Soil description, root distribution and belowground hydraulic conductances

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1 Soil description

Soil can be described using between 1 and 5 soil layers. For each soil layer s the following parameters are needed:

- Soil layer width (d_s, in mm).
- Soil texture: percent of sand ($P_{sand,s}$), silt ($P_{silt,s}$) and clay ($P_{clay,s}$).
- Macroporosity (percent of macropores).
- Percentage of rock fragment content ($P_{rocks,s}$).

Soil texture (i.e. percent of sand, silt and clay), bulk density and rock fragment content can differ between soil layers. Specifying a deep rocky layer is important because Mediterranean plants may extend their roots into cracks existing in the parent rock (Ruffault et al., 2013).

Relative soil moisture content is tracked at each layer s using the pair of coupled state variables:

- Ψ_s, the soil water potential (in MPa).
- $W = \theta(\Psi_s)/\theta_{fc,s}$, the proportion of volumetric soil moisture in relation to field capacity $\theta_{fc,s}$

Following Reynolds et al. (2000), volumetric soil moisture $\theta(\Psi_s)$ corresponding to a given water potential Ψ_s (in MPa) is calculated using the pedotransfer functions of Saxton et al. (1986):

$$\theta(\Psi_s) = (\Psi_s/A_s)^{(1/B_s)} \tag{1}$$

where $A_s = -0.1 \cdot e^{(-4.396-0.0715 \cdot P_{clay,s} - 0.0004880 \cdot P^2_{sand,s} - 0.00004285 \cdot P^2_{sand,s} \cdot P_{clay,s})}$ and $B = -3.140 - 0.00222 \cdot P^2_{clay,s} - 0.00003484 \cdot P^2_{sand,s} \cdot P_{clay,s}$. Here $P_{clay,s}$ and $P_{sand,s}$ are the percentage of clay and sand, respectively. Soil water holding capacity (V_s, in mm) in soil layer s is defined as the volumetric water content at field capacity:

$$V_s = d_s \cdot ((100 - P_{rocks,s})/100) \cdot \theta_{fc,s} \tag{2}$$

where d_s is the depth of the soil layer (in mm) and $P_{rocks,s}$ is the percentage of rock fragments. The following code shows the properties of a soil initialized using three layers and default values for texture, bulk density, rock fragment content and layer width:

```
> s = soil(defaultSoilParams(3))
> print(s)

Soil depth (mm): 2000

Layer  1  [ 0  to  300 mm ]
    clay (%): 25 silt (%): 50 sand (%): 25 organic matter (%): NA [ Silt loam ]
    Rock fragment content (%): 20 Macroporosity (%): 10
    Theta FC (%): 30 Vol. FC (mm): 73 Vol. current (mm): 73
    Temperature (ºC): NA

Layer  2  [ 300  to  1000 mm ]
    clay (%): 25 silt (%): 50 sand (%): 25 organic matter (%): NA [ Silt loam ]
    Rock fragment content (%): 40 Macroporosity (%): 10
    Theta FC (%): 30 Vol. FC (mm): 127 Vol. current (mm): 127
    Temperature (ºC): NA

Layer  3  [ 1000  to  2000 mm ]
    clay (%): 25 silt (%): 50 sand (%): 25 organic matter (%): NA [ Silt loam ]
```

```
    Rock fragment content (%): 60 Macroporosity (%): 10
    Theta FC (%): 30 Vol. FC (mm): 121 Vol. current (mm): 121
    Temperature (ºC): NA

Total soil water holding capacity (mm): 322

Total current Volume (mm): 322
```

Unless specified, volumetric water content is initialized at field capacity (i.e. $\Psi_s = -0.033$ MPa, $\theta(\Psi_s) = \theta_{fc,s}$ and $W = 1.0$).

