178.
97. Ellsworth PZ, Sternberg LSL (2015) Seasonal water use by deciduous and evergreen woody species in a scrub community is based on water availability and root distribution. *Ecohydrology* 551(JULY 2014):n/a-n/a.
98. Esler KJ, Rundel PW (1999) Comparative patterns of phenology and growth form diversity in two winter rainfall deserts: the Succulent Karoo and Mojave Desert ecosystems. *Plant Ecology* 142(1–2):97–104.
99. Estrada-Medina H, Graham RC, Allen MF, Jimenez-Osornio JJ, Robles-Casolco S (2013) The importance of limestone bedrock and dissolution karst features on tree root distribution in northern Yucatan, Mexico. *Plant and Soil* 362(1–2):37–50.
100. Fan Y, et al. (2012) Water adaptive traits of deep-rooted C3 halophyte (Karelinia caspica (Pall.) Less.) and shallow-rooted C4 halophyte (Atriplex tatarica L.) in an arid region, Northwest China. *Journal of Arid Land* 4(4):469–478.
101. Farrington P, Greenwood EAN, Bartle GA, Beresford JD, Watson GD (1989) Evaporation

from Banksia woodland on a groundwater mound. *Journal of Hydrology* 105(1–2):173–186.
102. Farrish KW (1991) Spatial and temporal fine-root distribution in three Louisiana forest soils. *Soil Science Society of America journal* 55(6):1752–1757.
103. February EC, Allsopp N, Shabane T, Hattas D (2011) Coexistence of a C4 grass and a leaf succulent shrub in an arid ecosystem. The relationship between rooting depth, water and nitrogen. *Plant and Soil* 349(1–2):253–260.
104. February EC, Cook GD, Richards AE (2013) Root dynamics influence tree-grass coexistence in an Australian savanna. *Austral Ecology* 38(1):66–75.
105. Fenner M (1980) Some measurements on the water relations of Baobab trees. *Biotropica* 12(3):205–209.
106. Fisher RA, et al. (2007) The response of an Eastern Amazonian rain forest to drought stress: results and modelling analyses from a throughfall exclusion experiment. *Global Change Biology* 13(11):2361–2378.
107. Foldats, Ernesto, Rutkis E (1975) Ecological studies of Chaparro (Curatella americana L.) and Manteco (Byrsonima crassifolia H.B.K.) in Venezuela. *Ecological Studies* 2(3):159–178.
108. Flombaum P, Sala O (2011) Effects of plant species traits on ecosystem processes. *Ecology* 93(2):227–234.
109. Follett R, Allmaras R, Reichman G (1974) Distribution of corn roots in sandy soil with a declining water table. *AGRONOMY JOURNAL* 66:288–292.
110. Frangi JL, Lugo AE (1985) Ecosystem dynamics of a subtropical floodplain forest. *Ecological Monographs* 55(3):351–369.
111. Franzluebbers AJ, Stuedemann JA (2009) Soil-profile organic carbon and total nitrogen during 12 years of pasture management in the Southern Piedmont USA. *Agriculture, Ecosystems and Environment* 129(1–3):28–36.
112. Freycon V, et al. (2014) Tree roots can penetrate deeply in African semi-deciduous rain forests: evidence from two common soil types. *Journal of Tropical Ecology* 31(1):13–23.
113. Gaines KP, et al. (2016) Reliance on shallow soil water in a mixed-hardwood forest in central Pennsylvania. *Tree Physiology* 36(4):444–458.
114. Gary L (1963) Distribution of five-stamen tamarisk seepwillow and arrowweed. *Forest Science* 9(3):311–314.
115. Gaze SR, Brouwer J, Simmonds LP, Bromley J (1998) Dry season water use patterns underGuiera senegalensisL. shrubs in a tropical savanna. *Journal of Arid Environments* 40(1):53–67.
116. Gemmer EW (1928) The root system of a longleaf pine. *The Scientific Monthly* 27(4):384–384.
117. Gentile RM, Martino DL, Entz MH (2003) Root characterization of three forage species grown in southwestern Uruguay. *Canadian Journal of Plant Science* 83(4):785–788.
118. Germon A, et al. (2016) Unexpected phenology and lifespan of shallow and deep fine roots of walnut trees grown in a silvoarable Mediterranean agroforestry system. *Plant and Soil* 401(1–2):409–426.
119. Gevorkiantz SR, Rudolf PO, Zehngraff PJ (1943) A tree classification for aspen, jack pine, and second-growth red pine. *Journal of Forestry*:268–274.
120. Gibbens RP, Lenz JM (2001) Root systems of some Chihuahuan Desert plants. *Journal of Arid Environments* 49(200 1):221–263.
121. Glover PE (1950) The root systems of some British Somaliland plants. *East African agricultural journal* 16(2–4):98–113.
122. Glover JD, et al. (2010) Harvested perennial grasslands provide ecological benchmarks for

agricultural sustainability. *Agriculture, Ecosystems and Environment* 137(1–2):3–12.
123. Greenland DJ, Kowal JML (1960) Nutrient content of the moist tropical forest of Ghana. *Plant and Soil* 12(2):154–174.
124. Gries D, et al. (2003) Growth and water relations of Tamarix ramosissima and Populus euphratica on Taklamakan desert dunes in relation to depth to a permanent water table. *Plant, Cell and Environment* 26(5):725–736.
125. Groeneveld DP, Crowley DE (1988) Root system response to flooding in three desert shrub species. *Functional Ecology* 2(4):491.
126. Haase P, et al. (1996) An investigation of rooting depth of the semiarid shrub Retama sphaerocarpa (L.) Boiss. by labelling of ground water with a chemical tracer. *Journal of Hydrology* 177:23–31.
127. Haasis FW (1921) Relations between soil type and root form of western yellow pine seedlings. *Ecology* 2(4):292–303.
128. Haigh H (1966) Root development in the sandy soils of Zulu land. *Forestry in South Africa* 7:31–36.
129. Hao Y, et al. (2006) Roots of pioneer trees in the lower sub-tropical area of Dinghushan, Guangdong, China. *Journal of Zhejiang University Science B* 7(5):377–385.
130. He WM, Zhang XS (2003) Responses of an evergreen shrub Sabina vulgaris to soil water and nutrient shortages in the semi-arid Mu Us Sandland in China. *Journal of Arid Environments* 53(3):307–316.
131. Hellmers H, Horton JS, Juhren G, O'Keefe J (1955) Root systems of some Chaparral plants in southern California. *Ecology* 36(4):667–678.
