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Global-Scale Shifts in Rooting Depths Due To Anthropocene Land Cover Changes Pose Unexamined Consequences for Critical Zone Functioning

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Key Points:

- Rooting depths are changing globally; the depth to which 99% of crop roots extend is shallower by ~60 cm compared to natural systems
- In other regions, such as those experiencing woody encroachment, roots are deepening by ~38 cm compared to previous dominant vegetation
- These opposing phenomena result in average rooting depths that are ~8 cm shallower today and projected to become ~30 cm shallower by 2100

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Rooting depth is an ecosystem trait that determines the extent of soil development and carbon (C) and water cycling. Recent hypotheses propose that human-induced changes to Earth's biogeochemical cycles propagate deeply into Earth's subsurface due to rooting depth changes from agricultural and climate-induced land cover changes. Yet, the lack of a global-scale quantification of rooting depth responses to human activity limits knowledge of hydrosphere-atmosphere-lithosphere feedbacks in the Anthropocene. Here we use land cover data sets to demonstrate that root depth distributions are changing globally as a consequence of agricultural expansion truncating depths above which 99% of root biomass occurs (D99) by ~60 cm, and woody encroachment linked to anthropogenic climate change extending D99 in other regions by ~38 cm. The net result of these two opposing drivers is a global reduction of D99 by 5%, or ~8 cm, representing a loss of ~11,600 km^3 of rooted volume. Projected land cover scenarios in 2100 suggest additional future D99 shallowing of up to 30 cm, generating further losses of rooted volume of ~43,500 km^3, values exceeding root losses experienced to date and suggesting that the pace of root shallowing will quicken in the coming century. Losses of Earth's deepest roots—soil-forming agents—suggest unanticipated changes in fluxes of water, solutes, and C. Two important messages emerge from our analyses: dynamic, human-modified root distributions should be incorporated into earth systems models, and a significant gap in deep root research inhibits accurate projections of future root distributions and their biogeochemical consequences.

Plain Language Summary

The distribution of plant roots helps determine the extent of nutrient, C, and water cycling beneath Earth's surface. Human activities, including land use and climate change, can change the distribution of plant roots and their activities across the globe. Here, we used global land cover data sets in combination with field-generated rooting depth equations to estimate global scale changes to roots both now and into the future. Globally, roots are shallower than they would be in the absence of human activity due to extensive land conversion to agriculture. In some regions, human-promoted woody encroachment induces root elongation, but this effect is overwhelmed by the spatial extent of agricultural conversion. In the future, roots likely will become shallower at an even faster pace. In future projections, deep roots appear especially vulnerable to loss, prompting numerous questions for additional field- and modeling-based studies about the ways nutrients, C, and water will cycle in a future with fewer deep roots. We provide a foundation for those questions by demonstrating human influence on the roots that shape the character of Earth's skin.

1. Introduction

Roots are subsurface engineers, and their distributions drive ecosystem-scale processes (Maeght et al., 2013; Pierret et al., 2016; Sullivan et al., 2022) such as soil development (Austin et al., 2018; Brantley et al., 2017; Hasenmueller et al., 2017), release of mineral-bound nutrients (Austin et al., 2018; Hasenmueller et al., 2017; Jobbagy & Jackson, 2001), subsoil water flow paths and residence time (Fan et al., 2017; Y. Zhang et al., 2015), and deep C fluxes (S. A. Billings et al., 2018; Fan et al., 2017; Pierret et al., 2016; Richter & Markewitz, 1995; Schenk, 2007). The dominant drivers of rooting distributions are plant functional type (PFT, Jackson et al., 1996) and variation in water availability and temperature (Fan et al., 2017; Nippert & Knapp, 2007; Schenk, 2007; Tumber-Dávila et al., 2022), all of which are changing in response to anthropogenic land cover conversion, as well as altered atmospheric composition and concomitant changes in climate (Cramer et al., 2001; Edgeworth et al., 2015; Ellis et al., 2010). This observation suggests that rooting depth distributions are likely undergoing changes due to human activities in the critical zone (CZ, Earth's living skin, Jordan et al., 2001).

Quantifying large-scale, human-induced changes to rooting distributions and how they may differ regionally is a critical step towards a greater understanding of how roots govern large-scale, sub-surface, and surface processes. In spite of widespread recognition of the importance of rooting depth (Maeght et al., 2013; Pierret et al., 2016) and a growing recognition of the great depths to which roots can penetrate (Canadell et al., 1996; Fan et al., 2017; Nepstad et al., 1994; Schenk & Jackson, 2002a, 2002b; Stone & Kalisz, 1991), large-scale responses of rooting depths to anthropogenic perturbations of the biosphere have been poorly characterized. This knowledge gap is due in part to the challenges of accessing relatively deep soil horizons (Maeght et al., 2013), as well as the challenge of unraveling the vast complexity of Earth's subsurface systems. One consequence of poorly defined rooting distributions at large spatial scales is generalized representations of rooting parameters in land models (Iversen et al., 2017; McCormack et al., 2015, 2017). Although many land models, such as the Community Land Model (CLM), represent changes to roots with land use change (Lawrence et al., 2019), some land cover types are not well represented in these models. For example, crops in CLMs are assigned the same rooting depth as C3 grasses (Lawrence et al., 2019), though row crops, in particular, typically have far shallower roots than perennial plants (S. A. Billings et al., 2018; Canadell et al., 1996; DuPont et al., 2014). Given the plethora of CZ functions influenced by roots (Maeght et al., 2013; Pierret et al., 2016), poor characterization of rooting depths likely limits the accuracy of projected responses of the coupled terrestrial water, energy, and C cycles to climate in the Anthropocene.

Two Anthropocene phenomena occur at sufficient magnitude to potentially alter rooting distributions at the global scale. First, many regions have experienced conversion to annual row crops (Ellis et al., 2010; Ramankutty & Foley, 1999), a process that induces mortality of deep perennial root systems and replaces them with relatively shallow roots (S. A. Billings et al., 2018). In contrast, climate change and increasing atmospheric CO_2 concentrations are linked to root extension of extant woody plants (Iversen, 2010), and shifting ecoregion ranges may increase rooting depths where more deeply rooted woody vegetation becomes increasingly abundant in grasslands and tundra (Harsch et al., 2009; Jackson et al., 1996; Stevens et al., 2017; Wang et al., 2019). Studies exploring rooting depth typically focus on absolute rooting depths and their responses to climate or atmospheric CO_2 (Kleidon, 2003; Kleidon & Heimann, 1998) or, separately, land cover changes in specific regions of interest (DuPont et al., 2010; Hertel et al., 2009; Jaramillo et al., 2003). Despite known changes in global land cover (Ellis et al., 2010) that are associated with distinct rooting depths (Jackson et al., 1996; Zeng, 2001), as well as global analyses of the maximum extent of contemporary rooting depths (Schenk & Jackson, 2002a, 2002b, 2005), to date, no one has directly quantified the net change in rooting distributions at the global scale as a consequence of these opposing human activities.

