A Representation of Variable Root Distribution in Dynamic Vegetation Models

Vivek K. Arora* and George J. Boer

Canadian Centre for Climate Modelling and Analysis, Meteorological Service of Canada, University of Victoria, Victoria, British Columbia, Canada

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ABSTRACT: Root distribution is treated as a static component in most current dynamic vegetation models (DVMs). While changes in leaf and stem biomass are reflected in leaf area index (LAI) and vegetation height via specific leaf area (SLA) and allometric relationships, most DVMs assume that changes in root biomass do not result in changes in the root distribution profile and rooting depth. That is, the fraction of roots in soil layers, which is used to estimate transpiration, is taken to be constant and independent of root biomass and/or vegetation age. A methodology for parameterizing root distribution as a function of root biomass is proposed for use in dynamic vegetation models. In this representation, root distribution and rooting depth evolve and increase as root biomass increases, as is expected intuitively and as is seen in observations. Root biomass data from temperate coniferous, tropical evergreen, and tundra sites show that the approach successfully represents, to the first order, the change of root distribution and rooting depth as a function of root biomass.

KEYWORDS: Dynamics vegetation models, Root distribution

* Corresponding author address: Vivek Arora, Canadian Centre for Climate Modelling and Analysis, Meteorological Service of Canada, University of Victoria, PO Box 1700, STN CSC, Victoria, BC V8W 2Y2, Canada.
E-mail address: vivek.arora@ec.gc.ca
1. Introduction

Vegetation affects climate by modifying the energy, momentum, and hydrologic balance of the land surface. Boundary layer exchanges of heat and momentum, evapotranspiration, and the absorption of solar radiation, are all influenced by vegetation and have important feedbacks on the global and regional climate. Vegetation influences climate via its physiological (stomatal conductance) and structural (leaf area index, root depth and distribution, height, and albedo) properties. Biophysical effects of vegetation have been considered in a number of studies that investigate the effects of deforestation (Charney, 1975; Lean and Rowntree, 1997), the effects of changes in the structural and physiological characteristics of vegetation (Pollard and Thompson, 1995; Douville et al. 2000), and the effects of anthropogenic land cover change (Chase et al., 2000; Zhao et al., 2001). At the global scale, vegetation also affects atmospheric processes through its effects on CO₂ exchange and the emission of other radiatively active trace gases (Shaver et al., 1992). Changes in the structural and physiological properties of vegetation, in response to increases in atmospheric CO₂ concentration and climate warming, are expected to have important effects on the overall sensitivity of the climate system.

The interaction between vegetation and climate is represented by soil–vegetation–atmosphere transfer (SVAT) schemes and most existing SVAT schemes do not consider vegetation as a dynamic component. However, SVAT schemes with partly dynamic vegetation (e.g., Dickinson et al., 1998; Sellers et al., 1996) and dynamic vegetation models (DVMs) (e.g., Foley et al., 1996; Kucharik et al., 2000) are emerging. The most complex DVMs include a SVAT scheme coupled to a terrestrial ecosystem model that provides the SVAT scheme with time-varying structural and physiological vegetation characteristics, and dynamic geographical distribution of vegetation. Arora (Arora, 2002), for instance, illustrates how various time-varying components of vegetation, simulated in dynamic vegetation models, can be used to change the structural attributes of vegetation that are assumed constant in most SVAT schemes and hydrological models. The primary difference between coupling an atmospheric model to a standard SVAT scheme, rather than a dynamic vegetation model, is that a SVAT scheme uses prescribed surface roughness length (based on an assumed distribution of vegetation height) and a prescribed seasonal evolution of leaf area index (LAI) rather than calculating these quantities prognostically and interactively in response to local conditions as is done in a dynamic vegetation model.

