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Mapping the global distribution of deep roots in relation to climate and soil characteristics

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Abstract

Global data sets of rooting depths, long-term means of monthly precipitation and potential evapotranspiration, and soil texture were used to predict the probability of deep rooting around the globe. Rooting depths were considered to be deep if 5% or more of all roots in a profile were located below 2 m depth. Spatially explicit global predictions were based on empirical models relating the probability of deep rooting with climate and soil texture. Based on these predictions, deep roots are most likely to occur in seasonally dry, semiarid to humid tropical regions under savanna or thorn-scrub vegetation or under seasonally dry semideciduous to evergreen forests. Deep roots are least likely to occur in arctic, boreal or cool-temperate regions and in per-humid climates such as equatorial rain forests. Under warm-temperate to tropical climates, rooting depths are more likely to be deep in coarse-textured and fine-textured soil than in soils of medium texture. These observations agree well with predictions based on a previously published conceptual model, according to which water infiltration depths and evaporative demand are the main climatic factors to determine vertical root distributions on a global scale.

Keywords: Roots; Rooting depths; Global maps; Global root distributions; Natural vegetation; Evapotranspiration; Soil texture; Soil water balance

1. Introduction

Information on soil depths is essential for a good understanding of hydrological and biogeochemical processes. Unfortunately, the lower boundary that separates soil from the material underneath is often difficult to define (Richter and Markewitz, 1995). In some sites, soil is clearly defined by its boundary at solid bedrock, but in other sites, soils grade into the regoliths underneath, which can be very deep, especially in humid and tropical climates (Brady and Weil, 2001; Richter and Markewitz, 1995).

Roots define the biologically and chemically most active zone of the soil profile. They transport water

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and nutrients, are a major source of organic material in soils, are the primary source of energy for many soil organisms, and contribute to the weathering of minerals with their mechanical actions and exudates (Bormann et al., 1998) and modify soil structure (Johnson-Maynard et al., 2002). The question "where do deep soils occur?" therefore is largely synonymous with the question "where do deep roots occur?"

Past studies of global plant rooting depths have offered only partial answers to this question (Canadell et al., 1996; Jackson et al., 1996; Kleidon and Heimann, 1998). Large continental regions have never been sampled for rooting depths, and less than 10% of published data on vertical root distributions include measurements all the way to the maximum rooting depth (Schenk and Jackson, 2002a). Previous studies have found that globally rooting depths are related to climate and soil characteristics and that the deepest rooting depths are most likely to occur in seasonally water-limited ecosystems of warm-temperate to tropical regions (Schenk and Jackson, 2002a,b). Because direct measurements of rooting depths are not available for many regions of the Earth, climate and soil characteristics may be used as a predictor for the probability of deep rooting for any given location. For this study, deep rooting was defined as a soil profile containing a substantial proportion (at least 5%) of all roots below 2 m depth.

This study had the following three goals: (1) to map the global distribution of locations known to have deep roots, (2) to quantify relationships between climatic variables, soil variables, and the probability of deep rooting for natural vegetation, and (3) to use these relationships for predicting the global, geographical probability distribution of deep roots in natural vegetation, including regions for which no data on deep roots are currently available.

Root data collected from the primary literature were used to identify locations with deep roots globally. Because direct measurements of complete root profiles down to the maximum rooting depth are rarely reported in the primary literature (we found only 56 such profiles globally), we also used two other approaches to identify locations that have a high likelihood of containing at least 5% of all roots below 2 m depth. (1) Data from incompletely sampled root profiles obtained from the primary literature (n=463) were extrapolated to greater depths using methods described by Schenk and Jackson (2002a) to estimate the percentage of roots below 2 m and identify locations meeting our definition of deep rooting. (2) Rooting depths of individual plants were collected from the primary literature (n=2449). Individual plant rooting depths of 4 m or more were considered to be an indication that a substantial proportion of roots occurred below 2 m depth.

2. Material and methods

2.1. Databases used in the study

Two independent global data sets of rooting depths were used to identify locations where substantial amounts of roots occurred below 2 m soil depth. The first data set, here referred to as the RPGE data set (the acronym stands for "Root Profiles of Global Ecosystems"), is a collection of vertical root profiles, interpolated, and in some cases extrapolated, to obtain estimates for the soil depths containing 95% of all roots (Schenk and Jackson, 2002a). The second data set, here referred to as the RSIP data set (the acronym stands for "Root Systems of Individual Plants"), contains sizes and shapes of root systems for individual plants and has been described by Schenk and Jackson (2002b). Both of these global databases include root data collected from the primary literature for many terrestrial vegetation types, including natural vegetation and vegetation affected by human activities. Excluded are root data from croplands, fertilized or ploughed soils, and wetlands.

For this study, the RPGE database of 475 root profiles described in Schenk and Jackson (2002a) was expanded by adding 44 more recently published data sets. The RPGE data set is available from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) at http://www.daac.ornl.gov/. For each root profile, the database contains the geographic coordinates, and, where available, mean monthly precipitation (R_m; n=514), and estimates for mean monthly potential evapotranspiration (PET_m; n=514), taken from the global 0.5° gridded data set of Choudhury (1997) and Choudhury and DiGirolamo (1998). Of these profiles, 442 include information on soil texture, classified into the three broad categories defined by Zobler (1986) [coarse (sand, loamy sand, gravel), medium (sandy loam, loam, clay loam, silt, silty clay loam, silt loam, sandy clay), and fine (clay, silty clay)].

Cumulative vertical root profiles were interpolated using a logistic dose–response function to calculate the depths containing 95% (D_{95}) of all roots in the profiles (Schenk and Jackson, 2002a). Incompletely sampled profiles (those not sampled to the maximum rooting depth or to at least 3 m depth) were extrapolated using the same function. Interpolation and extrapolation procedures and tests of their accuracy have been described previously (Schenk and Jackson, 2002a). Deep rooting ($D_{95} \geq 2$ m) was observed for 50 profiles (9.6% of the RPGE database).

The RSIP database contains sizes and shapes of root systems for individual plants, as well as information on plant growth form and, where available, data on mean annual precipitation (R_a; $n=2198$) and mean annual evapotranspiration (PET_a; $n=2214$). For this study, the RSIP database was expanded from the 1305 records in Schenk and Jackson (2002b) to 2449 records from many global vegetation types, with a majority of the data from water-limited environments. Maximum rooting depths of $D_i \geq 4$ m from the RSIP database were considered to be indicators of root profiles that had a substantial proportion of roots below 2 m depth, which was the case for 222 plants globally (9.1% of all maximum rooting depths in the RSIP database, including 108 trees, 58 shrubs, 19 semishrubs, and 37 perennial herbaceous plants).