Here we provide a first estimate of the extent to which rooting depths increase or decrease in response to land use and climate change and the volume of soil affected by this change. We also project how rooting depths and rooted volumes may change throughout the 21st century as more land is converted to agricultural and urban use, and as biome ranges continue to shift with changing climate. We emphasize that our focus is not on maximum rooting depths. Indeed, there is a growing appreciation of the great depths to which vegetation can root (Fan et al., 2017; Maeght et al., 2013; Pierret et al., 2016; Schenk & Jackson, 2002a, 2005; Stone & Kalisz, 1991) though the true maximum rooting depth may never be known in some systems (Fan et al., 2017; Kleidon, 2003; Pierret et al., 2016). Instead, we focus on the depths to which most or half (i.e., 99%, 95%, and 50%) of the root biomass of an ecosystem extends (Zeng, 2001), as well as changes to rooted soil volume. These metrics highlight the depths within which most roots reside as well as the soil volume through which most rooting distribution changes occur, both functionally consequential measures. Additionally, these metrics represent those for which much data exist, enabling the cross-system comparisons necessary to estimate the spatial extent of rooting depth changes in the Anthropocene. Our work thus reveals how anthropogenic, global-scale changes in rooting depth metrics are changing, thereby illuminating critical next steps to help us understand future CZ functioning.

Table 1
Data Sets Used for Each Timepoint Mapped in the Described Analyses and the Resolution at Which Each Can Be Downloaded

Landcover Timepoint	Data set	Resolution
Potential (prior to human influence)	Ramankutty and Foley (1999), Ramankutty et al. (2010)	9 km
Contemporary (2005)	GLC2000, Bartolome and Belward (2005)	1 km
Future (2100)	Land Use Harmonization 2, Hurtt et al. (2020)	25 km

2. Materials and Methods

We estimated the volume of soil influenced by human-promoted modification of rooting distributions. To do this, we estimated potential (i.e., no human influence), contemporary, and projected root distributions at the global scale by combining biome-specific rooting depth functions derived from empirical studies (described below) with spatially explicit land cover data sets. For all vegetation scenarios (potential, contemporary, and future) except those above 60°N (described below), we estimated biome-specific rooting depths by assigning rooting depth functions derived from empirical data compiled in the Fine Root Ecology Database (FRED) and the National Ecological Observatory Network (NEON) database (Iversen et al., 2021; NEON, 2021). These data sets have recently expanded rooting depth knowledge beyond earlier works (e.g., Jackson et al., 1996; Schenk & Jackson, 2005; Zeng, 2001) by accumulating new datapoints detailing root trait and distribution patterns in diverse biomes (Andrade et al., 2020; Krasowski et al., 2018; Lozanova et al., 2019; Montagnoli et al., 2018). However, to date no one has harmonized and analyzed these data sets to produce equations describing global rooting depth distributions. Their use here thus represents an advance in the ways we represent rooting depths and their distributions across the globe. Specifically, we used these data sets to estimate the depths by which rooting systems exhibit 50% (D50), 95% (D95), and 99% (D99) of their total biomass in each land cover type.

To generate rooting depth functions, we assigned FRED and NEON rooting depth data to biomes according to the position of each datapoint on our modified version of the Global Land Cover 2000 (GLC2000) map. Each set of points was checked using Google Earth (Google Earth Pro 7.3, 2022) to ensure that datapoints were correctly assigned. Due to the resolution of the GLC2000 map, some shrubland and woodland categories were incorrectly identified as cropland; for these points, we reassigned shrub-covered areas to the open-closed deciduous shrubland class and woodlands to the open broadleaved deciduous forest class. We then fit depth-decay curves to each set of points for each biome using the model presented by Zeng (2001). Parameter values from the equations and their confidence intervals were obtained for depth-decay curves using a bootstrap procedure where curves were fit to randomly selected samples (with replacement) of each set of points 1,200 times as recommended by Lander (2013). Parameter values are listed in Table S1 in Supporting Information S1. By using the Zeng (2001) model, we assumed that rooting depth distributions remain similar for each vegetation functional type in the potential, contemporary, and future scenarios. The merit of this assumption may vary with time but keeping the rooting depth of each biome's vegetation type consistent across the Holocene and into the future allows us to parse the influence of land cover change on rooting depths from that of less well-characterized phenomena. These equations represent biome-generalized rooting depths that do not account for site specific differences that may result from climate and soil variability; however, they represent our best approximation of rooting distributions at such broad scales.

We applied D99, D95, and D50 values calculated from biome-specific equations to maps describing global distributions of biomes for potential, contemporary, and future scenarios (Table 1). To analyze the depth distribution of roots in the absence of human activity (potential rooting depths), we used satellite-derived, potential vegetation representing 15 land cover classes (Haxeltine & Prentice, 1996) and their potential global distribution at a 9 km spatial resolution (Ramankutty & Foley, 1999; Ramankutty et al., 2010). The Ramankutty et al. (2010) data set serves as the only spatially quantified representation of potential land cover in the absence of human activity, allowing for detailed hindcasting of estimates of human-induced changes to roots. While other historic landcover data sets exist, such as the Land Use Harmonization historic data (LUH2, Hurtt et al., 2020), these data sets designate coarser land cover classifications that do not permit as detailed analyses of root depths. Importantly for our purposes here, the LUH2 data set also does not capture pre-agricultural time. In contrast, Ramankutty et al. (2010)'s potential vegetation map permits us to isolate human influence as a variable for analysis.

