Global-scale shifts in Anthropocene rooting depths pose unexamined consequences in critical zone functioning

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Abstract

Rooting depth is an ecosystem trait that determines the extent of soil development and carbon 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 global rooting depths have become shallower in the Anthropocene, and are likely to become yet shallower this century. Specifically, globally averaged depths above which 99% of root biomass occurs (D99) are 8.7%, or 16 cm, shallower relative to those for potential vegetation. This net shallowing results from agricultural expansion truncating D99 by 82 cm, and woody encroachment linked to anthropogenic climate change extending D99 by 65 cm. Projected land cover scenarios in 2100 suggest further D99 shallowing of 63 to 72 cm, exceeding that 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 carbon. Our work constrains rooting depth distributions for global models, allowing the land modeling community to explore cascading effects of rooting depth changes on water, carbon, and energy dynamics, and can guide design of field-based efforts to quantify deep anthropogenic influences. Understanding human influence on biota's reach into Earth's subsurface will improve predictions of interactive functioning of the biosphere, lithosphere, and hydrosphere.

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Key Points:

- Globally averaged rooting depths have become shallower by 16 cm in the Anthropocene and will be truncated by up to 72 cm by 2100.
- In agricultural lands, the depth to which 99% of crop roots extend is shallower by up to 82 cm compared to natural systems.
- Where woody encroachment is occurring, analogous rooting zones are deepened by up to 65 cm compared to previous dominant vegetation.

Abstract

Rooting depth is an ecosystem trait that determines the extent of soil development and carbon 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 global rooting depths have become shallower in the Anthropocene, and are likely to become yet shallower this century. Specifically, globally averaged depths above which 99% of root biomass occurs (D99) are 8.7%, or 16 cm, shallower relative to those for potential vegetation. This net shallowing results from agricultural expansion truncating D99 by 82 cm, and woody encroachment linked to anthropogenic climate change extending D99 by 65 cm. Projected land cover scenarios in 2100 suggest further D99 shallowing of 63 to 72 cm, exceeding that 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 carbon. Our work constrains rooting depth distributions for global models, allowing the land modeling community to explore cascading effects of rooting depth changes on water, carbon, and energy dynamics, and can guide design of field-based efforts to quantify deep anthropogenic influences. Understanding human influence on biota's reach into Earth's subsurface will improve predictions of interactive functioning of the biosphere, lithosphere, and hydrosphere.

Plain Language Summary

The depth of plant roots helps determine the extent of nutrient, carbon 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 will become

shallower at an even faster pace. In both contemporary and future projections, deep roots are especially vulnerable to loss, suggesting that the extent of element and water cycles may get shallower in the future, too. This opens numerous questions for additional field- and modeling-based studies about the ways nutrients, carbon, and water will cycle in a future with fewer deep roots. We provide a foundation for those questions by demonstrating humans' influence on the roots that shape the character of Earth's skin.

1 Introduction

Roots are subsurface engineers, and their depth distributions drive ecosystem-scale processes (Maeght et al., 2013; Pierret et al., 2016) such as soil development (Brantley et al., 2017; Hasenmueller et al., 2017; Austin et al., 2018), release of mineral-bound nutrients (Jobbagy and 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 depths 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 and altered atmospheric composition (Edgeworth et al, 2001; Cramer et al., 2010; Ellis et al., 2010). This observation suggests that rooting depth distributions should be undergoing changes due to human activities in the critical zone (CZ, Earth's living skin, Jordan et al., 2001).

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 (Nepstad et al., 1994; Canadell et al., 1996), 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 depths at large spatial scales is generalized representations of rooting parameters in Earth Systems Models (ESMs; Smithwick et al., 2014; Clark et al., 2015). 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 carbon cycles to climate in the Anthropocene.

