

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/319908381>

Hydrologic regulation of plant rooting depth

Article in *Proceedings of the National Academy of Sciences* · September 2017

DOI: 10.1073/pnas.1712381114

CITATIONS

0

READS

395

5 authors, including:



Ying Fan

Rutgers, The State University of New Jersey

40 PUBLICATIONS 1,805 CITATIONS

SEE PROFILE



Gonzalo Miguez-Macho

University of Santiago de Compostela

82 PUBLICATIONS 1,373 CITATIONS

SEE PROFILE



Esteban Jobbágy

National Scientific and Technical Research C...

222 PUBLICATIONS 11,755 CITATIONS

SEE PROFILE



Carlos Otero Casal

University of Santiago de Compostela

5 PUBLICATIONS 2 CITATIONS

SEE PROFILE

Some of the authors of this publication are also working on these related projects:



Ecosystem and Socio-Ecosystem Functional Types (E&SEFT Project): Integrating biophysical and social functions to characterize and map the ecosystems of the Anthropocene [View project](#)



“Flatness, Flooding and Farming (F3): Adapting to climatic and hydrological changes in the plains of Argentina and Paraguay” [View project](#)

All content following this page was uploaded by [Esteban Jobbágy](#) on 26 September 2017.

The user has requested enhancement of the downloaded file.



Hydrologic regulation of plant rooting depth

Ying Fan^{a,1}, Gonzalo Miguez-Macho^b, Esteban G. Jobbágy^c, Robert B. Jackson^{d,e,f}, and Carlos Otero-Casal^b

^aDepartment of Earth and Planetary Sciences, Rutgers University, New Brunswick, NJ 08854; ^bNon-Linear Physics Group, Faculty of Physics, Universidade de Santiago de Compostela, E-15782 Santiago de Compostela, Galicia, Spain; ^cGrupo de Estudios Ambientales–Instituto de Matemática Aplicada San Luis, Consejo Nacional de Investigaciones Científicas y Técnicas, Universidad Nacional de San Luis, D5700HHW San Luis, Argentina; ^dDepartment of Earth System Science, Stanford University, Stanford, CA 94305; ^eWoods Institute for the Environment, Stanford University, Stanford, CA 94305; and ^fPrecourt Institute for Energy, Stanford University, Stanford, CA 94305

Edited by Thomas Dunne, University of California, Santa Barbara, CA, and approved August 23, 2017 (received for review July 11, 2017)

Plant rooting depth affects ecosystem resilience to environmental stress such as drought. Deep roots connect deep soil/groundwater to the atmosphere, thus influencing the hydrologic cycle and climate. Deep roots enhance bedrock weathering, thus regulating the long-term carbon cycle. However, we know little about how deep roots go and why. Here, we present a global synthesis of 2,200 root observations of >1,000 species along biotic (life form, genus) and abiotic (precipitation, soil, drainage) gradients. Results reveal strong sensitivities of rooting depth to local soil water profiles determined by precipitation infiltration depth from the top (reflecting climate and soil), and groundwater table depth from below (reflecting topography-driven land drainage). In well-drained uplands, rooting depth follows infiltration depth; in waterlogged lowlands, roots stay shallow, avoiding oxygen stress below the water table; in between, high productivity and drought can send roots many meters down to the groundwater capillary fringe. This framework explains the contrasting rooting depths observed under the same climate for the same species but at distinct topographic positions. We assess the global significance of these hydrologic mechanisms by estimating root water-uptake depths using an inverse model, based on observed productivity and atmosphere, at 30" (~1-km) global grids to capture the topography critical to soil hydrology. The resulting patterns of plant rooting depth bear a strong topographic and hydrologic signature at landscape to global scales. They underscore a fundamental plant–water feedback pathway that may be critical to understanding plant-mediated global change.

plant rooting depth | soil hydrology | global change biology | infiltration depth | water table depth