We compared potential vegetation classes to contemporary land cover as defined by the GLC2000 data set (GLC2000 databse, 2003; Bartolome & Belward, 2005). GLC2000 represents 22 land cover types at a 1 km resolution, which are designated according to plant functional types ascribed to satellite images and ground-truthed by regional analysts. We aligned contemporary vegetation classifications with potential vegetation classes according to previously published frameworks for ecoregion designation (Bartolome & Belward, 2005), and augmented these classes to include a class for permafrost regions where rooting depth is likely limited (W. D. Billings et al., 1977; Boike et al., 2018). These efforts resulted in 25 distinct land cover types for which rooting depths were assigned.

We selected the GLC2000 data set after examining multiple data sets describing contemporary global root distributions (Schenk & Jackson, 2009) and landcover scenarios across time (LUH2; Hurtt et al., 2011, 2020). We ultimately selected the GLC2000 data because the Schenk and Jackson data set does not describe roots in agricultural lands or wetlands (Schenk & Jackson, 2009), and is not divided into land cover classes that can be integrated with data sets describing potential and future land cover scenarios. Employing the GLC2000 vegetation classes permitted us to incorporate agricultural land cover classes. Further, GLC2000 allowed for a more detailed analysis of contemporary root depths and biomes than the land cover classes designated in the LUH2 data sets. For example, all forest types in LUH2 scenarios are grouped into "secondary" and "primary" forest rather than more region-specific forest classifications such as deciduous, evergreen, and tropical (Hurtt et al., 2020). Given well-defined, characteristic root distributions for relatively fine-scale biome classifications (Tumber-Dávila et al., 2022), using the GLC2000 data set allowed us to probe more nuanced changes in root distributions today in comparison to past and future scenarios, as land cover types undergo change. In contrast, use of LUH2 would limit our exploration of past and future rooting depth changes by requiring the use of a coarser land cover classification scheme. Use of the GLC2000 data set is therefore important for understanding the degree of human influence on rooting systems in multiple forest types particularly in boreal and tropical regions, both of which are undergoing rapid changes (Ellis et al., 2010; Hurtt et al., 2020) and exhibit distinct rooting patterns beyond those applicable across the successional stages emphasized by LUH2.

To assess potential effects of global-scale perturbations projected by the year 2100 on rooting depth distributions, we examined multiple land cover projections from the Intergovernmental Panel on Climate Change (IPCC). We developed projected vegetation classes for four Shared Socioeconomic Pathway (SSP) and Representative Concentrations Pathway (RCP) scenarios (SSP2 RCP4.5, SSP1 RCP2.6, SSP4 RCP6.0, and SSP5 RCP8.5) using spatial projections of gridded, 25 km resolution land covers for the year 2100 (Hurtt et al., 2011, 2020). For these projections, we used the LUH2 data set (Hurtt et al., 2020). Like all landcover projections, the LUH2 data makes assumptions that group land cover types into distinct classes. Though these groupings are different from classifications in the Ramankutty et al. (2010) and GLC2000 data sets, the LUH2 data represents the best available projections of future land cover classifications to date (Hurtt et al., 2020). We therefore opted to use LUH2 and align its land cover classification scheme as closely as possible with the other data sets used, as described below.

All maps—potential, contemporary, and future—were adjusted to the same resolution for comparison analyses using the Raster package in R (Hijmans et al., 2019, RStudio Team, 2017). When two maps were compared, both were adjusted to the resolution of the coarsest map. This resulted in maps at a 9 km resolution for comparisons of contemporary and potential vegetation and 25 km resolution for comparison of contemporary and future vegetation.

To match the land cover classifications used in potential and contemporary vegetation maps to biome classifications for which we have rooting depth equations, we modified estimated rooting depth distributions for several land covers based on findings from region-specific literature. For example, potential land cover data sets combine both polar and mid-latitude deserts into a single desert category based on hydrologic regimes, yet rooting depths in polar deserts are often constrained by permafrost. We thus separated these two desert regions, reassigning deserts in polar regions to the "tundra" classification above 60°N (T. Zhang et al., 2008). Further, in potential and contemporary vegetation data sets, we reassigned evergreen forest and mixed vegetation classes above 50°N to the "boreal" vegetation classification given previously generated vegetation maps of northern region forests (Brandt et al., 2013; Price et al., 2013), and also assigned herbaceous and shrubland classes above 60°N to the class "tundra" because these regions exhibit low stature vegetation and lie in previously described tundra areas (T. Zhang et al., 2008). To generate maps of rooting depth, we gave potential vegetation above 60°N that was previously assigned to the polar desert class a rooting depth specific to permafrost-underlain regions, where roots

Table 2
Mean Global Rooting Depth Metrics With 95% Confidence Intervals for Potential and Contemporary Land Cover Distributions Under Two Scenarios of User Assumptions

Metric	Potential mean rooting depth (m, 95% CI)	Contemporary mean rooting depth (m, 95% CI)	Change from potential (cm)
D99 (Desert excluded)	1.50 (±0.001)	1.41 ($\pm 1 \times 10^{-4}$)	−8.15 (5.4%)
D95 (Desert excluded)	0.88 ($\pm 6 \times 10^{-4}$)	0.82 ($\pm 6 \times 10^{-5}$)	−4.93 (5.6%)
D50 (Desert excluded)	0.07 ($\pm 7 \times 10^{-5}$)	0.057 ($\pm 8 \times 10^{-6}$)	−1.45 (20.7%)
D99 (Desert roots set to 0 m)	1.35 ($\pm 1.1 \times 10^{-3}$)	1.22 ($\pm 1 \times 10^{-4}$)	−14.7 (10.9%)
D95 (Desert roots set to 0 m)	0.79 ($\pm 6 \times 10^{-4}$)	0.72 ($\pm 7 \times 10^{-5}$)	−11.1 (14.1%)
D50 (Desert roots set to 0 m)	0.066 ($\pm 7 \times 10^{-5}$)	0.05 ($\pm 7 \times 10^{-6}$)	−1.7 (25.8%)

Note. The third column displays the difference in cm between potential and contemporary root distributions and the percent change in parentheses. The first three rows indicate global means excluding true desert regions. The second three rows include true deserts in calculations of global mean rooting depth metrics but set roots in those systems to a value of zero (see Methods text for details).

typically do not penetrate deeper than 30 cm and 50% of root biomass is typically found within 10 cm (W. D. Billings et al., 1977; Boike et al., 2018; Keuper et al., 2020; T. Zhang et al., 2008). For contemporary rooting depth maps, regions above 60°N were all assigned to either a permafrost underlain tundra class or boreal class, which reflect recent measurements in FRED and NEON data sets. Finally, because many remote sensing-based studies of regional ecosystem fluxes omit large, lower latitude desert regions from their analyses due to the lack of quantifiable ecosystem productivity in these systems (M. Zhao et al., 2005), we omitted mid-latitude deserts from rooting depth averages reported in the main text. Instead, we present rooting depth metrics that incorporate the potential contribution of these mid-latitude deserts to global root averages in Table 2. Comparison of these results with those reported in the text reveal an inflated influence of mid-latitude desert rooting depth estimates on global averages that likely does not represent reality due to the low density of plants in true deserts (Whitford & Duval, 2019). Ice-covered regions were also omitted from the analyses.