Leaf, stem, and root biomass, $B_{L}$, $B_{S}$, and $B_{R}$ (kg m$^{-2}$), respectively, are primary prognostic variables in dynamic vegetation models. Biomass in units of kilograms per square meter is closely associated to carbon content (kg C m$^{-2}$) since the ratio $r_{c}$ of carbon to biomass is fairly stable at about 0.5 (Ajtay et al., 1979). Structural vegetation attributes such as LAI and vegetation height, $h$ (m), are obtained from leaf and stem biomass using specific leaf area (SLA; m$^{2}$ kg C$^{-1}$), where $LAI = (1/r_{c}) \times B_{L} \times SLA$ and allometric relationships $h = f(B_{S})$. SLA is defined as the leaf area obtained per unit of dry mass of leaf biomass and is a vegetation-dependent parameter. Allometry represents the relative growth of a part in relation to the whole plant and allometric relationships relate attributes,
such as weight, height, length, diameter, or area, of various plant components to one another or to the entire plant, often via power-law relationships (e.g., Enquist and Niklas, 2002). SLA has been used as a prescribed vegetation-dependent constant in the Integrated Biosphere Simulator (IBIS; Kucharik et al., 2000) and estimated as a function of leaf life span in the Ecosystem Demography (ED) and Lund–Potsdam–Jena (LPJ) models (Moorcroft et al., 2001; Sitch et al., 2002; manuscript submitted to *Global Biogeochem. Cycles*). Vegetation height \((h)\) is related to stem biomass \((B_s)\) using a simple allometric relationship \((h \propto B_s^{0.4})\) in the terrestrial carbon cycle model, TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics) (Cox, 2001), while the ED model relates tree height to diameter \((D)\) as \(h \propto D\) (Moorcroft et al., 2001).

While LAI and vegetation height are treated as time-varying structural attributes in most dynamic vegetation models, root distribution and rooting depth are not. This is primarily because no allometric relationships exist that relate root biomass and/or vegetation age to a root distribution profile and a rooting depth. However, observational data show, not unexpectedly, that root distribution profiles and rooting depth change with plant age and root biomass. Root distribution and maximum rooting depth are also affected by soil texture and depth (Schenk and Jackson, 2002a) and by mean annual precipitation (Schenk and Jackson, 2002b).

Root distribution, among other factors, plays an important role in determining various ecosystem processes including vegetation distribution (Peters, 2002), preferential water use (Scott et al., 2000), and coexistence of different vegetation types (van Wijk and Rodriguez-Iturbe, 2002).

The use of an invariant root distribution in ecosystem models results in a constant fraction of roots in each soil layer, independent of plant age or root biomass, and this invariant root fraction is used in the calculation of transpiration and other quantities. The IBIS model (Kucharik et al., 2000), for example, assumes that the cumulative root distribution is given by \((1 - \beta^z)\), where \(z\) is the soil depth and \(\beta\) is a vegetation-dependent coefficient (Jackson et al., 1996), which is assumed to be time invariant. Since \(\beta\) does not change with vegetation age and/or root biomass, the rooting depth (defined as the depth containing 95\% of the roots) remains constant irrespective of the size of the plant. Thus a short young tree with a small root biomass, and a large old tree with a large root biomass are both assumed to have the same rooting depth, root distribution and, consequently, the same fraction of roots in each soil layer. Most vegetation and terrestrial carbon models, and almost all SVAT schemes, follow this approach (e.g., Sitch et al., 2002; Knorr, 2000; Bonan, 1996; Verseghy et al., 1993; Potter and Klooster, 1999).

The assumption that the root distribution profile and rooting depth does not change in time may be suitable for simulating energy and water balance dynamics of mature stands over a short period of time but is not expected to be optimum for dynamic vegetation models which are designed to capture the growth and death dynamics and the establishment or encroachment of vegetation in empty plots over decade to century time-scales. For example, based on stable isotope analysis in Arizona, USA, Weltzin and McPherson (Weltzin and McPherson, 1997) conclude that tree seedlings use shallow sources of soil water, while mature trees use deeper sources. The authors find that at two years of age trees were still
accessing water from shallow sources and competing with grasses. Donovan and Elheringer (Donovan and Elheringer, 1994) draw similar conclusions for shrubs. They find that the seasonal development of water stress in shrubs decreased with increasing size, age, and rooting depth. Irvine et al. (Irvine et al., 2002) find that while younger stands of ponderosa pine trees (∼14 years old) experience water stress and consequently show reduced transpiration rates in the later half of the growing season, the older trees (50 and 250 years old) did not show any such behavior. They suggest these responses are a consequence of deep and shallow rooting profiles of the older and younger trees, respectively. These studies indicate that as plants grow and their root biomass increases they access water from deeper soil layers due to their increased rooting depth and deeper root profiles.

