Extensions to CropRootBox: A functional-structural plant model for Maize roots in the CropBox modeling framework

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Abstract

Background

Root architecture is responsible for a plant's water and nutrient uptake. However, due to the opacity of soil and the difficulty and inaccuracy of many destructive methods, root systems are greatly understudied. As such, root architecture models and functional-structural plant models have found great utility in simulating the many functions root-soil-water interactions. CropRootBox is one such example that is slowly developing functionalities to better model the rhizosphere.

Methods

CropRootBox is a functional-structural plant model for roots written by Dr. Kyungdahm Yun in his Cropbox modeling framework, based on Dr. Andrea Schnepf's CRootBox model. While it was written by Dr. Yun as a proof-of-concept of Cropbox's capabilities, it has great potential to incorporate other functionalities to describe both experimental and real-world conditions. Cropbox, CropRootBox, and the modifications done in this paper are written in Julia, using other open-source mathematics and geometry packages.

Key Results

The modifications made to CropRootBox are demonstrated in 3 examples: (1) rhizobox-bound Maize growth rotated on the x and/or y axis; (2) translation of seedling starting point in rhizobox-bound Maize growth; (3) time-based dynamic diameter scaling of root segments throughout Maize growth. These modifications were done based on the CRootBox framework, as well as additional inspiration from OpenSimRoot.

Conclusions

CropRootBox and its extensions are successful as both a proof-of-concept for CropBox and as a functional 3D modeling system for Maize roots. It facilitates the simulation of experimental rhizobox systems through the container angle and position parameters, and the diameter scaling takes the model one step closer to real-world conditions.

Keywords: Cropbox, FSPM, Julia, Root architecture model, CRootBox, rhizobox

1.1 Introduction

Root architecture is responsible for a plant's water and nutrient uptake. However, due to the opacity of soil and the difficulty and inaccuracy of many destructive methods, root systems are greatly understudied. As such, root architecture models and functional-structural plant models have found great utility in simulating the many functions root-soil-water interactions.

Functional-structural plant models (FSPM) combine 3D modeling with plant physiological traits and functions (Louarn & Song, 2020). FSPMs can describe shoot systems, root systems, or a combination of the two in whole-plant modeling. Examples include HydroShoot, an FSPM for shoot-level hydraulic structure and gas exchange processes (Albasha *et al.*, 2019), and CRootBox, a C++ based root architecture model capable of simulating root growth in a variety of environmental and experimental conditions (Schnepf *et al.*, 2017).

CRootBox and its equations acted as the basis for CropRootBox, written by Dr. Kyungdahm Yun. It was done as a proof-of-concept for the capabilities of Cropbox, a crop modeling framework designed by Dr. Yun in Julia. While CropRootBox proved that Cropbox could do more than just traditional quantitative modeling, it has great potential to incorporate other functionalities to describe both experimental and real-world conditions.

CRootBox outlines a series of examples in their paper: (1) free root growth; (2) container-bound root growth; (3) field-scale root simulations; (4) variable soil conditions; and (5) water movement. Dr. Yun had already implemented free root growth, part of the container-bound root growth, and none of the rest. In their second example, CRootBox shows a figure of angled rhizotron growth that more accurately simulates experimental conditions than a standard upright rhizobox model.

Rhizoboxes are transparent plexiglass pots designed for the researcher to be able to non-destructively measure root parameters. However, they are imperfect in observing root conditions, and models such as CRootBox are useful in better understanding these conditions.

This project aims to (1) use the original implementation of CropRootBox to model *Zea mays* root growth in rhizotron pots; (2) design a new "Rhizobox2" to model angled rhizotron growth and add parameters for translation and rotation axes; (3) implement time-based diameter growth of roots; and (4) model *Populus trichocarpa* growth in angled rhizotrons, as a proof-of-concept for dicotyledonous growth, and for its utility as a model organism. Based on these steps, we hypothesize that this model will allow researchers to test for optimal experimental conditions and efficiently develop new research questions based on the simulations at hand.

1.2 Methods and implementation

The original implementation of CropRootBox was adapted from CRootBox and translated to Julia. Each root segment is defined by a set of parameters supplied by the user, and is visually represented in the 3D interface by a mesh in the GeometryBasics.jl package. The final 3D rendering is done in the GLMakie.jl package.