Plant rooting depth is a sensitive parameter in Earth system models for understanding past and predicting future global change (1–3) because it is a basic plant functional trait determining ecosystem resilience (4–6), plant biogeography (7, 8), pedogenesis (9, 10), and long-term carbon cycle (1, 10, 11). Unlike their aboveground counterparts, roots are difficult to observe, and basic knowledge such as their vertical extent remains limited, hindering mechanistic understanding and prediction of plant-mediated global change. Observation syntheses in the 1990s (12–14) revealed widely varying rooting depths (0.3–68 m; *SI Appendix, Fig. S1*) and broad associations with biome types; roots are shallow in boreal biomes on thinly thawed soils; roots of annual crops start from seeds each season reaching only shallow depths; and deep roots are found in arid, semiarid, and season-arid climates. In fact, a key finding from past syntheses is that both the shallowest and the deepest roots are found in dry biomes (3, 15). Because biomes are closely associated with climate, subclimate-scale factors likely explain the large within-biome spread. Candidates include species and age, but the same species/age displayed contrasting rooting depths in monoculture crops and plantations (16, 17), because roots are highly adaptive to local soil environments (18).

A frequently evoked subclimate-scale environmental factor is soil water status. Near the surface, coarse-grained soils with low water holding capacity allow deep infiltration encouraging deep roots (19–21); at the base, waterlogging and associated oxygen stress in topographic depressions inhibit deep roots (16, 17, 22,

23). Thus, variations in local soil water profile, driven by infiltration above and drainage below, are known causes for rooting depth variations (12). While climate and soil regulate infiltration, topography drives drainage; water flows toward topographic depressions creating shallow water tables in the latter. This is why the water table depth (WTD) reflects local topography as much as or more than regional climate (*SI Appendix, Fig. S2*); one finds deep and shallow water tables under most climates (24).

We hypothesize that along a topographic gradient, root–water relation shifts systematically (Fig. 1); on excessively drained uplands (position 1), the water table is deep or absent and rooting depth is limited to infiltration depth/frequency (25) (example in *SI Appendix, Fig. S3B*). At a lower position 2, roots may sense groundwater capillary rise; in climates with dry seasons, dimorphic roots (*SI Appendix, Fig. S3C*) are observed, with a shallow cluster using rain and a deep cluster using groundwater in dry seasons (26–28). At position 3, infiltration meets capillary rise and water is not limiting. At position 4, seasonal waterlogging limits roots to the oxygenated soils above the water table (*SI Appendix, Fig. S3D*); shallow or aerial roots are common in lowland forests (12, 29, 30). At position 5, permanent waterlogging selects wetland species insensitive to WTD.

To test this hypothesis, we compiled rooting depth observations (*SI Appendix and Dataset S1*), recording local drainage conditions neglected in earlier syntheses. The 2,200 observations (Fig. 2) represent >1,000 species under a range of climate, soil, and drainage conditions. Rooting depth varied from <0.01 to >70 m

Significance

Knowledge of plant rooting depth is critical to understanding plant-mediated global change. Earth system models are highly sensitive to this particular parameter with large consequences for modeled plant productivity, water–energy–carbon exchange between the land and the atmosphere, and silicate weathering regulating multimillion-year-timescale carbon cycle. However, we know little about how deep roots go and why. Accidental discoveries of >70-m-deep roots in wells and >20-m-deep roots in caves offer glimpses of the enormous plasticity of root response to its environment, but the drivers and the global significance of such deep roots are not clear. Through observations and modeling, we demonstrate that soil hydrology is a globally prevalent force driving landscape to global patterns of plant rooting depth.

Author contributions: Y.F. designed research; Y.F. and G.M.-M. performed research; Y.F. compiled rooting depth observations; G.M.-M. developed the inverse model and performed all model simulations; G.M.-M., E.G.J., R.B.J., and C.O.-C. contributed new reagents/analytic tools; Y.F., E.G.J., and R.B.J. wrote the paper; and C.O.-C. assisted modeling work and made all maps.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Data deposition: The model simulation results reported in this paper have been deposited in European Commission Earth2Observe (<https://wci.earth2observe.eu/thredds/catalog/usc/root-depth/catalog.html>).