Section 2 discusses the traditional exponential root distribution used in most vegetation models and SVAT schemes and illustrates its limitations. A method for representing root distribution profile as a function of root biomass is proposed in section 3, which is intended to overcome some of the limitation in the prescription of a static root distribution profile in dynamic vegetation models. In this representation, root distribution and rooting depth are functions of time through their dependence on evolving root biomass. A comparison against observed root biomass data is presented in section 4, the application of the approach is in section 5, and the results are summarized in section 6.

### 2. The traditional exponential root distribution

Total root density (kg m⁻²), consisting of both fine and coarse roots, provides the basic representation of root distribution, and we follow Jackson et al. (Jackson et al., 1996, hereafter J96) in adopting an exponential root density profile for vegetation type $i$ as

$$\rho_i(z, t) = A_i(t)\beta_i^z = A_i(t)e^{-a_i z}, \quad (1)$$

where $z$ is the depth (m), positive downward; $a_i = 1/L_i$, where $L_i$ is a vegetation-dependent e-folding length scale; and $A_i(t)$ is the surface root density that is a function of time $t$. Here $a_i = -\gamma \ln \beta_i$ connects J96’s representation with the exponential representation used here.

The root biomass $B_{Ri}$ above depth $z$, and omitting subscripts $i$ and $R$ for simplicity, is given by

$$B_z(t) = \int_0^z A(t)e^{-az} \, dz = \frac{A(t)}{a}(1 - e^{-az}), \quad (2)$$

and the total root biomass is $B(t) = B_a(t) = A(t)/a$. The cumulative root fraction at depth $z$ is

$$f(z) = \frac{B_z(t)}{B_a(t)} = (1 - e^{-az}), \quad (3)$$

and the rooting depth that contains the fraction $f$ of the total root mass is

$$d = \frac{-\ln(1 - f)}{a}. \quad (4)$$
The “rooting depth” is typically defined as the depth that contains 95% of the root biomass, but for simplicity we use \( f = 0.9502 \) and the term

\[
d = \frac{-\ln(1 - 0.9502)}{a} = \frac{3}{a}
\]  

(5)
is the rooting depth. Rewriting the root density (for a particular vegetation type) as

\[
\rho(z, t) = aB(t)e^{-az}
\]  

(6)
relates the three measures of root distribution, \( \rho, f, \) and \( d \) [in Equations (3)–(6)], to \( a \) and \( B(t) \). The use of a fixed \( a \) in these formulas implies a constant rooting depth \( d \) [Equation (5)] and a cumulative root fraction \( f \) [Equation (3)] independent of the age of the plant and the total root biomass \( B(t) \). However, the surface root density,

\[
\rho(0, t) = aB(t),
\]  

(7)
is directly proportional to root biomass. The result is the root density shown in Figure 1a and the constant cumulative root fraction, independent of \( B(t) \), shown in Figure 1b. The value \( a = 3 \) characterizing trees following J96 is used in the figure. J96 provide estimates of mean root biomass for different biomes and estimate a mean value of about 4.4 kg m\(^{-2}\) for trees for which the root profile is represented by the solid line in the figure. For other root profiles the root biomass ranges between 0.1 and 8.7 kg m\(^{-2}\).

### Table 1. Sources of the root biomass data used in this study.

<table>
<thead>
<tr>
<th>Biome</th>
<th>Reference</th>
<th>Root biomass (kg m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperate coniferous</td>
<td>Wright (1955)</td>
<td>0.8, 0.9, 1.27, and 2.0 kg m(^{-2}) for 12-, 22-, 45-, and 80-yr-old pines</td>
</tr>
<tr>
<td></td>
<td>12-, 22-, and 45-yr-old Corsican pine, and 80-yr-old Scots pine</td>
<td></td>
</tr>
<tr>
<td>Tropical evergreen</td>
<td>Mensah and Jenik (1968)</td>
<td>1.17</td>
</tr>
<tr>
<td></td>
<td>Huttel (1975)</td>
<td>2.10</td>
</tr>
<tr>
<td></td>
<td>Vance and Nedkarni (1992)</td>
<td>4.01</td>
</tr>
<tr>
<td></td>
<td>Ignatenko and Khamizyanova (1971)</td>
<td>1.03</td>
</tr>
<tr>
<td>Tundra</td>
<td>Dennis and Johnson (1970)</td>
<td>2.30</td>
</tr>
<tr>
<td></td>
<td>Khodacheck (1969)</td>
<td>3.50</td>
</tr>
</tbody>
</table>