2.2. Mathematical models and statistical analyses

To predict the relationship between the probability of deep rooting and climate and soil characteristics, an empirical model was developed of the general form:

$$P(D_{\mathrm{deep}}) = f(R_a, \mathrm{PET}_a) \times C(S_a) \times C(U) \qquad (1)$$

where $P(D_{\mathrm{deep}})$ is the probability of deep rooting, R_a and PET_a are long-term means of annual precipitation and annual potential evapotranspiration, respectively, $C(S_a)$ is a correction factor based on an index for deep soil water storage (S_a, defined in Eq. (3)), and $C(U)$ is a correction factor for soil texture.

For each rooting depth record, the climate is characterized by long-term means of R_a and PET_a. Together, these two variables broadly define the position of a given local climate within the global, terrestrial climatic continuum. All current regional climates form a continuum of triangular shape when plotted in a diagram with R_a on the x-axis and PET_a on the y-axis (Fig. 1). The following procedure (see Fig. 2) was used for both the RPGE and the RSIP databases to determine where deep roots are likely to occur within this global climatic continuum.

1. A grid spaced at increments of 0.4 m year^{-1} was placed over the global climatic continuum of PET_a vs. R_a, subdividing the continuum into a set of subclimates, hereafter referred to as the climatic grid.
2. Numbers of rooting depth records (Fig. 2a) were calculated for each node in the climatic grid using kernel density estimation, as described in Bailey and Gatrell (1995). The quartic kernel employed for this analysis uses points within a 0.4 m year^{-1} radius (bandwidth) around each node, while weighing points closer to the node more strongly than those located further away.
3. Numbers of records for deep roots (Fig. 2b) were calculated for each node in the climatic grid using the same methodology as in (2).
4. The probability of finding deep roots at each node within the climatic grid was determined by dividing the kernel density estimates for deep root records by the kernel density estimate for all root records (Fig. 2c).

To test whether $D_{95 \geq 2\ \mathrm{m}}$ and $D_{i \geq 4\ \mathrm{m}}$ are similar measures of deep rooting, we determined whether they were equally distributed in the climatic continuum. For all 18 nodes in the climatic grid for which both probabilities $P(D_{95 \geq 2\ \mathrm{m}})$ and $P(D_{i \geq 4\ \mathrm{m}})$ could be calculated, the two probabilities were linearly regressed against each other, using reduced major axis regression (RMA) to account for the fact that both variables were estimated with error (Sokal and Rohlf, 1995). RMA regressions were calculated using the program PAST, version 0.65 (Øyvind Hammer, Paleontological Museum, University of Oslo, Norway). The regression of $P(D_{i \geq 4\ \mathrm{m}})$ against $P(D_{95 \geq 2\ \mathrm{m}})$ was statistically significant ($p=0.03$; $r^2=0.251$) and resulted in a linear equation with an intercept of -0.01 ± 0.05 (not significantly different from 0) and a slope of 0.91 ± 0.19 (not significantly different from 1). It was concluded that $D_{95 \geq 2\ \mathrm{m}}$ and