132. Hendrick RL, Pregitzer KS, Hendrick RL, Pregitzer KS (1996) Temporal and Depth-Related Patterns of Fine Root Dynamics in Northern Hardwood Forests. *Journal of Ecology* 84(2):167–176.
133. Heyward F (1933) The root system of longleaf pine on the deep sands of western Florida. *Ecology* 14(2):136–148.
134. Higgins KB (1987) Root systems of selected plant species in mesic mountain fynbos in the Jonkershoek Valley Southwestern Cape Province South Africa. *South African journal of botany* 53:249–258.
135. Hipondoka MHT, Aranibar JN, Chirara C, Lihavha M, Macko SA (2003) Vertical distribution of grass and tree roots in arid ecosystems of Southern Africa: niche differentiation or competition? *Journal of Arid Environments* 54(2):319–325.
136. Hironaka M (1961) The Relative Rate of Root Development of Cheatgrass and Medusahead. *Journal of Range Management Archives* 14(5):263–267.
137. Hoffmann A (1978) Root studies in the Chilean matorral. *Oecologia1* 32(1):57–69.
138. Holdo RM, Timberlake J (2008) Rooting depth and above-ground community composition in Kalahari sand woodlands in western Zimbabwe. *Journal of Tropical Ecology* 24(2):169–176.
139. Horton KW (1958) *Rooting habits of lodgepole pine* doi:10.1038/180270a0.
140. Hosegood PH, Howland P (1966) A preliminary study of the root distribution of some exotic tree crops, evaluated by a rapid sampling method. *East African agricultural and forestry journal* 32:16–18.
141. Howard A (1925) The effects of grass on trees. *Proceedings of the Royal Society of London Series B* 97(683):284–321.
142. Hubble TCT, Docker BB, Rutherfurd ID (2010) The role of riparian trees in maintaining riverbank stability: A review of Australian experience and practice. *Ecological Engineering* 36(3):292–304.
143. Hulbert LC (1955) Ecological Studies of Bromus tectorum and Other Annual Bromegrasses.

Ecological Monographs 25(2):181–213.
144. Imai N, Kitayama K, Titin J (2010) Distribution of phosphorus in an above-to-below-ground profile in a Bornean tropical rain forest. *Journal of Tropical Ecology* 26(6):627–636.
145. Jackson RB, Moore LA, Hoffmann WA, Pockman WT, Linder CR (1999) Ecosystem rooting depth determined with caves and DNA. *Proceedings of the National Academy of Sciences of the United States of America* 96(20):11387–11392.
146. Jackson R, Banner J, Jobbágy E (2002) Ecosystem carbon loss with woody plant invasion of grasslands. *Nature* 277(July):623–627.
147. Jaramillo VJ, Ahedo-Hernndez R, Kauffman JB (2003) Root biomass and carbon in a tropical evergreen forest of Mexico: changes with secondary succession and forest conversion to pasture. *Journal of Tropical Ecology* 19(4):457–464.
148. Jennings CMH (1974) The Hydrogeology of Botswana. Dissertation (University of Natal). doi:10.1017/CBO9781107415324.004.
149. Jiménez EM, Moreno FH, Lloyd J, Peñuela MC, Patiño S (2009) Fine root dynamics for forests on contrasting soils in the colombian Amazon. *Biogeosciences Discussions* 6(2):3415–3453.
150. Jipp PH, Nepstad DC, Cassel DK, Reis De Carvalho C (1998) Deep soil moisture storage and transpiration in forests and pastures of seasonally-dry Amazonia. *Climatic Change* 39:395–412.
151. Jobbagy EG, Jackson RB (2004) Groundwater use and salinization with grassland afforestration. *Global Change Biology* 10(8):1299–1312.
152. Jobbágy EG, Nosetto MD, Villagra PE, Jackson RB (2011) Water subsidies from mountains to deserts: Their role in sustaining groundwater-fed oases in a sandy landscape. *Ecological Applications* 21(3):678–694.
153. Johnson DM, Domec JC, Woodruff DR, McCulloh KA, Meinzer FC (2013) Contrasting hydraulic strategies in two tropical lianas and their host trees. *American Journal of Botany* 100(2):374–383.
154. Jonasson S, Callaghan T V (1992) Root mechanical properties related to disturbed and stressed habitats in the Arctic. *The New Phytologist* 122(1):179–186.
155. Jones RH, Lockaby BG, Somers GL (1996) Effects of microtopography and disturbance on fine-root dynamics in wetland forests of low-order stream floodplains. *American Midland Naturalist* 136(1):57–71.
156. Jonsson K, Fidjeland L, Maghembe JA, Hogberg P (1988) The vertical distribution of fine roots of five tree species and maize in Morogoro, Tanzania. *Agroforestry Systems* 6:63–69.
157. Joslin JD, Gaudinski JB, Torn MS, Riley WJ, Hanson PJ (2006) Fine-root turnover patterns and their relationship to root diameter and soil depth in a 14C-labeled hardwood forest. *New Phytologist* 172(3):523–535.
158. Kalisz P, Zimmerman RW, Muller RN (1987) Root density, abundance, and distribution in the mixed mesophytic forest of eastern Kentucky. *Soil Science Society of America journal* 51(1):220–225.
159. Karasz I (1996) The root system of Juniperus communis L. in a sandy soil in Central Hungary. *Acta Phytogeogr Suec* 81:32–34.
160. Karimov KK, Molotkovski YI (1996) Root distribution of natrual vegetation at high altitudes in Pamiro-Alai in Tajikistan. *Acta Phytogeogr Suec* 81:83–85.
161. Karizumi N (1979) *Monograph - Root system forms and distributions of individual trees in Japan (in Japanese)* (Seibundo Shinkosha Publishing Co. Ltd., Tokyo) Available at: https://www.cabdirect.org/cabdirect/abstract/19870618641.
162. Karrfalt EE (1981) The comparative and developmental morphology of the root system of

Selaginella selaginoides (L.) Link. *American journal of botany* 68(2):244–253.
163. Kellman M (1990) Root proliferation in recent and weathered sandy soils from Veracruz, Mexico. *Journal of Tropical Ecology* 6(3):355.
164. Kenzo T, et al. (2009) Development of allometric relationships for accurate estimation of above- and below-ground biomass in tropical secondary forests in Sarawak, Malaysia. *Journal of Tropical Ecology* 25(4):371.
