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# Maximum rooting depth of vegetation types at the global scale

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**Abstract** The depth at which plants are able to grow roots has important implications for the whole ecosystem hydrological balance, as well as for carbon and nutrient cycling. Here we summarize what we know about the maximum rooting depth of species belonging to the major terrestrial biomes. We found 290 observations of maximum rooting depth in the literature which covered 253 woody and herbaceous species. Maximum rooting depth ranged from 0.3 m for some tundra species to 68 m for *Boscia albitrunca* in the central Kalahari; 194 species had roots at least 2 m deep, 50 species had roots at a depth of 5 m or more, and 22 species had roots as deep as 10 m or more. The average for the globe was 4.6±0.5 m. Maximum rooting depth by biome was 2.0±0.3 m for boreal forest, 2.1±0.2 m for cropland, 9.5±2.4 m for desert, 5.2±0.8 m for sclerophyllous shrubland and forest, 3.9±0.4 m for temperate coniferous forest, 2.9±0.2 m for temperate deciduous forest, 2.6±0.2 m for temperate grassland, 3.7±0.5 m for tropical deciduous forest, 7.3±2.8 m for tropical evergreen forest, 15.0±5.4 m for tropical grassland/savanna, and 0.5±0.1 m for tundra. Grouping all the species across biomes (except croplands) by three basic functional groups: trees, shrubs, and herbaceous plants, the maximum rooting depth was 7.0±1.2 m for trees, 5.1±0.8 m for shrubs, and 2.6±0.1 m for herbaceous plants. These data show that deep root habits are quite common in woody and herbaceous species across most of the terrestrial biomes, far deeper than the traditional view has held up to now. This finding has important implications for a better understanding of ecosystem function and its application in developing ecosystem models.

**Key words** Deep roots function · Terrestrial vegetation · Biomes · Plant forms · Root depth

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## Introduction

There is good evidence that some plant species are able to send roots very deep in the soil. This pattern is indicated by plants that grow well into the summer drought and by desert plants that grow for years with minimal or no rainfall (Batanouny and Abdel Wahab 1973; Poole and Miller 1975). In fact, survivorship of some species in arid systems has been shown to depend completely on a plant's ability to tap water from permanent water tables, which are sometimes located at depths of 18 m or more (Rawitscher 1948; Lewis and Burghy 1964). In addition, there have been direct observations of roots at depths below 2–3 m in caves, road cuts, mine shafts and trenches, and in some instances, roots of woody species have been seen exceptionally deep in the soil. This is the case of *Boscia albitrunca* and *Acacia erioloba* whose roots have been found at a depth of 68 m and 60 m, respectively, in the central Kalahari, Botswana (Jennings 1974), and the case of mesquite roots (*Prosopis juliflora*) found at 53 m deep in the Sonoran Desert, United States (Phillips 1963). Similarly, Stone and Kalisz (1991) reported 11 tree species rooted below 20 m depth. Hence, we know of the potential of some species to have very deep roots at few sites, yet very little is known about how common the habit of deep rooting is across species and environments.

There are two main reasons why this below-ground aspect of ecosystem structure, with its important functional implications, has been under-emphasized. First of all, there are a number of studies on root biomass distribution that show that most of the root biomass occurs within the first 50 cm of the soil, and that only a minimal fraction reaches depths below that depth (for a recent review see Jackson et al. 1996). Therefore, it has been assumed that a good understanding of the role of the root system regarding structure and function at the ecosystem level can be achieved by studying only the first 0.5 m of soil. Secondly, after a whole century of research on root systems, the means of obtaining data on root distribution and structure has not changed substantially: methods include the manual digging of trenches, the use of various mechanical excavation devices, dynamite, or high pressure water. When it comes to looking at patterns of maximum rooting depth, some of that technology is not even sufficient to provide access to deeper soil layers.

The functional significance of deep roots and their contribution to whole-ecosystem processes is still poorly understood. However, there is an increasing body of research in this field that shows the major role of deep roots, particularly for ecosystem water fluxes, as well as for carbon and nutrient cycling (Nepstad et al. 1994; Fisher et al. 1994; Richter and Markewitz 1985; Trumbore et al. 1995; Dawson 1996; Schulze et al. 1996).

The main objective of this review is to summarize what we know about the maximum rooting depth of the major terrestrial biomes ranging from tundra to tropical forest. The data set presented here provides information on plant structure which is relevant for a better mechanistic understanding of ecosystem function.

## Methods

We selected references which had species- or community-level information on root depth below 1.0 m, except for the tundra biome for which we considered all depths because permafrost usually limits root growth beyond 30–50 cm. Here we included references from journal papers, books, reports, and unpublished data when relevant, which cover all continents except Antarctica. The major biomes we considered were: boreal forest, croplands, desert, sclerophyllous shrubland and forest, temperate coniferous forest, temperate deciduous forest, temperate grassland, tropical deciduous forest, tropical evergreen forest, tropical grassland/savanna, and tundra. The species were grouped by biome which means that in some instances two different functional groups, such as grasses and shrubs, may be in the same biome category. This was the case of the tropical grasslands and savannas where both herbaceous and woody species occur together. Similarly, in the temperate grassland we also found a few common shrub species along with the bulk of herbaceous plants. Finally, root data for the commonest agricultural crops were collected, including wheat, soybean, alfalfa, barley, and a few other species.

For each rooting depth observation, we recorded the species from which the observation was made, and the community's dominant species when roots were not identified at the species level. For most of the references, the maximum root depth observed corresponded with the depth of the trench, road cut, mine pit, or other excavation, and it is safe to say that roots probably reached much deeper layers than those recorded. Almost all the data presented here came from direct observations of roots in road cuts, mine shafts, open-cut mines and trenches, and only a few values were inferred from the results of isotopic trace studies or plant and soil water potential measurements. Finally, we also recorded the soil type or any soil textural attribute available to characterize the soil environment in which roots were growing.

## Results and discussion

### Maximum rooting depth across biomes

We compiled a total of 290 observations of rooting depth which covered 253 different plant species from 11 biomes around the world. From this data set, 194 species had roots at least 2 m deep, 50 species had roots at a depth of 5 m or more, and 22 species had roots as deep as 10 m or more (Appendix 1). The average maximum rooting depth for the globe was 4.6±0.5 m, and the individual maximum rooting depth was 68 m for *Boscia albitrunca*, the roots of which were found during well drilling in deep sandy soils in the central Kalahari, Botswana (Jennings 1974). The ten deepest rooting species were in decreasing order: *Boscia albitrunca* (68 m), *Acacia erioloba* (60 m), *Prosopis juliflora* (53 m), *Eucalyptus marginata* (40 m), *Retama raetam* (20 m), *Tamarix aphylla* (20 m), *Andira humilis* (18 m), *Alhagi maurorum* (15 m), *Prosopis farcta* (15 m), and *Prosopis glandulosa* (15 m).

Figure 1 shows the maximum rooting depth for all species across biomes in which only the deepest rooting depth is plotted when a given species has more than one observation. Maximum rooting depth by biome was 2.0±0.3 m ($n$ = 6; highest value = 3.3 m) for boreal forest, 2.1±0.2 m ($n$ = 17; highest value = 3.7 m) for cropland, 9.5±2.4 m ($n$ = 22; highest value = 53 m) for desert, 5.2±0.8 m ($n$ = 57; highest value = 40) for sclerophyllous shrubland and forest, 3.9±0.4 m ($n$ = 17; highest value = 7.5 m) for temperate coniferous forest, 2.9±0.2 m ($n$ = 19; highest value = 4.4 m) for temperate deciduous forest, 2.6±0.2 m ($n$ = 82; highest value = 6.3 m) for temperate grassland, 3.7±0.5 m ($n$ = 5; highest value = 4.7 m) for tropical deciduous forest, 7.3±2.8 m ($n$ = 5; highest value = 18 m) for tropical evergreen forest, 15.0±5.4 m ($n$ = 15; highest value = 68 m) for tropical grassland/savanna, and 0.5±0.1 m ($n$ = 8; highest value = 0.9 m) for tundra.

Grouping all the species across biomes (except croplands) by three basic functional groups: trees, shrubs, and herbaceous plants, the maximum rooting depth was 7.0±1.2 m ($n$ = 82) for trees, 5.1±0.8 m ($n$ = 69) for shrubs, and 2.6±0.1 m ($n$ = 85) for herbaceous plants (Fig. 2).

Although differences are large among biomes, there are also important departures from the mean rooting depth pattern within a biome. In the boreal forest, for instance, the water table usually limits the downward growth of roots of *Larix laricina* and *Picea mariana*, whose roots are commonly found no deeper than 0.3 m. Other species, however, do have the capacity to grow below the water table down to a depth of 2 m (Strong and La Roi 1983).

