

SI Appendix

Hydrologic Regulation of Plant Rooting Depth

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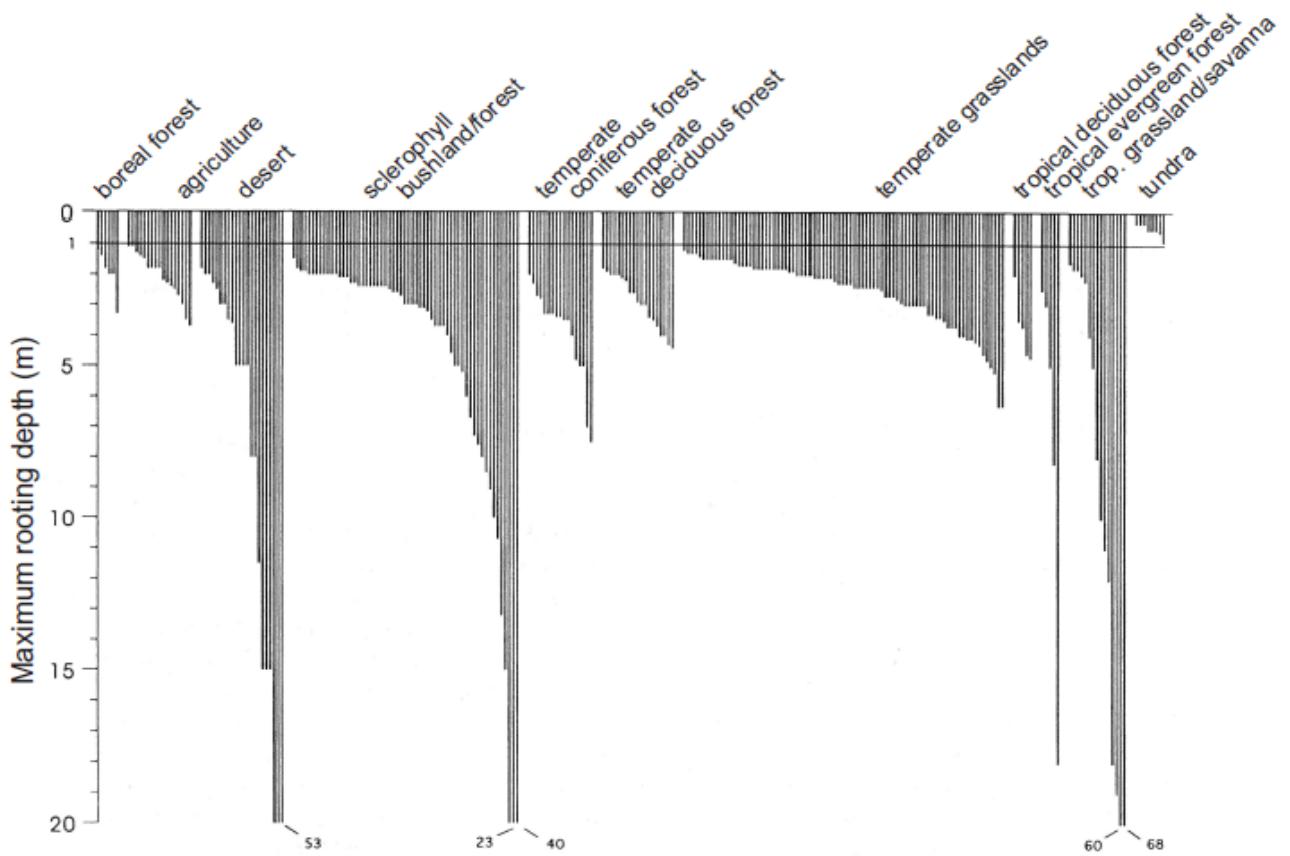


Fig. S1. Maximum rooting depth grouped by biomes (1).

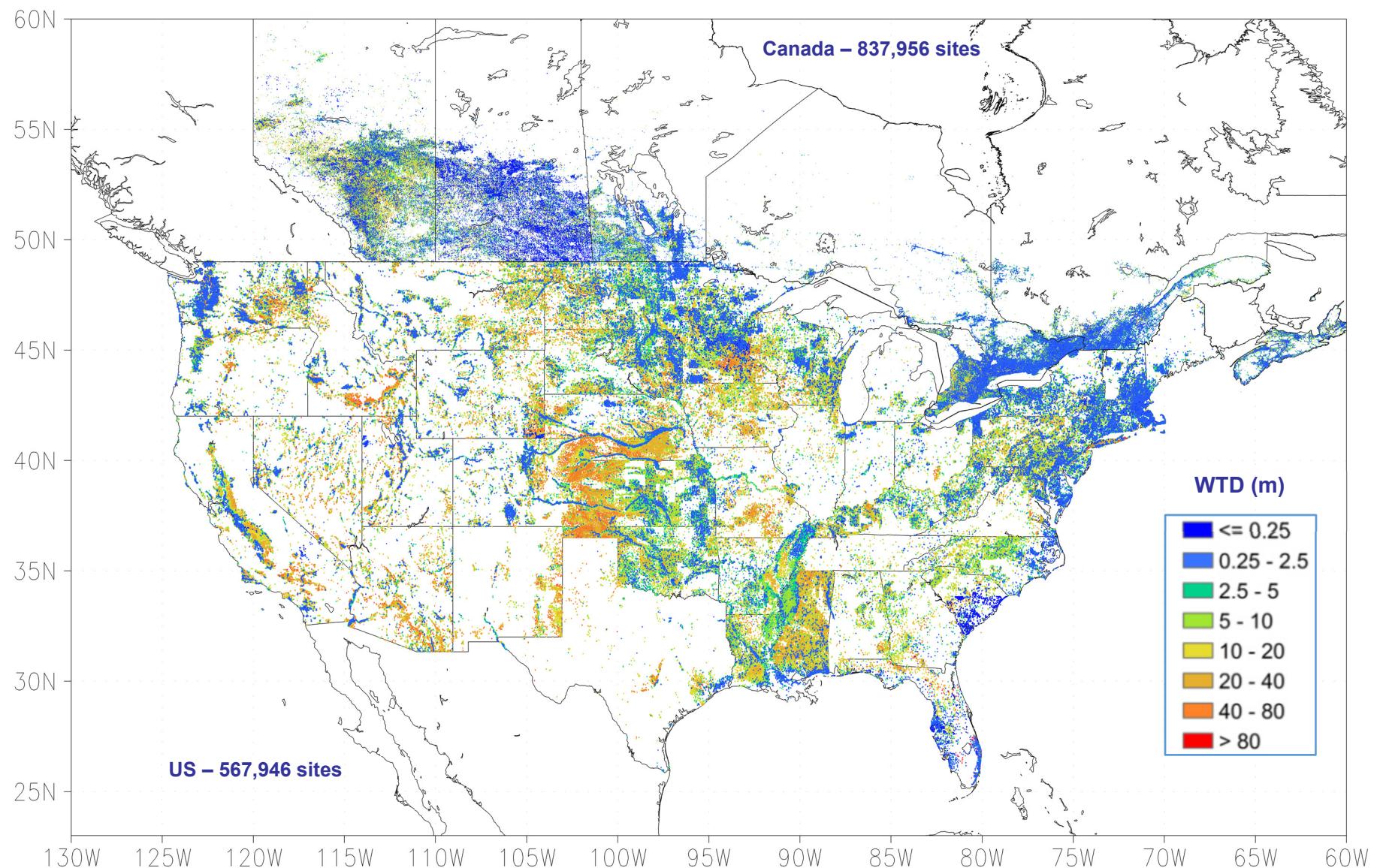


Fig. S2. Well observations of long-term mean water table depth (WTD) over North America (2).