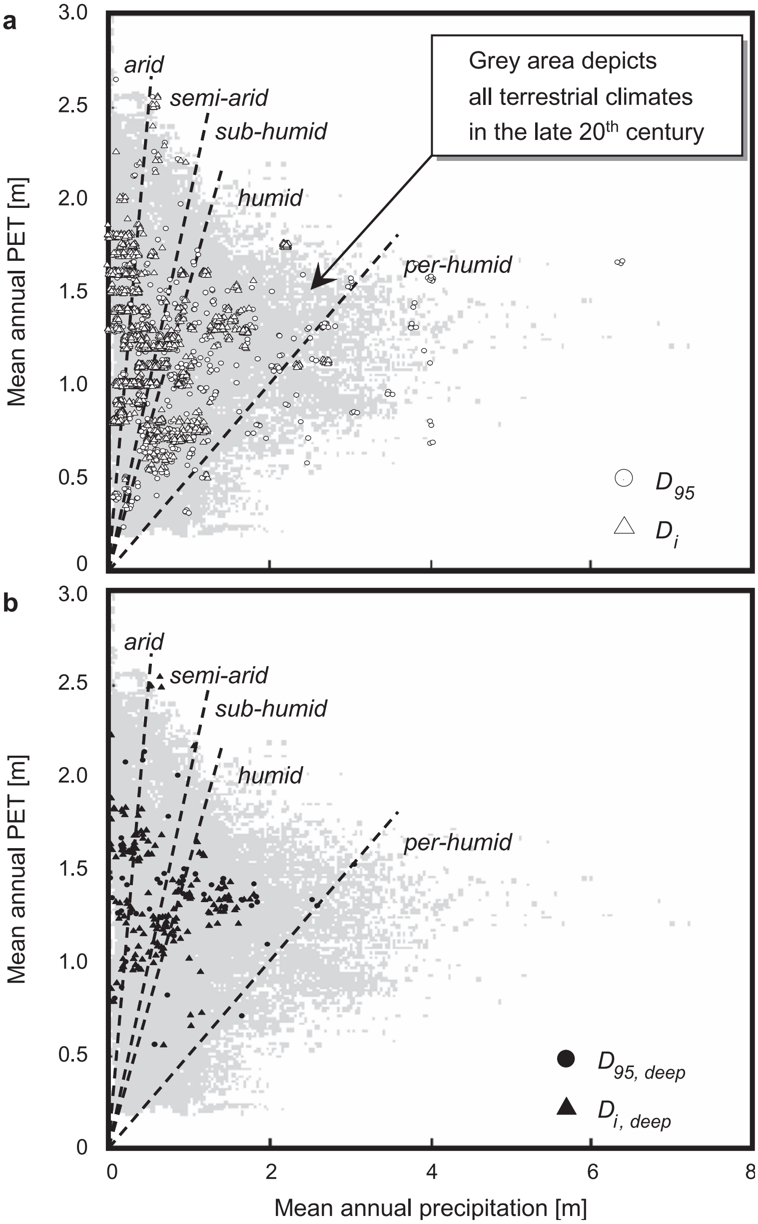
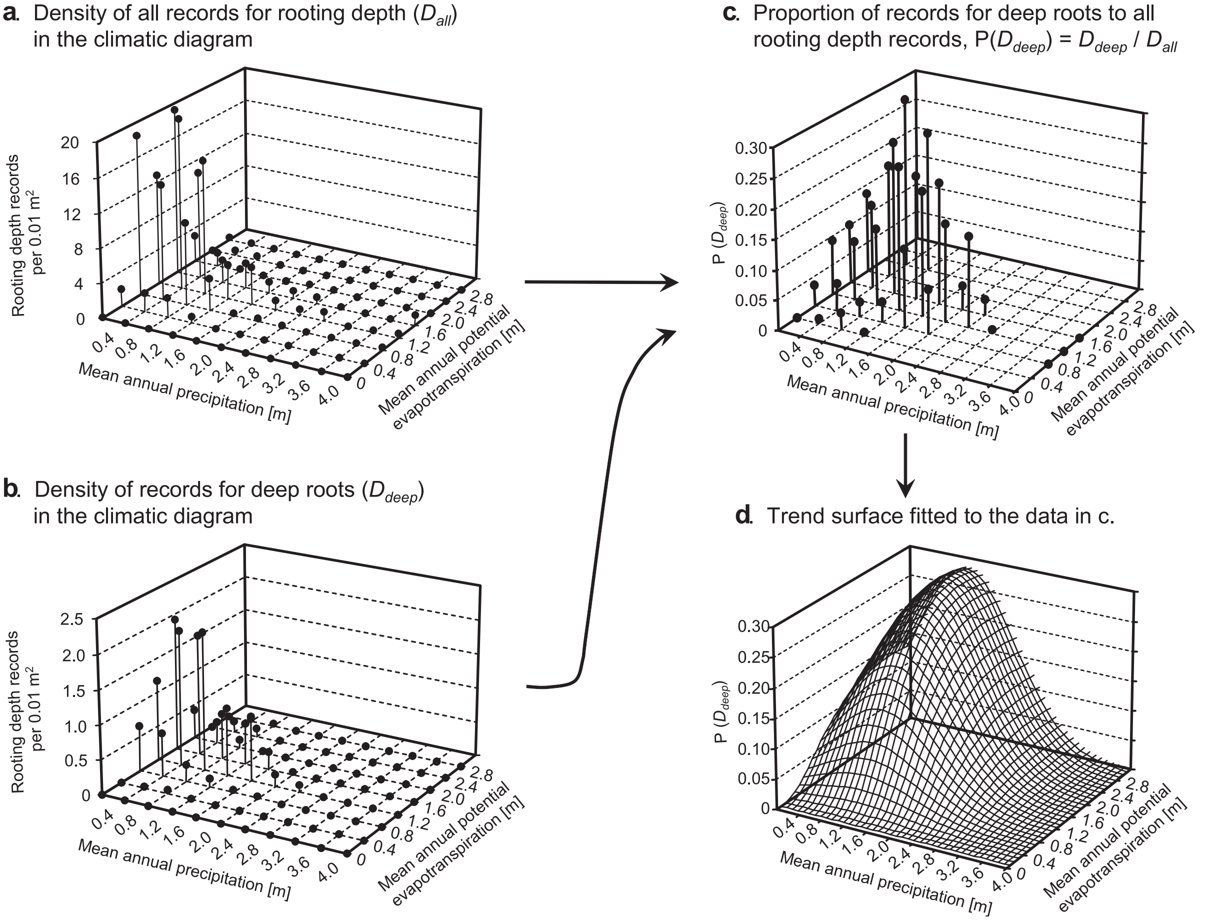


Fig. 1. Distribution of rooting depth records from the RPGE and RSIP databases (Schenk and Jackson, 2002a,b) in the global climatic continuum. The grey area in both graphs depicts the regional climates for all global, terrestrial 0.5° latitudinal grid cells in the late 20th century, based on gridded databases of mean annual precipitation (R_a) and mean annual potential evapotranspiration (PET_a). The climatic continuum is divided into the following humidity zones (UNEP, 1992): Arid ($R_a/PET_a \leq 0.2$), semiarid ($R_a/PET_a > 0.2$ to ≤ 0.5), subhumid ($R_a/PET_a > 0.5$ to ≤ 0.65), and humid ($R_a/PET_a > 0.65$ to ≤ 2.0). Per-humid climates are defined here as $R_a/PET_a > 2.0$. (a) Distribution of all root records in the RPGE (D_{95}) and RSIP (D_i) databases in the global climatic continuum. (b) Distribution of records for deep roots in the RPGE ($D_{95 \geq 2\ m}$) and RSIP ($D_{i \geq 4\ m}$) databases in the global climatic continuum.



a. Density of all records for rooting depth (D_{all}) in the climatic diagram

b. Density of records for deep roots (D_{deep}) in the climatic diagram

c. Proportion of records for deep roots to all rooting depth records, P(D_{deep}) = D_{deep} / D_{all}

d. Trend surface fitted to the data in c.

Fig. 2. Illustration of the procedure used to calculate the probability of deep rooting within the global climatic continuum. The bottom plane of graphs a–d depicts the R_a vs. PET$_a$ continuum divided into a climatic grid spaced at increments of 0.4 m year^{-1} (R_a or PET$_a$). (a) Densities of all rooting depth records from the RPGE and RSIP databases calculated for each node in the climatic grid using kernel estimation. (b) Densities of records for deep roots from both the RPGE and RSIP databases calculated for the climatic grid using the same methodology as in graph a. (c) Probability of finding deep roots for each node within the climatic grid, determined by dividing the kernel density estimates for deep root records (b) by the kernel density estimate for all root records (a). (d) Trend surface (Eq. (6)) fitted to the data in graph c.

$D_{i\geq 4\ \mathrm{m}}$ are similar indicators of deep rooting. Therefore, they were combined for each node of the climatic grid to a general probability of deep rooting, *P*(D_{deep}), defined as

$$P(D_{\mathrm{deep}}) = [\Sigma(D_{95\geq 2\ m}) + \Sigma(D_{i\geq 4\ m})]/[\Sigma(D_{95,\ \mathrm{all}}) + \Sigma(D_{i,\ \mathrm{all}})]. \tag{2}$$

To project the global distribution of $P(D_{\mathrm{deep}})$ as a function of climate, trend surfaces were fitted to the data for $P(D_{\mathrm{deep}})=f(R_a, \mathrm{PET}_a)$ using the software TableCurve 3D, version 3 (SPSS, Chicago, Illinois, USA). Of all equations fitted, we selected the one with the highest r^2 and meeting two conditions: that the model had (1) no more than five parameters that were all significant at $p<0.05$ and (2) no more than one peak. The second condition was imposed based on a conceptual model proposed by Schenk and Jackson (2002b), according to which the incidence of deep rooting is expected have a unimodal distribution within the PET$_a$ vs. R_a climatic continuum.