Plants from arid environments or from environments with a long dry season showed the deepest rooting habits of all. The presence of water at deep layers makes it possible for some plants to survive in the rainshadow environments by tapping water from layers as deep as 53 m in the desert of the southwestern United States (Phillips

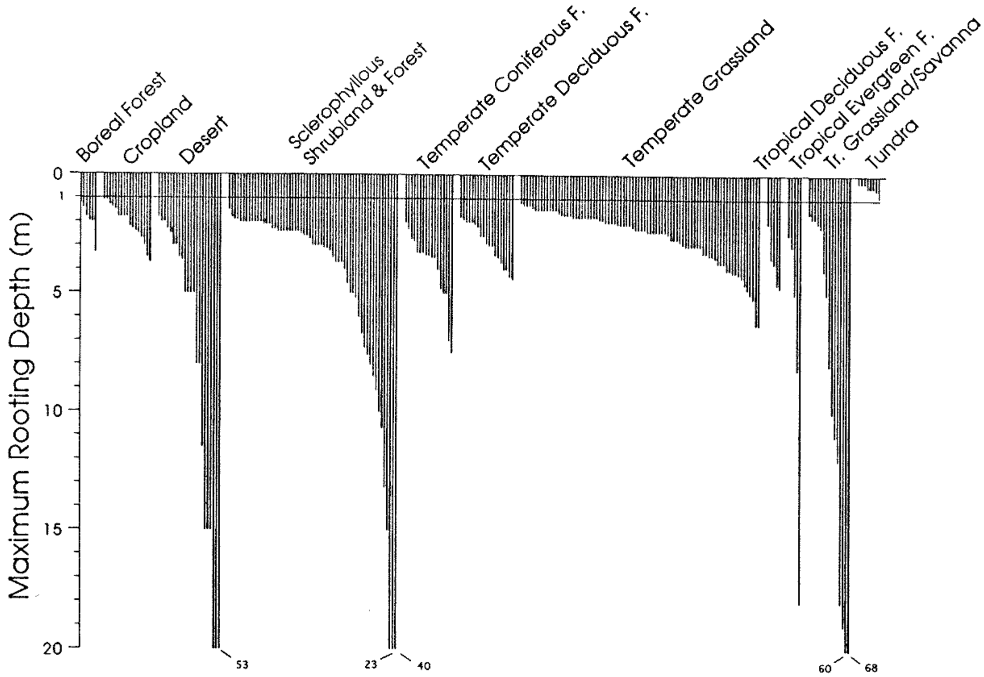


Fig. 1 Reported species maximum rooting depth (m) grouped by terrestrial biome. When there are more than one observations for a given species, only the maximum value is plotted

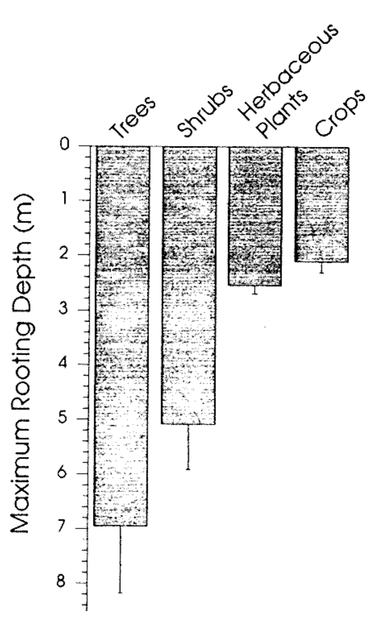


Fig. 2 Mean and SE of reported maximum rooting depth (m) by three major functional groups (trees, shrubs, and herbaceous plants) and crops

1963), and from 68 m deep, possibly even from 140 m deep where the water table was located, in the dry savanna of the central Kalahari (Jennings 1974). Likewise a group of species which also has a consistent pattern of deep rooting is that of the sclerophyllous trees, mostly made up of *Eucalyptus* spp. and *Quercus* spp. from the various Mediterranean regions of the world. The mean maximum rooting depth for sclerophyllous trees is 12.6±3.4 m ($n$ = 11), with *E. marginata* in Australia the deepest of all at about 40 m (Dell et al. 1983). Sclerophyllous shrubs, although with deep rooting habits, has a shallower rooting pattern with a maximum rooting depth of 3.5±0.3 m ($n$ = 48).

It is generally thought that roots in the evergreen tropical forest tend to be very shallow, but in this review the mean maximum rooting depth of 6 observations is 6.5±2.5 m. The only study that presented data from a depth beyond a few meters in the tropical forests of Brazil found roots all the way down to 18 m deep (Nepstad et al. 1994).

Another surprising result is the depth to which roots of herbaceous plants can descend, that was 2.4±0.1 m as average in this review. Weaver (1919) has published the most complete study to date, on rooting depth habits of herbaceous plants in a prairie in Nebraska, United StatesA. Of 33 species he studied, 18 species have roots that extend beyond depths of 1.5 m, most of them between 2.1 m and 2.7 m, and few to a maximum depth of from 4 m to 6.1 m.

These results offer plenty of evidence that many plant species have the capacity for deep rooting in the soil, and they provide enough data to challenge the dogma that plants are shallow rooted. Here we have presented, however, data on maximum rooting depth for individuals with the greatest depth. This value represents the observed maximum capacity of a given species to send roots deep into the soil, depths which may be reached by a small number of species and/or individuals within a community. In addition, an average or community weighted maximum rooting depth would also be functionally significant, yet data regarding this are hardly available for any biome. To illustrate the differences between absolute and average maximum rooting depth we shall present data from the root atlas published by Kutschera (1960). A random selection of 69 dicotyledonous species from grasslands in Mid Europe have an average maximum rooting depth of 1.1 m, the average of the 10 deepest species is 4.2 m and the absolute maximum rooting depth is 6.3 m. The average maximum rooting depth, which is the measurement most relevant to ecosystem functioning, will depend on species composition and density, and soil characteristics, all of which are fairly variable in space.

## Getting very deep

Plants show a variety of root types through which they have access to deep soil layers. The most common are tap roots, sinker roots and obliquely descending lateral roots, all of them important adaptations for reaching deep soils. The phenotypic expression of these root types is species dependent, but environmental conditions may completely change root structure, architecture, and depth to which roots are able to descend (Feldman 1984). Tap roots are probably the most specialized root type to access and transport water from deep soil horizons. Tap roots are very common across species and they were found in up to 75% of tropical trees (Klinge 1973), in 73 of 100 Mediterranean woody species (Canadell and Zedler 1995), and in 19 of 30 herbaceous species in the Rocky Mountains foothills, United States (Holch et al. 1941).

The downward growth of roots can be limited by a variety of factors, such as soil bulk density or shallow bedrock, but probably the most efficient barriers are horizontally stratified layers of shale or clay, permafrost, and water table (Dennis et al. 1978; Bennie 1991). There is a common notion that deep roots are mainly limited to sandy loose soils where mechanical impedance to root penetration is least. On the contrary, we have reported in this review a number of examples in which plants have found their way down to very deep layers, even in compact clay and rocky soils, and through hard pans (Appendix 1).

Bedrock and heavy clay soils allow varying degrees of deep root penetration through highly weathered material or through a network of cracks, fissures and channels. Channels, or low resistance pathways, are permanent features of the soil profile, and it has been suggested that they result from dissolution of laterite by humic acid produced by the root itself (Plum and Gosting 1973). Gaiser (1952) found more than 10,000 cavities and root channels per hectare in a hardwood forest in Ohio, United States, pathways that can be reused and expanded by each new generation of trees. Hence, the soil volume should be viewed as a complex network of fissures, cracks and channels on which new root growth largely depends. It has even been suggested that soil compaction in forests may not affect the overall forest productivity, provided that sufficient low resistance pathways allow adequate root development (Nambiar and Sands 1992).

Roots have also been observed penetrating through hard pans and caliche layers in a variety of systems (Silva et al. 1989; Dawson 1993; Day 1994), and into rocks through fissures and cracks (Hellmers et al. 1955, Davis and Pase 1977). Pre-existing old tree channels and earthworm tunnels have also been shown to be important in the downward root development in crop systems (Nambiar and Sands 1992; Nicoullaud et al. 1994).

Finally, some plants find their way deep into the soil by penetrating directly through the bedrock. This phenomenon has been reported for several Mediterranean woody species growing on porous calcareous soils in Israel (Oppenheimer 1958; Orshansky 1951).

## Ecological significance of deep roots

Although a small fraction of root biomass might be found at depths below 1 m, the functional significance of those roots may nevertheless be most important for ecosystem water and carbon fluxes, and nutrient cycling.

The water extracted by plants during the wet season comes from shallow layers where the root density is highest. However, as those layers dry there is a progressive shift towards using deeper water, which allows plants to keep stomata open and extend growth far into the dry season (for review see Gardner 1983). Although we know of the differential water sources in the soil profile, there are very few studies which have quantified the contribution of deep water to the whole ecosystem fluxes. Gregory et al. (1978) showed for winter wheat that few roots below 1 m (about 3% of the total root weight) were responsible for supplying 20% of the transpired water during dry periods. In an Amazonian tropical forest, Nepstad et al. (1994) found that had not considered roots deeper than 2 meters they would have underestimated evapotranspiration by >60% during the dry season. The water available to plants stored below 2 m in the soil provided >75% of the water extracted from the entire soil profile.

There is also plenty of evidence that plants with different rooting habits show different seasonal courses of water potential, and that the duration of water stress and the distribution of soil moisture with depth will determine whether a species can succeed in a particular environment (Davis and Mooney 1986; Crombie et al. 1988; Sala et al. 1989; Hodgkinson 1992).

For some species (e.g., phreatophytes), survival in arid systems depends exclusively on the capacity to send roots to permanent water tables, as in the case of *Prosopis tamarugo* in the virtually rainless Atacama Desert in Chile (Mooney et al. 1980). Stone and Kalisz (1991) gathered thirty references of plants having contact with water tables at depths from 1.5 to 35 m. In these cases, even if a very small fraction of the roots are tapping water from the water table, the amount of water transferred into the plant may be large. Reicosky et al. (1964) showed that roots tapping water from the water table are hundreds of times more efficient in absorbing it than roots in drier soil. Furthermore, tap roots often show cross sections with a high number of vessels per unit area, indicating a major water transport function (Higgins et al. 1987; see also Pate et al. 1995).

The functional significance of deep roots for water flux in ecosystems under high evaporative conditions has been shown regarding the "hydraulic lift" mechanism which has been reported for several species (Richards and Caldwell 1987; Caldwell and Richards 1989; Dawson 1993). During the night roots take up water from deep soil layers which is released from shallow roots back to the soil in the upper layers. The water is reabsorbed during the next day by the same plants and by shallow-rooted neighbors with no access to deep water. This mechanism has important ecological significance, allowing plants to maintain high transpiration rates during dry periods. Caldwell and Richards (1989) showed that hydraulic lift was responsible for a 30–50% increase of the daytime canopy water flux in artificial mixtures of *Artemisia tridentata* and *Agropyron desertorum* (see also Dawson 1996).