2 Root distribution

The rooting system of each cohort i (i.e. the proportions v_{ij}) can be defined assuming conic distribution of fine roots (see `root.conicDistribution()`). In this case, only rooting depth parameter is needed to determine fine root proportions. Alternatively, one can adopt the linear dose response model (Collins and Bras, 2007; Schenk and Jackson, 2002):

$$Y_i(z) = \frac{1}{1 + (z/Z_{50,i})^{c_i}} \tag{3}$$

where $Y_i(z)$ is the cumulative fraction of fine root mass located between surface and depth z; $Z_{50,i}$ is the depth above which 50% of the root mass is located; and c_i is a shape parameter related to $Z_{50,i}$ and $Z_{95,i}$ as $c_i = 2.94/\ln(Z_{50,i}/Z_{95,i})$ (see `root.ldrDistribution()`).

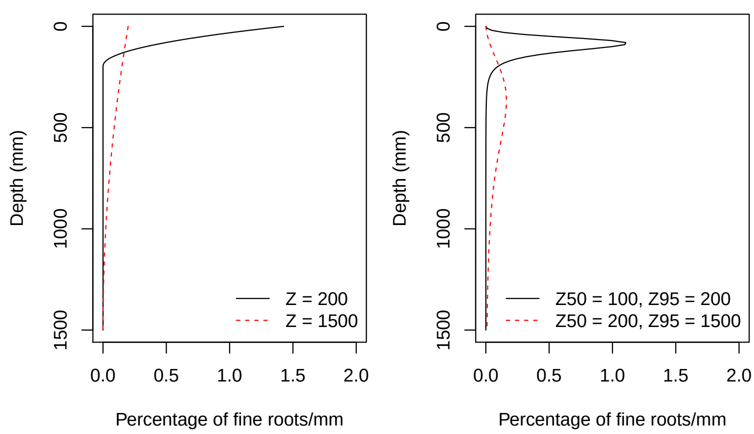

Fig. 1: Examples of root density profile according to a conic distribution (left) and the linear dose response model (right).

The depth of soil layers and the linear dose response model is used to determine $v_{i,s}$, the proportion of plant fine roots of cohort i that are in a given soil layer s. For example, if we define take the layer widths of the soil defined above:

```
> d = s$dVec
> d

[1]  300  700 1000
```

The proportion of fine roots in each layer, assuming a linear dose response model or a conic model, will be:

```
> Z50 = 200
> Z95 = 1500
> v1 = root.conicDistribution(Z95, d)
> v1

      [,1]     [,2]       [,3]
[1,] 0.488 0.474963 0.03703704

> v2 = root.ldrDistribution(Z50,Z95, d)
> v2

          [,1]      [,2]       [,3]
[1,] 0.6661036 0.2784153 0.05548106
```

The minor fraction of mass located below soil depth is redistributed within the existing layers and the proportion of roots in each soil layer is assumed proportional to the amount of water extracted from it.

3 Belowground hydraulic conductances

Belowground conductance parameter values will not be normally available. Therefore, we provide routines to estimate them from a minimum set of input parameters. In practice, this is done automatically in functions `swbInput()` and `forest2swbInput()`, but we describe the process here. Conductance of xylem elements is modelled using a two-parameter Weibull function as the vulnerability curve $k_x(\Psi)$:

$$k_x(\Psi) = k_{xmax} \cdot e^{-((\Psi/d)^c)} \tag{4}$$

where k_{xmax} is the xylem maximum hydraulic conductance (defined as flow per surface unit and per pressure drop), and c and d are species-specific parameters. We start defining the following parameter values for the vulnerability curve of stem xylem:

```
> kstemmax = 4 # in mmol·m-2·s-1·MPa-1
> stemc = 3
> stemd = -4 # in MPa
```

Root xylem is more vulnerable to cavitation:

```
> rootc = 3
> rootd = -2.5 #MPa
```

With these input values in the following we calculate root xylem and rhizosphere hydraulic conductances.