Because previous studies suggested that rooting depths are likely to be deepest where there is evaporative demand during dry seasons for water stored deeply in the soil (Schenk and Jackson, 2002b), the relationships between $P(D_{\mathrm{deep}})$ and an index of deep soil water storage was also analyzed. This annual water storage index S_{a} (in m year^{-1}) accounts for both the potential storage of water during a wet season and for the demand for such stored water during a dry season. It is defined as

$$S_{\mathrm{a}} = \min \lfloor W_{\mathrm{sur}}, W_{\mathrm{def}} \rfloor \tag{3}$$

with W_{sur} being the long-term, mean seasonal surplus of water that is potentially available for deep storage, and with W_{def} being the long-term mean, seasonal deficit of water, representing the potential transpirational demand for water stored deeply in the soil. These terms are defined by

$$W_{\mathrm{sur}} = \sum_{\mathrm{months}} (R_{\mathrm{m}} - \mathrm{PET}_{\mathrm{m}}) \tag{4}$$

for all months with $\mathrm{R_m}-\mathrm{PET_m}>0$
and

$$W_{\mathrm{def}} = \sum_{\mathrm{months}} (\mathrm{PET}_{\mathrm{m}} - R_{\mathrm{m}}) \tag{5}$$

for all months with $\mathrm{PET_m} - \mathrm{R_m}>0$

with R_{m} and $\mathrm{PET}_{\mathrm{m}}$ being long-term means of monthly precipitation and monthly potential evapotranspiration, respectively. Because S_{a} requires information on monthly climatic means, it could only be calculated for rooting depth records in the RPGE database (the RSIP database contains no monthly climate data).

The depth to which water infiltrates into a soil profile, and therefore the depth to which roots may penetrate, largely depends on the texture of the soil. To analyze the relationship between the probability of deep rooting, climate, deep soil water storage (S_{a}) and soil texture (U), the RPGE data set was divided into two broad climate types, arctic to cool-temperate ($\mathrm{PET_a} \leq 1.00$ m year^{-1}) and warm-temperate to tropical ($\mathrm{PET_a} > 1.00$ m year^{-1}). Within each of these two climate types, climates were further divided into those without pronounced dry/wet cycles ($S_{\mathrm{a}} \leq 0.15$ m year^{-1}) and those with pronounced dry/wet cycles ($S_{\mathrm{a}} > 0.15$ m year^{-1}). A cutoff point for deep soil water storage of $S_{\mathrm{a}} > 0.15$ m year^{-1} was chosen because this amount is sufficient in almost any climate type to supply at least one month's evaporative demand (Choudhury, 1997). Root profiles grouped into these four climatic subcategories were further divided into the three soil texture classes, coarse, medium, and fine (Zobler, 1986). For each broad climate type, the proportions of profiles containing deep roots in each climatic subcategory and each soil texture class were compared to null-models of homogenous distributions among these groups using a two-way contingency table and a chi-square test.

The mathematical relationships between R_{a}, $\mathrm{PET}_{\mathrm{a}}$, S_{a}, and soil texture were used to parameterize the empirical model described by Eq. (1), which was used to predict the global distribution of $P(D_{\mathrm{deep}})$ at a $1^{\circ} \times 1^{\circ}$ spatial scale based on global, gridded databases of R_{m} (Intergovernmental Panel on Climate Change (IPCC) Data Distribution Center, University of East Anglia, Norwich), $\mathrm{PET}_{\mathrm{m}}$ (Choudhury, 1997; Choudhury and DiGirolamo, 1998), and soil texture (Zobler, 1986, data available online at http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/ISLSCP/).

3. Results

Deep roots have been documented for every continent except Antarctica (Fig. 3). The clusters of records for North America and central Asia largely reflect the fact that many studies of rooting depths have been conducted in these areas. Some other patterns that are apparent include a sparseness of records at latitudes >50°, for regions with moist tropical forests and for regions with the most arid deserts.

The probability of deep rooting within the climatic diagram was related nonlinearly to both R_{a} and $\mathrm{PET}_{\mathrm{a}}$, peaking in semiarid to subhumid climates with $\mathrm{PET}_{\mathrm{a}}$ exceeding 1.5 m year^{-1}, i.e., in seasonally water-limited, subtropical to tropical climates (Fig. 2c). Of all linear and nonlinear equations tested that met the requirements outlined in Methods, the following offered the best fit by minimization of least squares ($r^2=0.77$, $df=31$, F-value=22.92, $p<0.0001$) to the data:

$$f(R_{\mathrm{a}},\mathrm{PET}_{\mathrm{a}}) = 0.2924e^{\left[-0.5\left(\left(\frac{R_{\mathrm{a}}-1.0877}{0.8860}\right)^2+\left(\frac{\ln\left(\frac{\mathrm{PET_a}}{2.6638}\right)}{0.7848}\right)^2\right)\right]} \tag{6}$$

The extrapolation of this model to the global scale on a 1×1 latitudinal grid is shown in Fig. 3. According to