Unlike water relations, much less is known about the contribution of deep soil nutrients to the overall plant nutritional demands. Richter and Markewitz (1995) showed the importance of biological processes in weathering materials in a 8 m-soil profile of a *Pinus taeda* forest in South Carolina, United States; the biological processes were tightly associated with soil influenced by root activity (rhizosphere) all along the soil profile. The importance of deep roots for ecosystem nutrient cycling has also been shown for tropical soils with seasonal drought, Cerrado (Schachtschabel et al. 1992). Nitrate salts from mineralization of organic matter cannot be fully utilized by the vegetation early in the rainy season, and so, are washed out of the top soil down to deep soil horizons. There, nitrate is immobilized by the positive charge balance of $Fe^{3+}$ and $Al^{3+}$ found at depths of 1.6 m or more; deep roots will then have access to this nitrate store later in the growing season.

In the deep rhizosphere of *Prosopis glandulosa* in the Chihuahuan desert, United States, a variety of microarthropod taxa has been found down to a depth of 13 m (Silva et al. 1989). The abundance of microarthropods was positively correlated with root biomass, which suggests that deep rhizosphere processes such as decomposition and mineralization operate in a similar way to those processes in shallow layers. It is also known that plant-feeding nematodes, which are found deep in the rhizosphere, increase nodulation and nitrogen fixation (Huang 1987), and provide infection sites for vesicular-arbuscular mycorrhizal fungi (Freckman and Virginia 1989). In fact, Jenkins et al. (1988) found $N_2$-fixing root nodules at a depth of 7 m in the Chihuahuan desert.

Deep roots, in addition to extract water and contribute to the cycling of nutrients, also provide carbon to the soil. In an Amazonian tropical forest Nepstad et al. (1994) found that deep soil layers below 1 m contain large active carbon stocks, 15% of which turns over on annual to decadal timescale. The possession of an active carbon cycle at depth seems to be fairly common in the highly wheathered soils in terra firme tropical forest of Amazonia (Trumbore et al. 1995), but almost nothing is known about how common it might be in other biome types.

Ecosystem models which predict carbon sequestration have conventionally used root functional depths between 0.3 m and 2.0 m, which are usually used as fixed factors that do not change or only change for different ecosystem types. The depth at which roots will decay and decompose is essential for determining the ultimate fate of that carbon, and therefore, the capacity of carbon sequestration by different ecosystems. Fisher et al. (1994) showed that increased abundance of introduced deep-rooted grasses in the tropical South American savannas account for an increased sequestration of 100–507 Mt carbon per year, which could explain a substantial part of the missing carbon-sink (Siegenthaler and Sarmiento 1993).

In this review we have shown that deep root habits are quite common in woody and herbaceous species across most of the terrestrial biomes. Roots commonly reach far deeper into the soil than the traditional view has held up to now. This structural trait has important implications for ecosystem water fluxes, as well as for carbon and nutrient cycling, and hence should be appropriately taken into account in the development of ecosystem models.

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**Appendix 1** Reported maximum rooting depth (m) by species with soil type, country and reference grouped by biome

| Species/ dominant species[a] | Maximum rooting depth (m) | Soil type | Country | Reference |
|---|---|---|---|---|
| *BOREAL FOREST* | | | | |
| *Latrix laricina* | 1.2 | medium-coarse sand/podzol | S-Canada | Bannan 1940 |
| *Latrix sibirica* | 1.8 | medium-loamy | Russia | Verzunov 1980 |
| *Picea glauca* | 1.8 | medium-loamy | Russia | Verzunov 1980 |
| *Pinus banksia* | 1.2 | medium-coarse sand/podzol | S-Canada | Bannan 1940 |
| *Pinus banksiana* | 2.0 | aeolian sands/Eutric brunisol | S-Canada | Strong and La Roi 1983 |
| *Pinus contorta* | 3.3 | – | S-Canada | Horton 1958 |
| *Populus tremuloides* | 2.0 | sandy substrate | S-Canada | Strong and La Roi 1983 |
| *CROPS* | | | | |
| *Andropogon sorghum* | 1.1 | lowland silt loam | Nebraska, USA | Weaver 1926 |
| *Avena sativa* | 1.8 | – | Kansas, USA | Weaver 1926 |
| *Beta vulgaris* | 1.8 | sandy loam | Nebraska, USA | Weaver 1926 |
| *Bromus inermis* | 1.1 | silty-clay to clay-loam alluvial | Canada | Leyshon 1991 |
| *Elymus angustus* | 3.5 | – | S-Canada | Lawrence 1975 |
| *Elymus junceus* | 1.8 | – | S-Canada | Lawrence 1975 |
| *Glycine max* | 1.8 | Muir silt loam | Kansas, USA | Mayaki et al. 1976 |
| *Helianthus annuus* | 2.7 | lowland silt loam | Nebraska, USA | Weaver 1926 |
| *Helianthus annuus* | 2.7 | Muir silt loam from alluvium | Kansas, USA | Jaafar et al. 1993 |
| *Hordeum vulgare* | 1.3 | Lowland silt loam | Nebraska, USA | Weaver 1926 |
| *Hordeum sp.* | 2.2 | loamy sand/Xeric Psamment | W-Australia | Hamblin and Tennant 1987 |
| *Lupinus angustifolius* | 2.5 | loamy sand/Xeric Psamment | W-Australia | Hamblin and Tennant 1987 |
| *Medicago sativa* | 3.7 | – | Nebraska, USA | Weaver 1926 |
| *Secale cereale* | 1.5 | silt loam/hard clayey subsoil | Nebraska, USA | Weaver 1926 |
| *Solanum tuberosum* | 1.4 | mellow loess soil | Nebraska, USA | Weaver 1926 |
| *Triticum aestivum* | 1.0 | – | England | Welbank et al. 1974 |
| *Triticum aestivum* | 1.4 | Muir silt loam | Kansas, USA | Chaudhuri et al. 1990 |
| *Triticum aestivum* | 1.5 | lowland silt loam | Nebraska, USA | Weaver 1926 |
| *Triticum aestivum* | 1.8 | – | Mid Europe | Kutschera 1960 |
| *Triticum aestivum* | 3.0 | loamy sand/Xeric Psamment | W-Australia | Hamblin and Tennant 1987 |
| *Triticum durum* | 2.3 | loess soil | Nebraska, USA | Weaver 1926 |
| *Zea mays* | 1.3 | deep clay loam | E-France | Pages and Pellerin 1994 |
| *Zea mays* | 2.4 | – | Nebraska, USA | Weaver 1926 |
| *DESERT* | | | | |
| *Alhagi maurorum* | 15.0 | river banks | Israel | Shmueli 1948 |
| *Artemisia monosperma* | 5.0 | sand dunes | Israel | Zohary and Fahn 1952 |
| *Artemisia tridentata* | 1.8 | shale/sandstone bedrock | Colorado, USA | Branson et al. 1976 |
| *Artemisia tridentata* | 2.2 | loamy-skeletal/Haploxerolls | Utah, USA | Richards and Caldwell 1987 |
| *Artemisia tridentata* | 2.3 | aeolian sandy loam | Idaho, USA | Reynolds and Fraley 1989 |
| *Atriplex halimus* | 8.0 | alluvia soils/run-on habitats | Israel | Zohary 1961 |
| *Chrysothamnus vicidiflorus* | 2.0 | aeolian sandy loam | Idaho, USA | Reynolds and Fraley 1989 |
| *Franseria deltoidea* | 1.8 | wash with hardpan (caliche) | Arizona, USA | Cannon 1911 |
| *Hammada salicornica* | 2.5 | sand dunes | Israel | Zohary and Orshan 1949 |
| *Leptadenia pyrotechnica* | 11.5 | sandy and silty/clay at depth | Egytp | Batanouny and Wahab 1973 |
| *Leymus cinereus* | 2.0 | aeolian sandy loam | Idaho, USA | Reynolds and Fraley 1989 |
| *Mulinum spinosum*[a] | 3.0 | fine sand/caliche layer at 0.6 m | S-Argentina | Schulze et al. 1996 |
| *Nassauvia glomerulosa*[a] | 3.0 | sandy loam/caliche at 0.7 m | S-Argentina | Schulze et al. 1996 |
| *Nitraria retusa* | 5.0 | sandy | Israel | Ginzburg 1966 |
| *Ochradenus baccatus* | 5.0 | sandy | Israel | Ginzburg 1966 |
| *Prosopis farcta* | 15.0 | river banks | Israel | Zohary and Orshan 1949 |
| *Prosopis glandulosa* | 2.0 | Nuvalde clay loam | Texas, USA | Heitschmidt et al. 1988 |
| *Prosopis glandulosa* | 6.0 | clay loam/sand, clay at depth | California, USA | Nilsen et al. 1983 |
| *Prosopis glandulosa* | 12.0 | sandy/Torrifluvent | New Mexico, USA | Freckman and Virginia 1989 |
| *Prosopis glandulosa* | 15.0 | clay loam | New Mexico, USA | Silva et al. 1989 |
| *Prosopis juliflora* | 53.0 | – | Arizona, USA | Phillips 1963 |
| *Prosopis tamarugo* | 3.5 | – | N-Chile | Mooney et al. 1980 |
| *Prosopis velutine* | 8.0 | – | Arizona, USA | Cannon 1911 |
| *Retama raetam* | 20.0 | sand dunes | Israel | Zohary and Fahn 1952 |
| *Tamarix aphylla* | 20.0 | alluvial soils/run-on habitats | Israel | Zohary 1961 |
| *Tamarix pentantra* | 3.6 | alluvial banks | Arizona, USA | Gary 1963 |
| *Zilla spinosa* | 5.0 | – | Israel | Ginzburg 1966 |