We also made some modifications to rooting depth values for projections of the future scenarios due to the distinct land cover classification scheme of the LUH2 data sets. The LUH2 data sets designate land cover classes more coarsely than either GLC2000 or potential vegetation data sets, delineating primary and secondary forest and non-forested regions, five agricultural classes, pastureland, rangeland, and urban regions (Hurtt et al., 2020). We assigned a rooting depth equation derived from agricultural croplands in the FRED and NEON data sets to all five agricultural classes in the LUH2 data set. For secondary non-forests, pastures, and rangelands we assigned rooting depth equations representing herbaceous and grassland systems in the FRED and NEON data sets. Because most secondary forests in these scenarios were in the boreal region, we assigned secondary forests the average root depth value (107.5 cm) of mixed forests (130 cm) and boreal forests (85 cm). Primary forests were assigned depth values generated from the average of all forest classes in the contemporary data set, and primary non-forests were assigned depths generated by averaging contemporary grassland and shrubland classes. Reflecting anticipated warming and large projected losses of permafrost in the northern hemisphere (Lawrence & Slater, 2005), rooting depths assigned in all future scenarios removed permafrost constraints.

Using the R raster package (Hijmans et al., 2019; RStudio Team, 2017), we assigned rooting depth values to each land cover classification of the potential, contemporary, and projected vegetation maps, and calculated global means of each depth metric. After determining the differences in rooting depths across scenarios, we examined the spatial extent of depth changes to determine differences in rooted volume across scenarios. We then compared metrics across time using 95% confidence intervals of the mean estimates of global rooting depth metrics. Estimates of rooting depth reflect measurement uncertainty, particularly at deeper depths (Schenk & Jackson, 2002b). However, because we applied root measurements in a consistent manner across potential, contemporary, and projected vegetation maps, we can assess relative differences of root distributions across these different scenarios. We performed correlated *t*-tests on pairs of rasterized parameter estimate maps (i.e., potential vs. contemporary and contemporary vs. projected) to determine whether differences between these estimated rooting depth metrics are significantly different from zero. Data were assessed to ensure they met the assumptions of correlated *t*-tests, including independence of observations, normal distribution of the dependent variable, and no dependent

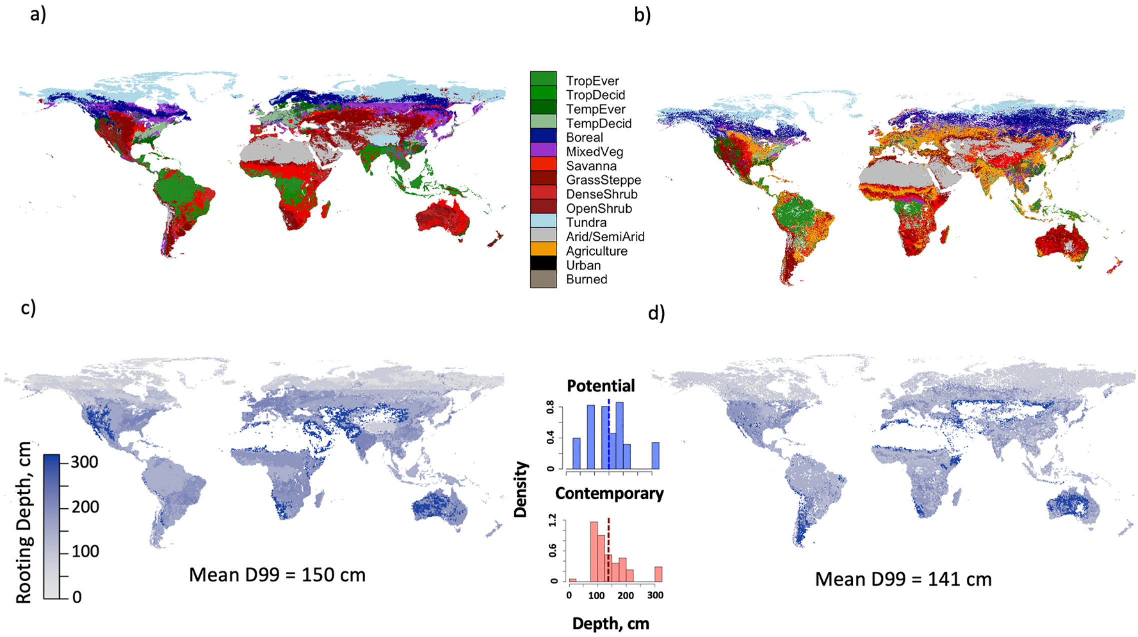

Figure 1. Land cover and associated rooting depths under potential vegetation in the absence of human influence (left column) and current vegetation distribution (right column). (a) Potential vegetation cover in the absence of human activity (Ramankutty et al., 2010). (b) Contemporary land cover distribution from Global Land Cover 2000 (GLC2000), modified to correspond to potential vegetation land cover classifications. (c, d) Depict depths by which 99% of rooting biomass occurs (D99) under (c) potential and (d) contemporary land cover types. Mean values are rounded to the nearest cm, although more precise mean values were used to determine the average difference between panels (c and d), generating the ~8 cm difference stated above. Inset histogram displays rooting depth distributions. Blue histogram reflects potential vegetation data, and red histogram contemporary land cover. Dashed vertical lines represent means. Appearance of a distinct color change from dark blue to light gray in Asia and Canada at 60°N in panel (c) is an artifact of restricting maximum rooting depth assignments to reflect well-characterized limitations imposed by frozen soils; this distinction is less evident in contemporary D99 maps (d) because of the higher spatial resolution of the GLC2000 data set. Appearance of a distinct line at 50°N, especially evident in panel (d), reflects reassignment of mixed forests to the boreal forest class above this latitude (Brandt et al., 2013; Price et al., 2013). See text for reassignment details. While these lines are unrealistic, it reflects our current knowledge about root depths in northern regions and demonstrates the remaining need for additional work combining cryospheric studies and soil science to characterize root systems at relatively high latitudes.

variable outliers. Where data did not meet the assumptions, we ran Wilcoxon tests on the data set pairs to assess differences in root depth metrics and reported the V-statistics and associated *P*-values generated from those tests.