Quantifying large-scale, human-induced changes to rooting depths 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. For example, a recent hypothesis proposes that anthropogenic changes to land cover that modify rooting depth distributions can alter natural elemental cycles deep belowground in ways important for soil and ecosystem development (Billings et al., 2018). Testing this hypothesis on a regional or global scale requires global-scale estimates of changes in rooting depths due to human activities. If explicitly calculated, these estimates would be a key component of projecting material fluxes via land surface models, and for elucidating the most critical foci for future laboratory and field efforts necessary to enhance our understanding of global change agents.

Two Anthropocene phenomena occur at sufficient magnitude to alter rooting depths in ways complicating their quantification. First, many regions have experienced conversion to annual row crops (Ramankutty and 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 and Heimann, 1998; Kleidon, 2003) or, separately, land cover changes in specific regions of interest (Jeremillo 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), to date, no one has directly quantified the net change in contemporary root depth distributions at the global scale as a consequence of these opposing human activities.

Here, we estimate the extent to which rooting depths increase or decrease in response to land use and climate change. We also project how rooting depths 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 (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 ecosystems' root biomass extends, metrics that highlight very deep roots as well as the depths at which most roots reside, both of which are functionally consequential measures. These metrics represent those for which much data exist, and facilitate the cross-system comparisons necessary to estimate the extent of rooting depth changes in the Anthropocene. Our work thus reveals how anthropogenic, global-scale changes in rooting depth metrics have influenced, and will continue to influence, spatially varying patterns of the belowground activities of ecosystems, thereby illuminating critical next steps to help us understand future CZ functioning.

2 Materials and Methods

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. We used satellite-derived, potential vegetation representing 15 land cover classes (Haxeltine and Prentice, 1996) and their potential global distribution in the absence of human activity at a 5-minute spatial resolution (Ramankutty and Foley, 1999). We compared potential vegetation classes to contemporary land cover as defined by the Global Land Cover 2000 (GLC2000) dataset (Bartolome and 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 and Belward, 2005), and augmented these classes to include a class for permafrost regions where rooting depth may be limited. 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).

For all vegetation datasets except those above 60°N latitude (described below), we estimated biome-specific rooting depths by assigning rooting depth functions derived from empirical data (Zheng, 2001). Specifically, we estimated the depths by which rooting systems exhibit 50% (D50), 95% (D95) and 99% (D99) of their total biomass in each land cover type. Invoking these functions (Zheng 2001) assumes 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 each biome's rooting depth 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.

We modified the estimated rooting depth distributions for four of the 25 land covers. First, the 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 degrees north, a point above which frozen soils often limit deep root development (Zhang et al., 2008). Second, because many remote sensing-based studies omit large, lower latitude desert regions from their analyses due to the lack of quantifiable ecosystem productivity in these systems (Zhao et al., 2005), we omitted true deserts from rooting depth averages reported in the main text. Instead, we present rooting depth metrics that incorporate mid-latitude deserts' potential contribution 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 and Duval, 2019). Finally, we reassigned evergreen forest and mixed vegetation classes above 50°N to the 'boreal' vegetation classification, and ecoregions above 60°N to the class 'tundra.' We gave all classes above 60°N a rooting depth specific to permafrost-underlain regions, where roots typically do not penetrate deeper than 30 cm (Billings et al., 1997; Boike et al., 2018).

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, 5 agricultural classes, pasture land, rangeland, and urban regions (Hurtt et al., 2011). We assigned a rooting depth equation derived from agricultural croplands (Zheng, 2001) to all 5 agricultural classes in the landuse harmonization dataset. For secondary non-forests, we assigned rooting depth equations representing herbaceous and grassland systems, and pastures and rangeland were assigned rooting depth equations derived from C4 grasslands and pastures (Zheng, 2001). Because most secondary forests in these scenarios were in the boreal region, we assigned the average root depth value of mixed forests (240 cm) and boreal forests (119 cm) to secondary forests. Reflecting anticipated warming, root depths assigned in all future scenarios removed permafrost constraints (Lawrence and Slater, 2005).

Using R's 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. We then compared metrics across time using 95% confidence intervals of the mean estimates of global rooting depth metrics. We performed correlated t-tests on pairs of rasters (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.

