Global-scale shifts in Anthropocene rooting depths 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.

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 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 datasets 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 datasets 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 (Brantley et al., 2017; Hasenmueller et al., 2017; Austin et al., 2018), release of mineral-bound nutrients (Jobbagy & Jackson, 2001; Hasenmueller et al., 2017; Austin et al., 2018), subsoil water flow paths and residence time (Zhang et al., 2015; Fan et al., 2017) , and deep C fluxes (Richter and Markewitz, 1995; Schenk, 2007; Pierret et al., 2016; Fan et al., 2017; Billings et al., 2018). The dominant drivers of rooting distributions are plant functional type (PFT, Jackson et al., 1996) and variation in water availability (Schenk, 2007; Nippert et al., 2007; Fan et al., 2017), both of which are changing in response to anthropogenic land cover conversion, as well as altered atmospheric composition and concomitant changes in climate (Edgeworth et al., 2001; Cramer et al., 2010; 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 root depth (Maeght et al., 2013; Pierret et al., 2016) and a growing recognition of the great depths to which roots can penetrate (Stone & Kalisz, 1991; Nepstad et al., 1994; Canadell et al., 1996; Schenk & Jackson, 2002a; Schenk & Jackson et al., 2002b; Fan et al., 2017), 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 (McCormack et al., 2015; Iversen et al., 2017; McCormack et al., 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 (Canadell et al., 1996; DuPont et al., 2014, Billings et al., 2018). 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 (Ramankutty & Foley, 1999; Ellis et al., 2010), a process that induces mortality of deep perennial root systems and replaces them with relatively shallow roots (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 (Jackson et al., 1996; Harsch et al., 2009; 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 & Heimann, 1998; Kleidon, 2003) or, separately, land cover changes in specific regions of interest (Jaramillo et al., 2003; Hertel et al., 2009; DuPont et al., 2010). 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 root depths (Schenk & Jackson, 2002a; Schenk & Jackson, 2002b; Schenk & Jackson, 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 (Stone & Kalisz 1991; Schenk & Jackson, 2002a; Schenk & Jackson, 2005; Maeght et al., 2013; Pierret et al., 2016; Fan et al., 2017) though the true maximum rooting depth may never be known in some systems (Kleidon, 2003; Pierret et al., 2016; Fan et al., 2017). 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 root 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.

2 Materials and Methods

We estimated the volume of soil influenced by human-promoted modification of root 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 datasets. As a part of this process, we examined multiple datasets that, in theory, could help us estimate how humans modify rooting distributions. First, we offer a description of selected datasets followed by an explanation of our selection from those available.

We used satellite-derived, potential vegetation representing 15 land cover classes (Haxeltine & Prentice, 1996) and their potential global distribution in the absence of human activity at a 5-minute spatial resolution (Ramankutty & Foley, 1999). We compared potential vegetation classes to contemporary land cover as defined by the Global Land Cover 2000 (GLC2000) dataset (Bartolome & Belward, 2005). GLC2000 represents 22 land cover types, 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 (Billings et al., 1997; Boike et al., 2018). These efforts resulted in 25 distinct land cover types for which rooting depths were assigned. Projected vegetation classes were similarly developed for four Shared Socioeconomic Pathway (SSP) and Representative Concentrations Pathway (RCP) scenarios using spatial projections of gridded, 0.5° x 0.5° resolution land covers for the year 2100 (Hurtt et al., 2011). All maps were adjusted to the same resolution for analyses using the Raster package in R (Hijmans et al., 2019).

For all vegetation datasets 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 datasets have recently expanded rooting depth knowledge beyond earlier works (e.g., Jackson et al., 1996; Zeng, 2001; Schenk and Jackson, 2005) by accumulating new datapoints detailing root trait and distribution patterns in diverse biomes (Krasowski et al., 2018; Montagnoli et al., 2018; Lozanova et al., 2019; Andrade et al., 2020). However, to date no one has harmonized and analyzed these datasets 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 datasets 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 GLC2000 land cover map. Each set of points was checked using Google Earth 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 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 1200 times as recommended by Lander (2013). 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.