**Appendix 1** (continued)

| Species/ dominant species[a] | Maximum rooting depth (m) | Soil type | Country | Reference |
|---|---|---|---|---|
| *SCLEROPHYLLOUS SHRUBLAND AND FOREST* | | | | |
| *Shrubs* | | | | |
| *Adenostoma fasciculatum* | 2.4 | silt sandy | California, USA | Hanes 1965 |
| *Adenostoma fasciculatum* | 7.6 | sandy loam on anorthosiste | California, USA | Hellmers et al. 1955 |
| *Adenostoma sparsifolium* | 2.4 | silt sandy | California, USA | Hanes 1965 |
| *Arbutus unedo* | 3.5 | sandy loam | NE Spain | J Canadell, unpublished work |
| *Arctostaphylos glandulosa* | 5.2 | sandy loam on granodiorite | California, USA | Hellmers et al. 1955 |
| *Arctostaphylos glauca* | 2.6 | sandy loam on granodiorite | California, USA | Hellmers et al. 1955 |
| *Arctostaphylos glutinosa* | 2.5 | shallow on fractured shales | California, USA | Davis 1972 |
| *Arctostaphylos pallida* | 4.0 | shallow on fractured shales | California, USA | Davis 1972 |
| *Banksia marginata* | 2.4 | sandy | SE-Australia | Specht and Rayson 1957 |
| *Banksia ornata* | 2.4 | sandy | SE-Australia | Specht and Rayson 1957 |
| *Baccharis pilularis* | 3.2 | packed sand like a rock | California, USA | Wright 1928 |
| *Banksia spp.* | 5.0 | podsolized sand | SW-Australia | Low and Lamont 1990 |
| *Calytrix flavescens* | 2.0 | grey sands with hardpan | SW-Australia | Dodd et al. 1984 |
| *Casuarina muelleriana* | 2.0 | sandy | SE-Australia | Specht and Rayson 1957 |
| *Casuarina pusilla* | 2.4 | sandy | SE-Australia | Specht and Rayson 1957 |
| *Ceanothus leucodermis* | 3.7 | sandy loam on granodiorite | California, USA | Hellmers et al. 1955 |
| *Ceanothus megacarpus* | 2.4 | sandstone with fissures | California, USA | Thomas and Davis 1989 |
| *Ceanothus oliganthus* | 1.8 | clay loam on diorite | California, USA | Hellmers et al. 1955 |
| *Ceanothus spinosus* | 3.1 | sandstone with fissures | California, USA | Thomas and Davis 1989 |
| *Daviesia brevifolia* | 2.0 | sandy | SE-Australia | Specht and Rayson 1957 |
| *Eremaea beaufortioides* | 6.0 | alluvial sand with colluvium | SW-Australia | Hnatiuk and Hopkins 1980 |
| *Eremaea pauciflora* | 2.4 | grey sands with hardpan | SE-Australia | Dodd et al. 1984 |
| *Erica arborea* | 2.0 | sandy loam | NE-Spain | J. Canadell, unpublished work |
| *Hibbertia hypericoides* | 2.1 | grey sands with hardpan | SW-Australia | Dodd et al. 1984 |
| *Jacksonia floribunda* | 3.1 | grey sands with hardpan | SW Australia | Dodd et al. 1984 |
| *Jacksonia furcellata* | 2.0 | grey sands with hardpan | SW Australia | Dodd et al. 1984 |
| *Laudonia behrii* | 2.0 | sandy | SE-Australia | Specht and Rayson 1957 |
| *Leptospermum myrsinoides* | 2.3 | sandy | SE-Australia | Specht and Rayson 1957 |
| *Leucadendron salignum* | 3.0 | loamy medium sand | South Africa | Higgins et al. 1987 |
| *Lithraea caustica* | 5.0 | – | Central Chile | Giliberto and Estay 1978 |
| *Melaleuca scabra* | 2.0 | grey sands with hardpan | SW-Australia | Dodd et al. 1984 |
| *Melaleuca seriata* | 2.1 | grey sands with hardpan | SW-Australia | Dodd et al. 1984 |
| *Petrophile linearis* | 2.0 | grey sands with hardpan | SW-Australia | Dodd et al. 1984 |
| *Photinia arbutifolia* | 2.1 | clay loam on diorite | California, USA | Hellmers et al. 1955 |
| *Phyllota pleurandroides* | 2.3 | sandy | SE-Australia | Specht and Rayson 1957 |
| *Phyllota remota* | 2.4 | sandy | SE-Australia | Specht and Rayson 1957 |
| *Protea neriifolia* | 3.0 | loamy medium sand | South Africa | Higgins et al. 1987 |
| *Protea repens* | 3.0 | loamy medium sand | South Africa | Higgins et al. 1987 |
| *Quercus calliprinos*[a] | 4.6 | terra-rossa on limestone | Israel | Shachori et al. 1967 |
| *Quercus dumosa* | 8.5 | clay loam on diorite | California, USA | Hellmers et al. 1955 |
| *Quercus turbinella* | 6.4 | fracturated granite | Arizona, USA | Davis and Pase 1977 |
| *Quercus turbinella* | 9.1 | alluvial and redish brown | Arizona, USA | Saunier and Wagle 1967 |
| *Quillaja saponaria* | 8.0 | – | Central Chile | Giliberto and Estay 1978 |
| *Rhus glabra* | 6.7 | loess hills | Nebraska, USA | Weaver 1919 |
| *Rhus laurina* | 5.4 | sandstone with fissures | California, USA | Thomas and Davis 1989 |
| *Rhus laurina* | 13.2 | – | California, USA | DeSouza et al. 1986 |
| *Salvia apiana* | 1.5 | coarse, loose gravel | California, USA | Hellmers et al. 1955 |
| *Scholtzia involucrata* | 1.9 | grey sands with hardpan | SW-Australia | Dodd et al. 1984 |
| *Spyridium subochreatum* | 1.9 | sandy | SE-Australia | Specht and Rayson 1957 |
| *Stirlingia latifolia* | 2.6 | grey sands with hardpan | SW-Australia | Dodd et al. 1984 |
| *Xanthorrhoea australis* | 2.4 | sandy | SE-Australia | Specht and Rayson 1957 |
| *Trees* | | | | |
| *Eucalyptus marginata* | 15.0 | lateritic, sandy-clay at depth | SW-Australia | Kimber 1974 |
| *Eucalyptus marginata* | 20.0 | – | SW-Australia | Carbon et al. 1980 |
| *Eucalyptus marginata* | 40.0 | fissured granite, clay subsoil | SW-Australia | Dell et al. 1983 |
| *Eucalyptus regnans* | 2.7 | – | SW-Australia | Incoll 1969 |
| *Eucalyptus signata* | 3.0 | sandy | NE-Australia | Westman and Rogers 1977 |
| *Eucalyptus sp.* | 10.0 | sand dunes | NE-Australia | Westman and Rogers 1977 |
| *Quercus agrifolia* | 10.7 | – | California, USA | Cannon 1914 |
| *Quercus chrysolepis* | 7.3 | sandy loam on granodiorite | California, USA | Hellmers et al. 1955 |
| *Quercus douglasii* | 3.7 | alluvial loam | California, USA | Cannon 1914 |
| *Quercus ilex* | 3.7 | sandstone | NE-Spain | J. Canadell, unpublished work |
| *Quercus wislizenii*[a] | 22.9 | fractured rock | California, USA | Lewis and Burgy 1964 |