165. Kerfoot O (1963) The root systems of tropical trees. *The Commonwealth Forestry Review* 42(1):19–26.
166. Kleinhampl FJ, Koteff C (1960) *Botanical Prospecting for U rani urn in the Circle Cliffs Area Garfield County , Utah, USGS Bulletin 1085-C* (USGS).
167. Klepper EL, Gano KA, Cadwell LL (1985) *Rooting depth and distributions of deep-rooted plants in the 200 area control zone of the Hanford Site. Pacific Northwest Laboratory, Richland, Washington. PNL-5247*.
168. Kohzu A, Matsui K, Yamada T, Sugimoto A, Fujita N (2003) Significance of rooting depth in mire plants: Evidence from natural 15N abundance. *Ecological Research* 18(3):257–266.
169. Kokoreva II (1996) Root systems of Cratae gus L. in the Trans-Ili Alatau, Kazakhstan. *Acta Phytogeogr Suec* 81:35–38.
170. Koteen LE, Baldocchi DD, Harte J (2011) Invasion of non-native grasses causes a drop in soil carbon storage in California grasslands. *Environmental Research Letters* 6:44001.
171. Krishnamurthy L, Zaman-Allah M, Marimuthu S, Wani SP, Kesava Rao AVR (2012) Root growth in Jatropha and its implications for drought adaptation. *Biomass and Bioenergy* 39:247–252.
172. Kubota M, Tenhunen J, Zimmermann R, Adiku S, Kakubari Y (2005) Influences of environmental factors on the radial profile of sap flux density in. *Tree Physiology* (1998):545–556.
173. Kuiper LC (1992) Spatial disposition and extension of t he structu ral root system of Douglas-fir. *Forest ecology and management* 47(1):111–125.
174. Kuschera-Mitter L (1996) Growth strategies of plant roots in different climatic regions. *Acta Phytogeogr Suec* 81:12–16.
175. Laclau JP, et al. (2004) The function of the superficial root mat in the biogeochemical cycles of nutrients in congolese Eucalyptus plantations. *Annals of Botany* 93(3):249–261.
176. Laclau J-P, et al. (2013) Dynamics of soil exploration by fine roots down to a depth of 10 m throughout the entire rotation in Eucalyptus grandis plantations. *Frontiers in plant science* 4(July):243.
177. Lamont BB, Brown G, Mitchell DT (1984) Structure, environmental effects on their formation, and function of proteoid roots in Leucadendron laureolum (Proteaceae). *New Phytologist* 97(3):381–390.
178. Lawson GW, Jenik J, Armstrong-Mensah KO (1968) A study of a vegetation catena in Guinea savanna at Mole Game Reserve (Ghana). *The Journal of Ecology* 56(2):505–522.
179. Lawson AGW, K. O. Armstrong-Mensah, Hall JB (1970) A catena in tropical moist semi-deciduous forest near Kade, Ghana. *Journal of Ecology* 58(2):371–398.
180. Lee ACA, Lauenroth WK (1994) Spatial distributions of grass and shrub root systems in the shortgrass steppe. *American Midland Naturalist* 132(1):117–123.
181. LeRoux X, Bariac T, Mariotti A (1995) Spatial partitioning of the soil water resource between grass and shrub components in a West African humid savanna. *Oecologia* 104(2):147–155.
182. Lewis DC, Burgy RH (1964) The Relationship between oak tree roots and groundwater in fractured rock as determined by tritium tracing. *Journal of Geophysical Research*

69(12):2579.
183. Lichtenegger E, Kutschera-Mitter L (1991) Spatial root types. *Developments in agricultural and managed forest ecology* 24:359–365.
184. Lichtenegger E (1996) Root distribution in some alpine plants. *Acta Phytogeogr Suec* 81:1–5.
185. Lieffers VJ, Rothwell RL (1987) Rooting of peatland black spruce and tamarack in relation to depth of water table. *Canadian Journal of Botany* 65(5):817–821.
186. Link SO, et al. (1994) Effects of coppice dune topography and vegetation on soil water dynamics in a cold-desert ecosystem. *Journal of Agricultural Research* 27:265–278.
187. Liu G, Zhang X, Li X, Wei J, Shan L (2008) Adaptive growth of Tamarix taklamakanensis root systems in response to wind action. *Chinese Science Bulletin* 53(SUPPL. 2):164–168.
188. Livesley SJ, Gregory PJ, Buresh RJ (2000) Competition in tree row agroforestry systems. 1. Distribution and dynamics of fine root length and biomass. *Plant and Soil* 227(1–2):149–161.
189. Lopez B, Sabate S, Gracia CA (2001) Vertical distribution of fine root density, length density, area index and mean diameter in a Quercus ilex forest. *Tree Physiology* 21(8):555–560.
190. Low AB, Lamont BB (1990) Aerial and below-ground phytomass of Banksia scrub-heath at Eneabba, south-western Australia. *Australian Journal of Botany* 38:351–359.
191. Lyford WH, Wilson BF (1964) Development of the root rystem of Acer rubrum L. *Harvard Forest Paper* 10(10):17.
192. Ma L hui, Liu X li, Wang Y ke, Wu P te (2013) Effects of drip irrigation on deep root distribution, rooting depth, and soil water profile of jujube in a semiarid region. *Plant and Soil* 373(1–2):995–1006.
193. Ma L hui, Wu P te, Wang X (2014) Root distribution chronosequence of a dense dwarfed jujube plantation in the semiarid hilly region of the Chinese Loess Plateau. *Journal of Forest Research* 19(1):62–69.
194. MacDougal D (1937) Root systems and volumes of giant Sequoias. *American Journal of Botany* 24(1):1–2.
195. Martin MH (1968) Conditions affecting the distribution of Mercurialis perennis L. in certain Cambridgeshire woodlands. *Journal of Ecology* 56(3):777–793.
196. Martin D, Chambers J (2002) Restoration of riparian meadows degraded by livestock grazing: Above-and belowground responses. *Plant Ecology* 163(1):77–91.
197. Matthes-Sears U, Larson DW (1995) Rooting characteristics of trees in rock: A study of Thuja occidentalis on cliff faces. *International Journal of Plant Sciences* 156(5):679–686.
198. Mauer O, Palátová E (2012) Root system development in douglas fir (Pseudotsuga menziesii [Mirb.] Franco) on fertile sites. *Journal of Forest Science* 58(9):400–409.