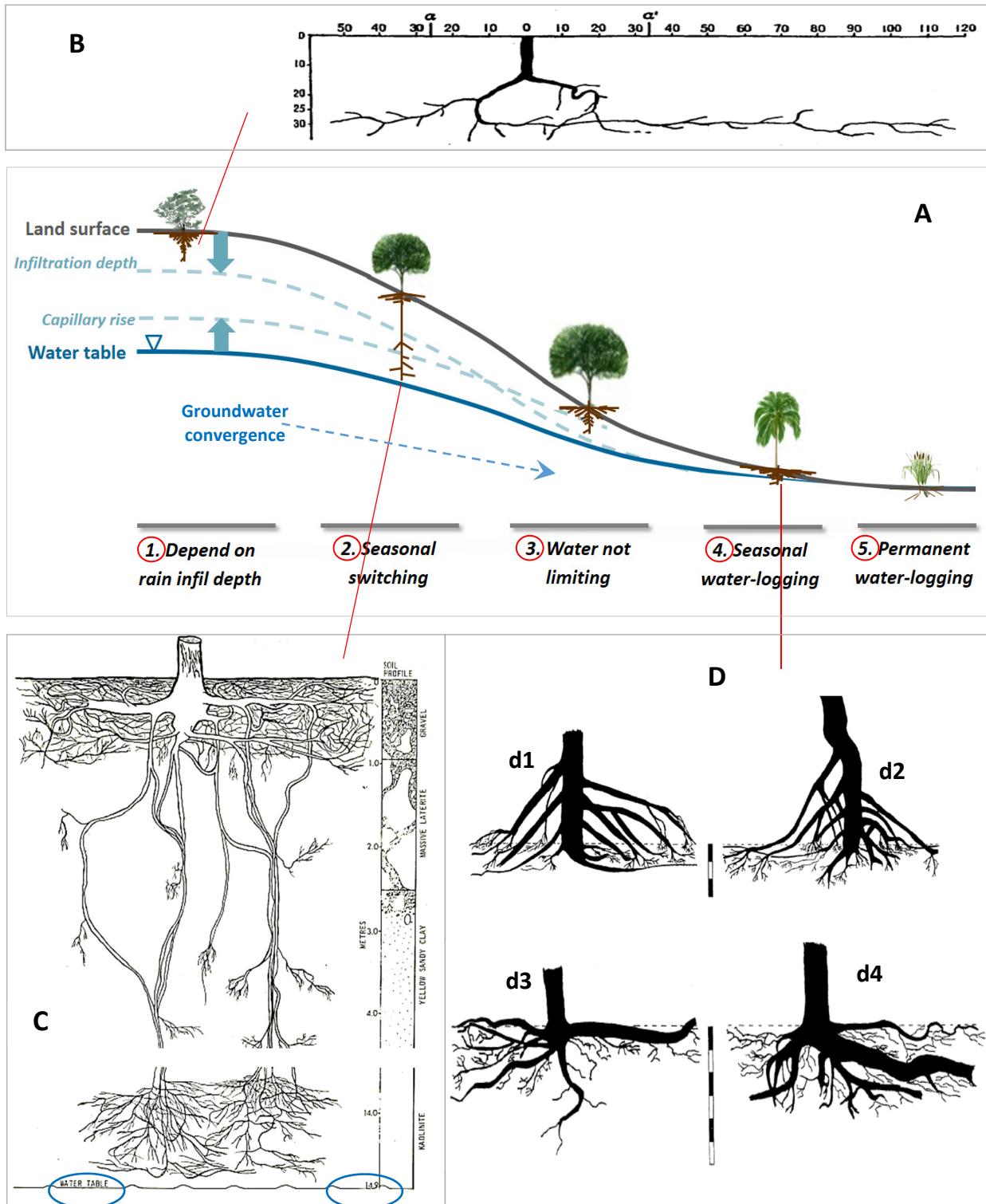


Fig. S3. (A) Schematic of root-water relations along a drainage gradient, (B) shallow and wide (cm) *Salsola rigida* roots in Israel limited by rare and shallow infiltration (3), (C) dimorphic roots of *Eucalyptus marginata* in Western Australia (4) (WTD=14.9m), and (D) aerial and shallow roots of *Cecropia 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We compiled rooting depth observations from published literature, government papers, and unpublished theses and reports.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	<i>Carex</i>	Sedge	0.59	0.37	23
2	<i>Opuntia</i>	Prickly Pear	0.68	0.51	6
3	<i>Picea</i>	Spruce	0.74	0.47	82
4	<i>Fagus</i>	Beech	0.83	0.46	8
5	<i>Bouteloua</i>	Grama Grass	0.84	0.40	18
6	<i>Larix</i>	Larch	0.90	0.67	14
7	<i>Zea mays</i>	Maize	0.91	0.36	15
8	<i>Stipa</i>	Feather grass	1.01	0.48	25
9	<i>Pseudotsuga</i>	Douglas fir	1.03	0.37	15
10	<i>Bromus</i>	Brome grass	1.19	0.51	12
11	<i>Festuca</i>	Fescue	1.23	0.84	23
12	<i>Abies</i>	Fir	1.30	0.67	28
13	<i>Combretum</i>	Bushwillow	1.32	0.70	13
14	<i>Agropyron</i>	Wheatgrass	1.34	0.41	22
15	<i>Atriplex</i>	Saltbush	1.35	1.13	13

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

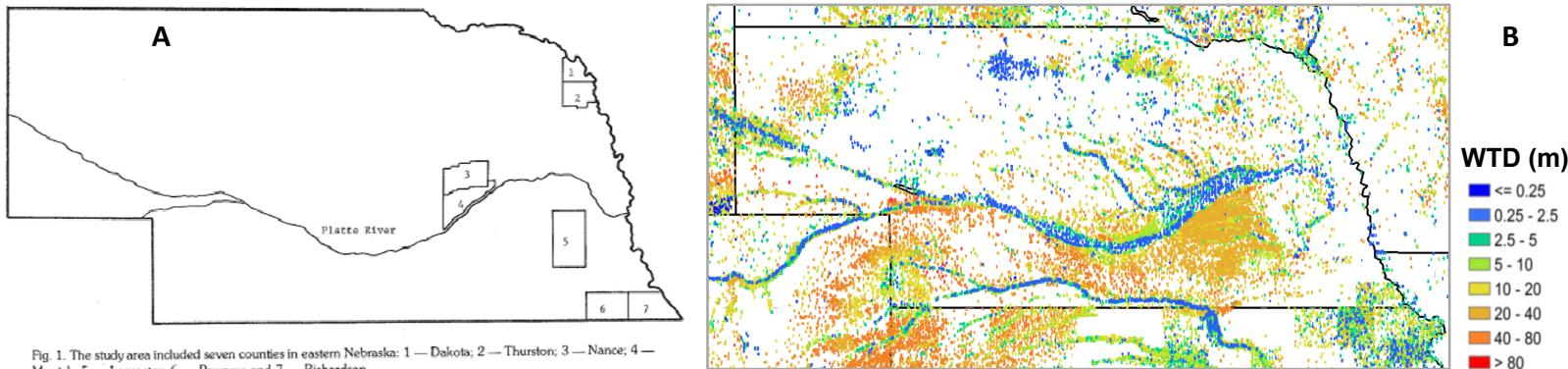


Fig. 1. The study area included seven counties in eastern Nebraska: 1 — Dakota; 2 — Thurston; 3 — Nance; 4 — Merrick; 5 — Lancaster; 6 — Pawnee; and 7 — Richardson.