Figure 1a requires that young plants attain their rooting depth early in life with long skinny roots and a small root biomass, and that older plants with large root biomass follow the same distribution so that rooting depth, and the fraction of roots in soil layers, are the same at all ages. This implies that after attaining their rooting depth with a small root biomass, roots essentially grow only horizontally. That is, at any depth the horizontal increase in root density is directly proportional to the increase in root biomass and the rooting depth does not change. This contrasts with the cumulative root distribution data in Figure 2 from four temperate coniferous sites, three tropical evergreen sites, and three.
Figure 1. (a) Root density $\rho(z) = aB(t)e^{-az}$ (kg m$^{-2}$) and (b) cumulative root fraction $f = (1 - e^{-az})$ plotted against soil depth (m) for the root biomass varying from 0.1 to 8.7 kg m$^{-2}$. A value of $a = 3$ characterizing trees is used following J96. Since $a$ is constant and independent of the root biomass, the cumulative root fraction profile does not change with the root biomass.
tundra sites for a range of root biomasses. These data (kindly made available by R. Jackson) are a subset of the data used in J96 from the sources listed in Table 1. The data show that a constant rooting depth and root distribution profile are not very realistic. For all three biomes an increase in root biomass is associated with an increase in rooting depth and a change in the root distri-
bution profile such that a larger fraction of roots exists in deeper soil layers as the root biomass increases. The data from 12-, 22-, and 45-yr-old Corsican Pine (temperate coniferous) sites in Figure 2a provide a chronological sequence, while data from the other two biomes are from sites with a range of root biomasses.

3. Relating root distribution profile to root biomass

We see from Figure 2, and expect physiologically, that young plants have shallower roots and smaller rooting depths than older, larger plants. This suggests that to the first order \( d \propto B \propto 1/a \); that is, the parameter \( a \) in Equation (6) is a function of root biomass \( B(t) \). A power-law relation is consistent with the assumed exponential root profile and we set

\[
a(t) = \frac{b}{B^a(t)},
\]

which yields

\[
\rho(z, t) = a(t)B(t)e^{-a(t)z} = bB^{(1-a)(t)} \exp\left[-\frac{b}{B^a(t)}z\right],
\]

\[
f(z, t) = 1 - e^{-a(t)z} = 1 - \exp\left[-\frac{b}{B^a(t)}z\right], \quad \text{and}
\]

\[
d(t) = \frac{3}{a} = \frac{3B^a(t)}{b},
\]

where \( a, \alpha, \) and \( b \) all depend on vegetation type. Equations (9)–(11) indicate how \( \rho, f, \) and \( d \) vary over time in conjunction with \( B(t) \) in this formulation. The potential virtue of this representation is that the rooting depth is initially zero and increases with plant age and root biomass. The root profile also varies with the root biomass as expected.

Figures 1 and 3 illustrate the characteristics of this representation in terms of \( \alpha \). For \( \alpha = 0, b = a \), and the original formulation [Equations (1)–(6)] is recovered where roots grow only horizontally, without an increase in rooting depth, as \( B(t) \) increases (see Figure 1) and cumulative root fraction \( f \) and rooting depth \( d \) do not depend on time and root biomass. For \( \alpha = 1 \), by contrast,

\[
\rho(z, t) = b \exp\left[-\frac{b}{B(t)}z\right], \quad f(z, t) = 1 - \exp\left[-\frac{b}{B(t)}z\right], \quad d(t) = \frac{3B(t)}{b},
\]

and roots grow mainly vertically downward as shown in Figures 3a and 3b. That is, the surface root density stays constant while rooting depth increases in direct proportion to root biomass. For values of \( \alpha \) between 0 and 1 roots grow both horizontally and vertically as shown in Figures 3c and 3d for the example of \( \alpha = 1/2 \). We term \( \alpha \) the “root growth direction” parameter since its value determines the rate at which roots evolve both horizontally and vertically as \( B \) increas-
Figure 3. The effect of root growth direction parameter $\alpha$ on root density $\rho$ and cumulative root fraction $f$. Values of the mean root distribution profile parameter ($\bar{a} = 3$) and the mean root biomass ($\bar{B} = 4.4$ kg m$^{-2}$) corresponding to trees are used. Root biomass values range from 0.1 to 8.7 kg m$^{-2}$ in intervals of 0.86 kg m$^{-2}$ for values of $\alpha$ equal to (top) 1 and (bottom) 0.5.

es. The representation proposed here expresses the root distribution profile and rooting depth as a function of root biomass via the root growth direction parameter, $\alpha$.