¹To whom correspondence should be addressed. Email: yingfan@eps.rutgers.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1712381114/-DCSupplemental.

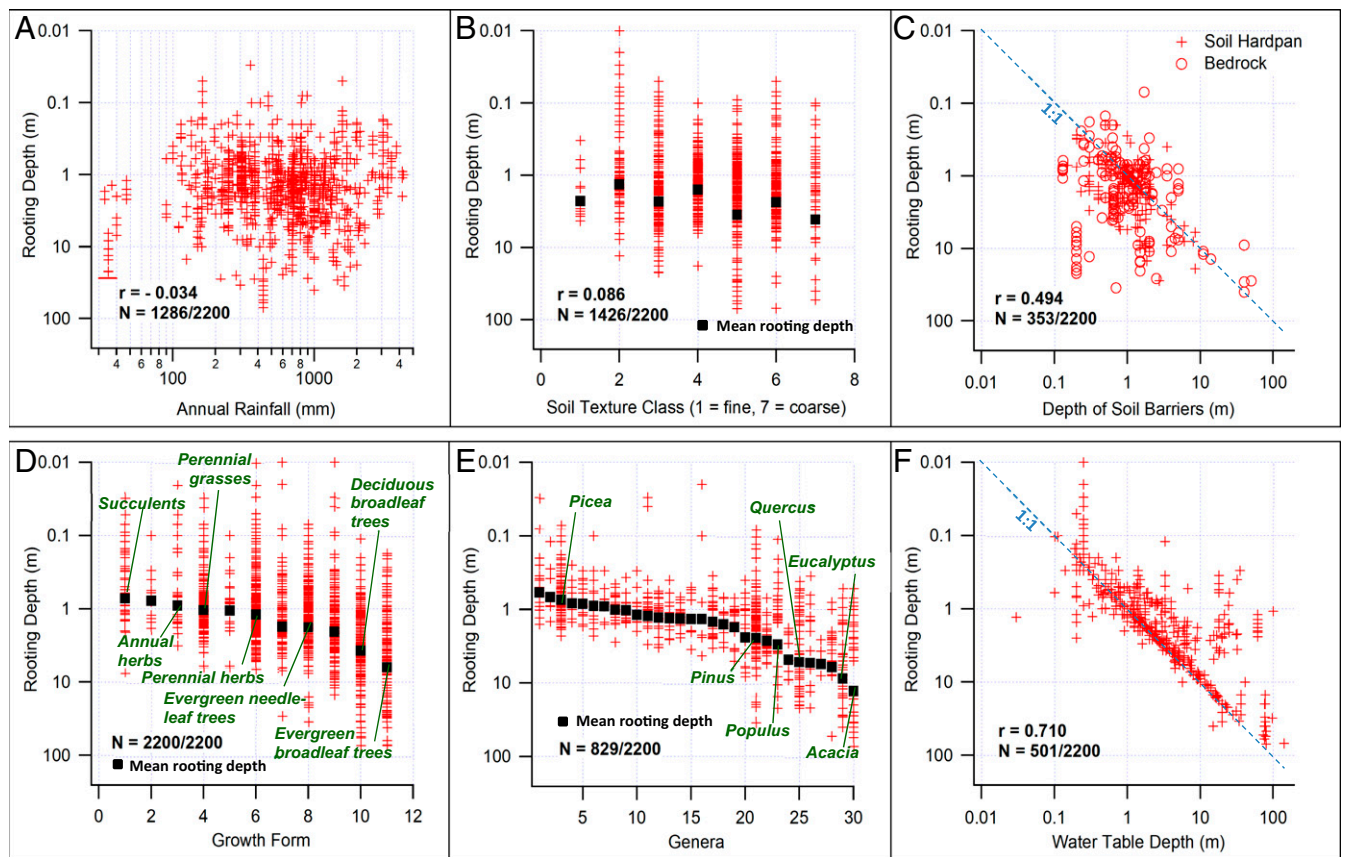


Fig. 3. Rooting depth (log-scale) vs. (A) mean annual rainfall, (B) soil texture (*SI Appendix, Table S1A*), (C) depth of soil barriers, (D) growth form (*SI Appendix, Table S1B*), (E) genera (*SI Appendix, Table S1C*), and (F) WTD, giving Pearson correlation coefficient r (on original data) and sample size N out of 2,200 observations.