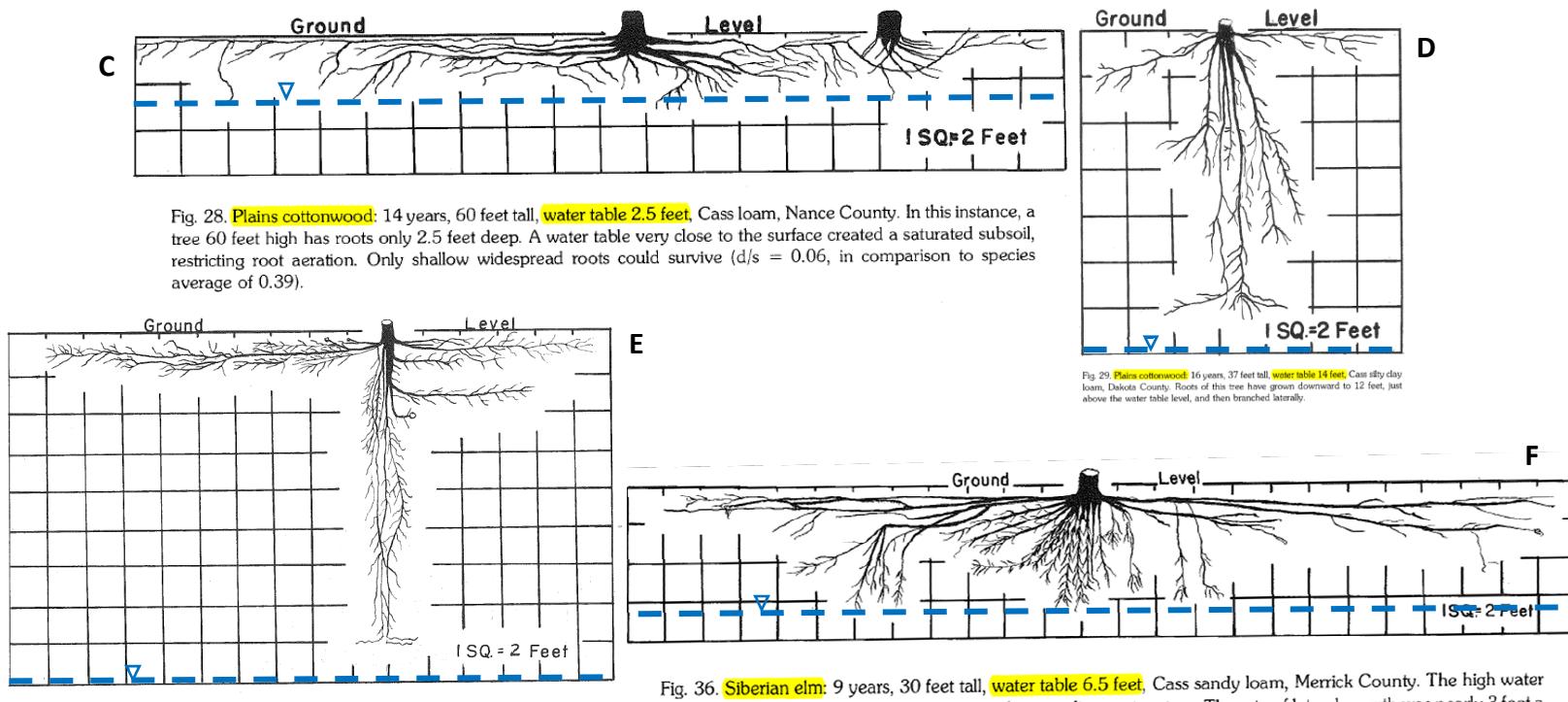


Fig. 37. **Siberian elm**: 11 years, 29 feet tall, **water table 16 feet**. Sarpy very fine sandy loam, Dakota County. Roots penetrated directly to the water table at 16 feet; lateral development was limited mostly to the surface 2 feet of soil.

Fig. 36. **Siberian elm**: 9 years, 30 feet tall, **water table 6.5 feet**, Cass sandy loam, Merrick County. The high water table typically results in a shallow but very wide-spreading root system. The rate of lateral growth was nearly 3 feet a year.

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.

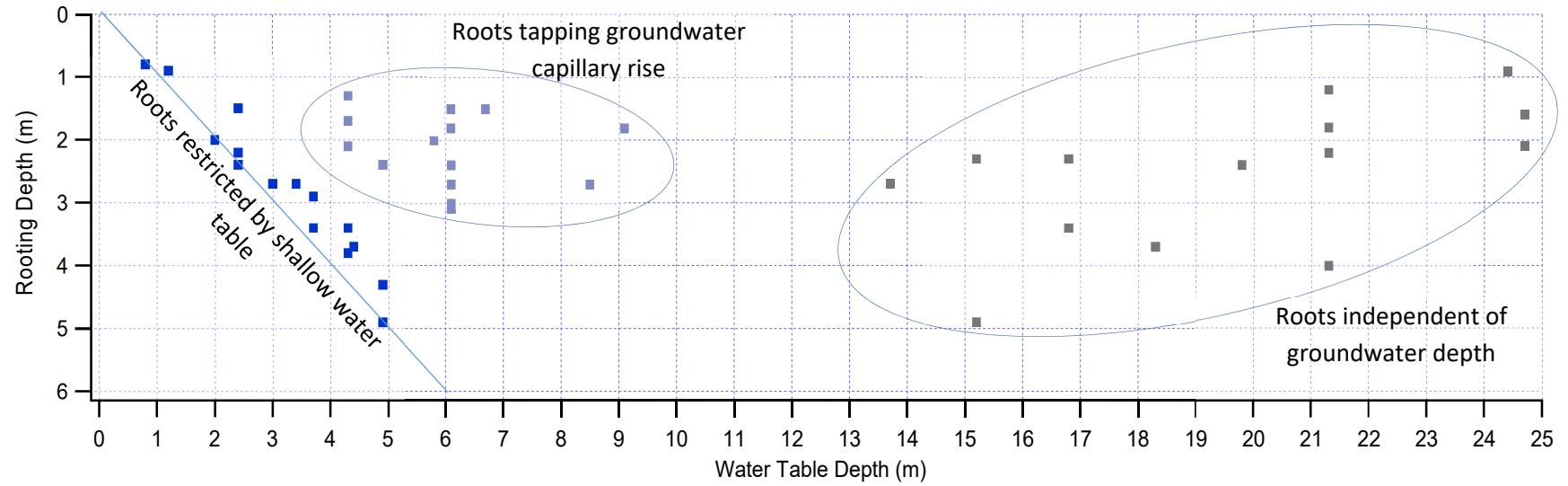


Fig. S5. Rooting depth vs. WTD for 46 trees (37 species) in Eastern Nebraska (288) indicating three types of root-WTD relations.