199. Mclaughlin J (2011) Abiotic and biotic factors used to assess decline risk in red pine (Pinus resinosa Ait.) plantations. *Forestry Chronicle* 87(1):99–115.
200. McQuilkin WE (1936) Root development of pitch pine, with some comparative observations on shortleaf pine. *Journal of Agricultrual Researcj* 51(11):983–1016.
201. Meinzer OE (1927) *Plants As Indicators of Ground Water, USGS Water-Supply Paper 577*.
202. Mendes MP, Ribeiro L, David TS, Costa A (2016) How dependent are cork oak (Quercus suber L.) woodlands on groundwater? A case study in southwestern Portugal. *Forest Ecology and Management* 378:122–130.
203. Mensah KO, Jenik J (1968) Root systems of tropical trees. 2. Features of the root system of Iroko (Chlorophora excelsa Benth. et. Hook). *Preslia Prague* 40:21–27.
204. Mensforth LJ, Walker GR (1996) Root dynmnics of Melaleuca halmaturorum in response to fluctuating saline groundwater. *Plant and Soil* 184:75–84.
205. Midwood AJ, Boutton TW, Archer SR, Watts SE (1998) Water use by woody plants on

contrasting soils in a savanna parkland: Assessment with H2 and O18. *Plant and Soil* 205(1):13–24.
206. Montoroi J-P, et al. (2016) Some Convincing Evidences of a Deep Root System Within an Interfluve Aquifer of Northeast Thailand. *IOP Conference Series: Earth and Environmental Science* 44:52057.
207. Mooney HA, Gulmon SL, Rundel PW, Ehleringer J (1980) Further observations on the water relations of Prosopis tamarugo of the northern Atacama Desert. *Oecologia* 44:177–180.
208. Moore GW, Barre DA, Owens MK (2010) Changes in soil chloride following shrub removal and subsequent regrowth. *Geoderma* 158(3–4):148–155.
209. Mordelet P, Menaut J-C, Mariotti A (1997) Tree and grass rooting patterns in an African humid savanna. *Journal of Vegetation Science* 8(1):65–70.
210. Moreno-Chacón M, Lusk CH (2004) Vertical distribution of fine root biomass of emergent Nothofagus dombeyi and its canopy associates in a Chilean temperate rainforest. *Forest Ecology and Management* 199(2–3):177–181.
211. Mulia R, Dupraz C (2006) Unusual fine root distributions of two deciduous tree species in southern France: What consequences for modelling of tree root dynamics? *Plant and Soil* 281(1–2):71–85.
212. Mundell TL, Landha SM, Lieffers VJ (2007) Effects of Corylus cornuta stem density on root suckering and rooting depth of Populus tremuloides. *Canadian Journal of Botany* 85(11):1041–1045.
213. Nardini A, et al. (2016) Rooting depth, water relations and non-structural carbohydrate dynamics in three woody angiosperms differentially affected by an extreme summer drought. *Plant, Cell and Environment* 39(3):618–627.
214. Nesterova S (1996) Root structure of plants in the Zailiisky Alatau Range, Kzakhstan. *Acta Phytogeogr Suec* 81:86–87.
215. Neykova N, et al. (2011) Vertical root distribution in single-crop and intercropping agricultural systems in Central Kenya. *Journal of Plant Nutrition and Soil Science* 174(5):742–749.
216. Nicoll B, Ray D (1996) Adaptive growth of tree root systems in response to wind action and site conditions. *Tree Physiology* 16(11–12):891–891.
217. Nie ZN, et al. (2008) Field evaluation of perennial grasses and herbs in southern Australia. 2. Persistence, root characteristics and summer activity. *Australian journal of experimental agriculture* 48(4):424–435.
218. Nie YP, Chen HS, Wang KL, Ding YL (2014) Rooting characteristics of two widely distributed woody plant species growing in different karst habitats of southwest China. *Plant Ecology* 215(10):1099–1109.
219. Niiyama K, et al. (2010) Estimation of root biomass based on excavation of individual root systems in a primary dipterocarp forest in Pasoh Forest Reserve, Peninsular Malaysia. *Journal of Tropical Ecology* 26(3):271.
220. Niklas KJ, et al. (2002) The Biomechanics of Pachycereus pringlei Root Systems. *American Journal of Botany* 89(1):12–21.
221. Nijland W, van der Meijde M, Addink EA, de Jong SM (2010) Detection of soil moisture and vegetation water abstraction in a mediterranean natural area using electrical resistivity tomography. *Catena* 81(3):209–216.
222. Nilsen ET, Sharifi MR, Rundel PW, Jarrell WM, Ross A (1983) Diurnal and seasonal water relations of the desert phreatophyte Prosopis glandulosa (Honey Mesquite) in the Sonoran Desert of California. *Ecology* 64(6):1381–1393.
223. Nippert JB, et al. (2010) Patterns of Tamarix water use during a record drought. *Oecologia*

162(2):283–292.
224. Nobel PS, Zutta BR (2005) Morphology, ecophysiology, and seedling establishment for Fouquieria splendens in the northwestern Sonoran Desert. *Journal of Arid Environments* 62(2):251–265.
225. Nulsen RA, Bligh KJ, Baxter IN, Solin EJ, Imrie DH (1986) The Fate of Rainfall in a Mallee and Heath Vegetated Catchment in Southern Western Australia. *Australian Journal of Ecology* 11(4):361–371.
226. Obakeng OT, de Vries JJ, Lubczynski MW (2007) Soil moisture dynamics and evapotranspiration at the fringe of the Botswana Kalahari, with emphasis on deep rooting vegetation. Dissertation (Wageningen University, The Netherlands). Available at: http://www.itc.nl/library/papers_2007/phd/obakeng.pdf.
227. Ohnuki Y, et al. (2008) Seasonal change in thick regolith hardness and water content in a dry evergreen forest in Kampong Thom Province, Cambodia. *Geoderma* 146(1–2):94–101.
228. Oliveira RS, et al. (2005) Deep root function in soil water dynamics in cerrado savannas of central Brazil. *Functional Ecology* 19(4):574–581.
229. Oosterbaan a., Nabuurs GJ (1991) Relationships between oak decline and groundwater class in The Netherlands. *Plant and Soil* 136(1):87–93.
230. Pearson ALC (1965) Primary Production in Grazed and Ungrazed Desert Communities of Eastern Idaho. *Ecology* 46(3):278–285.