1.2.1 Original CropRootBox parameters

Because CropRootBox has only been implemented for monocotyledonous plants thus far, only those relevant parameters have been included. Table 1 contains these user parameters and their units.

Description	**Parameter Name**	**Unit**
Length of apical zone	*lb*	cm
Length of basal zone	*la*	cm
Length between lateral branches	*ln*	cm
Maximal root length	*lmax*	cm
Parent segment length	*lp*	cm
Sibling segment length	*ls*	cm
Initial elongation rate	*r*	cm d^{-1}
Resolution along root axis	Δx	cm
Standard deviation of random angular change	σ	cm^{-1}
Insertion angle	θ	°
Number of trials (tropism strength)	*N*	
Root radius	*a*	cm

Table 1: Complete list of externally controlled parameters in original CropRootBox

The majority of these parameters are implemented as they are in each RootSegment development, except for the random angular change which gets normalized to

$$\sigma_{\Delta x} = \sqrt{\Delta x} \cdot \sigma$$

and controls random and directed changes in the root segment growth.

The initial direction of a lateral root is controlled by the insertion angle θ, drawn from randomly by the user-defined mean and standard deviation, and a radial angle uniformly randomly chosen from 0° to 360°.

Each root segment also obeys plagiotropism, gravitropism, and exotropism rules.

Lastly, CropRootBox, like CRootBox, is a stochastic model – each parameter is chosen from a truncated normal distribution and each simulation is therefore one of many possible combinations of a parameter set.

1.2.2 Container-bound root growth

The original implementation of CropRootBox has 4 possible Container options: Pot, Rhizobox, SoilCore, and SoilLayer. Each container has parameters to define their dimensions. Each new root segment generated by RootSegment calls a signed distance function defined in each of these containers. These functions determine whether the root segment is inside the container and how far it is from the closest boundary.

Each new root segment is defined by axial and radial angles as described by $\sigma_{\Delta x}$. If the root segment is restricted by the signed distance function, it chooses new axial and radial angles that are tested sequentially until an optimal direction is found. This simulates realistic root growth at boundaries, or thigmotropism.

1.2.3 Angled rhizobox root growth

In CRootBox, angled rhizobox growth is made easy because root segments interact directly with the 3D mesh rather than the parameters defining them, and simply rotating the mesh is enough to implement it. However, in CropRootBox and Julia, the GeometryBasics.jl package does not support this interaction. In order to implement the additional functionality of angled rhizobox growth, two steps needed to take place: rotation of the GeometryBasics.jl mesh (or pot), and rotation of the frame of reference. These are all done in a new Container, Rhizobox2.

Mesh rotation is done by deconstructing the mesh into coordinates and faces, and then applying a Rotations.jl rotation to the coordinates. The faces are then re-applied to the coordinates by index, and the mesh is re-generated as a rotated mesh.

Frame of reference rotation is used because rotating the actual model is both inefficient and difficult to cover all conditions. This implementation instead inverts the Rotations.jl rotation such that the root segment points are back in the frame of reference of the unrotated rhizobox, and the original signed distance function is called.

These rotations are implemented on two axes, along the width and the length of the rhizobox base.

Rhizobox2 also has parameters for the starting position of the root growth relative to the top of the rhizobox. It is written as a Rotations.jl translation along the width and length axes, scaled from 0 to 1 from the midpoint to the edge of the respective axis.

1.2.4 Secondary growth of root segments

CRootBox does not have parameters for secondary growth of root segments, justified by the idea that the model is designed more for root system topology and shape. However, because root thickness can be an important factor in nutrient and water uptake, we decided it was necessary to implement it in CropRootBox.

The RootSegment method originally contains a simple parameter for radius, a. With the updated implementation, there are three parameters fed into the radius: an initial radius, growth rate, and threshold for maximum diameter. The growth rate operates based on the system clock tick, and scales from the initial radius to the maximum threshold.