3. Results

Comparisons of potential and contemporary land cover (Figures 1a and 1b) and their estimated rooting depths (Figures 1c and 1d) suggest that spatially averaged, global values of D99 are the net result of two competing phenomena: shallowing of roots in agricultural regions and deepening of roots in regions experiencing woody encroachment. Specifically, the global average D99 is 5% shallower (8 cm) under contemporary land cover distributions than if potential vegetation cover types covered Earth's terrestrial surface ($V = 7.11 \times 10^{11}$, Wilcoxon $P < 0.0001$; Figures 1c and 1d, Table 2). This represents a loss of rooted volume of ~11,600 km^3. Values of D95 for contemporary land cover also express similar trends of root shallowing (6% or 5 cm, loss of ~7,250 km^3; $V = 7.06 \times 10^{11}$, Wilcoxon $P < 0.0001$; Figures S1a and S1b in Supporting Information S1). Depth to 50% root biomass (D50), by comparison, displays relatively greater variation between contemporary and potential land cover, becoming 21% shallower (1.5 cm, 1,300 km^3, $V = 5.32 \times 10^{11}$, Wilcoxon $P < 0.0001$) on average (Figure S2 in Supporting Information S1).

Agricultural land conversion serves as a dominant influence on these global trends (Figures 2 and 3, Figure S3 in Supporting Information S1). Regions where roots experienced shallowing during the shift from potential to contemporary land cover are on average 43 cm shallower (23%) than potential vegetation distributions and represent ~48% of Earth's land surface (7.01×10^7 km^2; Figure 3). Thirty three percent of shallowing regions (2.28×10^7 km^2) experience agricultural expansion. In these areas, perennial vegetation has been converted to agricultural land (defined here as annual crops and managed pasture), such that D99 has decreased by as much

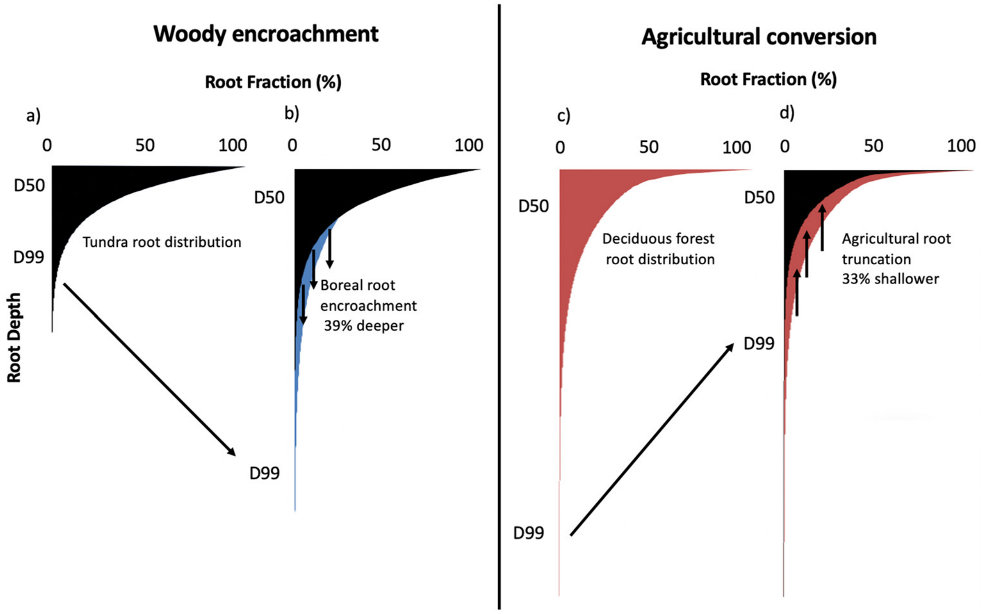

Figure 2. (a, b) Representation of rooting depth elongation due to woody encroachment and (c, d) rooting depth truncation due to agricultural expansion, generated using data from the Fine Root Ecology Database and National Ecological Observatory Network database for tundra and boreal biomes in panels (a and b) and deciduous forests and agricultural lands in panels (c and d). Blue region in panel (b) demonstrates the belowground increase in roots displayed in blue in Figure 3. Red region in panel (d) exemplifies loss of rooting system depth for red regions in Figure 3.

as 33% (60 cm). The remaining shallowing occurs primarily in some northern and arid regions, possibly due to increased disturbance (Harsch et al., 2009; Hurtt et al., 2020; Wang et al., 2019), urbanization (Day et al., 2010; Lindsey & Bassuk, 1992), and desertification (Lal, 2001; H. L. Zhao et al., 2005). Where woody encroachment is evident in contemporary land cover data, such as in African, Australian and South American savannas (Stevens et al., 2017) as well as tundra regions (Wang et al., 2019), D99 increased relative to potential vegetation by up to 39% (38 cm; note that here we use the phrase "woody encroachment" to refer to both shrubland encroachment into grasslands, and forest encroachment into Arctic and alpine tundra). This result may overestimate current rooting depths if the rooting depths we assigned were derived from well-established, mature systems, given that

