

## SUPPLEMENTARY DATA

### *1: Water uptake algorithm*

The potential water uptake of the plant is calculated as follows. A series of points are placed along the length of the root, each spaced  $d_{\text{wu}}$  apart. Each of these points represents a collection of fine roots able to take up water, and assumed to be able to access the water within the voxel in which the point is located, and no other voxel's water. Based on the definition of  $u_{\text{max}}$ , the potential uptake of the fine roots represented by the point is assumed to be  $u_{\text{max}} \times d_{\text{wu}}$ . The value of  $d_{\text{wu}}$  was chosen to be small compared to voxel size to ensure that roots had access to the water in any voxel they intersect.

The potential water uptakes of all points in a voxel are summed to give the total potential water uptake of the voxel. If this is less than or equal to the total water available in the voxel then the actual amount of water taken up by each point in the voxel is equal to its potential. On the other hand, if the total potential water uptake of the voxel is more than the total water available in the voxel, then the actual amount of water taken up by each point in the voxel is equal to the total water available divided by the number of points.

The root segment is assumed to only be able to take up water from within its own soil voxel, and possible diffusion between voxels is ignored; this means that the edge length of the voxels defined by the model parameter  $l_{\text{watervoxel}}$  is a model parameter defining an important characteristic of the soil by representing in a relatively simple way how far water can move through the soil. More complex, continuous and realistic representation of soil-water dynamics were avoided to make the simulation computationally fast and because we believed that this representation is realistic enough for our purposes.

Any length of root within a wet crack is defined to always have maximum water uptake  $u_{\text{max}}$ . This is likely to be a reasonable assumption during the simulated period of the wet season where there is regular rain and replenishment of water stored in rock cracks.

### *2: Rooting economics*

Growing more and longer roots benefits a plant by increasing the volume of soil that can be accessed for water uptake. However, it also has a cost in terms of the resources required to construct and maintain the roots. The economics of these costs and benefits of rooting needed to be represented in our model, and thus they need a 'currency'. In this study, for simplicity, we assumed a linear relationship between water uptake and biomass production. The base 'currency' of the model could thus be thought of as either water taken up or biomass, since the two are directly convertible with biomass equal to water uptake multiplied by the conversion efficiency parameter  $e_{\text{con}}$ . However, in general we chose to emphasise biomass as the base currency.

It is clear that the cost of a root will increase with the length of the root. The simplest option might seem to be to represent cost as an increasing linear function of root length. However, this implies that all roots are a constant thickness. More realistically, longer roots are also likely to take up and transport more water, and thus it seems likely that they will need to be thicker. This means that the volume and thus the cost of a root would be likely to increase 'more than linearly', that is the rate of increase of the cost of a root with an increase in length is also likely to increase with length.

For this study, we thought the simplest way to represent this was to assume that the cost of a root increases in proportion to the square of the length of the root. This idea can be justified as follows. We assume that each unit length of a main or lateral root is associated with a similar amount of finer roots and thus has the potential to take up the same amount of water. We also assume that the cross sectional area of a root at a given point along the root corresponds to its capacity to transport water at that point. Therefore the cross sectional area of a root at a given point is proportional to the length of root that lies further away from the base of the plant, towards the root tip, at that point. More specifically, we can define the cross-sectional area of the root to be  $u_{\max}$  times  $e_{\text{trans}}$  times the distal root length, where  $u_{\max}$  is the maximum water uptake per unit of root length and  $e_{\text{trans}}$  is a fixed parameter defining the transport efficiency of a root segment of a given cross-sectional area (Table 1). This ensures that the root would be able to transport all water taken up if all parts of the root were taking water up at the maximum rate  $u_{\max}$ . It also means that the lateral root forms a solid of revolution with volume equal to

$$\frac{1}{2} \times u_{\max} \times e_{\text{trans}} \times l_{\text{root}}^2, \quad (\text{S1})$$