231. Pelaez D V., Distel RA, Boo RM, Elia OR, Mayor MD (1994) Water relations between shrubs and grasses in semi-arid Argentina. *Journal of Arid Environments* 27:71–78.
232. Pereira HC, Hosegood PH (1962) Comparative water-use of softwood plantations and bamboo forest. *Journal of soil science1* 13:299–313.
233. Phillips WS. (1963) Depth of roots in soil. *Ecology* 44(2):424–424.
234. Pinheiro EAR, Costa CAG, De Araújo JC (2013) Effective root depth of the Caatinga biome. *Journal of Arid Environments* 89:1–4.
235. Preston RJ (1942) Growth and development of root systems of juvenile lodgepole pine. *Ecological Monographs* 12(4):449–468.
236. Price SR (1911) The roots of some North African desert grasses. *New Phytologist* 10(9–10):328–340.
237. Pulling H. (1918) Root habit and plant distribution in the far north. *Plant World* 21:223–233.
238. Putz FE, Holbrook NM (1989) Strangler Fig rooting habits and nutrient relations in the Llanos of Venezuela. *American Journal of Botany* 76(6):781–788.
239. Querejeta JI, Estrada-Medina H, Allen MF, Jiménez-Osornio JJ (2007) Water source partitioning among trees growing on shallow karst soils in a seasonally dry tropical climate. *Oecologia* 152(1):26–36.
240. Ram J, et al. (2007) Biodrainage potential of Eucalyptus tereticornis for reclamation of shallow water table areas in north-west India. *Agroforestry Systems* 69(2):147–165.
241. RASTIN N (1991) *Influence of Waterlogging on Root Distribution, Fine-Root Biomass and Mycorrhizal Number of Norway Spruce* (Elsevier Science Publishers B.V.) doi:10.1016/B978-0-444-89104-4.50046-3.
242. Ray D, Schweizer S (1994) A study of the oxygen regime and rooting depth in deep peat under plantations of Sitka spruce and lodgepole pine. *Soil Use and Management* 10(3):129–136.
243. Ray D, Nicoll BC (1998) The effect of soil water-table depth on root-plate development and stability of Sitka spruce. *Forestry* 71(2):169–182.
244. Rawitscher F (1948) The water economy of the vegetation of the “Campos Cerrados” in Southern Brazil. *Journal of Ecology* 36(2):237–268.

245. Rawitscher F (1952) The ecology of the “caatingas” vegetation. *Anais da Academia Brasileira de Ciências* 34(1):287–301.
246. Raz-Yaseef N, Koteen L, Baldocchi DD (2013) Coarse root distribution of a semi-arid oak savanna estimated with ground penetrating radar. *Journal of Geophysical Research: Biogeosciences* 118(1):135–147.
247. van Rees K, Comberford N (1986) Vertical Root Distribution and Strontium Uptake of a Slash Pine Stand on a Florida Spodosof. *Soil Science Society of America Journal* 50(4):1041–1046.
248. Restom TG, Nepstad DC (2004) Seedling growth dynamics of a deeply rooting liana in a secondary forest in eastern Amazonia. *Forest Ecology and Management* 190(1):109–118.
249. Reynolds E (1970) Root distribution and the cause of its spatial variability in Pseudotsuga taxifolia (poir.) Britt. *Plant and Soil* 32(2):501–517.
250. Reynolds TD, Fraley L (1989) Root profiles of some native and exotic plant species in southeastern Idaho. *Environmental and Experimental Botany* 29(2):241–248.
251. Richards JH, Caldwell MM (1987) Hydraulic lift: Substancial nocturnal water transport between soil layers by Artemisia tridentata roots. *Oecologia* 73:486–489.
252. Richter DD, Markewitz D (1995) How deep is soil? *BioScience* 45:600–609.
253. Riestenberg MM (1994) Anchoring of thin colluvium by roots of sugar maple and white ash on hillslopes in Cincinnati. *US GEOLOGICAL SURVEY BULLETIN* 2059–E.
254. Roberts EA., Herty SD (1934) Lycopodium complanatum Var . Flabelliforme Fernald : Its Anatomy and a Method of Vegetative Propagation. *American Journal of Botany* 21(10):688–697.
255. Robinson N, Harper RJ, Smettem KRJ (2006) Soil water depletion by Eucalyptus spp. integrated into dryland agricultural systems. *Plant and Soil* 286(1–2):141–151.
256. Roering JJ, Almond P, Tonkin P, McKean J (2002) Soil transport driven by biological processes over millennial time scales. *Geology* 30(12):1115–1118.
257. Rood SB, Bigelow SG, Hall AA (2011) Root architecture of riparian trees: River cut-banks provide natural hydraulic excavation, revealing that cottonwoods are facultative phreatophytes. *Trees - Structure and Function* 25(5):907–917.
258. Rose KL, Graham RC, Parker DR (2003) Water source utilization by Pinus jeffreyi and Arctostaphylos patula on thin soils over bedrock. *Oecologia* 134(1):46–54.
259. Roupsard O, et al. (1999) Reverse phenology and dry season water uptake by Fadherbia albida (Del.) A. Chev. in an agroforestry parkland of Sudanense Africa. *Functional Ecology* 13:460–472.
260. Roux JP, Hopper SD, Smith RJ (2009) Isoetes eludens (Isoetaceae), a new endemic species from the Kamiesberg, Northern Cape, South Africa. *Kew Bulletin* 64(1):123–128.
261. Rutherford M (1983) Growth rates, biomass and distribution of selected woody plant roots in Burkea africana-Ochna pulchra savanna. *Vegetatio* 52(1):45–63.
262. Sainju UM, Good RE (1993) Vertical root distribution in relation to soil properties in New Jersey Pinelands forests. *Plant and Soil* 150:87–97.
263. Salis SM, Lehn CR, Mattos PP, Bergier I, Crispim SMA (2014) Root behavior of savanna species in Brazil’s Pantanal wetland. *Global Ecology and Conservation* 2:378–384.
264. Sanford RL (1989) Root systems of three adjacent old growth Amazon forests and associated transition zones. *Journal of Tropical Forest Science* 1(3):268–279.
265. Satterlund DR (1969) Some inter-relationships between groundwater and swamp forests in the western Upper Peninsula of Michigan. Dissertation (University of Michigan).
266. Schmid I, Kazda M (2001) Vertical distribution and radial growth of coarse roots in pure and mixed stands of Fagus sylvatica and Picea abies. *Canadian Journal of Forest Research-*

Revue Canadienne De Recherche Forestiere 31(3):539–548.