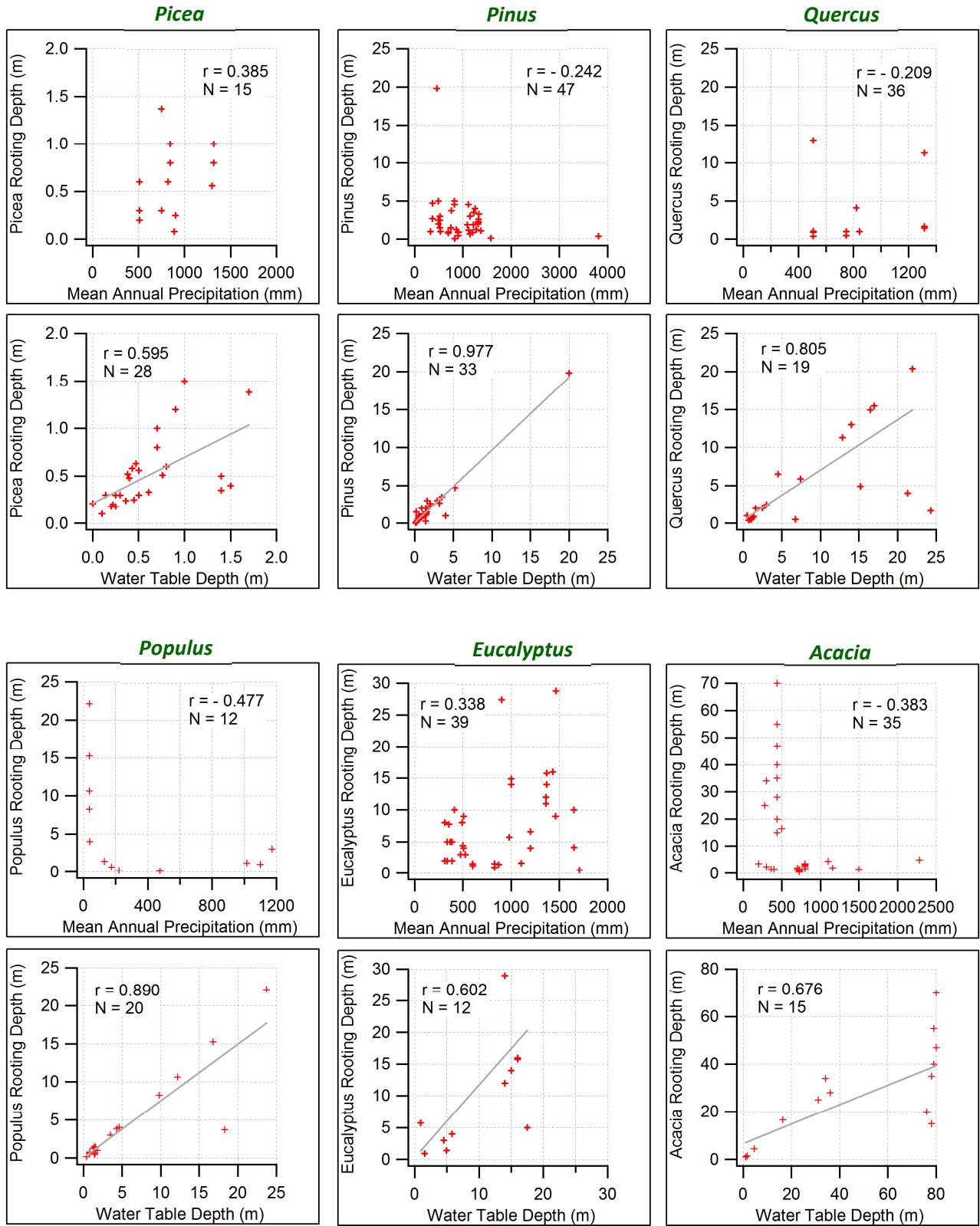


Fig. S6. Rooting depth vs. precipitation (top) and WTD (bottom) for the six best observed genera (marked in green in Fig. 4e and Table S1C), with Pearson correlation coefficient r and the sample size N . Note vertical scale difference. Not all sites have both precipitation and water table data.

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.

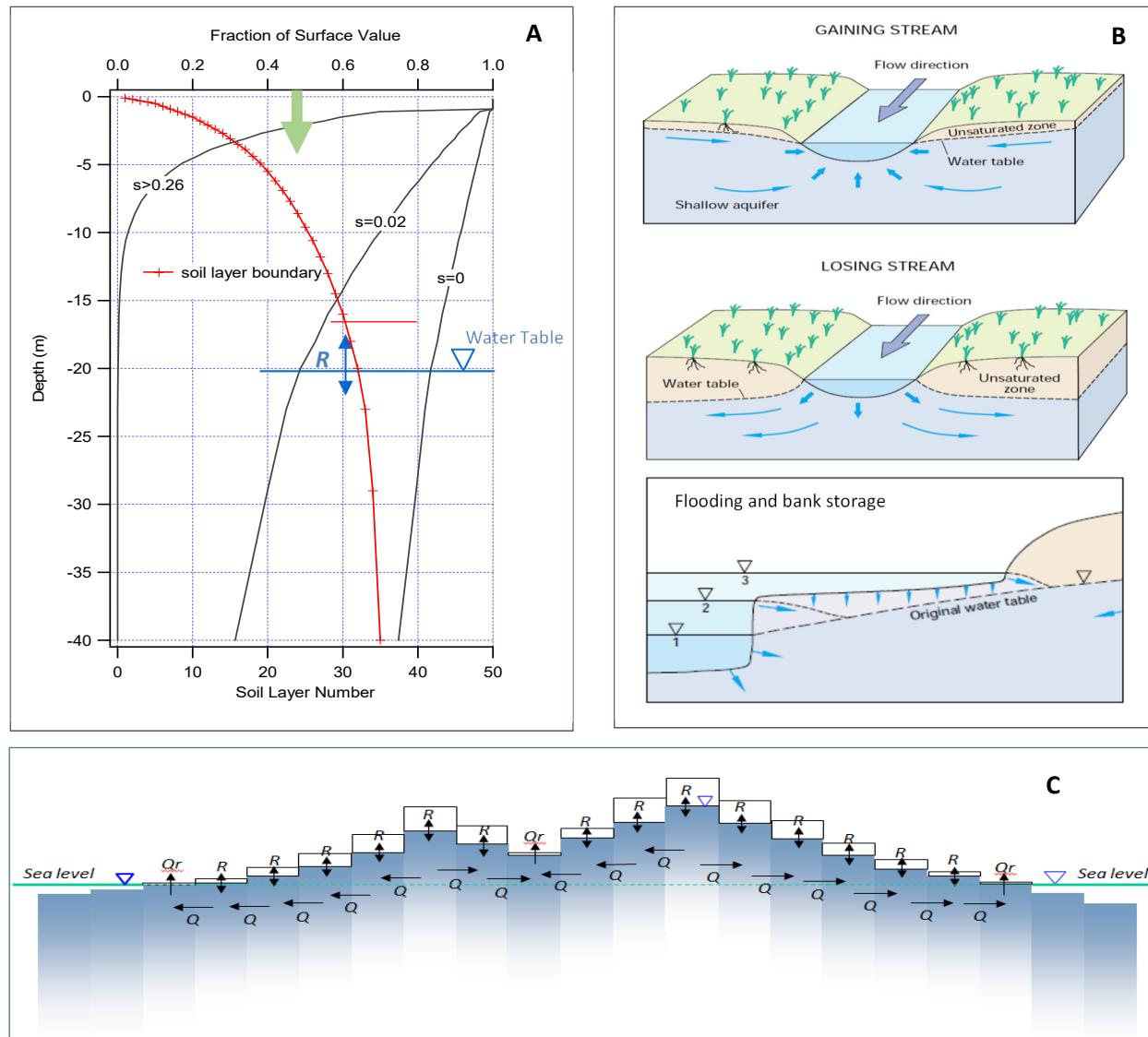


Fig. S7. Structure of the hydrology model: (A) soil layer thickness increases with depth (to 1km), porosity/permeability decrease with depth depending on land slope s (3 examples shown), and a dynamic water table that rises and falls depending on recharge R , 2-way exchange with rivers and floodplains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