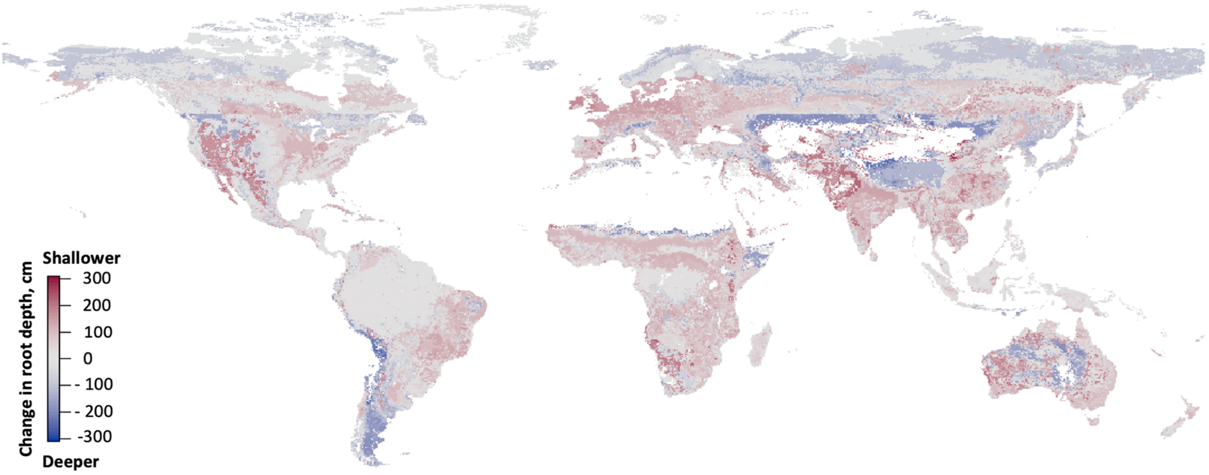

Figure 3. Mapped differences between potential and contemporary rooting depths. Red cells indicate a decrease in the depth to 99% of rooting biomass (D99) while blue cells indicate an increase in D99 resulting from contemporary vegetation distributions. Appearance of a distinct color change from dark blue to light gray and red in Asia and Canada at 50°N reflects reassignment of mixed forests to the boreal forest class above this latitude (Brandt et al., 2013; Price et al., 2013). See Figure 1 caption for additional explanation.

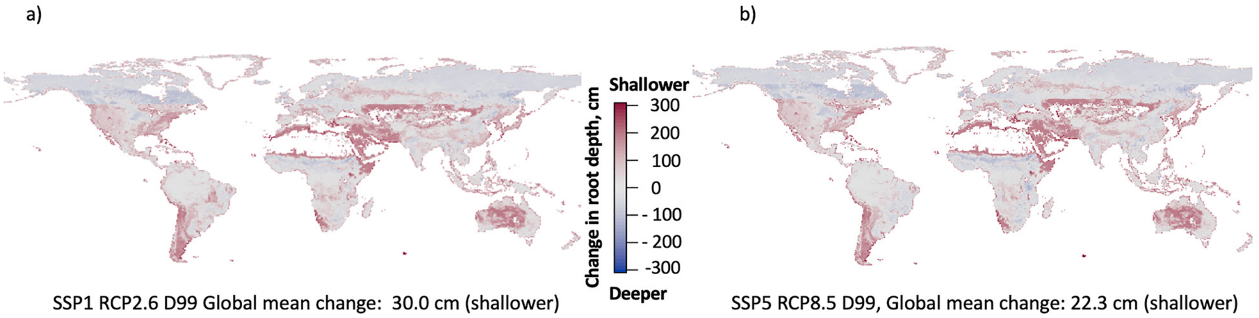

Figure 4. Projected changes of depth to 99% rooting biomass (D99) by the year 2100 relative to contemporary rooting depth distributions. Projections are based on land use and emissions changes under two combinations of Shared Socioeconomic Pathways and Representative Concentration Pathways, (a) SSP1 RCP2.6 and (b) SSP5 RCP8.5. These two maps represent the scenario of greatest and least projected change, respectively. Red colors indicate root depth truncation or shallowing, and blue indicates elongation or deepening. Appearance of a distinct color change from dark red to light gray in Asia at 50°N reflects reassignment of mixed forests to the boreal forest class above this latitude (Brandt et al., 2013; Price et al., 2013, see text for reassignment details).

woody plants in recently encroached systems likely have not yet achieved such depths (S. A. Billings et al., 2018; Stevens et al., 2017). Despite this possible overestimation, root deepening via woody encroachment does not overcome the effect of root shallowing, in part because of the smaller total fraction of Earth's terrestrial surface experiencing woody encroachment (35% or 5.06×10^7 km^2).

Changes to rooting distributions by the year 2100 vary under different potential scenarios of climate and land use change as well as different societal responses to those changes. The SSP scenarios examined here represent global narratives including a scenario with few roadblocks to both mitigation of and adaptation to climate change (SSP1), moderate challenges to mitigation and adaptation (SSP2), a scenario of social inequality with many challenges to adaptation but few for mitigation (SSP4), and a strategy of fossil fuel dependence with many challenges to mitigation but few to social adaptation (SSP 5, Riahi et al., 2017). These narratives are used in conjunction with projected land use and climate (RCP) scenarios to model future societal and ecological conditions, on which we rely for our rooting distribution estimates.

Projections for the year 2100 suggest that the scenario with the largest cropland increase and relatively low radiative forcing enhancement from current levels (SSP1 RCP2.6, Figure 4a) generates the most extreme reduction of deep roots, truncating values of D99 by 30 cm ($V = 2.16 \times 10^{10}$, Wilcoxon $P < 0.0001$). This represents over three times as much shallowing as that which occurred in the previous ~10,000 years (Gupta, 2004) of anthropogenic land cover change. The smallest shallowing of D99, 22.3 cm ($V = 1.77 \times 10^{10}$, Wilcoxon $P < 0.0001$), occurs under the highest emissions scenario (SSP5 RCP8.5, Figure 4b). As a result, the future rooted volume will be reduced by ~32,400 to ~43,500 km^3.

Values of D50 for the year 2100 experience a shallowing of 3 cm across all assessed scenarios ($V = 2.47 \times 10^{10}$, Wilcoxon $P < 0.0001$; Figure S5 in Supporting Information S1), representing a loss of rooted soil volume of ~4,400 km^3. Though small relative to changes in deep root systems, this D50 shallowing is double that occurring during the previous ~10,000 years (Gupta, 2004) of anthropogenic land conversion (Figure S6 in Supporting Information S1).

4. Discussion

Our estimates of rooting depth and rooted soil volume suggest that root biomass throughout Earth's soils, even deep in the subsurface, has been and will continue to be vulnerable to human influence (Figures 2–4). Although maximum rooting depths are poorly characterized and are likely deeper than is typically appreciated (Fan et al., 2017; Maeght et al., 2013; Pierret et al., 2016), we demonstrate that the depths to which most or half of all rooting biomass reach (i.e., D99, D95, and D50) currently reflect human-induced, global-scale changes in land cover (Figure 1). We further demonstrate that root shallowing in agricultural regions (~60 cm across 2.28×10^7 km^2 for D99) and root deepening in regions experiencing woody encroachment (~38 cm across 5.06×10^7 km^2 for D99) result in a globally averaged estimate of net 8 cm shallowing of D99 values. This represents a net loss of ~11,600 km^3 of rooted volume to date in the Anthropocene.