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 datasets 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 (Zhang et al., 2008). Further, in potential and contemporary vegetation datasets, 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 (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 typically do not penetrate deeper than 30 cm and 50% of root biomass is typically found within 10 cm (Billings et al., 1997; Zhang et al., 2008; Boike et al., 2018; Keuper et al. 2020). 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 datasets. 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 (Zhao et al., 2005b), 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 1 of the Supporting Information. 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.

To assess potential effects of global-scale perturbations projected by the year 2100 on rooting depth distributions, we examined multiple SSP and RCP land cover projections from the Intergovernmental Panel on Climate Change (IPCC). Projected vegetation classes were developed for 4 SSP RCP scenarios (SSP2 RCP4.5, SSP1 RCP2.6, SSP4 RCP6.0, SSP5 RCP8.5). Landuse Harmonization datasets designate land cover classes more coarsely than either GLC2000 or potential vegetation datasets, delineating primary and secondary forest regions, primary and secondary non-forest regions, five agricultural classes, pastureland, rangeland, and urban regions (Hurtt et al., 2011). We assigned a rooting depth equation derived from agricultural croplands in the FRED and NEON datasets to all five agricultural classes in the Landuse Harmonization dataset. For secondary non-forests, pastures, and rangelands we assigned rooting depth equations representing herbaceous and grassland systems in the FRED and NEON datasets. 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 dataset, 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.

We examined multiple datasets describing contemporary global root distributions (Schenk and Jackson, 2009) and landcover scenarios across time (Hurtt et al., 2011) as potential candidates for addressing the degree to which humans modify the rooted volume of Earth's subsurface. Such datasets have been pivotal in developing our understanding of and appreciation for the depths of deep roots (Schenk & Jackson, 2005; Schenk, 2005; Pierret et al., 2016), and the Landuse Harmonization (LUH) scenarios represent the best available data for future land cover classifications to date (Hurtt et al., 2020). However, the Schenk and Jackson dataset does not describe roots in agricultural lands, ploughed and fertilized lands, or wetlands (Schenk and Jackson, 2005), and is not divided into land cover classes that can be integrated with datasets describing potential and future land cover scenarios. The LUH scenarios combine land cover classes in ways that result in the loss of important nuances in root distribution estimates in past and contemporary scenarios. For example, all forest types in LUH scenarios are grouped into 'secondary' and 'primary' forest rather than more region-specific forest classifications (Hurtt et al., 2020). In contrast, employing the GLC2000 vegetation classes with rooting depths derived from FRED and NEON data, which include data from Jackson et al. (1996), permitted us to examine two key features of interest. First, this approach permitted incorporation of agricultural land cover classes — a feature that is absent in datasets featuring root distributions alone. Second, the Ramankutty and Foley (1999) dataset serves as the only spatially quantified representation of the potential land cover in the absence of human activity at a 5-minute resolution, allowing for detailed backcasting of estimates of human-induced changes to roots.

Using the R raster package (RStudio Team, 2017; Hijmans et al., 2019), 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 and 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 variable outliers. Where data did not meet the assumptions, we ran Wilcoxon tests on the dataset 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 b) and their estimated rooting depths (Figures 1c and d) 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 d, Table S1). 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 ~7250 km^3; $V = 7.06 \times 10^{11}$, Wilcoxon $P < 0.0001$; Figures S1a and b). Depth to 50% root biomass (D50), by comparison, displays relatively greater variation between contemporary and potential land cover, becoming 21% shallower (1.5 cm, 1300 km^3, $V = 5.32 \times 10^{11}$, Wilcoxon $P < 0.0001$) on average (Figure S2).