While time-varying root distribution and rooting depth with plant age and/or root biomass is not yet a feature of most global applications of dynamic vegetation models, some agricultural and small-scale ecosystem models do incorporate such a relationship. Kage et al. (Kage et al. 2000) simulate the increasing rooting depth of cauliflower as a function of the cumulative temperature sum (the sum of daily temperatures above a certain threshold, which is used as a measure of accumulated heat) after the planting date. In their model the rooting depth increases at an exponential rate in the early days after planting and at a linear rate thereafter. Rasse et al. (Rasse et al. 2001) model the downward expansion of roots of beech and Scots pine trees as a linear function of stand age up to 100 years of age, after which the rooting depth is assumed to remain
constant. These models simulate the change in rooting depth and root distribution profile as a function of the cumulative heat and plant age, respectively, rather than root biomass. By contrast, the approach proposed here takes an “allometric” view that results in a time-dependent root density distribution and rooting depth as a function of the time-dependent root biomass.

4. Parameter estimation and verifying the representation

Ideally we would estimate $b$ and $\alpha$ and verify the appropriateness of Equations (9)–(11) for each vegetation type by fitting each to observed data. Rooting data are not widely available, however, and as a practical matter we would like to represent $\alpha$ and $b$ in terms of more readily available information. We appeal to the mean $e$-folding length information $\bar{a} = -\gamma \ln \bar{B}$ and the mean root biomass $\bar{B}$ from J96 for different biomes (and other similar information) and propose that Equation (8) also holds for these mean quantities (i.e., $\bar{a}$, and $\bar{B}$). This implies that $b = \bar{a}\bar{B}^{\alpha}$ and that

$$a = \alpha \left( \frac{\bar{B}}{\bar{B}} \right)^{\alpha}$$

in Equations (9)–(11). When we know $\bar{a}$ and $\bar{B}$ it only remains to obtain $\alpha$ that can then be used to describe the varying root distribution profile. Finally if $\alpha$ does not vary greatly among vegetation types, then some reasonable value can be used in general. Equation (13) implies that when root biomass $\bar{B}$ for a plant is equal to its mean root biomass $\bar{B}$ it attains a mean root distribution profile characterized by $a = \bar{a}$ in Equations (9)–(11), while root biomasses higher and lower than the mean root biomass yield root distribution profiles that are deeper ($a < \bar{a}$) and shallower ($a > \bar{a}$) than the mean root profile, respectively.

How well do Equations (9)–(11) characterize root distribution in general and is (13) a reasonable assumption? We use the data in Figure 2 to estimate the root growth direction parameter $\alpha$. We first estimate $\bar{a}$ in a manner similar to J96 by minimizing

$$\Psi = \sum_{jk} \left[ f_{jk} - (1 - e^{-\bar{a}z_j}) \right]^2,$$

where $k$ is the depth index and $j$ is the “biomass” or profile index labeling the individual profiles. That is, we estimate the mean exponential root distribution profile represented by $\bar{a}$ in a least squares sense by fitting it to the observed cumulative root fraction data, for the three biomes, as shown in Figure 2. We apply this analysis to a subset of the J96 data to illustrate methodology, but in the general case we would adopt $\bar{a}$ from J96 or from other sources based on observations. The mean exponential root distribution profile, obtained by minimizing $\Psi$, for $\bar{a}$, is shown as the dark line in Figure 4. The resulting values of the sum of the square of errors ($\Psi')$ and the coefficient of efficiency ($E$) (Nash and Sutcliffe, 1970) are also shown. The coefficient of efficiency is given by $E = $
Figure 4. The fitted mean cumulative root fraction curve \( f_i = 1 - \exp(-\alpha z) \) for selected (a) temperate coniferous, (b) tropical evergreen, and (c) tundra sites. The values of the sum of the square of errors \( (\psi_i) \) and coefficient of efficiency \( (E) \) are also shown.