OpenSimRoot, another FSPM for root growth, has an implementation for dynamic root diameter based on the length of root branch it's occupying (Postma *et al.*, 2017). Their design is based on data gathered by a study on Maize root growth parameters in relation to root length (Wu *et al.*, 2015). Due to the limitations of GeometryBasics.jl meshes, however, it is inefficient to try to trace back to parent root segments and update their radius based on the length. As such, we decided to operate the growth rates on a time basis instead and estimated the parameter values from Wu *et al.*'s data. Time-based growth leads to some morphological inaccuracy but is unfortunately limited by the capabilities of the supporting Julia packages.

1.2.5 Updated CropRootBox parameters

Table 2 contains the new parameters and their units in the updated CropRootBox.

Description	Parameter Name	Unit

Angle of rhizobox incident to ground, width axis	*θ_w*	°
Angle of rhizobox incident to ground, length axis	*θ_l*	°
Width starting point of roots	*w_scale*	0 to 1
Length starting point of roots	*l_scale*	0 to 1
Initial radius	*ri*	cm
Maximum radius	*thr*	cm
Radius growth rate	*gr*	mm hr^{-1}

Table 2: List of new externally controlled parameters in the updated CropRootBox

It is important to note that a, the radius originally defined in CropRootBox, is no longer an externally controlled parameter, and is instead replaced by ri, thr, and gr.

1.3 Results

Results of both the original and modified CropRootBox are presented following extensive testing for any non-functioning edge cases within morphological and biological reason.

1.3.1 Example 1: Rhizobox generation from original CropRootBox

Figure 1 shows the unrotated and untransformed generation of *Zea mays* root growth in a rhizobox based on the original CropRootBox implementation.

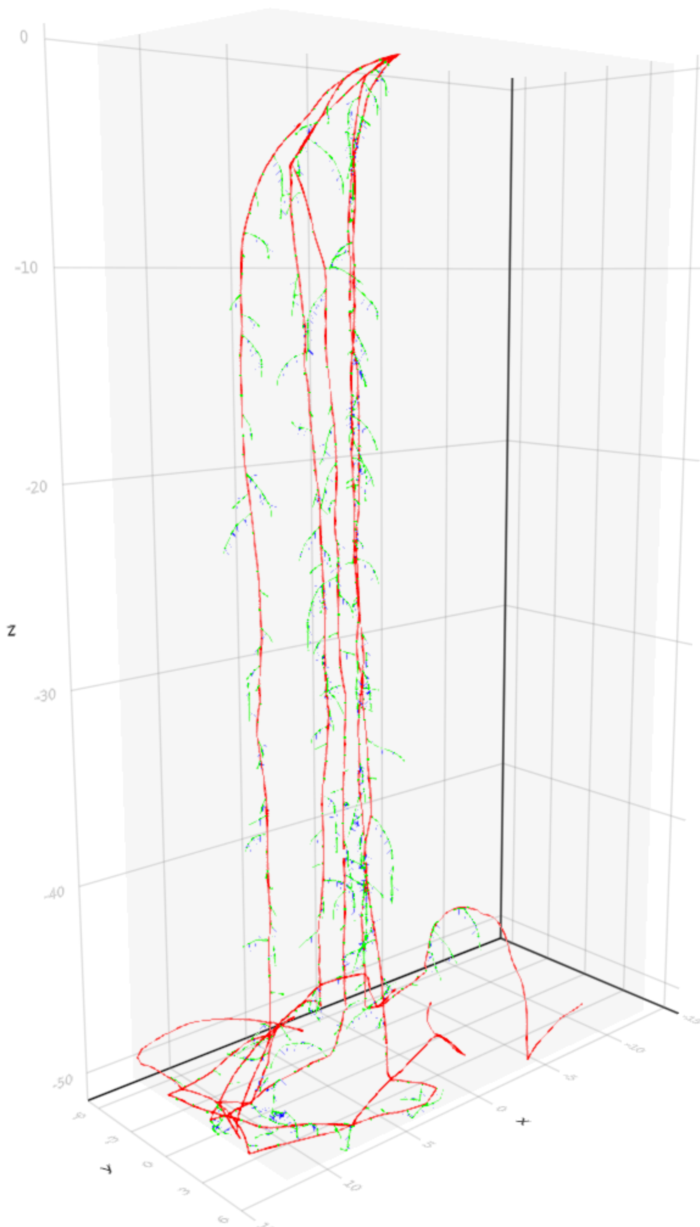

Figure 1: 3D root architecture of maize simulated over 100 days in a confined Rhizobox Container. The simulation is drawn from the original CropRootBox implementation. Parameter values are adapted from CRootBox. The roots follow unconfined growth until they reach the base of the rhizobox, where new angles for growth are tested.