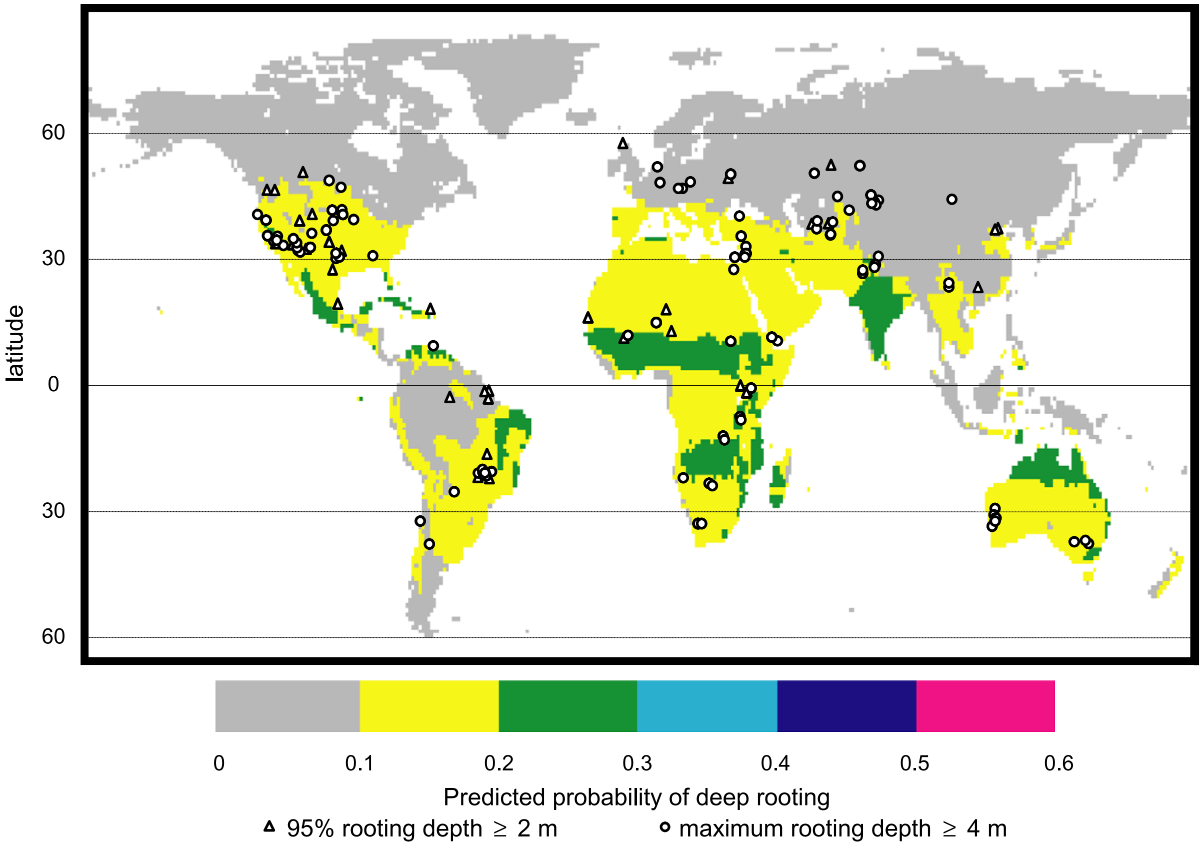


Fig. 3. Global distribution of literature records for deep roots collected in the RPGE ($D_{95\geq 2\text{ m}}$) and RSIP ($D_{i\geq 4\text{ m}}$) databases. The contour map shows the predicted probability of deep rooting calculated for 1°×1° grid cells by the climate-based model (Eq. (6)).

this climate-based model, the highest probabilities for deep rooting exist in regions with seasonal, tropical climates surrounding the equatorial regions of moist tropical rain forests, such as in Central America, Southeastern Brazil, North and South of the African Congo Basin, in most of India, southeastern Asia, and northern Australia. The lowest probabilities are predicted for arctic to cool-temperate and arid regions and equatorial rain forest regions.

Probabilities of deep rooting for arctic to cool-temperate climates with $\mathrm{PET_a} \leq 1.0$ m year^{-1} were low ($P(D_{\mathrm{deep}})=0.02$ overall) and not affected by soil water storage ($\chi^2=0.148$, $df=1$, $p=0.701$) or soil texture ($\chi^2=1.920$, $df=2$, $p=0.383$; data not shown). Warm-temperate to tropical regions with $\mathrm{PET_a}>1.0$ m year^{-1}, had an overall probability of deep rooting of $P(D_{\mathrm{deep}})=0.16$, with significant effects of the combined evaporative demand for and availability of deep soil water and soil texture (Fig. 4a). Soil profiles in such climates with pronounced dry/wet cycles ($S_a>0.15$ m year^{-1}) were 1.7 times as likely to be deeply rooted than profiles in climates without such pronounced cycles ($\chi^2=4.163$, $df=1$, $p=0.041$). Comparisons between the seasonal surplus of water during the wet season and the potential evaporative demand during the dry season in such highly seasonal climates suggested that use of deeply stored water could potentially account for between 1 and 6 months of ecosystem transpiration during dry seasons.

Soil texture also had a significant effect on the probability of deep rooting in warm-temperate to tropical climates (Fig. 4a; $\chi^2=8.549$, $df=2$, $p=0.014$). Medium-textured soils were least likely to have deep roots, while fine- and coarse-textured soils were much more likely to contain deep roots.