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 up to 8.7% shallower (16 cm) under contemporary land cover distributions than if potential vegetation cover types covered Earth's terrestrial surface ($t = -128.08$, $P < 0.0001$; Figures 1c and d, Table S1). Values of D95 for contemporary land cover also express trends of root shallowing, though less so than D99 (7.8% or 8 cm; $t = -85.342$, $P < 0.0001$; Figures S1a and b). Depth to 50% root biomass (D50), by comparison, displays relatively little variation between contemporary and potential land cover, becoming less than 1 cm shallower (2.5%; t = - 111.75, $P < 0.0001$) on average (Figure S2). The comparatively small change in globally averaged D50 values is a consequence of relatively rapid root establishment in shallow horizons of cultivated systems.

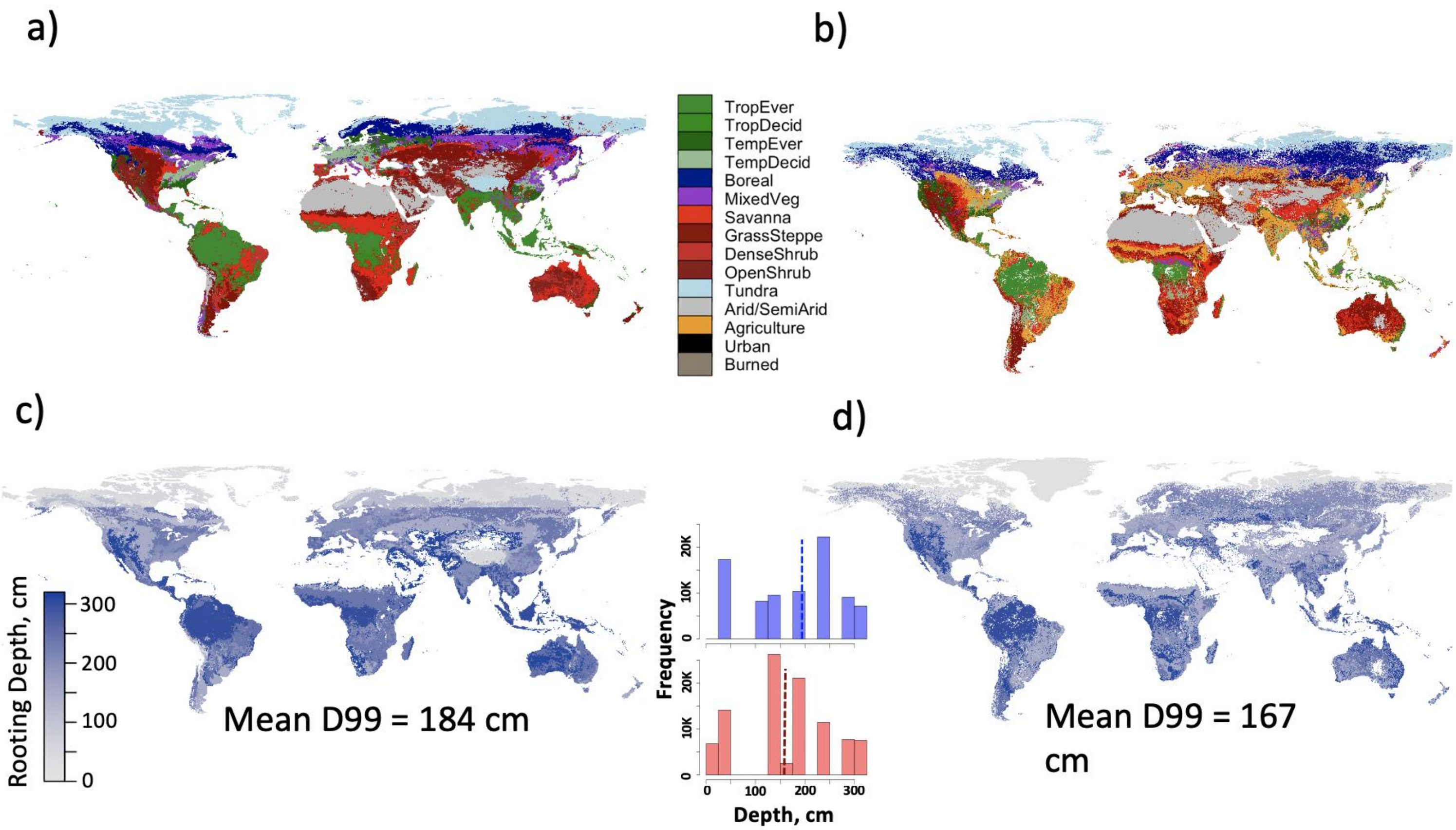

Figure 1. Land cover and associated rooting depths under potential vegetation in the absence of human influence (left column) and today's vegetation distribution (right column). (a) Potential vegetation cover in the absence of human activity modified to accommodate permafrost regions, where all plants regardless of functional type are depth-limited by frozen soils. (b) Contemporary land cover distribution from Global Land Cover 2000 (GLC2000), modified to correspond to potential vegetation land cover classifications. Subsequent maps 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 histograms reflect potential vegetation data, and red histograms contemporary land cover. Dashed lines represent means. Appearance of a distinct line at 50°N in potential vegetation rooting depth coverages is an artifact of restricted maximum rooting depth assignments to reflect limitations imposed by frozen soils. Note that most of Greenland is assigned a rooting depth of zero in all maps because of ice cover, which is denoted in white and grey in potential and contemporary root coverages, respectively.

Agricultural land conversion serves as the dominant influence on these global trends (Figures 2 and 3). Where perennial vegetation has been converted to agricultural land (defined here as annual crops and managed pasture), D99 has decreased by as much as 35% (82 cm) across 2.4 x 10^9 ha (15% of Earth's terrestrial surface). In contrast, where woody encroachment is evident in contemporary land cover data, D99 increased relative to potential vegetation by up to 52% (65 cm). This result is likely an overestimate of current root depths because we assigned rooting depths derived from well-established systems (Zheng, 2001) although woody plants in recently encroached systems likely have not yet achieved such depths (Stevens et al., 2017; Billings et al., 2018). In spite of this possible overestimation, root deepening via woody encroachment does not overcome the effect of root shallowing in agricultural lands because of the smaller fraction of Earth's terrestrial surface experiencing woody encroachment (9.3 x 10^7 ha, or 0.6%).