267. Schmid I, Kazda M (2005) Clustered root distribution in mature stands of Fagus sylvatica and Picea abies. *Oecologia* 144:25–31.
268. Schultz JD (1969) The vertical rooting habit in black spruce, white spruce, and balsam fir. Dissertation (University of Michigan).
269. Schultz RP (1972) Root development of intensively cultivated slash pine. *Proceedings Soil Science Society of America Journal* 36(1):158–162.
270. Schulze E-D, et al. (1996) Rooting depth, water availability, and vegetation cover along an aridity gradient in Patagonia. *Oecologia* 108(3):503–511.
271. Scully NJ (1942) Root distribution and environment in a maple-oak forest. *Botanical Gazette* 103(3):492–517.
272. Seghieri J (1995) The rooting patterns of woody and herbaceous plants in a savanna; are they complementary or in competition? *African journal of ecology* 33(4):358–365.
273. Shafroth PB, Stromberg JC, Patten DT (2000) Woody riparian vegetation response to different alluvial water table regimes. *Western North American Naturalist* 60(1):66–76.
274. Shaver GR, Billings WD (1975) Root production and root turnover in a wet tundra rcosystem, Barrow, Alaska. *Ecology* 56(2):401.
275. Sherff E (1912) The vegetation of Skokie Marsh, with special reference to subterranean organs and their interrelationships. *Botanical Gazette* 53(5):415–435.
276. Shiponeni N, Allsopp N, Carrick PJ, Hoffman MT (2011) Competitive interactions between grass and succulent shrubs at the ecotone between an arid grassland and succulent shrubland in the Karoo. *Plant Ecology* 212(5):795–808.
277. Sierra CA, et al. (2007) Total carbon stocks in a tropical forest landscape of the Porce region, Colombia. *Forest Ecology and Management* 243(2–3):299–309.
278. Silva JS, Rego FC (2003) Root distribution of a Mediterranean shrubland in Portugal. *Plant and Soil* 255(2):529–540.
279. Silva JS, Rego FC (2004) Root to shoot relationships in Mediterranean woody plants from Central Portugal. *Biologia Bratislava* 59(13):1–7.
280. Šimonovic V (1991) Biomass of roots in natural oak-hornbeam ecosystem. *Plant roots and their environment*:273–279.
281. Slavich PG, Smith KS, Tyerman SD, Walker GR (1999) Water use of grazed salt bush plantations with saline watertable. *Agricultural Water Management* 39(2–3):169–185.
282. Sobotik M (1996) The anatomical root structure of Kochia prostrata (L.) Scrad. *Acta Phytogeogr Suec1* 81:48–52.
283. Soethe N, Lehmann J, Engels C (2006) Root morphology and anchorage of six native tree species from a tropical montane forest and an elfin forest in Ecuador. *Plant and Soil* 279(1–2):173–185.
284. Sommer R, Denich M, Vlek PLG (2000) Carbon storage and root penetration in deep soils under small-farmer land-use systems in the Eastern Amazon region , Brazil. *Plant and Soil* 219:231–241.
285. Spence LE (1937) Root studies of important range plants of the Boise River watershed. *Journal of Forestry* 35(8):747–754.
286. Sperry TM (1935) Root systems in Illinois prairie. *Ecology* 16(2):178–202.
287. Sperry J, Hacke U (2002) Desert shrub water realtions with respect to soil characteristics and plant functional type. *Functional Ecology* 16(3):367–378.
288. Sprackling JA, Read RA (1979) Tree root systems in Eastern Nebraska. *Nebraska Conservation Bulletin 37*.
289. Srivastava SK, Singh KP, Upadhyay RS (1986) Fine root growth dynamics in teak (Tectona

grandis Linn. F.). *Canadian Journal of Forest Research* 16(6):1360–1364.
290. Stoeckeler JH, Kluender WA (1938) The hydraulic method of excavating the root systems of plants. *Ecology* 19(3):355–369.
291. Stringer JW, Kalisz PJ, Volpe JA (1989) Deep tritiated water uptake and predawn xylem water potentials as indicators of vertical rooting extent in a Quercus-Caryaforest. *Canadian Journal of Forest Research* 19(5):627–631.
292. Strong WL (1983) Rooting depths and successional development of selected boreal forest communities. *Canadian Journal of Forest Research* 13(1):577–588.
293. Sturges DL., Trlica MJ. (1978) Root weights and carbohydrate reserves of big sagebrush. *Ecology* 59(6):1282–1285.
294. Sudmeyer R a, Speijers J, Nicholas BD (2004) Root distribution of Pinus pinaster, P. radiata, Eucalyptus globulus and E. kochii and associated soil chemistry in agricultural land adjacent to tree lines. *Tree physiology* 24(12):1333–1346.
295. Svejcar TJ, Trent JD (1995) Gas-exchange and water relations of Lemmons willow and Nebraska sedge. *Journal of Range Management* 48(2):121–125.
296. Sweet AT (1933) *Soil profile and root penetration as indicators of apple production in the lake shore District of western New York, USDA Circular No. 303* (USDA).
297. Syahrinudin (2005) The potential of oil palm and forest plantations for carbon sequestration on degraded land in Indonesia.
298. Tabler RD (1964) The root system of Artemisia tridentata at 9,500 feet in Wyoming. *Ecology* 45(3):633–636.
299. Teskey RO, Hinekley TM (1981) Influence of temperature and water potential on root growth of white oak. *Physiologia Plantarum* 52(3):363–369.
300. Thomas FM (2000) Vertical rooting patterns of mature Quercus trees growing on different soil types in northern Germany. *Plant Ecology* 147(1):95–103.
301. Timberlake JR, Calvert GM (1993) *Preliminary Root Atlas for Zimbabwe and Zambia*.
302. Turehanova R (1996) Roots syem formation of Hippophae rhamnoides L. (seabuckthorn). *Acta Phytogeogr Suec*:57–58.
303. Turner LM (1936) A comparison of roots of southern shortleaf pine in three soils. *Ecology* 17(4):649–658.
304. Vance ED, Nadkarni NM (1992) Root biomass distribution. *Plant and Soil* 142:31–39.
305. Verzunov AI (1980) Growth of the larch and resistance of cultivated phytocenoses with its domination on semihydromorphic soils in the forest steepe in north Kazakhstan. *Ekologiya* 2:38–44.