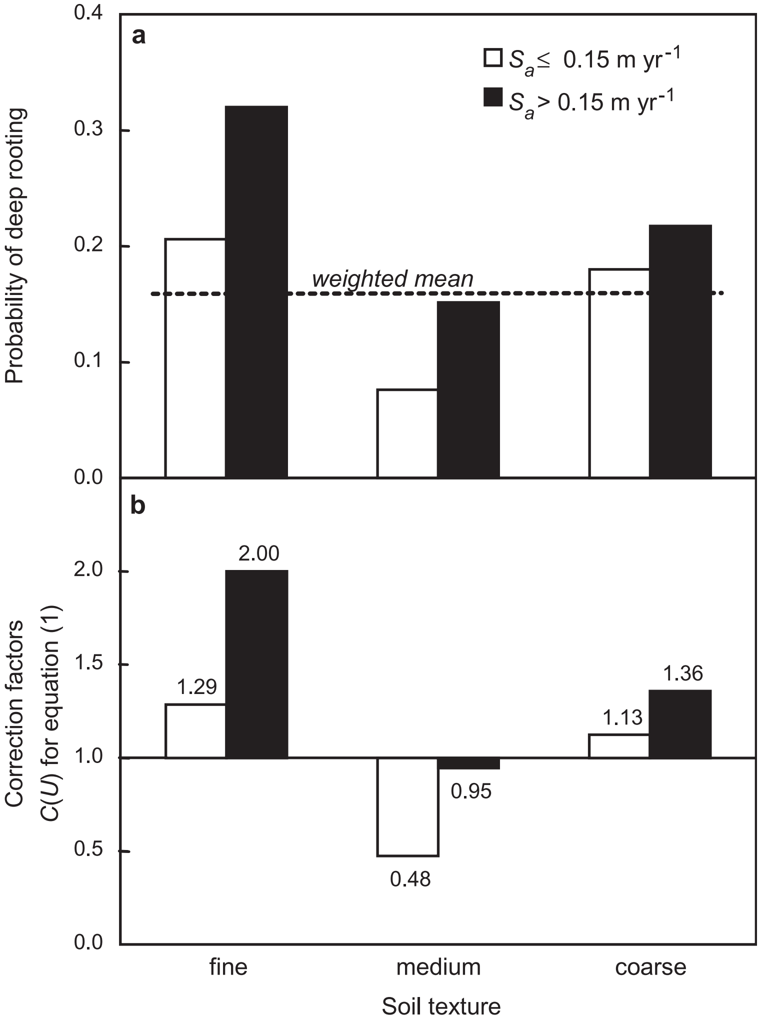


Fig. 4. (a) Probability of deep rooting for soil profiles in the RPGE database from warm-temperate to tropical climates ($PET_a > 1.00$ m year^{-1}). Climates with $S_a > 0.15$ m year^{-1} have pronounced seasonal dry/wet cycles and therefore a potential for storage of deep soil water and for plant use of such deep water during the dry season. Climates with $S_a \leq 0.15$ m year^{-1} lack such pronounced dry/wet cycles. Effects of soil texture and of S_a on the probability of deep rooting were both statistically significant at the $p < 0.05$ level. Soil texture categories were defined following Zobler (1986). (b) Correction factors for use in Eq. (1) to adjust probabilities calculated by Eq. (6) for effects of deep soil water storage and soil texture. These correction factors were calculated by dividing the individual probabilities for each climate and soil combination in panel a by the weighted mean probability also depicted in panel a.

To account for effects of deep soil water storage and soil texture on the probability of deep rooting in warm-temperate to tropical climates, Eq. (6) was multiplied by the correction factors shown in Fig. 4b resulting in a model conforming to Eq. (1). This climate and soil-based model was also used to predict the global distribution of $P(D_{\mathrm{deep}})$ on a 1°×1° global grid (Fig. 5). Soil texture and soil water storage modify the global distribution of deep rooting predicted by the climate-based model (Fig. 3) to some degree. The climate- and soil-based model differs from the climate-based model in predicting stronger "hot spot" of deep rooting for the Brazilian Cerrado, for the southern Sahel zone in Africa from Ethiopia to Senegal, for the Miombo woodlands in southern Africa reaching from Mozambique to Angola, for North-central India, especially the states of Madhya Pradesh and Mahârâshtra, and for the southwestern

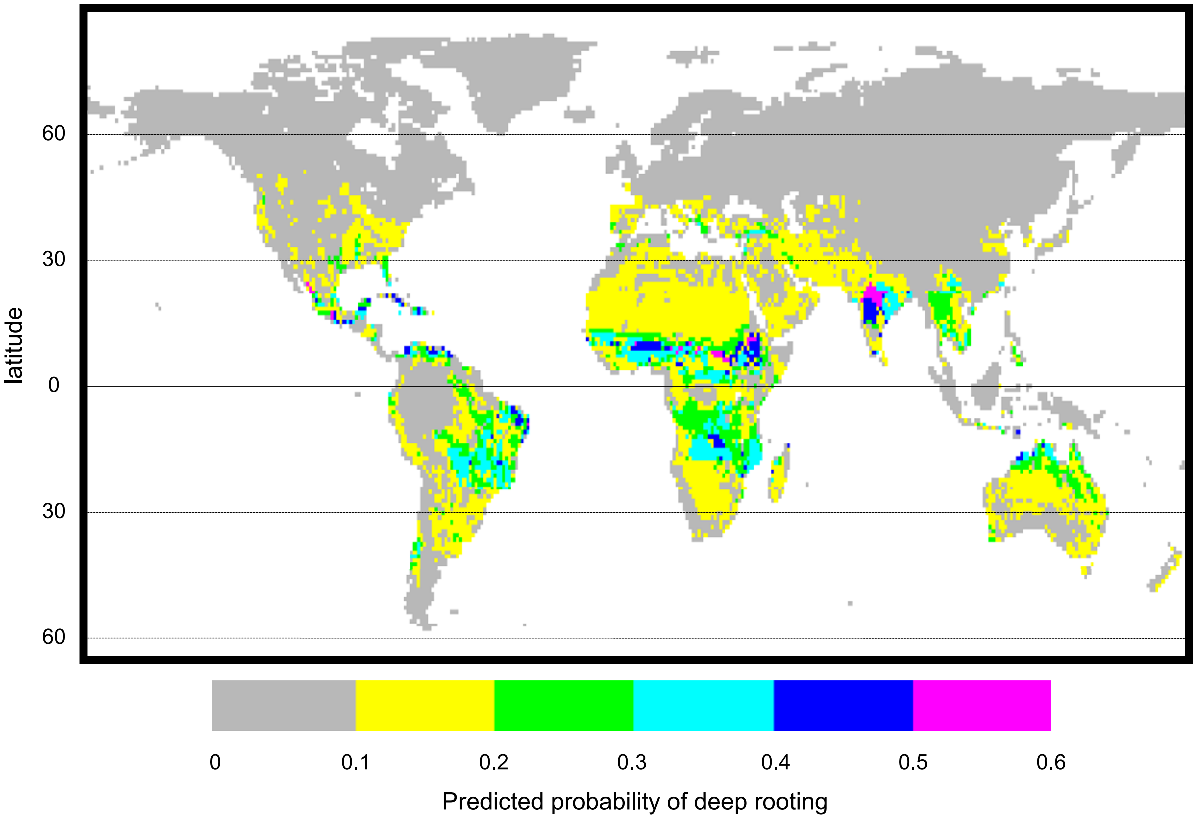


Fig. 5. Global distribution of the predicted probability of deep rooting $P(D_{\mathrm{deep}})$ for 1°×1° grid cells, calculated by a climate- and soil-based model (Eqs. (1) and (6), with correction factors from Fig. 4b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

coast of Mexico. The model also predicts a lower probability of deep rooting than the climate-based model for the medium-textured soils that cover much of North America.

4. Discussion

The probability of deep rooting is strongly related to climate- and soil-variables that affect the soil water balance (Figs. 2 and 4). The strength of these relationships is surprising, given the many biotic and abiotic variables that affect rooting depths. The precision of such predictions is likely to increase further when other factors, such as vegetation type or plant growth forms, are taken into account. For example, rooting depths are correlated with aboveground plant sizes (Schenk and Jackson, 2002b), and shrubs and trees are about 4 to 6 times more likely to be deeply rooted (i.e., to have roots ≥4 m deep) than semishrubs and perennial herbaceous plants. Annual plants apparently almost never achieve such rooting depths.