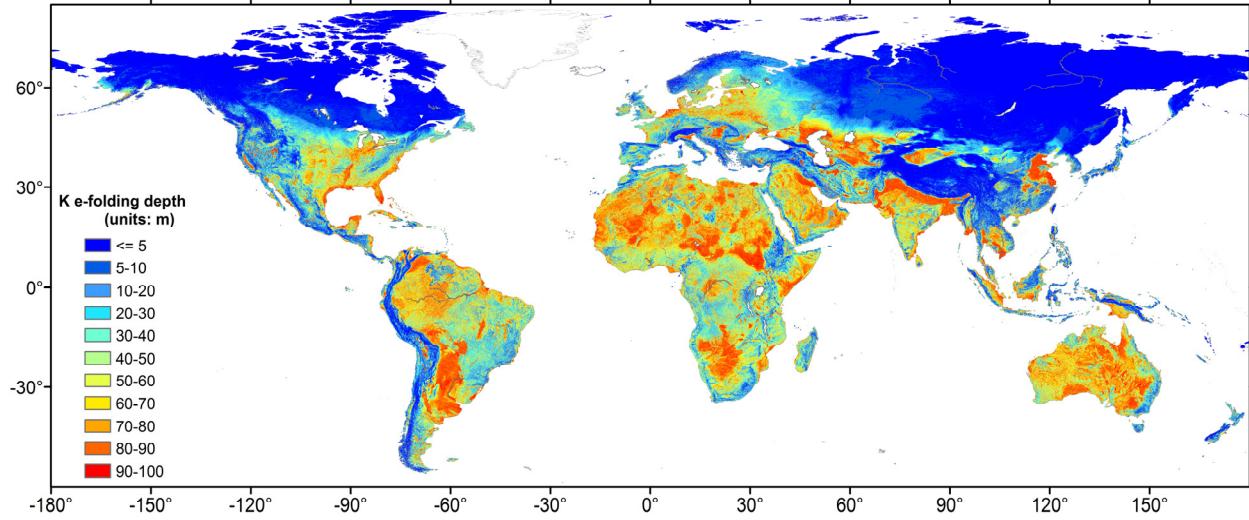


Fig. S8. The e-folding depth of exponential decrease with depth in permeability and porosity, obtained from local terrain slope and winter temperature (defining permafrost depth).

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/mcd_15a3) 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)
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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.

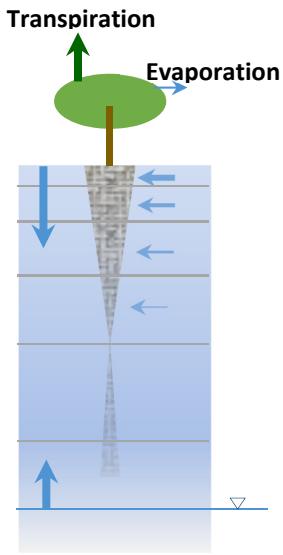


Fig. S9. Root water uptake from “parallel-connected” soil layers.

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):

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

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 ease 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

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:

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

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

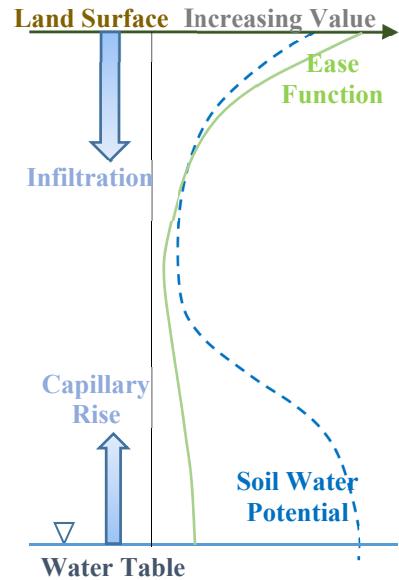


Fig. S10. Schematic profiles of the soil water potential (blue dashed line) and the ease function (green solid line).

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 decreasing 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-activated 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 earthH2Observe Water Cycle Integrator (WCI), a public data portal (<https://wci.earth2observe.eu/>).

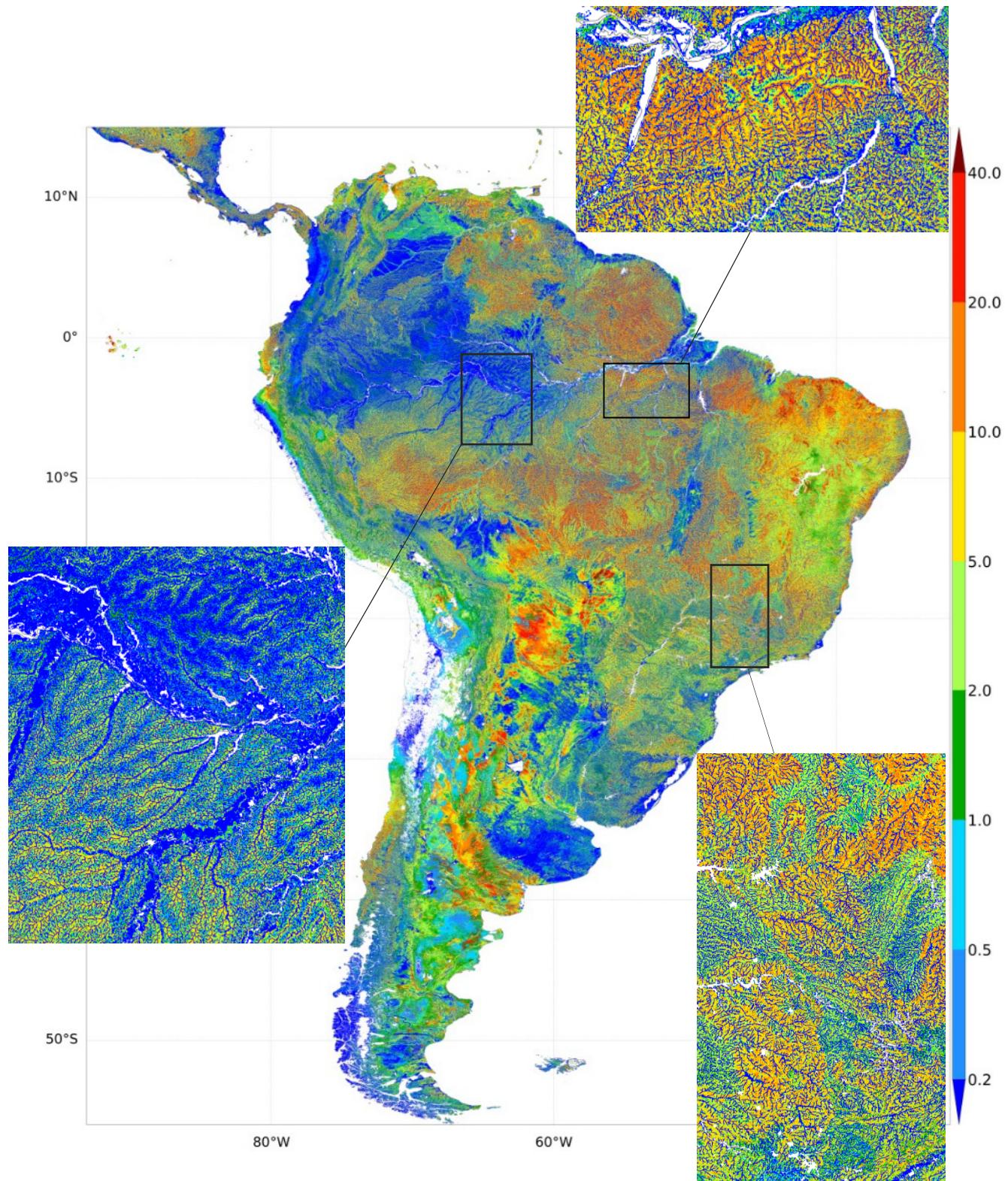


Fig. S11. Maximum depth of root water uptake (m) in S. America, averaged over 10yrs, with details over three regions. White grid cells have leaf area index (LAI) not detectable by MODIS and hence are not modeled.