306. Veste M, Breckle S-W (1996) Root growth and water uptake in a desert sand dune ecosystem. *Acta Phytogeogr Suec* 81:59–62.
307. Vonlanthen B, Zhang X, Bruelheide H (2010) On the run for water - Root growth of two phreatophytes in the Taklamakan Desert. *Journal of Arid Environments* 74(12):1604–1615.
308. Wagg JWB (1967) *Origin and development of white spruce root-forms, Forestry Branch Departmental Publiscation No 1192* (Queen's Printer and Controller of Stationery Ottawa).
309. Wallace AE, Romney E, Cha J (1980) Depth distribution of roots of some perennial plants in the Nevada Test Site area of the northern Mojave Desert. *Great Basin Naturalist Memoirs* 4:201–207.
310. Wang P, et al. (2016) Seasonal changes and vertical distribution of root standing biomass of graminoids and shrubs at a Siberian tundra site. *Plant and Soil* 407(1–2):55–65.
311. Watson AJ, Tombleson JD (2002) Toppling in juvenile pines: A comparison of the root system characteristics of direct-sown seedlings, and bare-root seedlings and cuttings. *Plant and Soil* 239:187–196.

312. Weaver JE (1915) A study of the root-systems of prairie plants of southeastern Washington. *The Plant World* 18(1915):227–248.
313. Weaver JE (1919) The Ecological Relations of Roots. *Digital Commons @ University of Nebraska-Lincoln* (1919):122–127.
314. Weaver JE, Kramer J (1932) Root System of Quercus macrocarpa in Relation to the Invasion of Prairie. *Botanical Gazette* 94(1):51–85.
315. Wei YF, Fang J, Liu S, Zhao XY, Li SG (2013) Stable isotopic observation of water use sources of Pinus sylvestris var. mongolica in Horqin Sandy Land, China. *Trees - Structure and Function* 27(5):1249–1260.
316. Werner PA, Murphy PG (2001) Size-specific biomass allocation and water content of above- and below-ground components of three Eucalyptus species in a northern Australian savanna. *Australian journal of botany* 49(2):155–167.
317. Westman WE, Rogers KW (1977) Nutrient stocks in a subtropical eucalypt forest, North Stradbroke Island. *Australian Journal of Ecology* 2:447–460.
318. White DP, Wood RS (1958) Growth variations in a red pine plantation influenced by a deep-lying fine soil layer. *Proceedings Soil Science Society of America Journal* 22(2):174–177.
319. Whittle CA, Duchesnel LC, Needham T (1998) Soil Seed Bank of a Jack Pine (Pinus banksiana) Ecosystem. *International Journal of Wildland Fire* 8(2):67–71.
320. Wittmann F, Parolin P (2005) Aboveground roots in Amazonian floodplain trees. *Biotropica* 37(4):609–619.
321. Wright SJ, Machado JL, Mulkey SS, Smith AP (1992) Drought acclimation among tropical forest shrubs (Psychotria, Rubiaceae). *Oecologia* 89(4):457–463.
322. van Wyk WL (1963) *Ground-Water Studies in Northern Natal, Zulu Land and Surrounding Areas*.
323. Xu GQ, Li Y (2008) Rooting depth and leaf hydraulic conductance in the xeric tree Haloxyolon ammodendron growing at sites of contrasting soil texture. *Functional Plant Biology* 35(12):1234–1242.
324. Xu Q, et al. (2011) Water use patterns of three species in subalpine forest, Southwest China: the deuterium isotope approach. *Ecohydrology* 244:236–244.
325. Yeager AF (1935) Root systems of certain trees and shrubs grown on prairie soils. *Journal of Agricultural Research* 51(12):1085–1092.
326. Yeatman CW (1955) *Tree root development on upland heaths, Forestry Commission Bulletin No. 21*.
327. Yuen JQ, Ziegler AD, Webb EL, Ryan CM (2013) Uncertainty in below-ground carbon biomass for major land covers in Southeast Asia. *Forest Ecology and Management* 310:915–926.
328. Zerihun A, Montagu KD (2004) Belowground to aboveground biomass ratio and vertical root distribution responses of mature Pinus radiata stands to phosphorus fertilization at planting. *Canadian Journal of Forest Research* 34(9):1883–1894.
329. Zerihun A, Montagu KD, Hoffmann MB, Bray SG (2006) Patterns of below- and aboveground biomass in Eucalyptus populnea woodland communities of northeast Australia along a rainfall gradient. *Ecosystems* 9(4):501–515.
330. Zhang H, Morison JIL, Simmonds LP (1999) Transpiration and water relations of poplar trees growing close to the water table. *Tree Physiology* 19(9):563–573.
331. Zhang CB, Chen LH, Jiang J (2014) Vertical root distribution and root cohesion of typical tree species on the Loess Plateau, China. *Journal of Arid Land* 6(5):601–611.
332. Zhaparova NK (1996) Root development of Ostrowskia magnifica Regel, a rare species in Kazakhstan. *Acta Phytogeogr Suec* 81.

333. Zhou H, Zhao W, Zheng X, Li S (2015) Root distribution of Nitraria sibirica with seasonally varying water sources in a desert habitat. *Journal of Plant Research* 128(4):613–622.
334. Zhou H, Zhao W, Zhang G (2017) Varying water utilization of *Haloxylon ammodendron* plantations in a desert-oasis ecotone. *Hydrological Processes* 31(4):825–835.
335. Miguez-Macho G, Fan Y (2012) The role of groundwater in the Amazon water cycle: 1. Influence on seasonal streamflow, flooding and wetlands. *Journal of Geophysical Research* 117(D15):D15113.
336. Miguez-Macho G, Fan Y (2012) The role of groundwater in the Amazon water cycle: 2. Influence on seasonal soil moisture and evapotranspiration. *Journal of Geophysical Research Atmospheres* 117(15). doi:10.1029/2012JD017540.
337. Sternberg PD, Anderson MA, Graham RC, Beyers JL, Tice KR (1996) Root distribution and seasonal water status in weathered granitic bedrock under chaparral. *Geoderma* 72(1–2):89–98.
338. Poot P, Lambers H (2008) Shallow-soil endemics: Adaptive advantages and constraints of a specialized root-system morphology. *New Phytologist* 178(2):371–381.
339. Schenk HJ (2008) Soil depth, rooting plant and species' niches strategies. *The New Phytologist* 178(2):223–225.
340. Schwinning S (2010) Ecohydrology Bearing - Invited Commentary Transformation ecosystem change and ecohydrology. *Ecohydrology* 3:238–245.