1.3.2 Angled rhizobox growth in modified CropRootBox

Figure 2 shows Maize root growth in an angled rhizobox simulated from Rhizobox2.

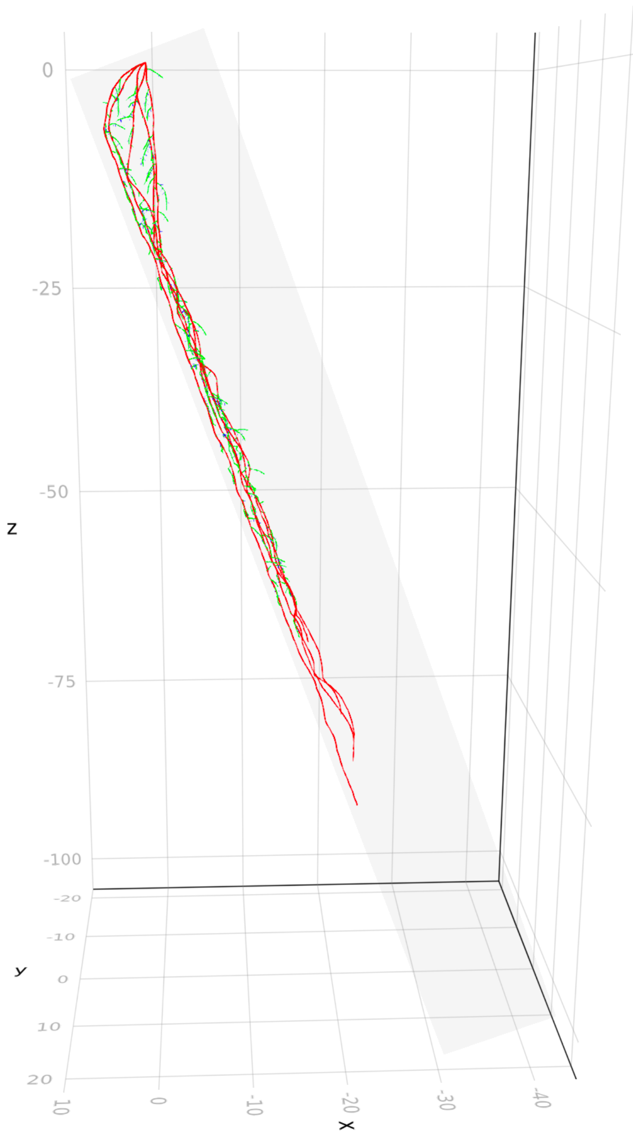

Figure 2: 3D root architecture of maize simulated over 100 days in a confined Rhizobox2 Container. The pot is angled 70° incident to the ground along the width axis. The dimensions of the rhizobox are adjusted for visual clarity such that angled growth is demonstrated. The roots follow unconfined growth until they reach the angled base of the pot and it then follows that angle.

1.3.3 Transformation of root position and additional rotation axis in modified CropRootBox

Figure 3 displays translation of the starting point for the root system relative to the top-down view of the rhizobox.