\[
1 - \frac{\left[\Sigma f_{jk} - \bar{f}\right]^2}{\bar{f}} ,
\]

where \( f_{jk} \) are the observed cumulative root fractions, and \( \bar{f} \) is their mean. Given \( \bar{\alpha} \), the parameter \( \alpha \) may be estimated by minimizing

\[
\Psi_2 = \sum_{jk} \left[ f_{jk} - \left\{ 1 - \exp\left[-\bar{\alpha} \left(\frac{B}{B_j}\right)^\alpha z_k\right]\right\}\right] ,
\]  

(15)
where $B_j$ is the biomass of profile $j$ and $\overline{B}$ is the mean over all profiles. That is, we estimate the value of the root growth direction parameter $\alpha$ such that the predicted profiles corresponding to the different root biomasses $B_j$ are fitted to the observed data in a least squares sense. The value of $\alpha$ thus obtained and of $\overline{\alpha}$ and $\overline{B}$ are summarized in Table 2. The resulting individual cumulative distribution profiles,

$$f_j = 1 - \exp\left(-\alpha\left(\frac{B}{B_j}\right)^{\alpha}\right),$$

for different biomasses are shown in Figure 5 for the three biomes. The value of $\overline{\alpha}$, obtained via minimizing $\Psi$, for the subset of data used here does not differ much from the $\overline{\alpha}$ values given by J96 based on a more extensive dataset (Table 2). We obtain values of $\alpha$ equal to 0.70, 0.78, and 0.90 for temperate coniferous, tropical evergreen, and tundra biomes, respectively. The resulting values of $E = 1 - [\Psi(\Sigma f_j (\hat{f}_j - \hat{f})^2)]$ and the sum of square of errors ($\Psi_j$) for each biome are also shown in Figure 5. The $E$ values in Figure 5 are higher, and the sum of the square of errors are lower, than that in Figure 4 because of a better fit to the cumulative root fraction data. Figure 5 indicates that Equation (16), with these values of $\alpha$, captures the first-order effect of the change in the root distribution profile with the root biomass. A value of $\alpha$ larger than 0.5 implies that the rate of root growth is larger in the vertical direction than in the horizontal direction as the root biomass increases in time. The change in the root distribution profile with increasing biomass is captured especially well by Equation (16) for the three tundra sites, as seen in Figure 5c. For the temperate coniferous (Figure 5a) and tropical evergreen (Figure 5b) sites the model does somewhat less well in capturing the shallow root profile associated with the lowest root biomass.

<table>
<thead>
<tr>
<th>Biome</th>
<th>$\overline{B}$ (kg m$^{-2}$)</th>
<th>$\overline{\alpha}$</th>
<th>$\overline{\alpha}$ from J96</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperate coniferous</td>
<td>1.25</td>
<td>2.88</td>
<td>2.43</td>
<td>0.70</td>
</tr>
<tr>
<td>Tropical evergreen</td>
<td>2.43</td>
<td>4.40</td>
<td>3.90</td>
<td>0.78</td>
</tr>
<tr>
<td>Tundra</td>
<td>2.28</td>
<td>9.99</td>
<td>9.00</td>
<td>0.90</td>
</tr>
</tbody>
</table>

The root growth direction parameter $\alpha$ may itself be a function of a plant’s age. For example, roots may tend to grow vertically early in a plant’s age and then may start growing horizontally as well. However, in the absence of a detailed analysis of chronological sequences of root biomass data from a variety of sites and biomes we cannot infer the extent to which $\alpha$ changes with plant age. A constant value of $\alpha$ appears to capture the first-order effect of change in the root distribution profile with the root biomass.