In the future, rooting depth scenarios might be expected to reflect the elongating effects of woody encroachment on D99, D95, D50, and rooted soil volume to a yet greater extent, given the apparent role of rising atmospheric CO_2 concentrations in promoting woody encroachment (Devine et al., 2017). However, the four IPCC scenarios explored here suggest that by 2100, globally averaged rooting distributions may become yet shallower relative to contemporary rooting depths (Figure 4, Figures S4 and S5 in Supporting Information S1). Reduced rooting depths by 2100 are driven by substantial root shallowing across regions of Africa, the Middle East, Asia and Australia (Figure 4), where deeply rooted shrublands are projected to transition to herbaceous grasslands and where there is continued agricultural and pasture expansion (Hurtt et al., 2020). In both cases, a more shallowly rooted, herbaceous vegetation cover replaces the current, more deeply rooted vegetation, either as a consequence of shifting climate or land cover change. These transitions result in a nearly three-fold decrease in our two relatively deep rooting depth metrics (D95 and D99) and a two-fold decrease in D50 by the year 2100, suggesting that roots across Earth's subsurface will be subject to extensive additional anthropogenic changes in the future and that the deepest roots appear especially vulnerable to loss.

These future rooting depth trends reflect a great deal of uncertainty regarding impending land cover transitions in multiple regions of the globe. Future projections suggest that multiple regions may experience rooting depth trends that are the inverse of what they have already experienced in the Anthropocene, particularly in Africa and South America (compare Figures 3 and 4, Figures S5 and S6 in Supporting Information S1). These opposing patterns over time point toward the uncertainty of future vegetation cover in regions that are currently understudied and lack extensive data sets (Iversen et al., 2021; NEON, 2021). Many of these regions are anticipated to experience shifts in land uses as parts of South America and Africa experience fire suppression as well as agricultural abandonment as a consequence of a changing climate; both of these phenomena promote woody encroachment (Rosan et al., 2019; Stevens et al., 2017). As these transitions occur, other agricultural regions likely will need to be established. Changes in woody versus agricultural landcover are also likely to drive changes in regional water availability (Eshleman, 2004; Huxman et al., 2005), further complicating projections of vegetation rooting depths. The uncertainty surrounding these land cover transitions is inherently represented in future projections (Figure 4) through the reduction in the number of land cover classifications in the LUH2 data.

The global patterns we observed in both Figures 3 and 4 are strongly driven as well by trends in boreal and tundra regions, where mapped scenarios suggest patterns of both root shallowing and deepening (Figures 2, 3 and 4, Figures S5 and S6 in Supporting Information S1), and thus uncertainty about temporal dynamics of roots. While some studies hint that roots may deepen as soils currently designated as permafrost thaw (Harsch et al., 2009; Malhotra et al., 2020; Sistla et al., 2013; Wang et al., 2019), others suggest that long term changes in snowpack will produce extremes in soil freeze/thaw cycles that will reduce vegetation survival and rooting depth (Blume-Werry et al., 2016; Groffman et al., 2001). Most of our scenarios suggest deepening of D99 and D95 in northern regions over time, lending support to findings of deepening roots as permafrost thaws (Figures 3 and 4). However, contemporary D50 maps demonstrate shallowing relative to potential vegetation in these same regions (Figure S6 in Supporting Information S1), implying that roots in boreal and tundra regions may be experiencing a more general change in the curvature of rooting depth distributions instead of consistently deepening over time. These observations support findings of altered root distributions where permafrost experiences altered seasonal cycles, such as longer growing seasons (Blume-Werry et al., 2019). Data describing rooting depths in these regions are more limited than in many other ecoregions (Iversen et al., 2021; NEON, 2021), resulting in less certainty about future rooting depths in areas currently underlain by permafrost, and likely leading to the varied findings in our maps.

In maps of D50, some regions, especially in the Arctic, also suggest that rooting depth distributions are undergoing a general change in curvature as a response to anthropogenic change. Shallowing D50 values are evident across potential, contemporary, and future scenarios (Figures S5 and S6 in Supporting Information S1), and these D50 metrics appear to become shallower to a greater extent between contemporary and future (i.e., 2100) scenarios compared to the D50 changes that appear to have taken place already. This finding suggests that anthropogenically induced changes in the root abundances of surficial soil horizons within the coming decades will likely exceed those of the past several millennia. Shallowing D50 values occur alongside both shallowing and deepening of D99 and D95 values in different regions of the globe, hinting of a trend of reshaped root distributions. This is especially apparent in northern regions where D99 and D95 increase but D50 decreases in contemporary maps. Recently collected data from the FRED and NEON databases make this change in curvature more apparent than some of the individual data sets on which they build (Canadell et al., 1996; Schenk & Jackson, 2005;

Zeng, 2001), highlighting the importance of continuing to characterize the distribution of roots across the globe for understanding both the depths to which roots proliferate, and the shape of their depth distributions. These most recent advances in FRED and NEON D50 data emphasize that even relatively shallow soil horizons (i.e., those expressed by D50), where both natural and agricultural species root, will undergo redistribution in the coming decades, with roots shifting the curvature of their distributions in response to regional changes in land use and climate.

There are myriad feasible consequences of altered rooting depth distributions for biogeochemical and hydrological fluxes that prompt intriguing hypotheses. For example, roots beneath the zone of maximum rooting density are attributed to developing the soils that mantle Earth's surface, so much so that they are referred to as the planet's biotic weathering front, where life—roots and microbes—promotes the dissolution of bedrock (Berner et al., 2003; Brantley et al., 2012; Dontsova et al., 2020; Pawlik, 2013; Richter & Markewitz, 1995). Results from the current study suggest that these biotic weathering forces in many temperate and tropical regions do not reach as deeply into the regolith as they did prior to human influence (Figure 3), prompting the hypothesis that the intensity of biotic processes responsible for soil formation at the bottom of the soil profile have declined in the Anthropocene. Further, a smaller volume of soil explored by rooting systems of some regions prompts the hypothesis that soil water storage capacity, nutrient replenishment, and solute losses from freshly weathered material have similarly declined (Berner, 1998; Nepstad et al., 1994; Swank, 1986). In contrast, in regions where root deepening is occurring, we might expect increases in the influences of biotic weathering deep in the soil profile.