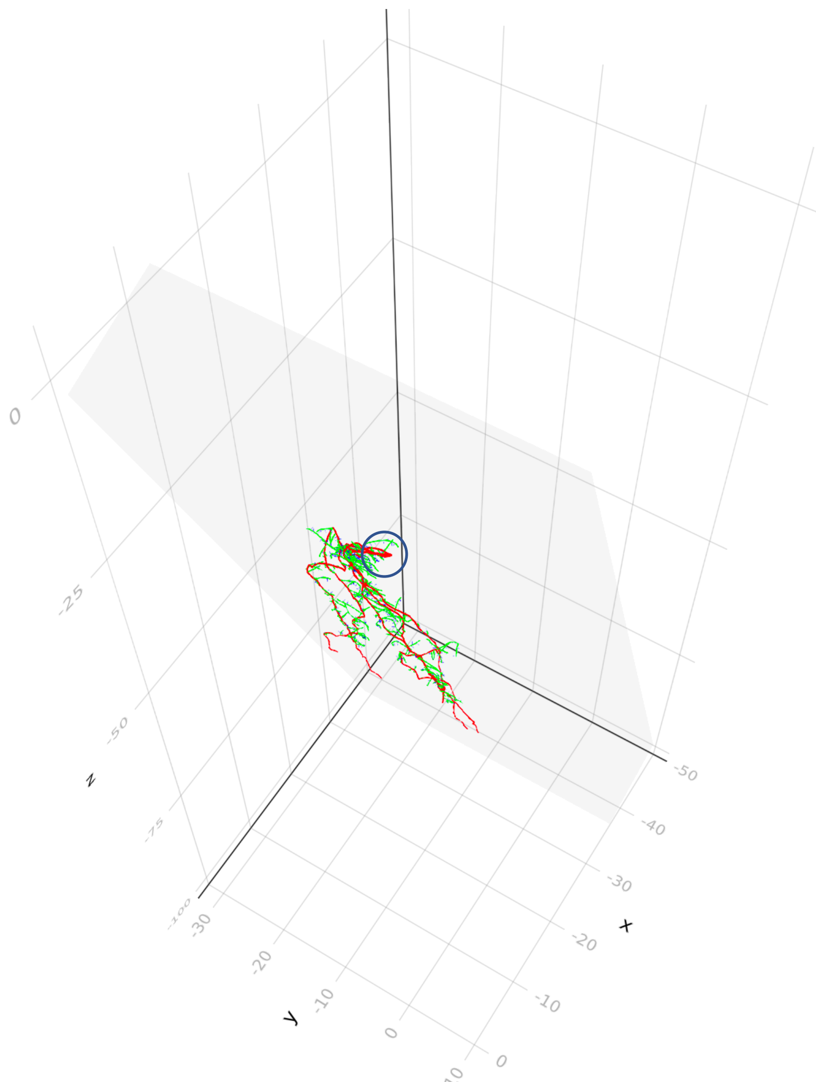

Figure 3: 3D root architecture of maize simulated over 100 days in a confined Rhizobox2 Container with a translated starting point. The pot is angled 70° incident to the ground along the

width axis. The width point is scaled by ¼ and the length point is scaled by 1, according to the translation parameter definitions (see methods and implementation). A blue circle highlights the starting point for visual clarity.

Figure 4 demonstrates a second axis for rotation in Rhizobox2, along the length axis of the rhizobox.