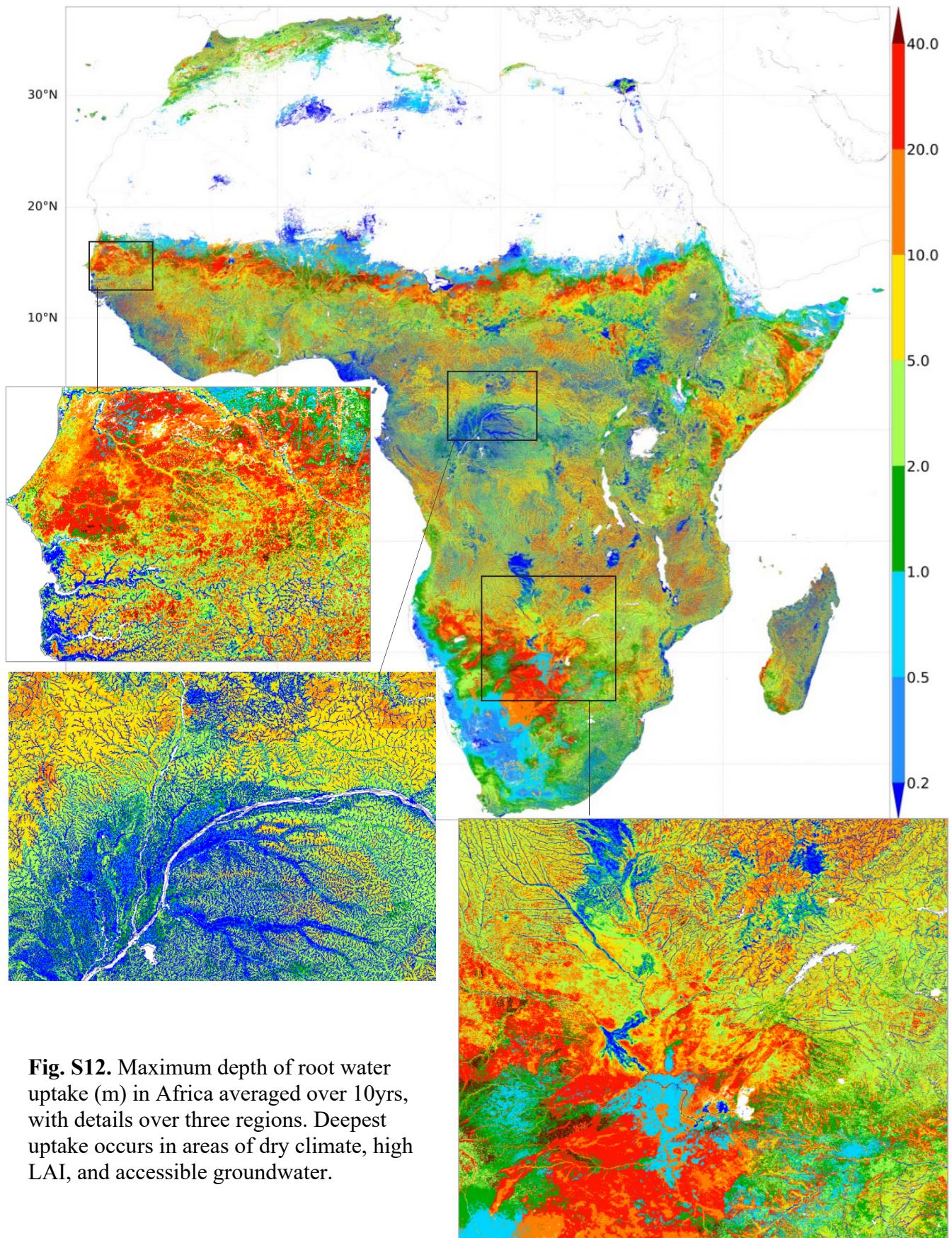


Fig. S12. Maximum depth of root water uptake (m) in Africa averaged over 10yrs, with details over three regions. Deepest uptake occurs in areas of dry climate, high LAI, and accessible groundwater.

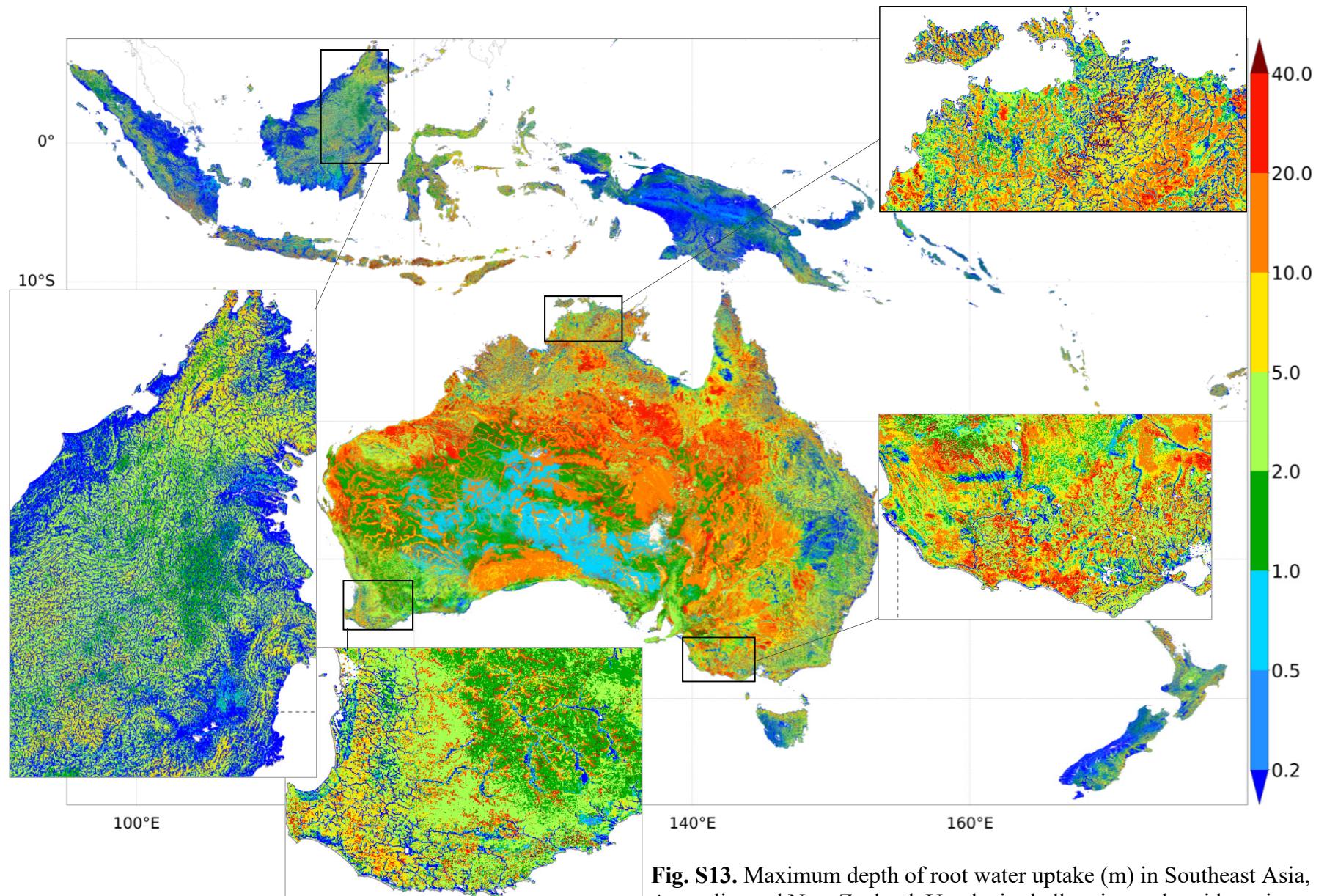


Fig. S13. Maximum depth of root water uptake (m) in Southeast Asia, Australia, and New Zealand. Uptake is shallow in per-humid tropics and deep in arid regions with high LAI and accessible water table.