37). In a season-dry climate on well-drained uplands (case 4), ample wet-season rain wets the soil deeply, enabling deeper roots necessitated by higher productivity in season-wet biomes, but groundwater is out of reach (4, 5). Down gradient (case 5), groundwater becomes accessible; deep roots are frequently observed in upland trees in season-dry climates (26–28). In a per-humid climate on well-drained slopes (cases 7 and 8), the ample rain wets the soils completely, but with frequent surface wetting roots do not need deep water. Across all climates, waterlogging in lowlands (cases 3, 6, and 9) plus high salinity in arid climates restrict roots; observations reveal ubiquitously shallow and wide roots, aerial roots, or short ephemeral roots tracking seasonal water table rise/fall (12, 16, 22, 23, 30).

Within this framework, the role of soil texture can be understood by how it regulates the downward infiltration and the upward capillary rise (Fig. 5). From the top, infiltration is stronger—deeper in coarse, and weaker/shallower in fine, textured soils, leading to systematic shifts in rooting depth (19–21, 38). However, the presence of a water table can confound such a simple relationship; a shallow water table in a coarse soil can push roots shallower, and a deep water table in a finer soil can pull roots deeper, contributing to the poor correlation between rooting depth and soil texture (Fig. 3B).

This framework accounts for the influence of regional-scale, fast-changing atmosphere from the top, and landscape-scale, slower-changing topography from below, in jointly shaping soil water–oxygen profiles that roots sense and exploit. The following question arises: what is the global significance of such landscape-scale root–water relations?

We use inverse modeling to estimate the necessary depths of root–water uptake (*SI Appendix*). First, we calculate the soil water supply profile driven by the observed atmosphere, soil texture, and topography using a hydrology model that tracks the store and fluxes in the soil water, groundwater, rivers, and wetlands (39, 40). This gives the soil water profile as shown in Figs. 4 and 5 at each grid cell at each time step. To capture the local drainage emphasized here with computational feasibility, we use 30-arcsecond global grids (<1-km) at hourly intervals over eleven years (2003–2013). Second, we calculate the ecosystem water demand from satellite-observed leaf area index and observed-reanalysis atmosphere, based on the Shuttleworth and Wallace (41) formula of the Penman–Monteith equation separating plant transpiration from soil evaporation. Third, given plant water demand and the soil water supply profile, we estimate the necessary depths of water uptake to meet the demand, based on Ohm’s law for parallel-connected conductors (details in *SI Appendix*). We assume that the many individual plants within a model grid cell behave collectively to withdraw soil water to meet the transpiration demand of grid-level productivity observed from space.

Fig. 6 gives the model maximum depth of root uptake averaged over ten years (2004–2013). Continent maps are in *SI Appendix, Figs. S11–S15*. At the global scale, climate and major biomes are visible (e.g., shallow in boreal, deep in seasonal forests), consistent with earlier syntheses and models (3, 13, 14, 20), but under a given climate or within a biome, the topographic structure emerges as a powerful force (Fig. 6, *Insets* and *SI Appendix, Figs. S11–S15*) as it is the primary driver of land drainage. Topography is visible in both the infiltration depth (*SI Appendix, Fig. S16*) and the WTD (*SI*

ACKNOWLEDGMENTS. We thank those who conducted painstaking root investigations in the field and the Rutgers University Libraries who brought these observations to our desktop, making the synthesis possible. We thank Gabriel Tucker for the Japanese monograph on roots and Dai Yamazaki for providing global high-resolution terrain analyses. Funding comes from US Environmental Protection Agency (STAR-RD834190) and National Science

Foundation (AGS-1045110, EAR-1528298) (to Y.F.), the European Commission Seventh Framework Programme (Earth2Observe 603608) (to G.M.-M.), and US Department of Agriculture National Institute of Food and Agriculture (2012-68002-19795) (to R.B.J.). Computation is at the Centro de Supercomputación de Galicia (CESGA) at Universidade de Santiago de Compostela, Galicia, Spain.