where  $l_{\text{root}}$  is the length of the root. We assume that biomass is directly proportional to volume, and thus the biomass of the root is

$$\frac{1}{2} \times k_{\text{bm}} \times u_{\max} \times e_{\text{trans}} \times l_{\text{root}}^2, \quad (\text{S2})$$

where  $k_{\text{bm}}$  is the fixed root biomass per volume parameter (Table 1). Or in terms of the ‘alternative currency’, the total water uptake required to construct the lateral root itself is

$$\frac{1}{2} \times k_{\text{bm}} / e_{\text{con}} \times u_{\max} \times e_{\text{trans}} \times l_{\text{root}}^2, \quad (\text{S3})$$

where  $e_{\text{con}}$  is the fixed water uptake to biomass conversion efficiency parameter (Table 1).

However, the situation is complicated a little by the fact that the main root needs to transport the water that it uptakes itself, but also the water taken up by its lateral roots. To account for this, we assume that the cost of the main root structure required to transport the water taken up by a lateral root is proportional to the cross-sectional area of the lateral root at its widest point, ie where it meets the main root. From above, this area is

$$u_{\max} \times e_{\text{trans}} \times l_{\text{root}}, \quad (\text{S4})$$

and so the volume is

$$u_{\max} \times e_{\text{trans}} \times l_{\text{root}} \times L_{\text{root}}, \quad (\text{S5})$$

where  $L_{\text{root}}$  is the distance between the top of the main root and the start of the lateral root, and so the water uptake cost of this part of the main root structure needed to support the lateral root is

$$k_{\text{bm}} \times u_{\max} \times e_{\text{trans}} \times l_{\text{root}} \times L_{\text{root}}, \quad (\text{S6})$$

For the purpose of allocating resources to the growth of different roots, this cost is considered part of the cost of the lateral root, even though physically it is part of the main root.

Therefore the total biomass cost of a lateral root is the sum of expressions S6 and S2,

$$k_{\text{bm}} \times u_{\max} \times e_{\text{trans}} \times l_{\text{root}} \times (\frac{1}{2} \times l_{\text{root}} + L_{\text{root}}) \quad (\text{S7})$$

and the biomass cost of the main root is simply expression S2.

At each time step, each root is allocated an increment in biomass, which may be zero if no water has been taken up. If the allocated biomass is greater than zero, then it will result in an increment in root length. For laterals, the new root length is calculated using expression S7: since the new biomass  $M_n$  of the lateral and its supporting main root structures is equal to expression S7, then

$$k_{bm} \times u_{max} \times e_{trans} \times (\frac{1}{2} \times l_{root}^2 + L_{root} \times l_{root}) - M_n = 0$$

$$\frac{1}{2} \times l_{root}^2 + L_{root} \times l_{root} - M_n / (k_{bm} \times u_{max} \times e_{trans}) = 0$$

and so by the quadratic formula:

$$l_{root} = -L_{root} \pm \text{sqrt}(L_{root}^2 + 2 M_n / (k_{bm} \times u_{max} \times e_{trans})). \quad (S8)$$

The negative solution can be ignored, and the positive solution is the new root length. For the main root, the new length can be calculated simply from expression S2, as being

$$l_{root} = \text{sqrt}(2 M_n / (k_{bm} \times u_{max} \times e_{trans})). \quad (S9)$$

Maintenance costs are not explicitly included in the above justification. However, they can be considered to be implicitly included in the parameter  $e_{con}$  in a simple way, if that parameter includes the water uptake required to both construct and maintain a given quantity of biomass.