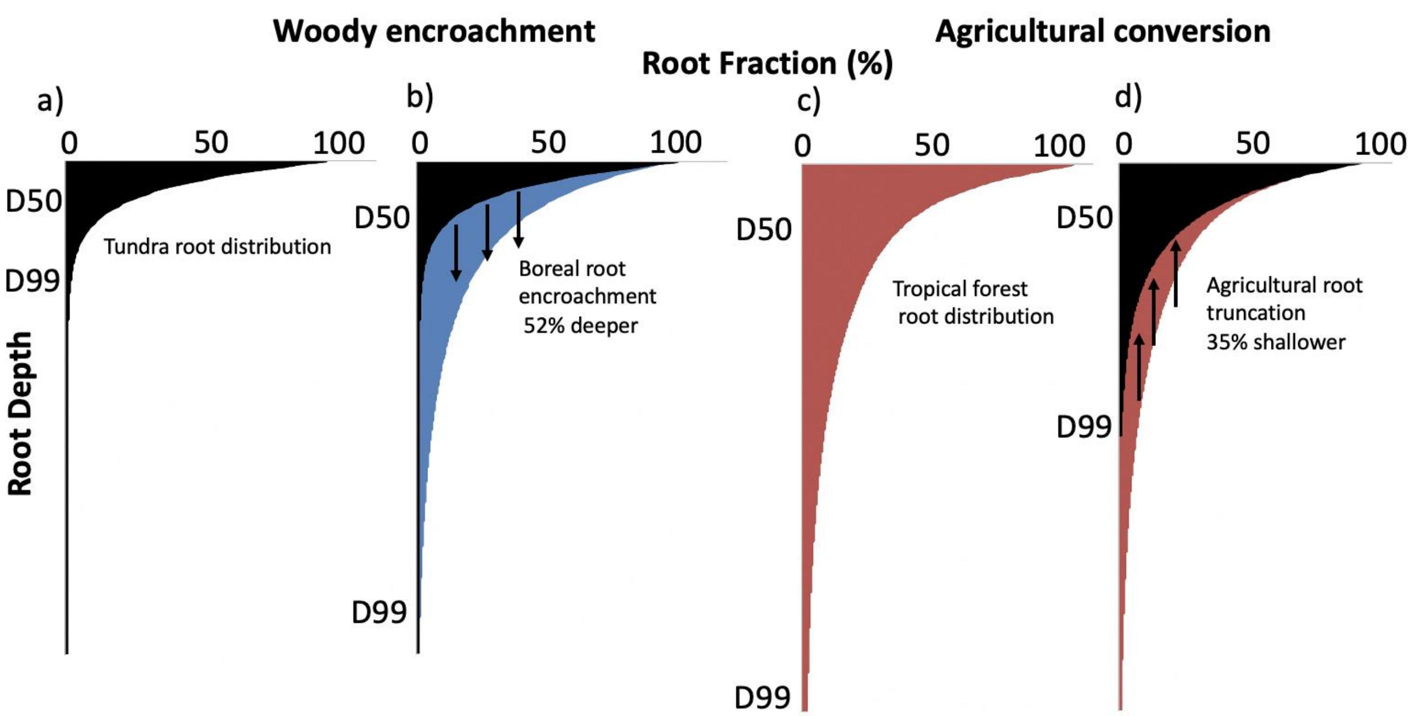

Figure 2. Representation of rooting depth elongation due to woody encroachment (a and b) and rooting depth truncation due to agricultural expansion (d and d). Blue region in B demonstrates the belowground increase in roots shown in blue in Figure 3. Red region in D exemplifies loss of rooting system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

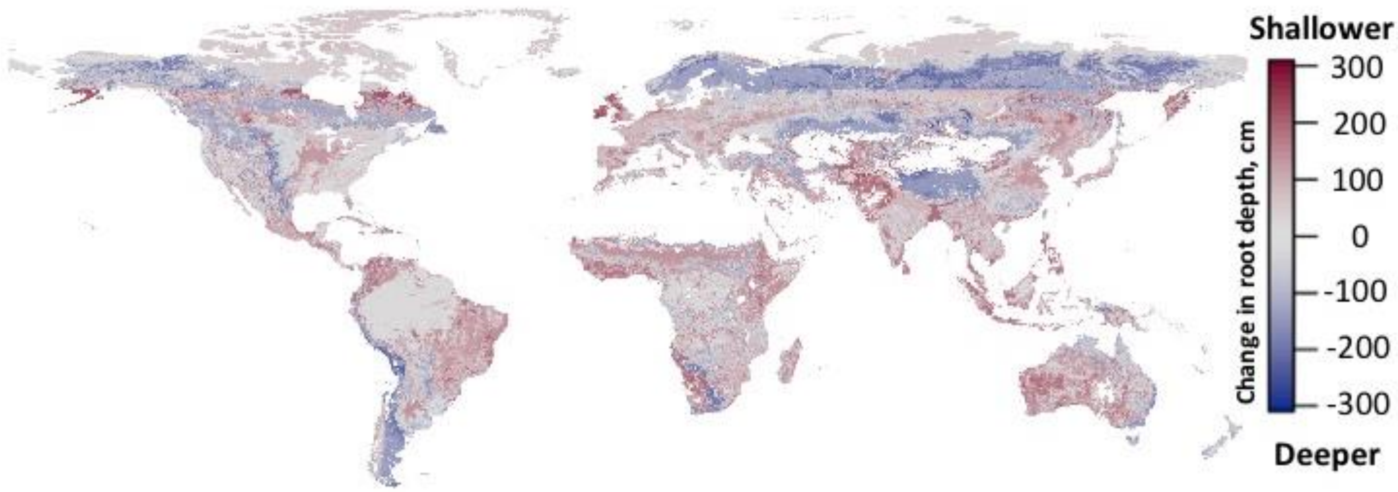

Figure 3. Mapped differences between potential and contemporary rooting depths. Red cells indicate a decrease in the depth to 99% of rooting biomass (D99) while blue cells indicate an increase in D99 resulting from contemporary vegetation distributions.