In a previous study (Schenk and Jackson, 2002b), we proposed a conceptual model which predicts the likelihood of deep rooting based on long-term means of soil water infiltration and evaporative demand. According to this model, the likelihood of deep rooting in water-limited environments should increase with increasing annual precipitation and therefore with increasing soil infiltration depths. This was previously confirmed for climates with R_a of less than 1 m year^{-1} (Schenk and Jackson, 2002b) and is again supported here for a wider range of climates. The conceptual model further predicts that rooting depths in humid to per-humid environments should increase with evaporative demand, but not with precipitation, because infiltration depths are not likely to limit plant transpiration in such environments. In the current study, this second prediction was supported, as the probability of deep rooting in such climates declined with increasing R_a. The third prediction of the model was that deep roots are most likely to occur in subtropical and tropical semiarid to humid environments with seasonal drought periods. This prediction was also strongly supported in the present study.

Despite the evident match between theory and observations, there are several limitations to the approach used here to predict the global distribution of deep roots. Few root profiles were available for steep terrain, for shallow or very rocky soils, for weathered bedrock, or for karst systems. Rooting depths under those conditions may differ substantially from those predicted by our models (Jackson et al., 1999). It should also be noted that rooting depths of croplands and wetlands were not included in this study. A few older data sets were available for rooting depths of natural vegetation on deep soils that are now predominantly under cultivation, such as in Ukraine and in the North American Midwest (e.g., Shalyt, 1950; Weaver and Darland, 1949). However, because our study excluded croplands from the analysis, it makes no predictions for soils currently under cultivation.

The analysis presented in this study enables us to take a new look at the question of which vegetation types are most likely to be deeply rooted. We qualitatively compared the global distribution of deep roots predicted in Figs. 3 and 5 to maps of global land cover, based on satellite data (De Fries et al., 1998; Hansen et al., 2000). According to this comparison, natural vegetation types of regions with climates that have the highest probability ($P(D_{\mathrm{deep}})$>0.25) of deep rooting are primarily subtropical to tropical savannas in the broadest sense. This includes semiarid to humid shrub- and tree-savannas, thorn-scrub, and woodlands. Tropical forests are generally less likely to be deeply rooted, with the exception of strongly seasonal semideciduous or evergreen forests, such as those in eastern Brazil (Sommer et al., 2000; Sternberg et al., 1998). Hot deserts around the world have low probabilities of deep rooting overall, probably because deep-rooted desert plants are largely restricted to habitats with deep-water infiltration such as washes, wadis, or rock clefts. Outside of such habitats, rooting depths of desert plants are often restricted by shallow infiltration depths (Schenk and Jackson, 2002b).

In warm climates, medium-textured soils were found to be much less likely to contain deep roots than coarse or fine-textured soils (Fig. 4). This difference may at least partly be related to the capacities of soils to store plant-available water (PAW). Coarse-textured soils have lower field- and PAW capacities than medium-textured soils (Saxton et al., 1986), leading to deeper infiltration depths and potentially deeper rooting depths (Jackson et al., 2000). Our database includes few root profiles from weathered bedrock, for which a similar reasoning should apply. The low field and PAW capacities of rock, as well as preferential water flow along fissures, are likely to also cause deep rooting (Witty et al., 2003) and this may explain the occurrence of deep roots in some arid and semiarid systems for which they are not predicted by our model (Jackson et al., 2002).

The high probability of fine-textured soils to contain deep roots may be due to a combination of factors, depending on climate. Fine-textured soils in arid climates can develop deep fissures during soil drying, which support deep water infiltration at the beginning of the rainy season (Hillel, 1998; Scanlon et al., 1999) and may support deep rooting in these fissures. Fine-textured soils in wet tropical climates lack such fissures, but they often have relatively low PAW capacities (van den Berg et al., 1997) and they support forest vegetation which has low tolerance for even moderate water-stress (Maherali et al., 2004) and which may therefore not be able to deplete soil water contents as much as vegetation in drier climates. In addition, soils affect roots and root distributions in many ways, and some of the observed differences may well be due to effects of nutrient availability or other factors. Unfortunately, detailed information on soil profiles was not available for most of the data sets in the root databases.

According to our models' predictions, deep roots are expected to be most common in tropical areas, with the deep saprolites of humid to per-humid tropical regions being less likely to contain deep roots than deep regoliths and deeply weathered bedrock in semiarid to subhumid tropical regions. Unfortunately, data on rooting depths from tropical regions are sparse and soils in these regions have been rarely deeply sampled (but see Moreira et al., 2000; Nepstad et al., 1994; Sommer et al., 2000). Systematic and deep samples of roots in tropical regions along climatic gradients are urgently needed for a better understanding of the hydrology and biogeochemistry of these regions.

In this study, we used climate and soil texture as predictors for the probability of deep rooting because direct measurements of rooting depths are not available for many regions of the Earth. The empirical models that were used for these predictions fitted the data well and also conformed to the predictions made previously based on theoretical considerations (Schenk and Jackson, 2002b). This gives us confidence that the global map depicted in Fig. 5 is a reasonable spatially explicit hypothesis for the global distribution of deep roots. This map should be tested by further deep and systematic sampling of root profiles, preferably along predicted gradients in rooting depths.

List of abbreviations, acronyms, and symbols used in this paper

D_{95}	depth containing 95% of all roots in a soil profile (m)
D_I	maximum rooting depth for an individual plant i (m)
PAW	Plant-available water
$P(D_{\mathrm{deep}})$	the probability of deep rooting for a given area or a given climate type
$\mathrm{PET_a}$	mean annual evapotranspiration (m year^{-1})
$\mathrm{PET_m}$	mean monthly potential evapotranspiration (m month^{-1})
R_a	mean annual precipitation (m year^{-1})
R_m	mean monthly precipitation (m month^{-1})
RPGE	a data set of root profiles from global ecosystems
RSIP	a global data set of the sizes of root systems of individual plants
S_a	annual water storage index (m year^{-1}), defined in Eq. (3)
U	soil texture category (fine, medium, or coarse)
W_{def}	the long-term mean, seasonal deficit of water, defined in Eq. (5)
W_{sur}	the long-term, mean seasonal surplus of water, defined in Eq. (4)

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References

Bailey, T.C., Gatrell, A.C., 1995. Interactive Spatial Data Analysis. Longman Scientific & Technical, Harlow, UK. 413 pp.

Bormann, B.T., Wang, D., Bormann, F.H., Benoit, G., April, R., Snyder, M.C., 1998. Rapid, plant-induced weathering in an aggrading experimental ecosystem. Biogeochemistry 43 (2), 129–155.