**Appendix 1** (continued)

| Species/ dominant species[a] | Maximum rooting depth (m) | Soil type | Country | Reference |
|---|---|---|---|---|
| *TEMPERATE CONIFEROUS FOREST* | | | | |
| *Abies firma* | 3.3 | sandy soil | Japan | Karizumi 1979 |
| *Picea excelsa* | 2.3 | silt loam | Japan | Karizumi 1979 |
| *Pinus densiflora* | 3.4 | silt loam | Japan | Karizumi 1979 |
| *Pinus echinata* | 3.3 | sandy soil | New Jersey, USA | Lull and Axley 1958 |
| *Pinus elliottii* | 3.3 | – | Florida, USA | van Rees and Comerford 1986 |
| *Pinus halepensis*[a] | 7.3 | terra-rossa on limestone | Israel | Shachori et al. 1967 |
| *Pinus halepensis* | 7.5 | weathered granite | NE-Spain | J. Canadell, unpublished work |
| *Pinus luchuensis* | 3.5 | sandy loam | Japan | Karizumi 1979 |
| *Pinus palustris* | 4.8 | Norfold sand deep phase | Florida, USA | Heyward 1933 |
| *Pinus pinaster* | 7.0 | – | Australia | Butcher and Havel 1976 |
| *Pinus pinea* | 5.0 | weathered granite | NE-Spain | J. Canadell, unpublished work |
| *Pinus ponderosa* | 3.5 | clay loam soil | Oregon, USA | Zwieniecki and Newton 1994 |
| *Pinus radiata* | 2.0 | sandy soil | S-Australia | Nambiar and Sands 1992 |
| *Pinus resinosa* | 2.7 | Hinckley coarse sand | New York, USA | White and Wood 1958 |
| *Pinus resinosa* | 5.0 | sandy outwash | New York, USA | Leaf et al. 1955 |
| *Pinus rigida* | 2.7 | sandy soil | New Jersey, USA | McQuilkin 1935 |
| *Pinus rigida* | 3.4 | sandy soil | Japan | Karizumi 1979 |
| *Pinus strobus* | 2.8 | sandy soil | Japan | Karizumi 1979 |
| *Pinus sylvestris* | 2.7 | sand overlying chalky drift | United Kingdom | Roberts 1976 |
| *Pinus taeda* | 2.0 | fullerton and bodine | Tennessee, USA | Harris et al. 1977 |
| *Pinus taeda* | 4.0 | granite wheathered/Ultisol | S-Carolina, USA | Richter and Markewitz 1995 |
| *TEMPERATE DECIDUOUS FOREST* | | | | |
| *Acer negundo* | 4.0 | upland clay | Missouri, USA | Biswell 1935 |
| *Acer saccharum* | 3.7 | silty loams with hardpan | New York, USA | Dawson 1993 |
| *Carya spp.* | 1.8 | sandstone | Ohio, USA | Gaiser 1952 |
| *Corylus americana* | 3.5 | loess hills | Nebraska, USA | Weaver 1919 |
| *Fraxinus japonica* | 2.0 | fine texture clay | Japan | Karizumi 1979 |
| *Juglans nigra* | 3.0 | silt loam | Japan | Karizumi 1979 |
| *Latrix decidua* | 3.4 | fine silty sand at depth | New York, USA | White and Wood 1958 |
| *Nothofagus pumila* | 2.0 | orange loam/rocks at depth | S-Argentina | Schulze et al. 1996 |
| *Platanus orientalis* | 2.6 | medium texture | Japan | Karizumi 1979 |
| *Populus nigra* | 1.9 | silt loam | Japan | Karizumi 1979 |
| *Populus sargentii* | 2.6 | loam underlain with clay | Missouri, USA | Biswell 1935 |
| *Populus tremula* | 2.0 | clay subsoil | Sweden | Persson 1975 |
| *Populus tremuloides* | 2.3 | grey clay | Michigan, USA | Day 1944 |
| *Populus tremuloides* | 2.9 | sandy loam | Utah, USA | Gifford 1966 |
| *Prunus yedoensis* | 2.1 | fine texture clay | Japan | Karizumi 1979 |
| *Quercus dentata* | 4.3 | silt loam | Japan | Karizumi 1979 |
| *Quercus macrocarpa* | 4.3 | fine-textured loams | Nebraska, USA | Weaver and Kramer 1932 |
| *Quercus macrocarpa* | 4.4 | upland clay | Missouri, USA | Biswell 1935 |
| *Quercus sp-Carya sp*[a] | 4.0 | silt loam on sandstone/shale | Virginia, USA | Kochenderfer 1973 |
| *Quercus velutina* | 3.0 | medium texture | Japan | Karizumi 1979 |
| *Salix babylonica* | 2.2 | silt loam | Japan | Karizumi 1979 |
| *TEMPERATE GRASSLAND* | | | | |
| *Agropyron repens* | 2.4 | loose sandy | Nebraska, USA | Weaver 1919 |
| *Agropyron smithii* | 2.7 | silt loam | Colorado, USA | Weaver 1958 |
| *Agropyron spicatum* | 1.4 | med. textur. Benge series | Washington, USA | Harris 1967 |
| *Agropyron spicatum* | 1.5 | silt loam | Washington, USA | Weaver 1919 |
| *Amorpha canescens* | 5.0 | loose sandy | Nebraska, USA | Weaver 1919 |
| *Andropogon furcatus* | 1.5 | Judson silt loam | Nebraska, USA | Weaver and Darland 1949 |
| *Andropogon furcatus* | 2.8 | clay loam | Nebraska, USA | Weaver 1919 |
| *Andropogon gerardi* | 2.1 | lilt loam | Iowa, USA | Weaver 1958 |
| *Andropogon hallii* | 1.8 | sandy | Nebraska, USA | Tolstead 1942 |
| *Andropogon hallii* | 3.0 | sandy | Colorado, USA | Weaver 1958 |
| *Andropogon scoparius* | 1.5 | silt loam | Iowa, USA | Weaver 1958 |
| *Andropogon scoparius* | 1.8 | loam sandy | Colorado, USA | Weaver 1919 |
| *Aragallus lambertii* | 1.4 | loam sandy | Colorado, USA | Weaver 1919 |
| *Argemone platyceras* | 3.7 | loam sandy | Colorado, USA | Weaver 1919 |
| *Artemisia frigida* | 1.7 | dark brown soil on shales | S-Canada | Coupland and Johnson 1965 |
| *Artemisia cana* | 2.4 | dark brown soil on shales | S-Canada | Coupland and Johnson 1965 |
| *Atriplex nuttallii* | 1.8 | dark brown soil on shales | S-Canada | Coupland and Johnson 1965 |
| *Astragalus crassicarpus* | 2.0 | loam soil on hard joint clay | Nebraska, USA | Weaver 1919 |
| *Berberis repens* | 3.0 | silt loam | Washington, USA | Weaver 1919 |
| *Biscutella laevigata* | 2.1 | – | Mid Europe | Kutschera 1960 |

**Appendix 1** (continued)

| Species/ dominant species[a] | Maximum rooting depth (m) | Soil type | Country | Reference |
|---|---|---|---|---|
| *Bouteloua curtipendula* | 1.7 | silt loam | Colorado, USA | Weaver 1958 |
| *Bouteloua gracilis* | 1.7 | Colby silt loam | Nebraska, USA | Weaver and Darland 1949 |
| *Bouteloua gracilis* | 1.8 | silt loam | Colorado, USA | Weaver 1958 |
| *Bouteloua gracilis*[a] | 2.1 | – | Kansas, USA | Albertson et al. 1953 |
| *Brauneria pallida* | 2.4 | clay loam | Nebraska, USA | Weaver 1919 |
| *Buchloe dactyloides* | 1.8 | silt loam | Iowa, USA | Weaver 1958 |
| *Buchloe dactyloides* | 2.0 | Wabash silt loam | Nebraska, USA | Weaver and Darland 1949 |
| *Bulbilis dactyloides* | 1.9 | alluvial | Nebraska, USA | Weaver 1919 |
| *Calamovilfa longifolia* | 1.8 | dark borwn soil on shales | S-Canada | Coupland and Johnson 1965 |
| *Calamovilfa longifolia* | 3.0 | sandy | Colorado, USA | Weaver 1958 |
| *Carex arenaria* | 1.8 | – | Mid Europe | Kutschera 1960 |
| *Carex filifolia* | 1.5 | silt loam | Colorado, USA | Weaver 1958 |
| *Carlina acaulis* | 4.1 | – | Germany | Kutschera 1960 |
| *Centaurea scabiosa* | 3.3 | – | Germany | Kutschera 1960 |
| *Chrysopis villosa* | 2.4 | dark brown soil on shales | S-Canada | Coupland and Johnson 1965 |
| *Equisetum arvense* | 3.0 | sandy | Canada | Coupland and Johnson 1965 |
| *Equisetum palustre* | 2.5 | – | Mid Europe | Kutschera 1960 |
| *Eriogonum heracleoides* | 2.4 | silt loam | Washington, USA | Weaver 1919 |
| *Eriogonum jamesii* | 2.3 | loam with some sand | Colorado, USA | Weaver 1919 |
| *Eriogonum microthecum* | 3.0 | sandy | Colorado, USA | Weaver 1919 |
| *Erodium botrys* | 1.3 | gravelly clay loam | California, USA | McKell et al. 1962 |
| *Eryngium campestre* | 4.2 | – | Germany | Kutschera 1960 |
| *Eurotia lanata* | 1.8 | dark brown soil on shales | S-Canada | Coupland and Johanson 1965 |
| *Festuca arizonica* | 1.2 | sandy loam-sandy clay | Colorado, USA | Currie and Hammer 1979 |
| *Festuca arizonica* | 1.3 | – | Colorado, USA | Schuster 1964 |
| *Festuca arundinacea* | 2.7 | – | Germany | Kutschera 1960 |
| *Festuca pallescens*[a] | 2.0 | alluvial sandy loam & gravel | S-Argentina | Schulze et al. 1996 |
| *Gaillardia aristata* | 1.7 | dark brown soil on shales | S-Canada | Coupland and Johnson 1965 |
| *Geranium viscosissimum* | 2.9 | silt loam | Washington, USA | Weaver 1919 |
| *Grindelia squarrosa* | 1.9 | loose sand | Nebraska, USA | Weaver 1919 |
| *Heracleum sphondyleum* | 2.0 | – | Mid Europe | Kutschera 1960 |
| *Hieracium scouleri* | 2.2 | silt loam | Washington, USA | Weaver 1919 |
| *Hoorebekia racemosa* | 3.4 | silt loam | Washington, USA | Weaver 1919 |
| *Kochia prostrata* | 6.3 | – | Germany | Kutschera 1960 |
| *Kuhnia glutinosa* | 5.2 | – | Nebraska, USA | Weaver 1919 |
| *Lepachys pinnata* | 1.5 | brown silt loam | Illinois, USA | Sperry 1935 |
| *Lespedeza capitata* | 2.4 | lower slopes of loess hills | Nebraska, USA | Weaver 1919 |
| *Liatris punctata* | 2.1 | gravelly | S-Canada | Coupland and Johnson 1965 |
| *Liatris punctata* | 4.8 | clay | Nebraska, USA | Weaver 1919 |
| *Lithospermum gmelini* | 2.1 | sandy | Nebraska, USA | Tolstead 1942 |
| *Lupinus ornatus* | 4.0 | silt loam | Washington, USA | Weaver 1919 |
| *Lygodesmia juncea* | 3.0 | sandy | Nebraska, USA | Tolstead 1942 |
| *Lygodesmia juncea* | 3.0 | dark brown soil on shales | S-Canada | Coupland and Johnson 1965 |
| *Lygodesmia juncea* | 6.3 | loess | Nebraska, USA | Weaver 1919 |
| *Medicago falcata* | 4.3 | – | Germany | Kutschera 1960 |
| *Muhlenbergia montana* | 1.3 | sandy clay loam subsoil | Colorado, USA | Schuster 1964 |
| *Onobrychis natrix* | 2.3 | – | Mid Europe | Kutschera 1960 |
| *Ononis natrix* | 2.3 | – | Germany | Kutschera 1960 |
| *Panicum virgatum* | 2.7 | loose sand | Nebraska, USA | Weaver 1919 |
| *Parthenium integrifolium* | 1.8 | brown silt loam | Illinois, USA | Sperry 1935 |
| *Petalostemum purpureum* | 1.8 | brown silt loam | Illinois, USA | Sperry 1935 |
| *Peucedanum cervaria* | 4.1 | – | Germany | Kutschera 1960 |
| *Phalaris aquatica* | 1.2 | granite | Spain | Joffre et al. 1987 |
| *Pimpinella saxifraga* | 3.7 | – | Germany | Kutschera 1960 |
| *Potentilla blaschkeana* | 2.3 | silt loam | Washington, USA | Weaver 1919 |
| *Potentilla fruticosa* | 3.0 | gravelly | S-Canada | Coupland and Johnson 1965 |
| *Potentilla concinna* | 1.8 | dark brown soil on shales | S-Canada | Coupland and Johnson 1965 |
| *Psoralea tenuiflora* | 1.8 | loose sand | Nebraska, USA | Weaver 1919 |
| *Psoralea tenuiflora* | 3.7 | loam sandy, silt loam | Colorado, USA | Weaver 1919 |
| *Redfieldia flexuosa* | 1.5 | sandy | Colorado, USA | Weaver 1958 |
| *Ruellia ciliosa* | 1.5 | brown silt loam | Illinois, USA | Sperry 1935 |
| *Rumex crispus* | 3.3 | – | Germany | Kutschera 1960 |
| *Senecio riddellii* | 1.5 | sandy soil | Nebraska, USA | Tolstead 1942 |
| *Silphium integrifolium* | 1.7 | brown silt loam | Illinois, USA | Sperry 1935 |
| *Silphium laciniatum* | 1.8 | brown silt loam | Illinois, USA | Sperry 1935 |
| *Solidago canadensis* | 3.4 | loose sandy | Nebraska, USA | Weaver 1919 |
| *Solidago rigida* | 1.4 | brown silt loam | Illinois, USA | Sperry 1935 |
| *Spartina pectinata* | 4.0 | silt loam | Iowa, USA | Weaver 1958 |