Projections for the year 2100 suggest that the scenario with the largest cropland increase and relatively low radiative forcing enhancement from current levels (SPP1 RCP2.6, Figure 4a) generates the most extreme shallowing of deep roots, truncating values of D99 by 72 cm (t = 419.91, $P < 0.0001$). The smallest decline in D99, a shallowing of 63 cm (t = 370.35, $P < 0.0001$), occurs under a scenario of moderate cropland increase and stabilization of moderate to high radiative forcing at 6 Wm^{-2} by 2100 (SPP4 RCP6.0, Figure 4b). The highest emissions scenario (SSP5 RCP8.5) produces an intermediate D99 shallowing of 64 cm, the result of extensive conversion of forests into cropland (Figure S4) and root elongation in boreal and high-elevation regions (compare Figure 3 and Figure S4). Widespread, substantial root shallowing is evident in many regions but is particularly evident across the Amazon basin, consistent with multiple projections of rapidly transitioning vegetation cover in that region (Hurtt et al., 2011).

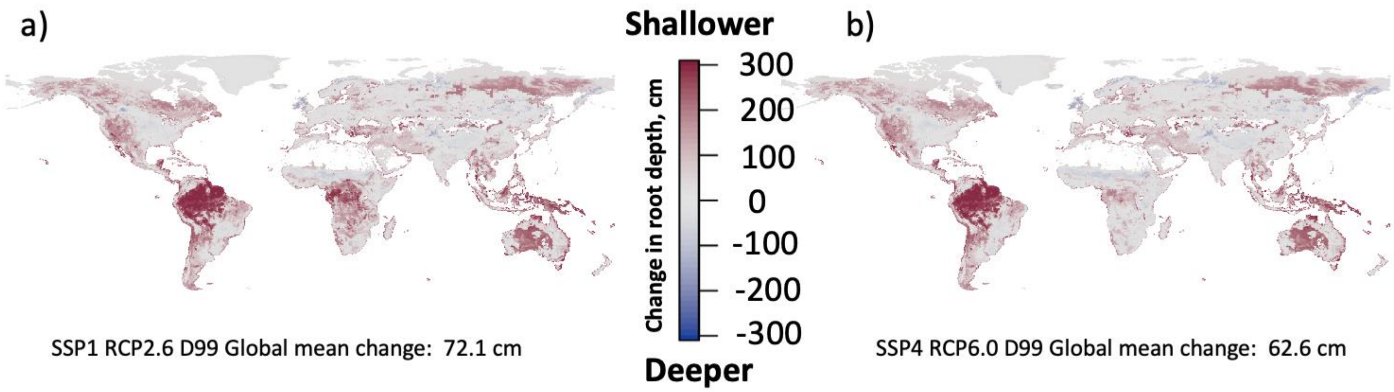

Figure 4. Projected changes of depth to 99% rooting biomass (D99) by the year 2100 relative to contemporary rooting depth distributions. Projections are based on land use and emissions changes under two combinations of Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCP), SSP1 RCP2.6 (a) and SSP4 RCP6.0 (b). These two maps represent the scenario of greatest projected change and least projected change. Grey and red colors indicate root depth truncation and blue indicates elongation.

Values of D50 for the year 2100 also reflect a consistent response to the rapidly transitioning vegetation that likely drives projected changes in D99 and D95, leading to a D50 shallowing of 5 to 6 cm across all assessed scenarios (t = 416.2, $P < 0.0001$; Figure S5). Though small relative to changes in deep root systems, this D50 shallowing is 4 to 5 cm more severe than that occurring during the previous ~10,000 y (Gupta, 2004) of anthropogenic land conversion to agriculture (Figure S6).