341. Schwinning S (2013) Do we need new rhizosphere models for rock-dominated landscapes? *Plant and Soil* 362(1–2):25–31.
342. Salve R, Rempe DM, Dietrich WE (2012) Rain, rock moisture dynamics, and the rapid response of perched groundwater in weathered, fractured argillite underlying a steep hillslope. *Water Resources Research* 48(11):1–25.
343. McDonald MG, Harbaugh AW (1988) *MODFLOW - A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model*.
344. Winter TC, Harvey JW, Franke OL, Alley WM (1998) Ground Water and Surface Water: A Single Resource. *USGS Publications Circular* 1139:79.
345. Freeze RA, CHerry JA (1979) *Groundwater* (Prentice Hall, Upper Saddle River, NJ).
346. Fan Y, Miguez-Macho G, Weaver CP, Walko R, Robock A (2007) Incorporating water table dynamics in climate modeling: 1. Water table observations and equilibrium water table simulations. *Journal of Geophysical Research* 112(10):D10125.
347. Miguez-Macho G, Fan Y, Weaver CP, Walko R, Robock A (2007) Incorporating water table dynamics in climate modeling: 2. Formulation, validation, and soil moisture simulation. *Journal of Geophysical Research Atmospheres* 112(13):1–16.
348. Anyah RO, Weaver CP, Miguez-Macho G, Fan Y, Robock A (2008) Incorporating water table dynamics in climate modeling: 3. Simulated groundwater influence on coupled land-atmosphere variability. *Journal of Geophysical Research: Atmospheres* 113:1–15.
349. Pokhrel YN, Fan Y, Miguez-Macho G, Yeh PJF, Han SC (2013) The role of groundwater in the Amazon water cycle: 3. Influence on terrestrial water storage computations and comparison with GRACE. *Journal of Geophysical Research: Atmospheres* 118(8):3233–3244.
350. Pokhrel YN, Fan Y, Miguez-Macho G (2014) Potential hydrologic changes in the Amazon by the end of the 21st century and the groundwater buffer. *Environmental Research Letters* 9(8):84004.
351. Hodnett MG, Tomasella J (2002) Marked differences between van Genuchten soil water-retention parameters for temperate and tropical soils: A new water-retention pedo-transfer functions developed for tropical soils. *Geoderma* 108(3–4):155–180.

352. Clapp RB, Hornberger GM (1978) Empirical equations for some soil hydraulic properties. *Water Resources Research* 14(4):601–604.
353. Shuttleworth WJ, Wallace JS (1985) Evaporation from sparse crops - An energy combination theory. *Quarterly Journal of The Royal Meteorological Society* 111(469):839–855.
354. Zhou MC, et al. (2006) Estimating potential evapotranspiration using Shuttleworth-Wallace model and NOAA-AVHRR NDVI data to feed a distributed hydrological model over the Mekong River basin. *Journal of Hydrology* 327(1–2):151–173.
355. Balsamo G, et al. (2015) ERA-Interim/Land: A global land surface reanalysis data set. *Hydrology and Earth System Sciences* 19(1):389–407.
356. Kleidon A, Heimann M (1998) A method of determining rooting depth from a terrestrial biosphere model and its impacts on the global water and carbon cycle. *Global Change Biology* 4(3):275–286.
357. Kleidon A (2004) Global datasets and rooting zone depth inferred from inverse methods. *Journal of Climate* 17(13):2714–2722.
358. Adiku SGK, Rose CW, Braddock RD, Ozier-Lafontaine H (2000) On the simulation of root water extraction: examination of a minimum energy hypothesis. *Soil Science* 165(3):226–236.
359. Arora VK, Boer GJ (2003) A representation of variable root distribution in dynamic vegetation models. *Earth Interactions* 7:1–19.
360. Laio F, D'Odorico P, Ridolfi L (2006) An analytical model to relate the vertical root distribution to climate and soil properties. *Geophysical Research Letters* 33(18):1–5.
361. Collins DBG, Bras RL (2007) Plant rooting strategies in water-limited ecosystems. *Water Resources Research* 43(6):1–10.
362. Schenk HJ (2008) The shallowest possible water extraction profile: A null model for global root distributions. *Vadose Zone Journal* 7(3):1119.
363. Schymanski SJ, Sivapalan M, Roderick ML, Beringer J, Hutley LB (2008) An optimality-based model of the coupled soil moisture and root dynamics. *Hydrology and Earth System Sciences* 12(3):913–932.
364. Guswa AJ (2008) The influence of climate on root depth: A carbon cost-benefit analysis. *Water Resources Research* 44(2):1–11.
365. McMurtrie RE, et al. (2012) Plant root distributions and nitrogen uptake predicted by a hypothesis of optimal root foraging. *Ecology and Evolution* 2(6):1235–1250.
366. Sivandran G, Bras RL (2013) Dynamic root distributions in ecohydrological modeling: A case study at Walnut Gulch Experimental Watershed. *Water Resources Research* 49(6):3292–3305.
367. Drewniak B, Song J, Prell J, Kotamarthi VR, Jacob R (2013) Modeling agriculture in the Community Land Model. *Geoscientific Model Development* 6(2):495–515.
368. Smithwick EAH, et al. (2013) Root stress and nitrogen deposition: Consequences and research priorities. *New Phytologist* 197(3):712–719.
369. Smithwick EAH, Lucash MS, McCormack ML, Sivandran G (2014) Improving the representation of roots in terrestrial models. *Ecological Modelling* 291:193–204.
370. Ichii K, et al. (2007) Constraining rooting depths in tropical rainforests using satellite data and ecosystem modeling for accurate simulation of gross primary production seasonality. *Global Change Biology* 13(1):67–77.
371. Yang Y, Donohue RJ, McVicar TR (2016) Global estimation of effective plant rooting depth: Implications for hydrologicalmodeling. *Water Resources Research*. doi:10.1002/2016WR019392.
372. Lynch JP, Nielsen KL, Davis RD, Jablokow AG (1997) SimRoot: Modelling and

visualization of root systems. *Plant and Soil* 188(1):139–151.
373. Warren JM, et al. (2015) Root structural and functional dynamics in terrestrial biosphere models--evaluation and recommendations. *The New phytologist* 205(1):59–78.
374. Diggle AJ (1988) ROOTMAP- a model in three-dimensional coordinates of the growth and structure of fibrous root systems. *Plant and Soil* 105:169–178.