**Appendix 1** (continued)

| Species/ dominant species[a] | Maximum rooting depth (m) | Soil type | Country | Reference |
|---|---|---|---|---|
| *Sporobolus cryptandrus* | 1.5 | deeply eroded loess | Nebraska, USA | Weaver 1919 |
| *Sporobolus heterolepsis* | 1.5 | silt loam | Iowa, USA | Weaver 1958 |
| *Stipa spartea* | 1.8 | silt loam | Iowa, USA | Weaver 1958 |
| *Taraxacum serotinum* | 4.6 | – | Germany | Kutschera 1960 |
| *Thermopsis rhombifolia* | 2.1 | gravelly | S-Canada | Coupland and Johnson 1965 |
| *Tradescantia reflexa* | 1.6 | brown | Illinois, USA | Sperry 1935 |
| *Vernonia baldwinii* | 3.5 | loose sand | Nebraska, USA | Weaver 1919 |
| *TROPICAL DECIDUOUS FOREST* | | | | |
| *Antiaris toxicaria* | 3.5 | red soil | China | Bang-Xing 1991 |
| *Baccaurea ramiflora* | 3.7 | red soil | China | Bang-Xing 1991 |
| *Gironniera subaequalis* | 4.7 | red soil | China | Bang-Xing 1991 |
| *Symplocos cochinchinensis* | 2.0 | red soil | China | Bang-Xing 1991 |
| *Xauthophyllum siamense* | 4.6 | red soil | China | Bang-Xing 1991 |
| *TROPICAL EVERGREEN FOREST* | | | | |
| *Apodytes dimidiata* | 8.2 | sandy loam on schists | Kenya | Kerfoot 1963 |
| *Chlorophora excelsa* | 2.0 | ferralitic | Ghana | Mensah and Jenik 1968 |
| *Chlorophora excelsa* | 3.0 | ferralitic | Ghana | Jenik 1971 |
| *Community* | 18.0 | clay | Brazil | Nepstad et al. 1994 |
| *Community* | 5.0 | – | Brazil | Poels 1987 |
| *Community* | 2.5 | Turraeantho on sandy soil | Ivory Coast | Huttel 1975 |
| *TROPICAL GRASSLAND AND SAVANNA* | | | | |
| *Acacia erioloba* | 60.0 | Kalahari sands | Botswana | Jennings 1974 |
| *Anacardium pumilum* | 10.0 | – | Brazil | Ferri 1961 |
| *Andira humilis* | 18.0 | reddish loamy earth | Brazil | Rawitscher 1948 |
| *Andira spp.* | 19.0 | – | Brazil | Rawitscher et al. 1943 |
| *Aristolachia giberti* | 1.8 | redish loamy earth | Brazil | Rawitscher 1948 |
| *Boscia albitrunca* | 68.0 | Kalahari sands | Botswana | Jennings 1974 |
| *Brachiaria brizantha*[a] | 8.0 | clay | Brazil | Nepstad et al. 1994 |
| *Brachystegia sp.* | 1.8 | – | Zimbabwe | Strang 1969 |
| *Capparis sp.* | 1.6 | sandy clay loam | Ghana | Okali et al. 1973 |
| *Curatella americana* | 4.0 | – | Venezuela | Foldats and Rutkis 1975 |
| *Jacaranda decurrens*[a] | 11.0 | – | Brazil | Rawitscher et al. 1943 |
| *Ochna pulchra* | 2.2 | structureless sand | South Africa | Rutherford 1983 |
| *Panicum maximum*[a] | 12.0 | clay | Brazil | Nepstad et al. 1994 |
| *Stipagrostis amabilis*[a] | 5.0 | Kalahari sands | South Africa | J. Canadell, unpublished work |
| *Stryphnodendron sp.* | 2.0 | reddish loamy earth | Brazil | Rawitscher 1948 |
| *TUNDRA* | | | | |
| *Cares aquatilis*[a] | 0.3 | – | Alaska, USA | Dennis et al. 1978 |
| *Dryas punctata*[a] | 0.5 | permafrost at 40–55 cm | N-Russia | Khodachek 1971 |
| *Dupontia fischeri*[a] | 0.3 | organic matter on sediments | Alaska, USA | Dennis 1977 |
| *Eriophorum vaginatum*[a] | 0.6 | silty soil on permafrost | Alaska, USA | Wein and Bliss 1974 |
| *Betula nana* | 0.5 | permafrost at 50 cm | Alaska, USA | S. Hobbie, unpublished work |
| *Luzula confusa* | 0.3 | loams | N-Canada | Bliss and Svoboda 1984 |
| *Salix glauca* | 0.5 | permafrost at 45–60 cm | W-Russia | Ignatenko and Khakimzy 1971 |
| *Salix planifolia* | 0.9 | coarse textured/bottom pit | Colorado, USA | Webber and May 1977 |

[a] Maximum rooting depth is not linked to the species name but to the dominant species in the community

## References


Albertson FW, Riegel A, Launchbaugh JL (1953) Effects of different intensities of clipping on short grasses in west-central Kansas. Ecology 34:1–20

Bang-Xing W (1991) Studies on the vertical structure of seasonal rain-forest in Xishuangbanna of Yunnan. Acta Bot Sin 33: 232–239

Bannan (1940) The root systems of northern Ontario conifers growing in sand. Am J Bot 27: 108–114

Batanouny KH, Abdel Wahab AM (1973) Eco-physiological studies on desert plants. VIII. Root penetration of *Leptadenia pyrotechnica* (Forsk.) Decne. in relation to its water balance. Oecologia 11: 151–161

Bennie ATP (1991) Growth and mechanical impedance. In: Waisel Y, Eshel A, Kafkafi U (eds) Plant roots: the hidden half (Books in soils, plants, and the environment). Marcel Dekker, New York, pp 393–414

Biswell HH (1935) Effects of environment upon the root habits of certain deciduous forest trees. Bot Gaz 9: 676–708

Bliss LC, Svoboda J (1984) Plant communities and plant production in the western Queen Elizabeth Islands. Holarct Ecol 7: 325–344

Branson FA, Miller RF, McQueen IS (1976) Moisture relationships in twelve northern desert shrub communities near Grand Junction, Colorado. Ecology 57: 1104–1124

Butcher TB, Havel JJ (1976) Influence of moisture relationships on thinning practice. NZ J For Sci 6: 158–170

Caldwell MM, Richards JH (1989) Hydraulic lift: water efflux from upper roots improves effectiveness of water uptake by deep roots. Oecologia 79: 1–5

Canadell J, Zedler PH (1995) Underground structures of woody plants in Mediterranean ecosystems of Australia, California, and Chile. In: Arroyo MTK, Zedler PH, Fox MD (eds) Ecology and biogeography of mediterranean ecosystems in Chile, California, and Australia. Springer, Berlin Heidelberg New York, pp 177–210

Cannon WA (1911) The root habits of desert plants. Carnegie Inst Wash Publ 131: 1–96

Cannon WA (1914) Specialization in vegetation and in environment in California. Plant World 17: 223–237

Carbon BA, Bartle GA, Murray AM, MacPherson DK (1980) The distribution of root length, and the limits to flow of soil water to roots in a dry sclerophyll forest. For Sci 26: 656–664

Chaudhuri UN, Kirkham MB, Kanemasu ET (1990) Root growth of winter wheat under elevated carbon dioxide and drought. Crop Sci 30: 853–857