Under the assumptions described above, lateral roots taper from their base to their tips, as do segments of main root in between lateral branching points. If we recall that finer roots are not represented explicitly in the model, but are assumed to join the lateral and main root at a constant rate along their lengths, then it is evident that the assumptions in fact correspond to da Vinci's rule. This rule, which states that cross-sectional area is preserved across branching intersections ie the sum of the cross-sectional area of daughter branches is equal to the cross-sectional area of the parent branch, corresponds to the well-known pipe-model commonly used in tree modelling (Shinozaki 1964, Mandelbrot 1983, Zimmerman 1983, Prusinkiewicz and Lindenmayer 1990). The increase in thickness of laterals from tips to base is due to the joining of these finer roots, as is the increase in thickness of the main root segments between lateral branching points. The additional increase in thickness of the main root at lateral branching points is simply the addition of the cross-sectional area coming from the lateral.

The assumption that the amount of water that can be transported by a root is linearly related to its cross-sectional area correlates with the idea that all internal conducting vessels are approximately the same radius, and that greater conductance is achieved by more vessels of the same size rather than larger vessels. The pipe model is essentially based on similar ideas. However, there is evidence that the diameter and frequency of internal conducting vessels may actually vary systematically through the tree structural hierarchy, including through the roots (see Tyree and Zimmerman 2002, Lintunen and Kalliokoski 2010) and rules such as Murray's law, based on maximisation of hydraulic conductance with a given investment, have been proposed as possible reasons for these patterns (McCulloh et al 2003). Further work is needed to investigate how integrating these alternative hypotheses regarding growth economics into our simple model would affect its predictions. Nonetheless, we believe that the simple rule of root cost increasing proportionally to the square of the root length captures the economic trade-off of root construction well enough for the purpose of this study.

### 3: Branching

As the main root grows, potential lateral branching points are generated along the main root at the end of the root segment added each day. Each potential lateral branching point has a probability of producing a lateral root when the main root is growing vertically down (before

it encounters an impermeable surface). This probability is determined from the following equation

$$P(\text{branch}) = p_{\text{downmax}} f_{\text{logistic}}(b_{\text{down}} (d_{\text{down}} - a_{\text{down}})) , \quad (\text{S10})$$

where  $p_{\text{downmax}}$ ,  $b_{\text{down}}$  and  $a_{\text{down}}$  are Strategy Parameters (Table 2),  $d_{\text{down}}$  is the distance down the main root from the soil surface in mm, and  $f_{\text{logistic}}$  is the standard logistic function

$$f_{\text{logistic}}(x) = 1 / (1 + \exp(x)). \quad (\text{S11})$$

This means that the probability of branching has a maximum of  $p_{\text{downmax}}$ , is equal to half this maximum at a distance of  $a_{\text{down}}$  mm from the soil surface, and increases with depth if  $b_{\text{down}}$  is positive. Whether the potential lateral branching point actually produces a lateral root is determined stochastically based on this probability. If it does produce a lateral, then this starts to grow  $t_{\text{del}}$  days after the production of the potential lateral branching point.

Each potential lateral branching point that does not produce a lateral while the main root is growing vertically down has a separate probability of producing a lateral root when the main root encounters an impermeable surface. This represents the effect of a hormonal signal produced by the main root tip in response to the impermeable surface. This probability is determined from the following equation

$$P(\text{branch}) = p_{\text{upmax}} f_{\text{logistic}}(b_{\text{up}} (d_{\text{up}} - a_{\text{up}})) , \quad (\text{S12})$$

where  $p_{\text{upmax}}$ ,  $b_{\text{up}}$  and  $a_{\text{up}}$  are Strategy Parameters (Table 2),  $d_{\text{up}}$  is the distance of the potential lateral branching point from the main root tip in mm, and  $f_{\text{logistic}}$  is the standard logistic function. This means that the probability of branching has a maximum of  $p_{\text{upmax}}$ , is equal to half this maximum at a distance of  $a_{\text{up}}$  mm up from the impermeable surface, and increases going up the main root if  $b_{\text{up}}$  is positive. In this case, if a lateral is actually produced based on this probability, then this lateral starts to grow immediately that the main root hits the impermeable surface, without delay.