4 Discussion

Our rooting depth estimates suggest that the portion of rooting biomass most vulnerable to human influence is, counterintuitively, deep in the soil profile (Figures 2 and 3). 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 metrics of most or half of all rooting biomass (i.e., D99, D95, and D50), no matter their absolute value, are currently a reflection of human-induced, global-scale changes in land cover (Figure 1). We further demonstrate that the globally-averaged estimate of a 16% shallowing of D99 values is the net result of root shallowing in agricultural regions and root elongation in regions of woody encroachment, with the area represented by agriculture dominating the effect.

With atmospheric CO_2 anticipated to continue increasing in the coming decades, we might expect woody encroachment's elongating effects on D99, D95, and D50 to effectively mitigate the root shallowing effect of land conversion to agriculture. However, the four IPCC scenarios explored here suggest that by 2100, rooting distributions may become yet shallower relative to contemporary rooting depths (Figures 3, S4 and S5). As observed for comparisons between potential and contemporary land cover, the deeper rooting metrics (D99 and D95) display greater changes in their global mean than D50 when comparing contemporary and projected land cover. Thus, both comparisons suggest that the deepest roots are the most vulnerable to loss via anthropogenic changes.

Unlike contemporary vs. potential vegetation comparisons, D50 metrics in future scenarios are considerably shallower than contemporary scenarios. These results highlight that anthropogenically-induced changes in surficial soil horizons' root abundances in the coming decades will likely exceed those of the past several millennia. They also 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.

There are myriad feasible consequences of altered rooting depths for biogeochemical and hydrological fluxes that prompt hypotheses for future research efforts. For example, roots beneath the zone of maximum rooting density are attributed with 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 and 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 regions do not reach as deeply into the regolith as they did prior to human influence, prompting the hypothesis that the intensity of biotic modes of soil formation at the bottom of the soil profile have declined in the Anthropocene. Further, if a smaller volume of soil is explored by rooting systems, it is plausible that soil water storage capacity, nutrient replenishment and solute losses from freshly weathered material could decline (Swank, 1986; Nepstad et al., 1994; Berner, 1998).

Such implications emphasize the importance of future numerical and empirical experiments exploring the climate and biogeochemical feedbacks of deep root losses. Because terrestrial vegetation exerts a fundamental global control on land-atmosphere exchanges of water, energy, carbon, 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 carbon, and the large-scale ramifications that changes in rooting depths have for climate. Well-designed numerical experiments would be able to elucidate the relative impacts of exogenous (e.g., agricultural conversion, woody encroachment) versus endogenous (e.g., water and nutrient limitation) changes in rooting depths on terrestrial cycling of water, energy, and carbon.

Future empirical studies examining the contribution of deep roots to soil structure, C and nutrient fluxes, and water flow paths also offer opportunities to characterize the biogeochemical consequences of shallowed rooting systems. More extensive empirical work can generate more accurate parameters for representing subsurface biogeochemical fluxes in ESMs, where highly non-linear feedbacks between these changes and climatic conditions can be examined. Specifically, 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 reveal quantitative relationships between rooting depth distributions and their impacts on soil formation processes, especially at depth. Given deep root contributions to soil C, nutrient and water fluxes, as well as soil formation (Maeght et al., 2013; Pierret et al., 2016; Rasse et al., 2005), revealing rooting depth feedbacks to Earth's biogeochemistry is critical for understanding the current and future function of Earth's critical zone.

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 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 root 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 similarly lengthy 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 (although see Drewniak, 2019 for an important counterexample). We present an opportunity to advance the 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). Future co-designed modeling, field and lab studies are needed to help clarify the consequences of rooting depth changes for contemporary and future CZ development. These studies will elucidate the ways that surficial anthropogenic activities radiate deep within Earth's subsurface, altering the developmental pace and character of Earth's critical zone.

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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.3975240).

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 and AF.

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