Rooting depth is also influenced by soil texture (Schenk and Jackson, 2002a) and may also be restricted by bedrock or permafrost. Rooting depth is also likely to be influenced by the nutrient status of the soils. For example, the poor nutrient status of northern soils may be a reason for the shallow rooting depths of boreal...
Figure 5. The cumulative root fraction curve \( f = 1 - \exp\left[-\alpha(\bar{B}/B)^2\right] \) for values of \( \alpha \) equal to 0.7, 0.78, and 0.90 for temperate coniferous, tropical evergreen, and tundra biomes, respectively. The individual curves in the diagrams are for different values of root biomass \( B \) and illustrate that the rooting profile and rooting depth evolution with \( B \) is captured, to the first order, by the proposed representation. The values of the sum of the square of errors (\( \psi^2 \)) and the coefficient of efficiency (\( E \)) are also shown.
forests (J96; Schenk and Jackson, 2002a) compared to temperate and tropical forests, although this may be at least partially captured in the distribution parameters ($\bar{\alpha}$, $\bar{B}$, and $\alpha$). While we suggest that the representation of root distribution and rooting depth as a function of root biomass proposed here better captures rooting behavior than the fixed profile used in most current DVMs, it is clear that other factors may also affect rooting behavior.

5. Application

The methodology proposed here for representing variable rooting depth and root distribution as a function of root biomass is intended to be used in the Canadian Terrestrial Ecosystem Model (CTEM; Arora, 2003) coupled to a SVAT scheme for inclusion in the Canadian Centre for Climate Modelling Analysis coupled climate model. Rooting depth will be limited to the total soil depth (which is essentially the depth to bedrock) used in the thermal and hydrological balances of the climate model’s land surface scheme (Verseghy et al., 1993). In particular, the implementation uses values of $\bar{\alpha}$ and $\bar{B}$ from J96 for different biomes, but adopts a universal constant (i.e., vegetation independent) value of $\alpha$ as a first approximation (in the absence of values of $\alpha$ for different biomes), except for the case when soil depth limits root growth.

Table 3. Estimated values of parameter $b = \bar{\alpha}B^*$ for different biomes. Values of $\bar{\alpha}$ and $\bar{B}$ are obtained from J96 and the root growth direction parameter $\alpha$ is assumed to be equal to 0.8. The two desert values are for the cold and warm desert, respectively.

<table>
<thead>
<tr>
<th>Biome</th>
<th>Parameter representing mean root distribution profile, $\bar{\alpha}$</th>
<th>Average standing root biomass, $\bar{B}$ (kg m$^{-2}$)</th>
<th>Parameter representing variable root distribution profile, $b = \bar{\alpha}B^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boreal forest</td>
<td>5.86</td>
<td>2.9</td>
<td>13.73</td>
</tr>
<tr>
<td>Crops</td>
<td>3.97</td>
<td>0.15</td>
<td>0.87</td>
</tr>
<tr>
<td>Desert</td>
<td>2.53</td>
<td>1.2, 0.4</td>
<td>2.93, 1.22</td>
</tr>
<tr>
<td>Sclerophyllous shrubs</td>
<td>3.67</td>
<td>4.8</td>
<td>12.87</td>
</tr>
<tr>
<td>Temperate coniferous forest</td>
<td>2.43</td>
<td>4.4</td>
<td>7.95</td>
</tr>
<tr>
<td>Temperate deciduous forest</td>
<td>3.46</td>
<td>4.2</td>
<td>10.91</td>
</tr>
<tr>
<td>Temperate grassland</td>
<td>5.86</td>
<td>1.4</td>
<td>7.67</td>
</tr>
<tr>
<td>Tropical deciduous forest</td>
<td>3.98</td>
<td>4.1</td>
<td>12.31</td>
</tr>
<tr>
<td>Tropical evergreen forest</td>
<td>3.87</td>
<td>4.9</td>
<td>13.80</td>
</tr>
<tr>
<td>Tropical grassland savanna</td>
<td>2.84</td>
<td>1.4</td>
<td>3.72</td>
</tr>
<tr>
<td>Tundra</td>
<td>8.99</td>
<td>1.2</td>
<td>10.40</td>
</tr>
</tbody>
</table>