- Berner RA (2005) The rise of trees and how they changed paleozoic atmospheric CO₂, climate, and geology. *A History of Atmospheric CO₂ and Its Effects on Plants, Animals, and Ecosystems*, eds Ehleringer JR, Cerling T, Dearing MD (Springer, New York).
- Feddes R, et al. (2001) Modeling root water uptake in hydrological and climate models. *Bull Am Meteorol Soc* 82:2797–2809.
- 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. *Glob Change Biol* 4:275–286.
- Nepstad DC, et al. (1994) The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. *Nature* 372:666–669.
- Oliveira RS, et al. (2005) Deep root function in soil water dynamics in cerrado savannas of central Brazil. *Funct Ecol* 19:574–581.
- Maeght J-L, Revault B, Pierret A (2013) How to study deep roots—and why it matters. *Front Plant Sci* 4:299.
- Weaver JE (1919) *The Ecological Relations of Roots* (Digital Commons @ University of Nebraska–Lincoln, Lincoln, NE), pp 122–127.
- Bowman DMJS, Prior DL (2016) Why do evergreen trees dominate the Australian seasonal tropics? *Aust J Bot* 53:379–399.
- Reubens B, Poesen J, Danjon F, Geudens G, Muys B (2007) The role of fine and coarse roots in shallow slope stability and soil erosion control with a focus on root system architecture: A review. *Trees (Berl)* 21:385–402.
- Algeo TJ, Scheckler SE (1998) Terrestrial-marine teleconnections in the Devonian: Links between the evolution of land plants, weathering processes, and marine anoxic events. *Philos Trans R Soc Lond B Biol Sci* 353:113–130.
- Beerling DJ, Berner RA (2005) Feedbacks and the coevolution of plants and atmospheric CO₂. *Proc Natl Acad Sci USA* 102:1302–1305.
- Stone EL, Kalisz PJ (1991) On the maximum extent of tree roots. *For Ecol Manage* 46: 59–102.
- Jackson RB, et al. (1996) A global analysis of root distributions for terrestrial biomes. *Oecologia* 108:389–411.
- Canadell J, et al. (1996) Maximum rooting depth of vegetation types at the global scale. *Oecologia* 108:583–595.
- Cannon WA (1913) Some relations between root characters, ground water and species distribution. *Science* 37:420–423.
- Wagg JWB (1967) *Origin and Development of White Spruce Root-Forms* (Queen's Printer and Controller of Stationery, Ottawa, Ontario, Canada), Forestry Branch Departmental Publication No. 1192.
- Follett R, Allmaras R, Reichman G (1974) Distribution of corn roots in sandy soil with a declining water table. *Agron J* 66:288–292.
- Hodge A (2004) The plastic plant: Root responses to heterogeneous supplies of nutrients. *New Phytol* 162:9–24.
- Sperry J, Hacke U (2002) Desert shrub water relations with respect to soil characteristics and plant functional type. *Funct Ecol* 16:367–378.
- Schenk HJ, Jackson RB (2005) Mapping the global distribution of deep roots in relation to climate and soil characteristics. *Geoderma* 126:129–140.
- Xu GQ, Li Y (2008) Rooting depth and leaf hydraulic conductance in the xeric tree *Haloxylon ammodendron* growing at sites of contrasting soil texture. *Funct Plant Biol* 35:1234–1242.
- Martin MH (1968) Conditions affecting the distribution of *Mercurialis perennis* L. in certain Cambridgeshire woodlands. *J Ecol* 56:777–793.
- Armstrong W, Booth TC, Priestley P, Read DJ (1976) The relationship between soil aeration, stability and growth of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) on upland peaty gleys. *J Appl Ecol* 13:585–591.