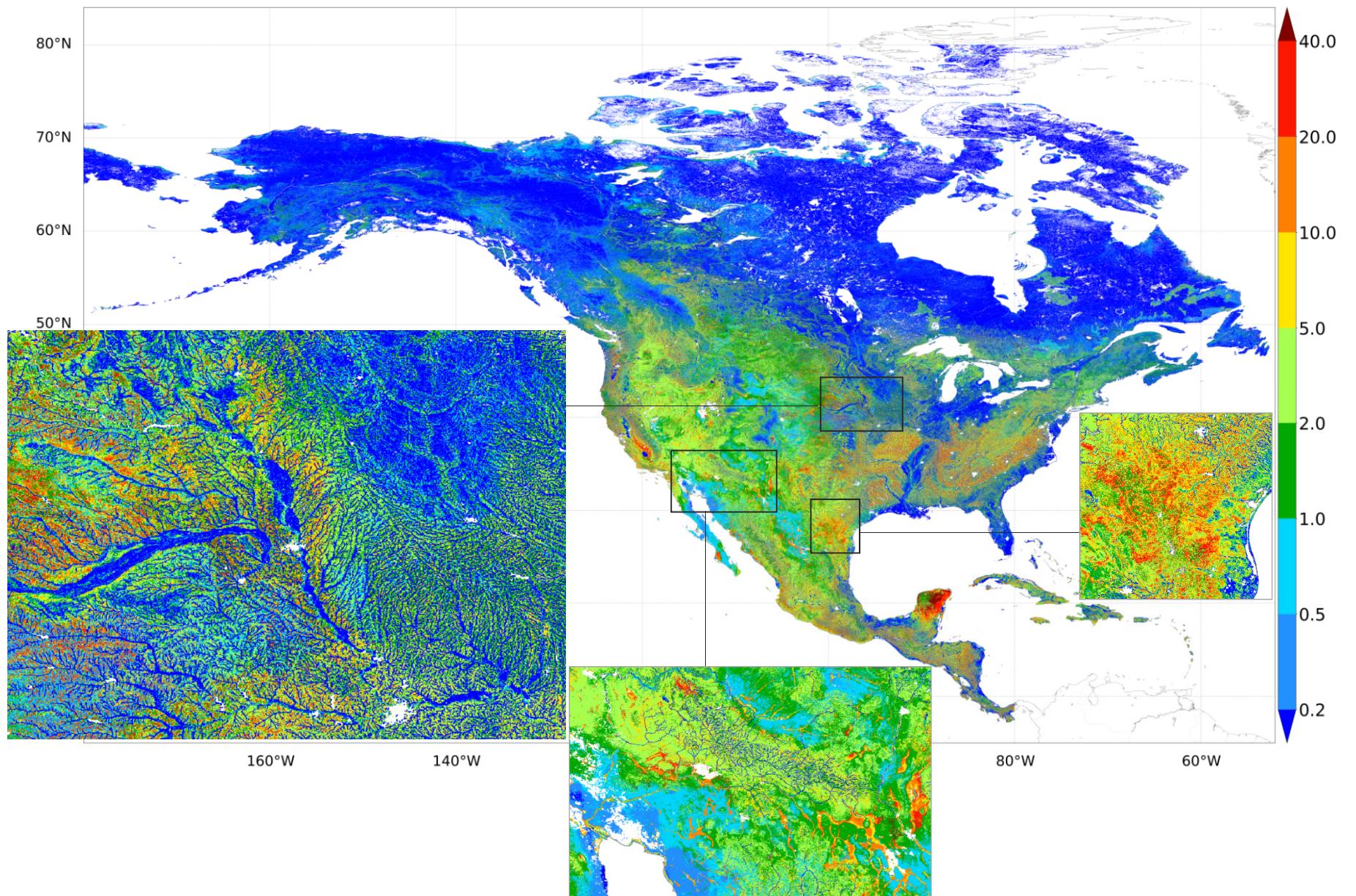


Fig. S14. Maximum depth of root water uptake (m) in North-Central America (details over E Nebraska and areas of known deep roots).

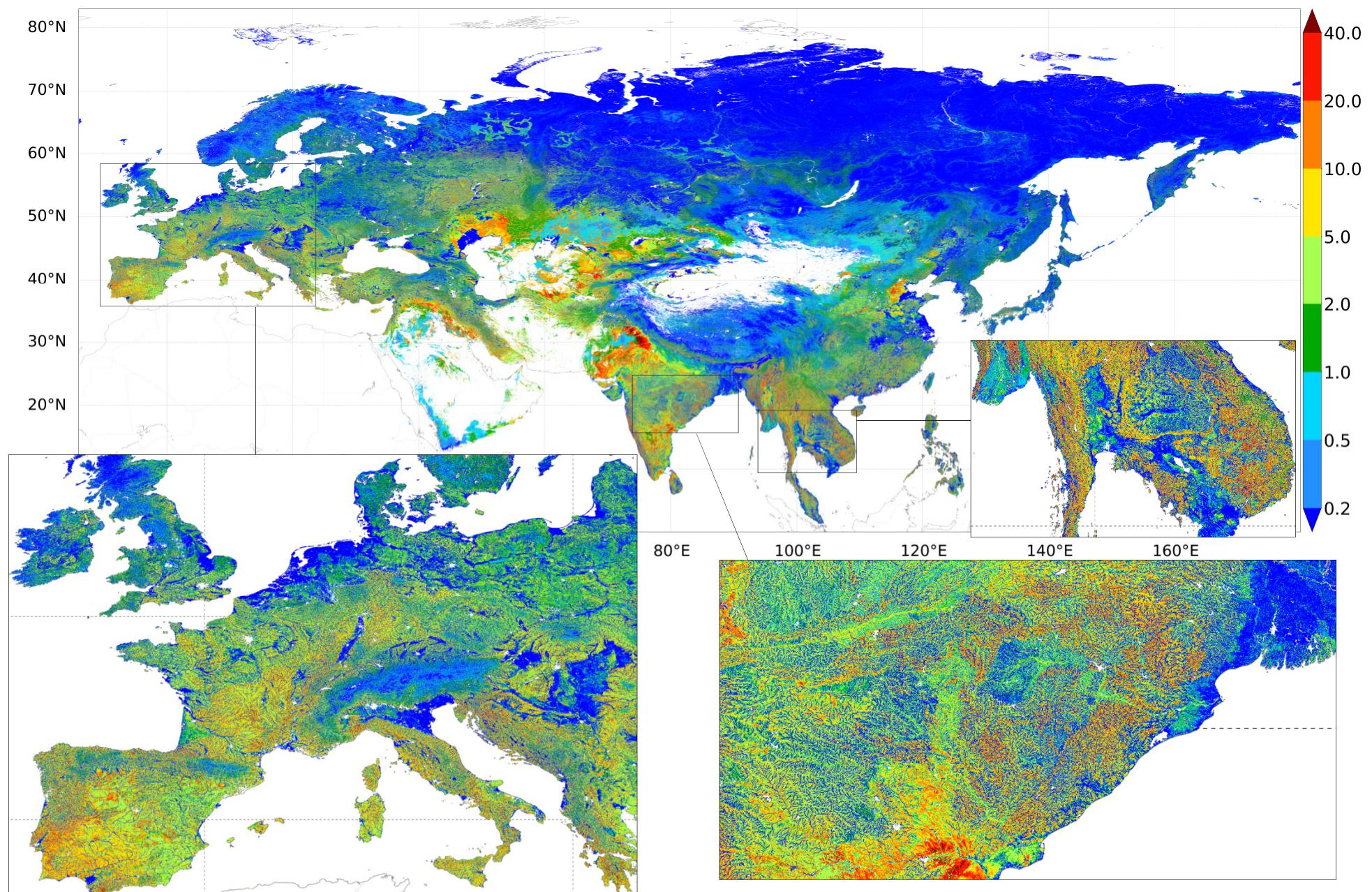


Fig. S15. Maximum depth of root water uptake (m) in Eurasia.