If the rooting depth estimated using Equation (11) exceeds the soil depth, the root distribution profile is not allowed to deepen with increasing root biomass. This is equivalent to reducing $\alpha$ since to keep $d$ constant at the soil depth $d^*$ requires that

$$d^* = \frac{3}{\bar{\alpha}} \left[ \frac{B(t)}{\bar{B}} \right]^\alpha,$$

hence, $\alpha = \ln(d^*\bar{\alpha}/3)/\ln[B(t)/\bar{B}]$. In this case $\alpha$ decreases as the root biomass
increases and roots grow in the horizontal direction once the rooting depth equals the soil depth. This is illustrated in Figure 6 where the special value of $\alpha = 1$ is used for clarity since root density in this case does not increase at the surface. A soil depth equal to 1.2 m is assumed. With $\alpha = 1$ roots grow vertically downward until the root biomass increases above a certain value (corresponding to $d = d^\ast$) when $\alpha$ begins to decrease and root growth occurs in the horizontal direction such that 95% of the root biomass is always contained within 1.2 m.

The proposed representation expresses the differences in the root distribution profile of various biomes through the vegetation-dependent parameter $b = \bar{\alpha} \bar{B}^\alpha$ used in Equations (9)–(11). Values of $b$ for different biomes are listed in Table 3 based on values of $\bar{\alpha}$ and $\bar{B}$ from J96, and assuming a constant value of $\alpha = 0.8$. The resulting value of $b$ is higher for boreal forests than for temperate and tropical forests so that rooting depth $d$ [Equation (11)] is shallower for boreal than that
for other forests with the same mean root biomass. Similarly, when comparing temperate grasslands and tundra, which have similar average root biomass, tundra plants have shallower root profiles than temperate grassland for the same root biomass. Equation (11) provides rooting depth as a function of root biomass while taking into account the difference in the root distribution profile of different biomes. The approach proposed here is an extension of the traditional exponential root distribution used in SVAT schemes and DVMs and is intended to represent the average root profile of many plants distributed over comparatively large regions, rather than the root profile of an individual tree or stand.

6. Summary and conclusions

While leaf area index and vegetation height, derived from leaf and stem biomass, are considered as time-varying structural attributes of vegetation in the current generation of dynamic vegetation models, rooting depth and root distribution are usually considered to be time invariant. This implies that the fractional root distribution in soil layers, which is used to estimate transpiration, does not change no matter what the vegetation age and/or root biomass may be.

We propose a simple representation in which the root distribution profile and rooting depth are functions of the root biomass. Following J96, the root profile is assumed to be exponential \( f = 1 - e^{-\alpha z} \) with an associated rooting depth of \( d = 3/a \). We connect parameter \( a \) of the exponential distribution to the time-dependent root biomass \( B(t) \) via a root growth direction parameter \( \alpha \) as \( a = bB^\alpha(t) \). When \( \alpha = 0 \) the original distribution is recovered and this is the representation used in most current dynamic vegetation models in which the root distribution profile is independent of time and root biomass. In that case plants attain their final rooting depth very early in life, with a very small biomass, and thereafter roots grow basically horizontally. When \( \alpha = 1 \), rooting depth increases in proportion to \( B(t) \) \( [d = 3B(t)b] \) and roots grow mainly in the vertical direction. Values of \( \alpha \) between 0 and 1 provide rooting profile behavior in which roots grow in depth as well as horizontally. Analysis of chronological sequences of root biomass data from a temperate coniferous site, and data from tropical evergreen and tundra sites give moderately different values of \( \alpha \). In the absence of a knowledge of \( \alpha \) for each biome a value of \( \alpha \approx 0.8 \) captures the first-order effect of changes in the root distribution profile with root biomass. The primary objective here is to illustrate that this approach can be used to represent the variable root distribution profile and rooting depth. Preliminary analysis of root biomass data from temperate coniferous, tropical evergreen, and tundra sites indicates that root distribution profiles change with an increase in root biomass in a manner similar to that proposed. Implementation of variable rooting depth and profile is also consistent with increased allocation of carbon to roots in response to water stress in DVMs, which incorporates dynamic allocation.

The approach proposed in this paper offers the possibility of a somewhat more realistic treatment of the root distribution profile and rooting depth than is used in most current DVMs. However, the effect of soil texture and other factors on the root distribution profile is only implicit in the rooting profiles of various biomes via the parameter \( b = \bar{a}B^\alpha \), which is based on biome-dependent mean
root distribution profiles and the average root biomass. The removal of fixed rooting depth and root distribution constraint is expected to improve the realism of simulated energy, water, and carbon balance in dynamic vegetation models.

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