Coupland RT, Johnson RE (1965) Rooting characteristics of native grassland species in Saskatchewan. J Ecol 53: 475–507

Crombie DS, Tippett JT, Hill TC (1988) Down water potential and root depth of trees and understory species in southwestern Australia. Aust J Bot 36: 621–631

Currie PO, Hammer FL (1979) Detecting depth and lateral spread of roots of native range plants using radioactive phosphorus. J Range Manage 32: 101–103

Davis CB (1972) Comparative ecology of six members of the *Arctostaphylos andersonii* complex. PhD dissertation, University of California, Davis

Davis SD, Mooney HA (1986) Water use patterns of four co-occurring chaparral shrubs. Oecologia 70: 172–177

Davis EA, Pase CP (1977) Root system of shrub live oak: implications for water yield in Arizona chaparral. J Soil Water Conserv 32: 174–180

Dawson TE (1993) Hydraulic lift and water use by plants: implications for water balance, performance and plant-plant interactions. Oecologia 95: 565–574

Dawson TE (1996) Determining water use by trees and forests from isotopic, energy balance and transpiration analyses: the roles of tree size and hydraulic lift. Tree Physiol 16: 263–272

Day MW (1944) The root system of aspen. Am Midl Nat 32: 502–509

Dell B, Bartle JR, Tacey WH (1983) Root occupation and root channels of jarrah forest subsoils. Aust J Bot 31: 615–627

Dennis JG (1977) Distribution patterns of belowground standing crop in artic tundra at Barrow, Alaska. In: Marshall JK (ed) The belowground ecosystem: a synthesis of plant-associated processes. Range Science Department, Colorado State University, Fort Collins

Dennis JG, Tieszen LL, Vetter MA (1978) Seasonal dynamics of above- and belowground production of vascular plants at Borrow, Alaska. In: Tieszen LL (ed) Vegetation and production ecology of the Alaskan Arctic tundra (Ecological studies 29). Springer, Berlin Heidelberg New York, pp 113–140

DeSouza J, Silka PA, Davis SD (1986) Comparative physiology of burned and unburned *Rhus laurina* after chaparral wildfire. Oecologia 71: 63–68

Dodd J, Heddle EM, Pate EM, Dixon KW (1984) Rooting patterns of sandplain plants and their functional significance. In: Pate JS, Beard JS (eds) Kwogan: plant life of the sandplain. University of Western Australia Press, Nedlands, pp 146–177

Feldman LJ (1984) Regulation of root development. Annu Rev Plant Physiol 35: 223–242

Ferri MG (1961) Problems of water relations of some brazilian vegetation types, with special consideration of the concepts of xeromorphy and xerophytism. Plant-water relationships in arid and semi-arid contions. In: UNESCO (ed) Arid zone research 16. UNESCO, Paris, pp 191–197

Fisher MJ, Rao IM, Ayarza MA, Lascano CE, Sanz JI, Thomas RJ, Vera RR (1994) Carbon storage by introduced deep-rooted grasses in the South American savannas. Nature 371: 236–238

Foldats E, Rutkis E (1975) Ecological studies of chaparro (*Curatella americana* L.) and manteco (*Byrsonima crassifolia* H.B.K.) in Venezuela. J Biogeogr 2: 159–178

Freckman DW, Virginia RA (1989) Plant-feeding nematodes in deep-rooting desert ecosystems. Ecology 70: 1665–1678

Gardner WR (1983) Soil properties and efficient water use: an overview. In: Taylor HM, Jordan WR, Sinclair TR (eds) Limitations to efficient water use in crop production. American Society of Agronomy, Madison, pp 45–64

Gaiser RN (1952) Root channels and roots in forest soils. Soil Sci Soc Proc 16: 62–65

Gary HL (1963) Root distribution of five-stamen tamarisk, seepwillow, and arrowwed. For Sci 9: 311–314

Gifford GF (1966) Aspen root studies on three sites in northen Utah. Am Midl Nat 75: 132–141

Giliberto J, Estay H (1978) Seasonal water stress in some Chilean matorral shrubs. Bot Gaz 139: 236–260

Ginzburg C (1966) Xerophytic structures in the roots of desert shrubs. Ann Bot 30: 403–418

Gregory PJ, McGowan M, Biscoe PV, Hunter B (1978) Water relations of winter wheat. I Growth of the root system. J Agric Sci 91: 91–103

Hamblin A, Tennant D (1987) Root length density and water uptake in cereals and grain legumes: how well are they correlated? Aust J Agric Res 38: 513–527

Hanes TL (1965) Ecological studies on two closely related chaparral shrubs in southern California. Ecol Monogr 35: 213–235

Harris GA (1967) Some competitive relationships between *Agropyron spicatum* and *Bromus tectorum*. Ecol Monogr 37: 89–111

Harris WF, Kinerson RS, Edwards NT (1977) Comparison of belowground biomass of natural deciduous forest and loblolly pine plantations. Pedobiologia 17: 369–381

Heitschmidt RK, Ansley RJ, Dowhower SL, Jacoby PW, Price DL (1988) Some observations from the excavation of honey mesquite root systems. J Range Manage 41: 227–231

Hellmers H, Horton JS, Juhren G, O'Keefe J (1955) Root systems of some chaparral plants in southern California. Ecology 36: 667–678

Heyward F (1933) The root system of longleaf pine on the deep sands of Western Florida. Ecology 14: 137–148

Higgins KB, Lamb AJ, Wilgen BW van (1987) Root systems of selected plant species in mesic mountain fynbos in the Jonkershoek Valley, south-western Cape Province. S Afr J Bot 53: 249–257

Hnatiuk RJ, Hopkins AJM (1980) Western Australian species-rich kwongan (sclerophyllous shrubland) affected by drought. Aust J Bot 28: 573–585

Hodgkinson DC (1992) Water relations and growth of shrubs before and after fire in a semi-arid woodland. Oecologia 90: 467–473

Holch AE, Hertel EW, Oakes WO, Whitwell HH (1941) Root habits of certain plants of the foothill and alpine belts of Rocky Mountain National Park. Ecol Monogr 11: 327–345

Horton KW (1958) Rooting habits of lodgepole pine (Forest Research Division technical note 67). Depart North Can. Dep. North. Aff. Natl. Resourc.

Huang JS (1987) Interactions of nematodes with rhizobia. In: Veech JA, Dickson DW (eds) Vistas on nematology: a commemoration of the twenty-fifth anniversary of the Society of Nematologists. Painter, DeLeon Springs, pp 301–306

Huttel C (1975) Root distribution and biomass in three Ivory Coast rain forest plots. In: Golley FB, Medina E (eds) Tropical ecological systems. (Ecological studies 11). Springer, Berlin Heidelberg New York, pp 123–130

Ignatenko V, Khakimzyanova FI (1971) Soils and total phytomass reserves in dwarf birch – white dryas and willow tundras of the east European northlands. Sov J Ecol 2: 300–305

Incoll WD (1969) Root excavation of *Euclayptus regnans* (Research activity 69). Forest Commission, Victoria, pp 15–16

Jaafar MN, Stone LR, Goodrum DE (1993) Rooting depth and dry matter development of sunflower. Agron J 85: 281–286

Jackson RB, Canadell J, Ehleringer JR, Mooney HA, Sala OE, Schulze E-D (1996) A global analysis of root distributions for terrestrial biomes. Oecologia 108: 389–411

Jeník J (1971) Root structure and underground biomass in equatorial forests. In: Duvigneaud P (ed) Productivity of forest ecosystems. Ecology and conservation 4. UNESCO Paris, pp 323–331

Jenkins MB, Virginia RA, Jarrel WM (1988) Depth distribution and seasonal populations of mesquite-nodulating rhizobia in warm desert ecosystems. Soil Sci Soc Am J 52: 1644–1650

Jennings CMH (1974) The hydrology of Botswana. PhD thesis, Univeristy of Natal, South Africa

Joffre R, Leiva MJ, Rambal S, Fernández R. (1987) Dynamique racinaire et extraction de l'eau du sol par des graminées perennes et annuelles méditerranéennes. Acta Oecol Oecol Plant 8: 181–194

Karizumi N (1979) Illustrations of tree roots. Seibundo Shinkosha, Tokyo, pp 1121

Kerfoot O (1963) The root system of tropical trees. Comm For Rev 42: 19–26

Khodachek EA (1971) Vegetal matter of tundra phytocoenoses in the Western Part of Taimyr peninsula (International tundra biome translation 5). IBP, University of Alaska, Fairbanks

Kimber PC (1974) The root system of jarrah (*Eucalypstus marginata*). (WA research paper 10), Forestry Department, Perth

Klinge H (1973) Root mass estimation in lowland tropical rain forests of Central Amazonia, Brazil. II. "Coarse root mass" of trees and palms in different height classes. An Acad Brasil Cienc 45: 595–609

Kochenderfer JN (1973) Root distribution under some forest types native to West Virginia. Ecology 54: 445–448

Kutschera L (1960) Wurzelatlas. DLG, Frankfurt

Lawrence T (1975) Comparison of root penetration of altai wild ryegrass and russian wild ryegrass. Can J Plant Sci 55: 851–852

Leaf AL, Leonard RE, Berglund JV (1955) Root distribution of plantation-grown red pine in an outwash soil. Ecology 52: 153–158

Lewis DC, Burgy RH (1964) The relationship between oak tree roots and groundwater in fractured rock as determined by tritium tracing. J Geophys Res 69: 2579–2588

Leyshon AJ (1991) Effect of rate of nitrogen fertilizer on the above- and below-ground biomass of irrigated bromegrass in southwest Saskatchewan. Can J Plant Sci 71: 1057–1067

Low AB, Lamont BB (1990) Aerial and below-ground phytomass of *Banksia* scrub-heath at Eneabba, South-western Australia. Aust J Bot 38: 351–359