- Fan Y, Li H, Miguez-Macho G (2013) Global patterns of groundwater table depth. *Science* 339:940–943.
- Cannon WA (1911) *The Root Habits of Desert Plants* (Carnegie Institution of Washington, Washington, DC).
- Howard A (1925) The effects of grass on trees. *Proc R Soc Lond B* 97:284–321.
- Kimber PC (1974) *The Root System of Jarrah (Eucalyptus marginata)* (Forests Department of Western Australia, Perth, WA, Australia), Research Papers No. 10.
- Dawson TE, Pate JS (1996) Seasonal water uptake and movement in root systems of Australian phreatophytic plants of dimorphic root morphology: A stable isotope investigation. *Oecologia* 107:13–20.
- Smith AP (1972) Butteressing of tropical trees: A descriptive model and new hypotheses. *Am Nat* 106:32–46.
- Pavlis J, Jenik J (2000) Roots of pioneer trees in Amazonian rain forest. *Trees (Berl)* 14: 442–455.
- Hellmers H, Horton JS, Juhren G, O'Keefe J (1955) Root systems of some chaparral plants in southern California. *Ecology* 36:667–678.
- 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 Soil* 362:37–50.
- Jackson RB, Moore LA, Hoffmann WA, Pockman WT, Linder CR (1999) Ecosystem rooting depth determined with caves and DNA. *Proc Natl Acad Sci USA* 96:11387–11392.
- 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 Resour Res* 48:1–25.
- Naumburg E, Mata-Gonzalez R, Hunter RG, McLendon T, Martin DW (2005) Phreatophytic vegetation and groundwater fluctuations: A review of current research and application of ecosystem response modeling with an emphasis on great basin vegetation. *Environ Manage* 35:726–740.
- Sprackling JA, Read RA (1979) *Tree Root Systems in Eastern Nebraska* (The Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, Lincoln, NE), Nebraska Conservation Bulletin 37.
- Meinzer OE (1927) *Plants as Indicators of Ground Water* (US Geological Survey, Washington, DC), USGS Water-Supply Paper, Vol 577.
- Zipper SC, Evren Soylu M, Booth EG, Loheide SP (2015) Untangling the effect of shallow groundwater and soil texture as drivers of subfield-scale yield variability. *Water Resour Res* 51:6338–6358.
- Miguez-Macho G, Fan Y (2012) The role of groundwater in the Amazon water cycle: 1. Influence on seasonal streamflow, flooding and wetlands. *J Geophys Res* 117: D15113.
- Miguez-Macho G, Fan Y (2012) The role of groundwater in the Amazon water cycle: 2. Influence on seasonal soil moisture and evapotranspiration. *J Geophys Res Atmos* 117:D15114.
- Shuttleworth WJ, Wallace JS (1985) Evaporation from sparse crops—An energy combination theory. *Q J R Meteorol Soc* 111:839–855.
- Richter Dd, Billings SA (2015) “One physical system”: Tansley's ecosystem as Earth's critical zone. *New Phytol* 206:900–912.
- Harper RJ, Tibbett M (2013) The hidden organic carbon in deep mineral soils. *Plant Soil* 368:641–648.
- Fan Y (2015) Groundwater in the Earth's critical zone: Relevance to large-scale patterns and processes. *Water Resour Res* 51:3052–3069.
- Cannon WA (1913) *Botanical Features of the Algerian Sahara* (Carnegie Institution of Washington, Washington, DC).
- Davidson E, et al. (2011) Carbon inputs and water uptake in deep soils of an eastern Amazon forest. *For Sci* 57:51–58.
- 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* 64:1381–1393.
- 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. *J Trop Ecol* 25:371–386.