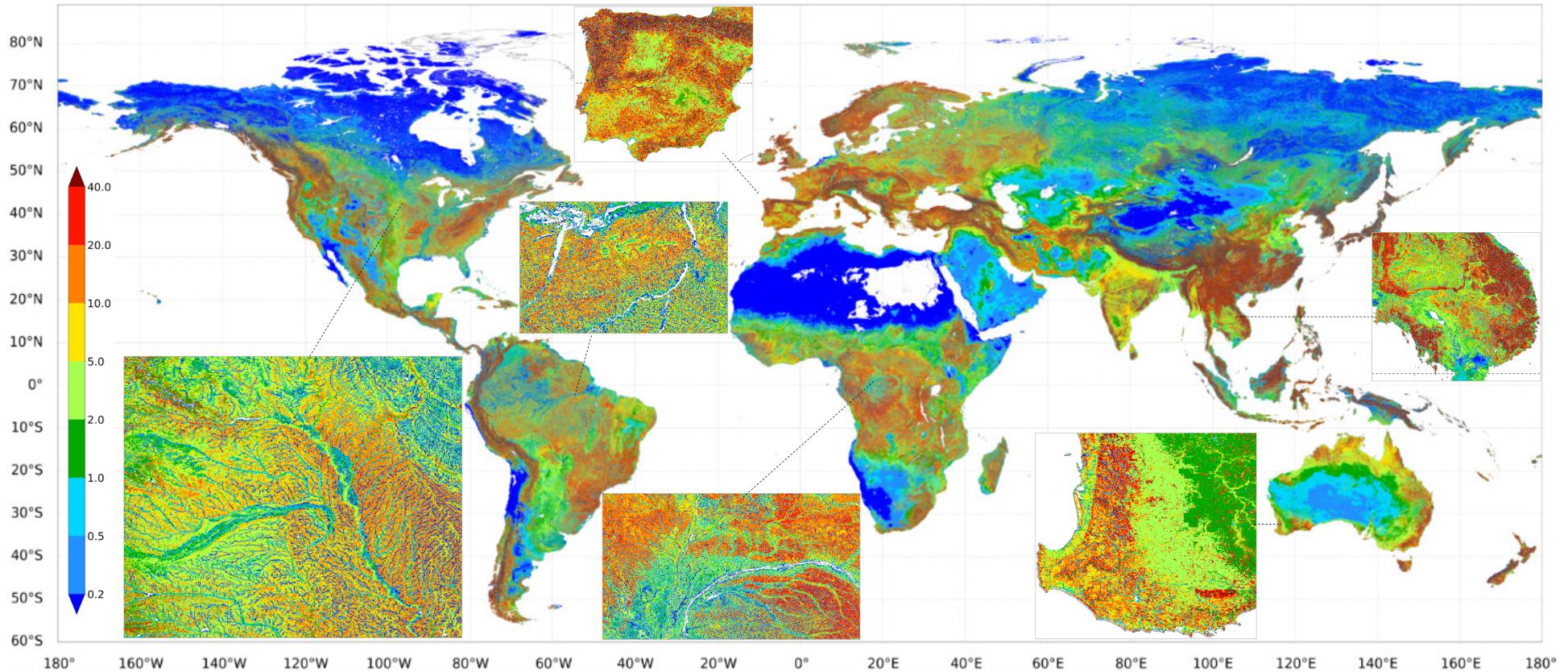


Fig. S16. Inverse-modeled 10yr-mean precipitation infiltration depth (m) with details over the same regions as in Fig. 6 of the main text. It reflects the climate (precipitation amount and frequency), soil texture giving it a patchy appearance, and the water table depth (Fig. S17), the latter sets the 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.

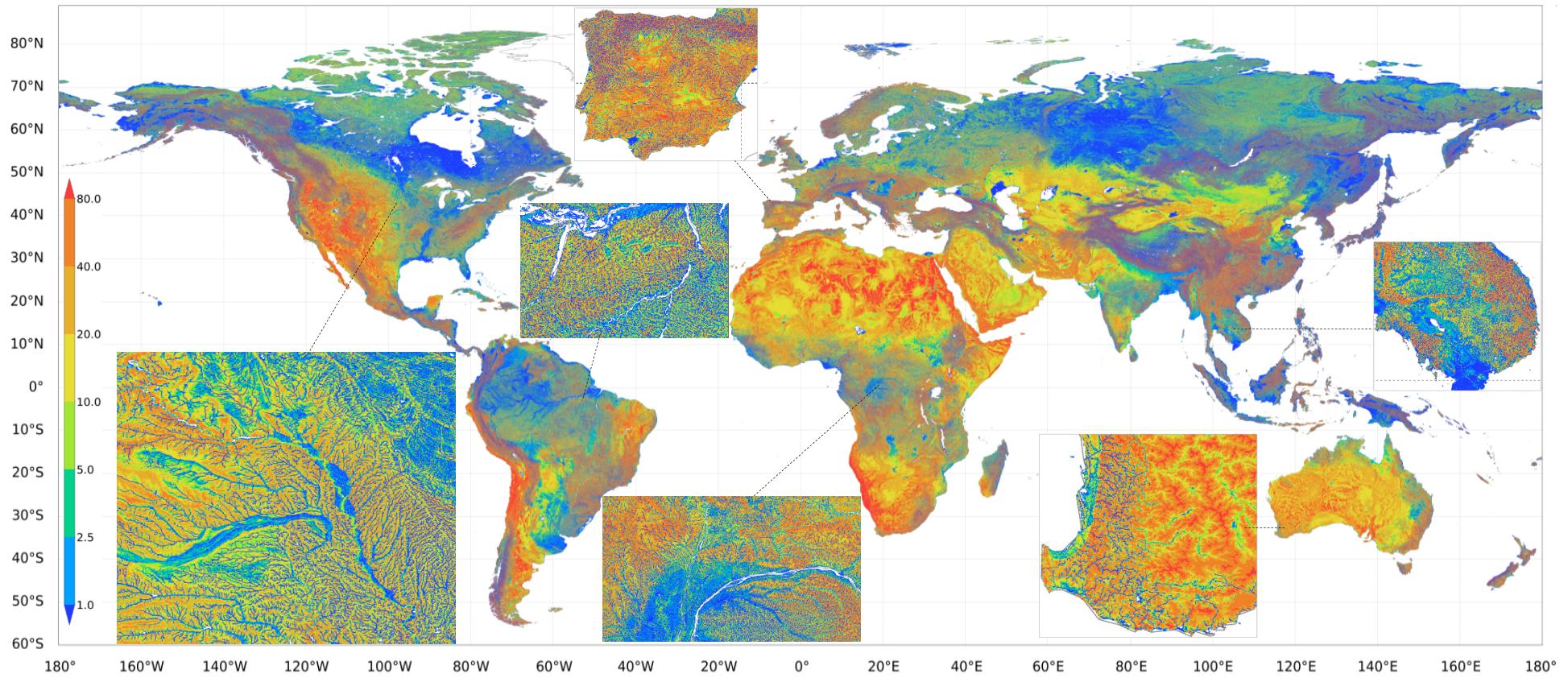


Fig. S17. Inverse-modeled 10yr-mean water table depth (m) with details over the same regions as in Fig. 6 of the main text. The color-scale is different from that of root uptake depth (Fig. 6, Fig. S11-15) and precipitation infiltration depth (Fig. S16) in order to display the very large range of water 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.

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