Lull HW, Axley JH (1958) Forest soil-moisture relations in the coastal plain sands of southern New Jersey. For Sci 4: 2–19

Mayaki JWC, Teare ID, Stone LR (1976) Top and root growth of irrigated and nonirrigated soybeans. Crop Sci 16: 92–94

McKell CM, Jones MB, Perrier ER (1962) Root production and accumulation of root material on fertilized annual range. Agron J 54: 459–462

McQuilkin WE (1935) Root development of pitch pine with some comparative observations on short-leaf pine. J Agric Res 51: 983–1016

Mensah KOA, Jenik J (1968) Root system of tropical trees. 2. Features of the root system of Iroko (*Clorophora excelsa* Beth et Hook.) Preslia Praha 40: 21–27

Mooney HA, Gulmon SL, Rundel PW, Ehleringer J (1980) Further observations on the water relations of *Prosopis tamarugo* of the northern Atacama desert. Oecologia 44: 177–180

Nambiar EKS, Sands R (1992) Effects of compaction and simulated root channels in the subsoil on root development, water uptake and growth of radiata pine. Tree Physiol 10: 297–306

Nepstad DC, de Carvalho CR, Davidson EA, Jipp PH, Lefebvre PA, Negreiros GH, da Silva ED, Stone TA, Trumbore SE, Vieira S (1994) The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. Nature 372: 666–669

Nicoullaud B, King D, Tardieu F (1994) Vertical distribution of maize roots in relation to permanent soil characteristics. Plant Soil 159: 245–254

Nilsen ET, Sharifi MR, Rundel PW, Jarrell WM, Virginia R (1983) Diurnal and seasonal water relations of the desert phreatophyte *Prosopis glandulosa* (honey mesquite) in the Sonoran desert of California. Ecology 64: 1381–1393

Okali DUU, Hall JB, Lawson GW (1973) Root distribution under a thicket clump on the Accra plains, Ghana: its relevance to clump localization and water relations. J Ecol 61: 439–454

Oppenheimer HR (1958) Further observations on roots penetrating into rocks and their structure. Bull Res Counc Israel 6: 18–31

Orshansky G (1951) Ecological studies on lithophytes. Palest J Bot Jerusalem 5: 119–128

Pages L, Pellerin S (1994) Evaluation of parameters describing the root system architecture of field grown maize plants (*Zea mays* L.). Plant Soil 164: 169–176

Pate JS, Jeschke WD, Aylward MJ (1995) Hydraulic architecture and xylem structure of the dimorphic root systems of South-West Australian species of Proteacea. J Exp Bot 46: 907–915

Persson H (1975) Deciduous woodland at Andersby, eastern Sweden: Field layer and below-ground production. Acta Phytogeogr Suec 62: 1–71

Phillips WS (1963) Depth of roots in soil. Ecology 44: 424

Plum KA, Gosting VA (1973) Origin of Australian bauxite deposits (record 1973/156). Bureau of Mineral Resources, Geology and Geophysics, Australian Department of Minerals and Energy

Poels RLH (1987) Soils, water and nutrients in a forest ecosystem in Surinam. Agricultural University, Waageningen, The Netherlands

Poole DK, Miller PC (1975) Water relations of selected species of chaparral and coastal sage communities. Ecology 56: 1118–1128

Rawitscher F (1948) The water economy of the vegetation of the Campos cerrados in southern Brazil. J Ecol 36: 237–268

Rawitscher F, Ferri MG, Rachid M (1943) Profundidade dos solos e vegetacao em campos cerrados do Brasil meridional. Ann Acad Bras Sci 15: 267–294

Rees KCJ van , Comerford NB (1986) Vertical root distribution and strontium uptake of a slash pine stand on a Florida spodsol. Soil Sci Soc Am J 50: 1042–1104

Reicosky DC, Millington RJ, Kute A, Peters DB (1964) Patterns of water uptake and root distribution of soybeans (*Glycine max*) in the presence of a water table. Agron J 64: 292–297

Reynolds TD, Fraley L Jr (1989) Root profiles of some native and exotic plant species in southeastern Idaho. Environ Exp Bot 29: 241–248

Richards JH, Caldwell MM (1987) Hydraulic lift: substantial nocturnal water transport between soil layers by *Artemisia tridentata* roots. Oecologia 73: 486–489

Richter DD, Makewitz D (1995) How deep is soil? BioScience 45: 600–609

Roberts J (1976) A study of root distribution and growth in a *Pinus sylvestris* L. (Scots pine) plantation in East Anglia. Plant Soil 44: 607–621

Rutherford MC (1983) Growth rates, biomass and distribution of selected woody plant roots in *Burkea african-Ochna pulchra* savanna. Vegetatio 52: 45–63

Sala OE, Golluscio RA, Laueronth WK, Soriano A (1989) Resource partitioning between shrubs and grasses in the Patagonian steppe. Oecologia 81: 501–505

Saunier RE, Wagle RF (1967) Factors affecting the distribution of shrub live oak (*Quercus turbinella* Greene). Ecology 48: 35–41

Schachtschabel P, Blume HP, Hartge H, Schwertmann U (1992) Lehrbuch der Bodenkunde. 13th edn. Ferdinand Emke, Stuttgart

Schulze E-D, Bauer G, Buchmann N, Canadell J, Ehleringer JR, Jackson RB, Jobbagy E, Loreti J, Mooney HA, Oesterheld M, Sala O (1996) Water availability, rooting depth, and vegetation zones along an aridity gradient in Patagonia. Oecologia 108: 503–511

Schuster JL (1964) Root development of native plants under three grazing intensities. Ecology 45: 63–70
Shachori A, Rosenzweig D, Poljakoff-Mayber A (1967) Effect of Mediterranean vegetation on the moisture regime. In: Sopper WE, Lull HW (eds) Forest hydrology. Pergamon, Oxford, pp 291–311
Shmueli E (1948) The water balance of some plants of the Dead Sea salines. Pal J Bot Jeresularem Ser IV: 117–144
Siegenthaler U, Sarmiento JL (1993) Atmospheric carbon dioxide and the ocean. Nature 365: 119–125
Silva S, Whitford WG, Jarrell WM, Virginia RA (1989) The microarthropod fauna associated with a deep rooted legume, *Prosopis glandulosa*, in the Chihuahuan desert. Biol Fert Soils 7: 330–335
Specht RL, Rayson P (1957) Dark Island Heath (Ninety-Mile Plain, South Australia). III. The root systems. Aust J Bot 5: 103–114
Sperry TM (1935) Root systems in Illinois praire. Ecology 16: 178–202
Stone EL, Kalisz PJ (1991) On the maximum extent of tree roots. For Ecol Manage 46: 59–102
Strang RM (1969) Soil moisture relations under grassland and under woodland in the Rhodesian Highveld. Commonw For Rev 48: 26–40
Strong WL, La Roi GH (1983) Root-system morphology of common boreal forest trees in Alberta, Canada. Can J For Res 13: 1164–1173
Thomas CM, Davis SD (1989) Recovery patterns of three chaparral shrub species after wildfire. Oecologia 80: 309–320
Tolstead WT (1942) Vegetation of the northern part of Cherry county, Nebraska. Ecol Monogr 12: 255–292
Trumbore SE, Davidson EA, Barbosa PC, Nepstad DC, Martinelli LA (1995) Belowground cycling of carbon in forests and pastures of Eastern Amazonia. Global Biogeochem Cycles 9: 515–528
Verzunov AI (1980) Growth of the larch and resistance of cultivated phytocenoses with its domination on semihydromorphic soils in the forest steppe in North Kazakhstan. Sov J Ecol 11: 98–103
Weaver JE (1919) The Ecological relations of roots. Carnegie Inst Wash Publ 286: 1–128
Weaver JE (1926) Root development of field crops. McGraw-Hill, New York
Weaver JE (1958) Summary and interpretation of underground development in natural grassland communities. Ecol Monogr 28: 55–78
Weaver JE, Darland RW (1949) Soil-root relationships of certain native grasses in various soil types. Ecol Monogr 19: 303–338
Weaver JE, Kramer J (1932) Root system of *Quercus macrocarpa* in relation to the invasion of prairie. Bot Gaz 94: 51–85
Webber PJ, May DE (1977) The magnitude and distribution of belowground plant structures in the alpine tundra of Niwot Ridge, Colorado. Arct Alp Res 9: 157–174
Wein RW, Bliss LC (1974) Primary production in artic cottongrass tussock tundra communities. Acrt Alp Res 6: 261–274
Welbank PJ, Gibb MJ, Taylor PJ, Williams ED (1974) Root growth of cereal crops. Experimental Station Annual Report 1973 Part 2, Rothamsted, pp 26–66
Westman WE, Rogers RW (1977) Biomass and structure of a subtropical Eucalypt forest, North Stradbroke Island. Aust J Bot 25: 171–191
White PD, Wood RS (1958) Growth variations in a red pine plantation influenced by a deep-lying fine soil layer. Soil Sci Soc Proc 22: 174–177
Wright CD (1928) An ecological study of *Baccharis pilularis*. Ms thesis, University of California, Berkeley
Zohary M (1961) On the hydro-ecological relations of the near east desert vegetation. In: UNESCO (ed) Arid zone research 16. UNESCO, Paris, pp 199–212
Zohary M, Fahn A (1952) Ecological studies on East Mediterranean dune plants. Bull Res Counc Israel 1: 38–53
Zohary M, Orshan G (1949) Structure and ecology of the vegetation in the Dead Sea regions of Palestine. Pal J Bot Jerusalem Ser IV: 177–207
Zwieniecki MA, Newton M (1994) Root distribution of 12-year forests at rocky sites in southwestern Oregon: effects of rock physical properties. Can J For Res 24: 1791–1796