3.1 Root xylem maximum hydraulic conductances

For root xylem, we may assume that minimum stem resistance (inverse of maximum conductance) represents a fixed proportion of the minimum total tree (stem+root) resistance (see function `defaultControl()`), which leads to maximum total tree conductance being:

```
> ktot = kstemmax*0.625
> ktot

[1] 2.5
```

and the maximum root xylem conductance is:

```
> krootmax = 1/((1/ktot)-(1/kstemmax))
> krootmax

[1] 6.666667
```

Note that the resistances add up because they are in series:

```
> 1/krootmax + 1/kstemmax

[1] 0.4

> 1/ktot

[1] 0.4
```

Now, we need to divide total maximum conductance of the root system xylem among soil layers we need weights inversely proportional to the length of transport distances (Sperry et al. 2016). Vertical transport lengths can be calculated from soil depths and radial spread can be calculated assuming cylinders with volume proportional to the proportions of fine root biomass. The calculation is done using `root.rootXylemConductanceProportions()`:

```
> w1 = root.xylemConductanceProportions(v1, d)
> w1
```

```
[1] 0.3029809 0.3354839 0.3615352
```

```
> w2 = root.xylemConductanceProportions(v2, d)
> w2
```

```
[1] 0.2762029 0.3968217 0.3269754
```

Xylem conductance proportions can be quite different than the fine root biomass proportions. This is because radial lengths are largest for the first top layers and vertical lengths are largest for the bottom layers. The maximum root xylem conductances of each layer will be the product of maximum total conductance of root xylem and weights:

```
> w1*krootmax
```

```
[1] 2.019873 2.236559 2.410235
```

```
> w2*krootmax
```

```
[1] 1.841352 2.645478 2.179836
```

3.2 Rhizosphere maximum hydraulic conductances

Rhizosphere conductance is regulated in the model using the van Genuchten function (van Genuchten, 1980):

$$
\begin{aligned}
k_r(\Psi) &= k_{rmax} \cdot v^{(n-1)/(2 \cdot n)} \cdot ((1-v)^{(n-1)/n} - 1)^2 && (5) \\
v &= [(\alpha\Psi)^n + 1]^{-1} && (6)
\end{aligned}
$$

where k_{rmax} is the maximum rhizosphere conductance, and n and α are texture-specific parameters (see Leij et al. 1996; Carsel & Parrish 1988). Parameters n and α for each soil layer were already available from soil initialization:

```
> s$VG_n
```

```
[1] 1.41 1.41 1.41
```

```
> s$VG_alpha
```

```
[1] 203.9955 203.9955 203.9955
```

but we need to know maximum rhizosphere conductance, which will depend on the rhizosphere surface in each layer. Instead of estimating them, we follow Sperry et al. (2016) we solve for maximum rhizosphere conductance in each layer from an inputed 'average percentage rhizosphere resistance'. The percentage of continuum resistance corresponding to the rhizosphere is calculated from the vulnerability curves of stem, root and rhizosphere at the same water potential. The average resistance is found by evaluating the percentage for water potential values between 0 and Ψ_{crit}. If we specify a 5% of average resistance in the rhizosphere (see function `defaultControl()`) the maximum rhizosphere conductance values for the three layers are found calling:

```
> krmax = rep(0,3)
> krmax[1]= hydraulics.findRhizosphereMaximumConductance(5,
+                       s$VG_n[1],s$VG_alpha[1],
+                       krootmax, rootc,rootd,
+                       kstemmax, stemc, stemd)
> krmax[2] = hydraulics.findRhizosphereMaximumConductance(5,
+                        s$VG_n[2],s$VG_alpha[2],
+                        krootmax, rootc,rootd,
+                        kstemmax, stemc, stemd)
> krmax[3] = hydraulics.findRhizosphereMaximumConductance(5,
+                        s$VG_n[3],s$VG_alpha[3],
+                        krootmax, rootc,rootd,
+                        kstemmax, stemc, stemd)
> krmax
```

```
[1] 14178605351 14178605351 14178605351
```

The values are the same because the texture of the three layers is the same in this case. If we take into account root distribution, actual maximum rhizosphere conductance values are:

```
> krmax*v1
```

```
           [,1]       [,2]      [,3]
[1,] 6919159411 6734312408 525133532
```

```
> krmax*v2
```

```
           [,1]       [,2]      [,3]
[1,] 9444420380 3947540871 786644101
```

4 References

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