Brady, N.C., Weil, R.R., 2001. The Nature and Properties of Soil. Prentice Hall, Upper Saddle River, NJ. 960 pp.

Canadell, J., Jackson, R.B., Ehleringer, J.R., Mooney, H.A., Sala, O.E., Schulze, E.D., 1996. Maximum rooting depth of vegetation types at the global scale. Oecologia 108 (4), 583–595.

Choudhury, B.J., 1997. Global pattern of potential evaporation calculated from the Penman–Monteith equation using satellite and assimilated data. Remote Sens. Environ. 61, 64–81.

Choudhury, B.J., DiGirolamo, N.E., 1998. A biophysical process-based estimate of global land surface evaporation using satellite and ancillary data: I. Model description and comparison with observations. J. Hydrol. 205 (3–4), 164–185.

De Fries, R.S., Hansen, M., Townshend, J.R.G., Sohlberg, R., 1998. Global land cover classifications at 8 km spatial resolution: the use of training data derived from Landsat imagery in decision tree classifiers. Int. J. Remote Sens. 19 (16), 3141–3168.

Hansen, M.C., DeFries, R.S., Townshend, J.R.G., Sohlberg, R., 2000. Global land cover classification at 1 km resolution using a classification tree approach. Int. J. Remote Sens. 21 (6/7), 1331–1364.

Hillel, D., 1998. Environmental Soil Physics. Academic Press, San Diego. 771 pp.

Jackson, R.B., Canadell, J., Ehleringer, J.R., Mooney, H.A., Sala, O.E., Schulze, E.D., 1996. A global analysis of root distributions for terrestrial biomes. Oecologia 108 (3), 389–411.

Jackson, R.B., Moore, L.A., Hoffmann, W.A., Pockman, W.T., Linder, C.R., 1999. Ecosystem rooting depth determined with caves and DNA. Proc. Natl. Acad. Sci. U. S. A. 96, 11387–11392.

Jackson, R.B., Sperry, J.S., Dawson, T.E., 2000. Root water uptake and transport: using physiological processes in global predictions. Trends Plant Sci. 5 (11), 482–488.

Jackson, R.B., Banner, J.L., Jobbágy, E., Pockman, W.T., Wall, D.H., 2002. Ecosystem carbon loss with woody plant invasion of grasslands. Nature 418, 623–626.

Johnson-Maynard, J.L., Graham, R.C., Wu, L., Shouse, P.J., 2002. Modification of soil structure and hydraulic properties after 50 years of imposed chaparral and pine vegetation. Geoderma 110, 227–240.

Kleidon, A., Heimann, M., 1998. A method of determining rooting depth from a terrestrial biosphere model and its impacts on the global water and carbon cycle. Glob. Chang. Biol. 4 (3), 275–286.

Maherali, H., Pockman, W.T., Jackson, R.B., 2004. Adaptive variation in the vulnerability of woody plants to xylem cavitation. Ecology 85 (8), 2184–2199.

Moreira, M.Z., Sternberg, L.d.S.L., Nepstad, D., 2000. Vertical patterns of soil water uptake by plants in a primary forest and an abandoned pasture in the eastern Amazon: an isotopic approach. Plant Soil 222, 95–107.

Nepstad, D.C., de Carvalho, C.R., Davidson, E.A., Jipp, P.H., Lefebvre, P.A., Negreiros, G.H., da Silva, E.D., Stone, T.A., Trumbore, S.E., Vieira, S., 1994. The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. Nature 372 (6507), 666–669.

Richter, D.D., Markewitz, D., 1995. How deep is soil? Bioscience 45 (9), 600–609.

Saxton, K.E., Rawls, W.J., Romberger, J.S., Papendick, R.I., 1986. Estimating generalized soil–water characteristics from texture. Soil Sci. Soc. Am. J. 50 (4), 1031–1036.

Scanlon, B.R., Langford, R.P., Goldsmith, R.S., 1999. Relationship between geomorphic settings and unsaturated flow in an arid setting. Water Resour. Res. 35 (4), 983–999.

Schenk, H.J., Jackson, R.B., 2002a. The global biogeography of roots. Ecol. Monogr. 72 (3), 311–328.

Schenk, H.J., Jackson, R.B., 2002b. Rooting depths, lateral spreads, and below-ground/above-ground allometries of plants in water-limited ecosystems. J. Ecol. 90 (3), 480–494.

Shalyt, M.S., 1950. Podzemnaja cast' nekotorykh lugovykh, stepnykh i pustynnykh rastenyi i fitocenozov. C. I. Travjanistye i polukustarnigkovye rastenija i fitocenozy lesnoj (luga) i stepnoj zon (Belowground parts of some meadow, steppe, and desert plants and plant communities: Part I. Herbaceous plants and subshrubs and plant communities of forest and steppe zones. In Russian). Tr. Bot. Inst. Im. V.L. Komarova, Akad. Nauk SSSR, Ser. III Geobot. 6, 205–442.

Sokal, R.R., Rohlf, F.J., 1995. Biometry: The Principle and Practice of Statistics in Biological Research. W.H. Freeman, New York. 887 pp.

Sommer, R., Denich, M., Vlek, P.L.G., 2000. Carbon storage and root penetration in deep soils under small-farmer land-use systems in the Eastern Amazon region, Brazil. Plant Soil 210, 231–241.

Sternberg, L.d.S.L., Green, L.V., Moreira, M.Z., Nepstad, D., Martinelli, L.A., Victória, R., 1998. Root distribution in an Amazonian seasonal forest as derived from δ^{13}C profiles. Plant Soil 205 (1), 45–50.

UNEP (Ed.), 1992. World Atlas of Desertification. United Nations Environment Programme. Edward Arnold, London, Baltimore. 69 pp.

van den Berg, M., Klamt, E., van Reeuwijk, L.P., Sombroek, W.G., 1997. Pedotransfer functions for the estimation of moisture retention characteristics of Ferrasols and related soils. Geoderma 78, 161–180.

Weaver, J.E., Darland, R.W., 1949. Soil–root relationships of certain native grasses in various soil types. Ecol. Monogr. 19 (4), 303–338.

Witty, J.H., Graham, R.C., Hubbert, K.R., Doolittle, J.A., Wald, J.A., 2003. Contributions of water supply from the weathered bedrock zone to forest soil quality. Geoderma 114 (3–4), 389–400.

Zobler, L., 1986. A world soil file for global climate modeling. NASA Technical Memorandum, TM-87802. National Aeronautics and Space Administration, Washington, DC, 33 pp.