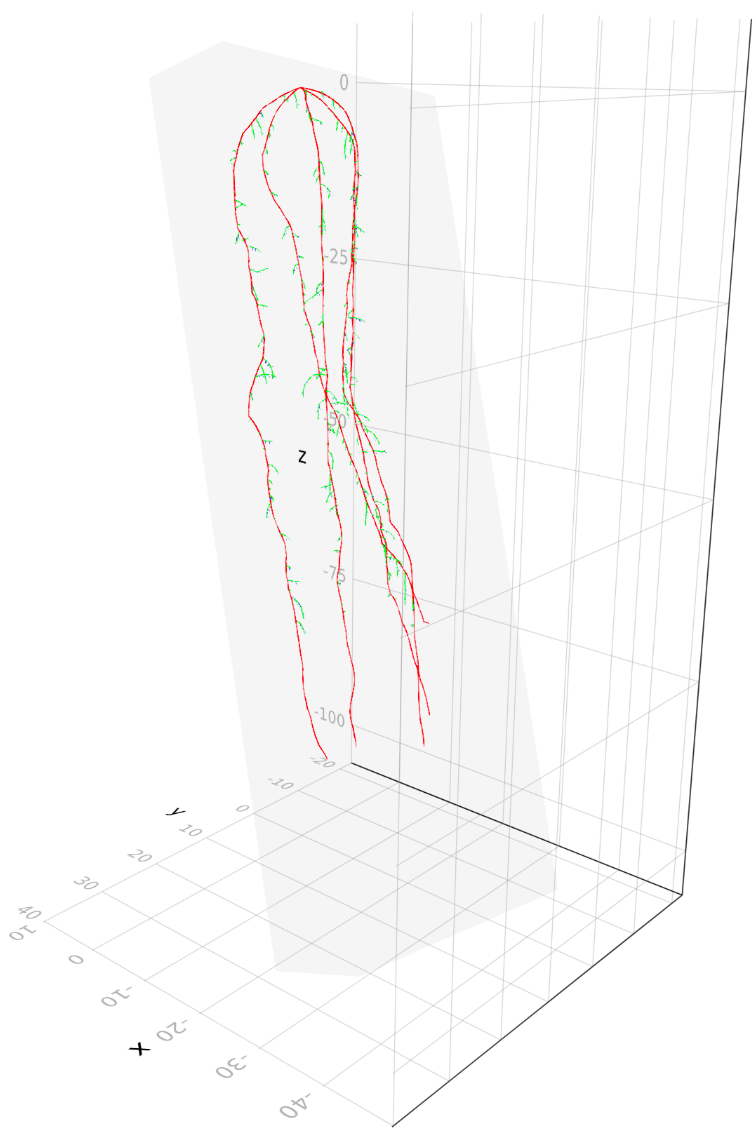

Figure 4: 3D root architecture of maize simulated over 100 days in a confined Rhizobox2 Container with an additional axis of rotation. The pot is angled 70° incident to the ground along the width axis and 80° incident to the ground along the length axis.

1.3.4 Secondary growth of root segments in modified CropRootBox

Figure 5 displays the secondary growth capabilities of the modified CropRootBox.