Our findings serve as a useful starting point for refining and probing these hypotheses. Although this study makes a first attempt at measuring the extent of anthropogenically induced changes in rooting systems at a global scale, it also points to key knowledge gaps. The uncertainty embedded in the projections reported here highlights the substantial need for better quantification of rooting distributions in diverse biomes, particularly for deep roots, and how we quantify their future dynamics. Few analyses exist describing how individual plant root distributions change as climate changes, leaving uncertainty in our analyses as to whether these rooting depth functions are the best representations for future scenarios. Further, existing vegetation classification schemes are not consistent across mapped projections of potential, contemporary, and future land covers, forcing difficult decisions about which data sets are best for comparisons across timescales. These incongruencies can result in estimated changes in regionally specific rooting depths that contrast with current knowledge about anticipated vegetation transitions. In the current study, place-based literature provided invaluable constraints on rooting depths for many ecosystems, but rooting depths in many regions of Asia, Australia, and Africa remain especially understudied. A lack of data describing contemporary rooting depth distributions in northern regions and estimates of vegetative cover and associated rooting depths in the future also emerged as important knowledge gaps (see especially Figure 1c). Additionally, there is a great deal of uncertainty in estimates of the deepest roots worldwide (Schenk & Jackson, 2002a, 2002b; Tumber-Dávila et al., 2022). Indeed, many of the deepest roots have been observed incidentally, suggesting that we have not yet sampled roots to their fullest extent (Fan et al., 2017). Our study represents a first step towards analyzing human influence in root distributions across the globe, but the continual emergence of new root and land cover data sets means that novel analyses can emerge that may improve the estimates reported here, especially for future rooting depth scenarios.

We suggest that CZ research combining empirical and modeling approaches could help focus future research efforts on these critical gaps. First, empirical studies clarifying the ways in which global rooting distributions are changing could help with the development of decadal- to centennial-scale responses of extant ecosystems to climate change. Specifically, the leveraging of on-going climate experiments (e.g., Caplan et al., 2019), naturally existing climatic gradients (e.g., Ziegler et al., 2017), and chronosequences (e.g., S. A. Billings et al., 2018) could demonstrate how rooting depths respond to global changes to temperature and precipitation, as well as reveal quantitative relationships between rooting depth distributions and their impacts on soil formation processes, especially at depth. Focusing these studies in regions with relatively less research will improve our understanding of root-induced processes at the global scale.

Additionally, empirical and modeling studies examining the biogeochemical consequences of rooting depth change are critical. More extensive work either directly measuring subsurface biogeochemical fluxes as they respond to changes in rooting depth distributions, or modeling of biogeochemical processes that project such fluxes, will be invaluable for generating input parameters representing subsurface biogeochemical fluxes in Earth system models (ESMs). Because terrestrial vegetation exerts a fundamental global control on land-atmosphere exchanges of water, energy, C, and other elements, improved representation of rooting distributions in global land models such as the CLM (Lawrence et al., 2019) is of critical importance. This is particularly true as more sophisticated aboveground and belowground vegetation and biogeochemical processes are incorporated into these models (e.g., Fisher et al., 2017; Kennedy et al., 2019; Tang et al., 2013). With improved fidelity to biophysical and biogeochemical processes comes the corresponding opportunity to explore the potential consequences of changes in global rooting depths on land-atmosphere exchanges of water, energy, and C, and the large-scale ramifications that changes in rooting depths have for climate. Well-designed numerical experiments could elucidate the relative impacts of exogenous (e.g., agricultural conversion, woody encroachment) versus endogenous (e.g., water and nutrient limitation) drivers of changes in rooting depths on terrestrial cycling of water, energy, and C. These modeling efforts can feedback into empirical studies by illuminating regions where rooting depth knowledge is not sufficient and by pointing toward parameters requiring more explicit definition to improve future predictions. Such integrative studies would strengthen the nascent interactions between ESM and CZ communities to address pressing questions about global change that cannot be solved without substantial input from both disciplines (National Academy of Sciences, Engineering and Medicine, 2020). The improved representation of changing rooting depth distributions can link these research communities, representing a critical collaboration for understanding current and future functioning of Earth's CZ and climate.

5. Conclusion

Losses of relatively deep roots suggest an overlooked and subtle mechanism by which humans alter soil and ecosystem development. It is well established that humans accelerate losses of surface soil via erosion, which can result in a thinning of Earth's skin of soil (Wilkinson & McElroy, 2007). In contrast, altered rooting depths deep in soil profiles and associated shifts in rooted volume due to anthropogenic land use and climate change suggest a means by which human actions may govern soil thickness near the bottom of soil profiles. These shifts in rooting distributions support the idea that signals of the Anthropocene penetrate deeply into the subsurface even in naturally occurring elemental cycles (S. A. Billings et al., 2018). Indications of widespread human transformation of land cover across millennia (Edgeworth et al., 2015) imply that reductions in deep root abundances have been underway in multiple regions for a similar length of time. Though improving process representation in land models continues apace (Fisher & Koven, 2020), the representation of rooting depth distributions remains largely a static function of only PFT (cf. Drewniak, 2019). We present an opportunity to advance a dynamic representation of roots in land models by better constraining how rooting depth distributions vary with global change, as well as by identifying specific ecological processes particularly suited to better quantifying the dynamics of rooting, both past and future (e.g., regions of woody encroachment). Co-designed modeling, field and lab studies are needed to help clarify the consequences of rooting depth changes for contemporary and future CZ development. Such studies can elucidate the ways in which surficial anthropogenic activities radiate deep within Earth's subsurface, altering the developmental pace and character of Earth's CZ.

Data Availability Statement

The original GLC2000 data set modified for this analysis can be accessed at https://forobs.jrc.ec.europa.eu/products/glc2000/products.php. The unmodified potential vegetation data can be found at https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=961. All future land use projections can be accessed through the Landuse Harmonization data portal at http://luh.umd.edu/data.shtml. Rasters modified as described in Methods for contemporary and potential land cover, along with root depth assignment .csv files and code are available on Zenodo (https://doi.org/10.5281/zenodo.6877815).

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