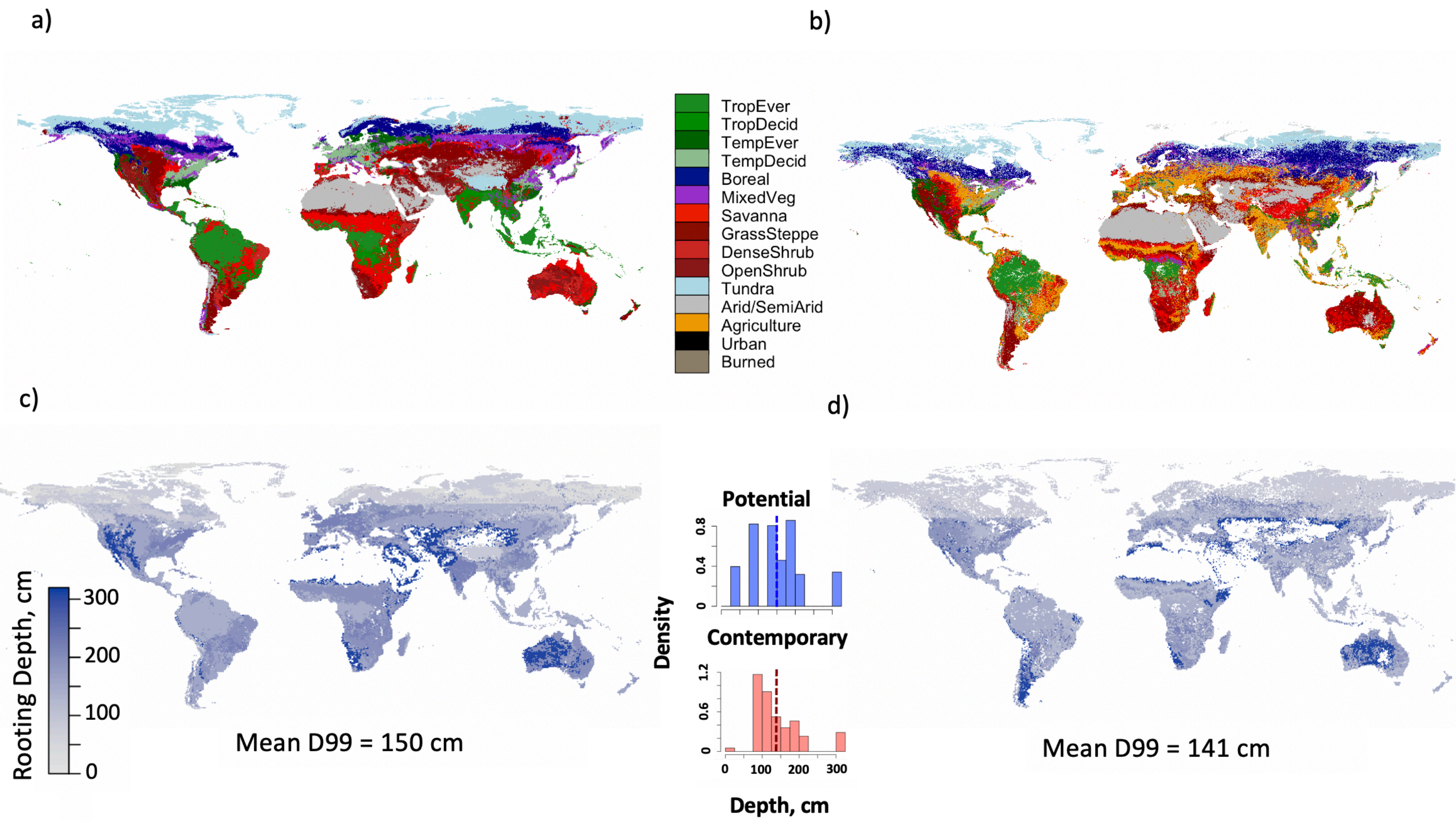

Figure 1. Land cover and associated rooting depths under potential vegetation in the absence of human influence (left column) and current vegetation distribution (right column). (a) Potential vegetation cover in the absence of

human activity (b) Contemporary land cover distribution from Global Land Cover 2000 (GLC2000), modified to correspond to potential vegetation land cover classifications. (c) and (d) depict depths by which 99% of rooting biomass occurs (D99) under potential (c) and contemporary (d) land cover types. 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 grey in Asia and Canada at 60°N in (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 dataset. Appearance of a distinct line at 50°N, especially evident in (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.