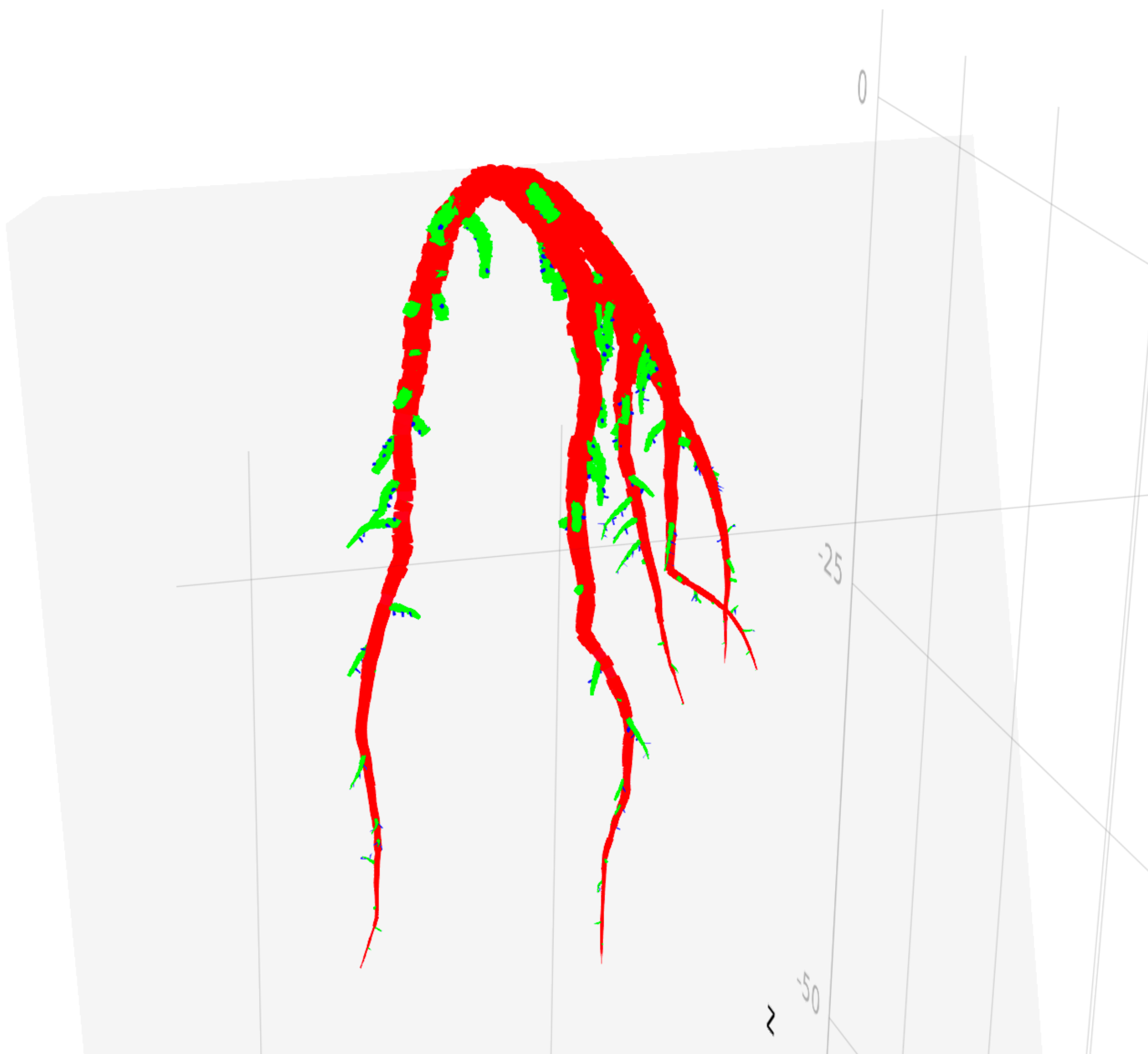

Figure 5: 3D root architecture of maize simulated over 10 days in a confined Rhizobox2 Container with time-scaled root diameters. The growth rate and maximum radius are increased tenfold for demonstration and visual clarity. The simulation is on a shorter time frame to avoid full mature growth and show the differences in root diameter.

1.4 Discussions

With the new implementation of CropRootBox, the user is successfully able to: (1) model angled rhizotron growth of *Zea mays*; (2) freely adjust the angle of the rhizotron pot incident to the ground along two axes; (3) freely adjust the starting position of the roots relative to the pot; (4) control parameters for initial root radius, radius growth rate, and maximum radius, for each root type. The main three aims were achieved, but nothing was completed involving *Populus trichocarpa*, due to the limitations in data collection and time available.

As the examples demonstrate, the model is sufficient and efficient for testing experimental rhizotron conditions. It allows the experimenter to test which angles and positions are best for optimal root growth and imaging. It also helps an experimenter determine what size of rhizotron pot is needed, and how long a seedling should be grown in the given size. Lastly, experimenters can test any relevant edge cases that would be otherwise cost- or time-inefficient to do in the real world.

Diameter scaling also brings the model one step closer to real-world conditions, as the thickness of a root can be important in root processes like water and nutrient uptake. Modeling these things can help a researcher better understand how to frame experiments around it. However, as discussed in the methods and implementation, time-based diameter growth is morphologically inaccurate for *Zea mays*, and will require more updates in the future.

1.4.1 Differences from CRootBox

While CropRootBox follows much of the model theory presented by CRootBox, there are key differences that are highlighted in the transition from C++ to Cropbox and Julia. Using the Cropbox modeling framework allows CropRootBox to be much more efficient both during code development and running simulations. However, Julia is greatly limited by the functionalities of its community-built packages, and more extensive processes such as length-based secondary root growth and point-mesh interactions are either incredibly inefficient or simply not possible.

1.4.2 Further steps

This set of extensions made to CropRootBox has been successful as a proof-of-concept for Cropbox's capabilities and as a usable 3D root modeling system. There are still always improvements to be made and additional steps to be taken, though. The first big step to take is to implement CRootBox's dicotyledonous plant parameters into CropRootBox and gather enough data for accurate *Populus trichocarpa* configuration. From there, many more modeling possibilities open up, including modeling endophyte effects on root growth based on experimental conditions.

There are other additional CRootBox capabilities that are also worth looking into, such as water movement and soil interactions with root growth. These can be built as separate models or be incorporated as highlightable metadata into the existing 3D visualization.

1.5 Literature cited

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