Agricultural land conversion serves as a dominant influence on these global trends (Figures 2 and 3). 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 x 10^7 ha; Fig. 3). Thirty three percent of shallowing regions (2.28 x 10^7 ha) 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 as 33% (60 cm). The remaining shallowing occurs primarily in some northern and arid regions, possibly due to increased disturbance (Harsch et al., 2009; Wang et al., 2020, Hurtt et al., 2020), urbanization (Lindsey & Bassuk, 1992; Day et al. 2010) and desertification (Lal, 2001, Zhao et al., 2005b). Where woody encroachment is evident in contemporary land cover data, 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 woody plants in recently encroached systems likely have not yet achieved such depths (Stevens et al., 2017; Billings et al., 2018). 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 x 10^7 ha).

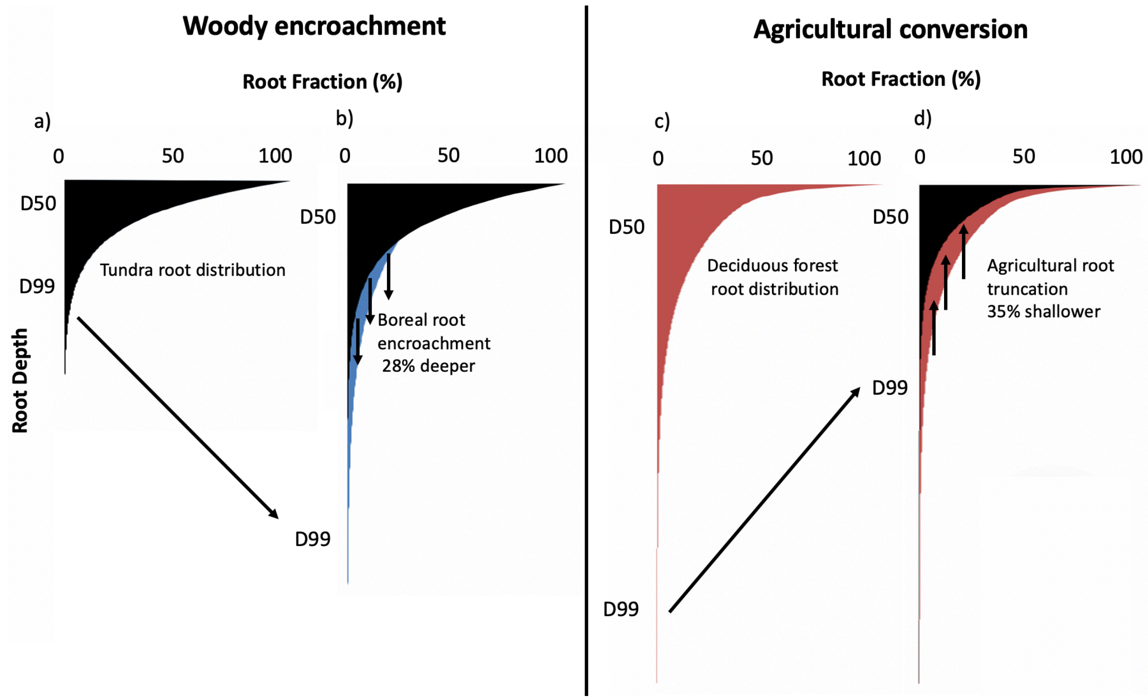

Figure 2. Representation of rooting depth elongation due to woody encroachment (a and b) and rooting depth truncation due to agricultural expansion (c and d). Blue region in B demonstrates the belowground increase in roots shown in blue in Figure 3. Red region in D exemplifies loss of rooting system depth for red regions in Figure 3.

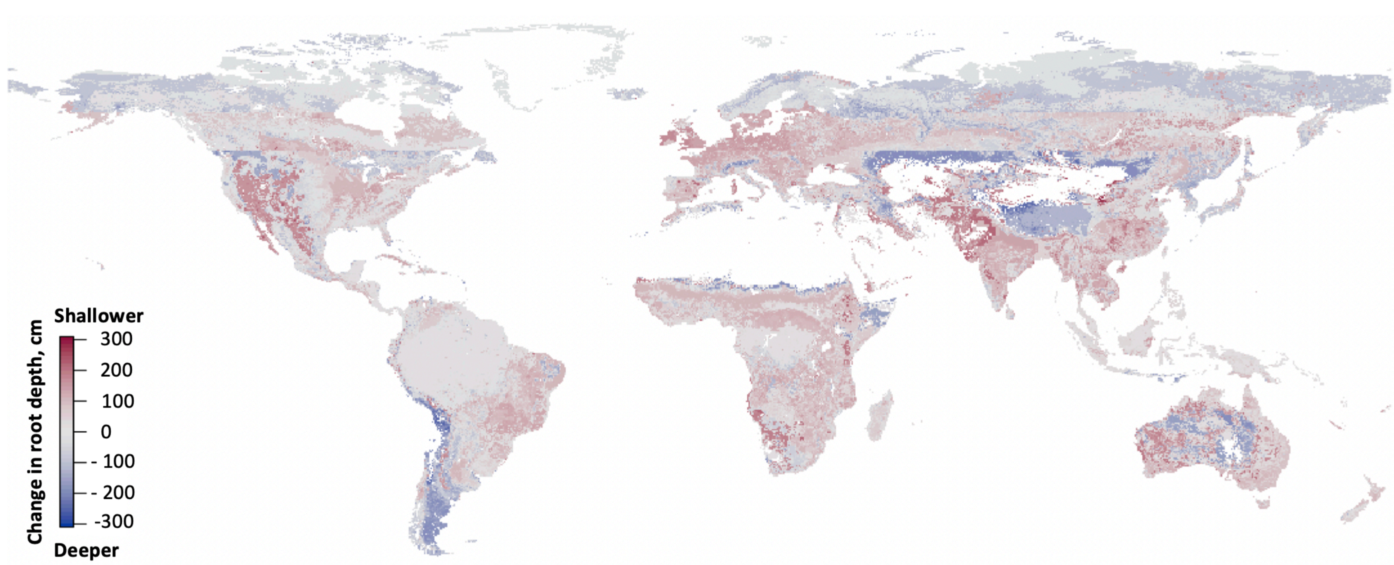

Figure 3. Mapped differences between potential and contemporary rooting depths. Red cells indicate a decrease in the depth to 99% of rooting biomass (D99) while blue cells indicate an increase in D99 resulting from contemporary vegetation distributions. Appearance of a distinct color change from dark blue to light grey 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.

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 x 10^{10}, Wilcoxon $P < 0.0001$). The smallest shallowing of D99, 22.3 cm (V = 1.77 x 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 km^3 to ~43,500 km^3.

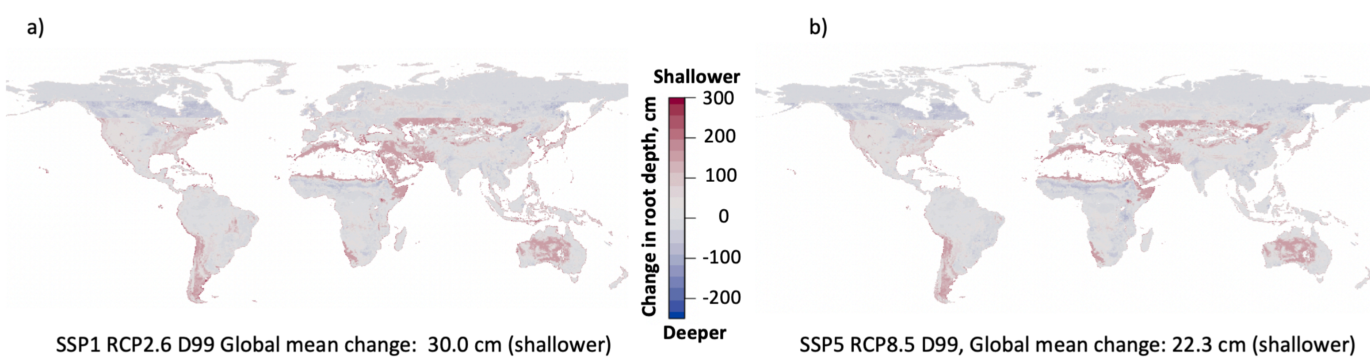

Figure 4. Projected changes of depth to 99% rooting biomass (D99) by the year 2100 relative to contemporary rooting depth distributions. Projections are based on land use and emissions changes under two combinations of Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCP), SSP1 RCP2.6 (a) and SSP5 RCP8.5 (b). 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 grey 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).

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), representing a loss of rooted soil volume of ~4400 km^3. Though small relative to changes in deep root systems, this D50 shallowing is double that occurring during the previous ~10,000 y (Gupta, 2004) of anthropogenic land conversion (Figure S6).

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, 3, 4). Although maximum rooting depths are poorly characterized and are likely deeper than is typically appreciated (Maeght et al., 2013; Pierret et al., 2016; Fan et al., 2017), 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 ha for D99) and root deepening in regions experiencing woody encroachment (~38 cm across 5.06×10^7 ha 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 (Figures 4, S4 and S5). Reduced rooting depths by 2100 are driven by substantial root shallowing across regions of Africa, the Middle East, Asia and Australia (Fig. 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.

The global patterns we observed are strongly driven by trends in boreal and tundra regions, where mapped scenarios suggest patterns of both root shallowing and deepening (Figs. 2, 4, S5, and S6), 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; Sistla et al., 2013; Malhotra et al., 2020; Wang et al., 2020), others suggest that long term changes in snowpack will produce extremes in soil freeze/thaw cycles that will reduce vegetation survival and rooting depth (Groffman et al., 2001; Blume-Werry et al., 2016). 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 (Figs. 3 and 4) . However, contemporary D50 maps demonstrate shallowing relative to potential vegetation in these same regions (Fig. S6), 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, additional regions 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 (Figs. 3, 4, S5 and S6), 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. Recently collected data from the FRED and NEON databases make this change in curvature more apparent than some of the individual datasets on which they build (Canadell et al., 1996; Zeng, 2001; Schenk and Jackson, 2005), 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 (Richter & Markewitz, 1995; Berner et al., 2003; Brantley et al., 2012; Pawlik, 2013; Dontsova et al., 2020). 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 (Swank, 1986; Nepstad et al., 1994; Berner, 1998). 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 formulating 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. One challenge to global root quantification is the lack of correspondence between potential, contemporary and future land cover classifications. These incongruencies sometimes 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 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 (Shenk & Jackson, 2002). 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).

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., 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 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 Community Land Model (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., Tang et al., 2013; Fisher et al., 2017; Kennedy et al., 2019). 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 and 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 (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 and 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.

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Data Availability and Code Availability

The original GLC2000 dataset 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.6522673).

Author Contributions

SAB and EMH conceived of the idea with input from PLS. Analyses were developed and implemented by EMH and SAB. The manuscript was written by EMH and SAB with input from PLS, ANF and DH.

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