Reviewer 1

Reviewers' comments are in black font, our responses are in blue and green is for new and revised text; to assist with navigation, we use codes, such as R1C1 for Reviewer 1 Comment 1.

The study describes the development of a new SPAC model. The study is of great relevance to hydrology ecohydrology and ecosystem modelling and clearly within the scope of the journal. The model couples the partial differential equations that describe water flow in the soils, and plants.

R1C1: My main concern regarding the paper is its novelty. The authors should more clearly illustrate the new features of the present model that have not been previously reported. For example, the plant water transport is very similar to FETCH2, the whole model set-up very similar to Huang, C-W et al., 2017 New phytologist (already cited in the paper). The authors should more clearly present the main novelties of the present model. I am not saying that the model is not novel, but rather the novelty needs to be better described in the manuscript.

The novelty of the model was one of the main concerns raised by both reviewers and the editor, especially in relation to the differences from FETCH and FETCH2. We decided to change the name of the model to FETCH3, and this is used in this document. Although the acronym no longer reflects the nature of the model and numerical scheme used to solve the equations, it easily relates to the developments that FETCH has had over the years. In addition, we have added further clarifications on how the three versions differentiate from each other. The differences between FETCH2 and the present model, FETCH3, are summarized in section 2.1 as:

"FETCH3 builds upon FETCH2 (Mirfenderesgi et al., 2016, 2018), which is based on its precursor, the finite element tree crown hydrodynamics (FETCH) model (Bohrer et al., 2005). FETCH simulates water flow along a tree's stem and branches accounting for the branch structure in three dimensions. Simulating the three-dimensional tree crown structure is computational demanding and can solely be applied to a single tree. As a result, FETCH2 was developed to offer a more mechanistic approach that could be scaled to entire ecosystems. To achieve this, FETCH2 simplifies branches along the vertical direction, leading to a 1D model; the equations in FETCH2 are solved using a finite difference scheme (Mirfenderesgi et al., 2016).

Similarly to FETCH and FETCH2, FETCH3 assumes that the water movement in the xylem resembles flow in porous media; as in FETCH2, a macroscopic approach is used to simulate the water fluxes across the soil, roots, and stems with the fluxes being described in one dimension along the vertical direction (Fig. 1). As a development from FETCH2, FETCH3 presents a clearer link between the three different components of the system (i.e., soil, roots and stem), based on the conservation of water in each of the components, as derived in the Supplementary Material. The links between the soil, roots, and stem xylem are clearer in FETCH3, thus providing a more precise coupling of the 3 components of the system. As a result, when combined, the quantities in the equations for the roots and stem are scaled to a reference ground area, consistently with the Richardson-Richards equation for the soil. This guarantees the conservation of mass as water flows from one component to the other. The system of equations in FETCH3 is also solved differently from FETCH2. As described in detail in the Supplementary Material, the equations in FETCH3 are discretised using the method by Celia et al. (1990) generating a system of algebraic equations combined into a single matrix, that is solved at the same time to guarantee the conservation of mass across the whole system comprising soil, roots and stem."

The water transport described in Huang et al. (2017) is different from the one in FETCH3. Huang et al. (2017) simplified their system by excluding a detailed description of the roots, assuming that the root water potential reaches very rapidly hydrostatic conditions dependent on the water potential at the base of the stem. We have added a new section in the manuscript to describe and discuss different modelling approaches (i.e., electric circuit equivalence, porous media).

R1C2: Regarding the model implementation itself, it is great to see comparisons between analytical solutions and previous numerical solutions for model confirmation.

We thank the reviewer for the encouraging comment.

R1C3: Regarding the complexity of the model, my main comment is that the model formulation seems incomplete for a SPAC model, as it mostly neglects the atmospheric component. I would expect a SPAC model to be forced with meteorological variables. At the current state tree transpiration is provided as a boundary condition, instead of being computed prognostically. The authors can consider expanding the model to have this capability.

FETCH3 is designed to allow the implementation of different transpiration formulations in Equation (5). For our study, we used a simpler transpiration function for section 3.1, where we tested the numerical scheme against analytical solutions, and used the Penman-Monteith equation (Allen et al., 1998) combined with a stomatal conductance formulation (Jarvis, 1976) for the test case with experimental data. Both Penman-Monteith and stomatal conductance formulations are forced by meteorological variables; the stomatal conductance also depends on the stem water potential, and thus transpiration is not provided as a boundary condition but is calculated by the model.

The equations can be found in the Supplementary Material, section S.3. To clarify these aspects, we added in section 2.2.1:

“The water lost to the atmosphere is calculated using a transpiration function that depends on meteorological variables and limits the amount of water leaving the stomata as a function of the stem water potential. FETCH3 allows for the implementation of different transpiration functions, and a complete description of the transpiration formulation applied in this study is in the Supplementary Material, section S.3.“

R1C4: To my understanding, the model in its current form, can only simulate a single dry-down period as no infiltration is implemented. This is something that the authors might want to include in the model as it cannot be currently used for continuous long term simulations.

FETCH3 includes infiltration implemented as a boundary condition at the top of the soil column, as described in the Supplementary Material, section S.2.2 (page 12). The term q_{inf} was modelled according to the rainfall rate and soil moisture at the surface layer (section 3.2.2, line 248). To further clarify this capability, we added more details in sections 2.1 and 3.2.2:

(Section 2.1)

“The water flow in the soil is modelled using the Richardson-Richards equation with a term simulating the exchange of water between the soil and the roots. This term is a function of the difference in water potential between the soil and root layers; it thus results in a water sink during the day, when the water potential in the roots is low due to water loss by transpiration, but may act as a source of water to the soil during some nights, depending on the water content in different soil layers. The boundary conditions at the top and bottom of the soil column can be expressed as a flux or a value of soil water potential (refer to the Supplementary Material, section S.2.2)."

(Section 3.2.2)

"At the surface, measured rainfall was used as a flux boundary condition to compute soil water infiltration (refer to the Supplementary Material, section S.2.2)."

R1C5: A finite difference method was used to solve the Richards' equation for both soils and plants. This numerical formulation does not guarantee mass conservation. As a sanity check I would advise the authors to report the total water mass conservation. Given the accuracy of the model in recovering the analytical solution, I am confident that any discrepancy is negligible but worth reporting nevertheless.

We thank the reviewer for the suggestion. We have added the water mass balance for the unsteady and steady cases, and for the case study.

For the unsteady and steady cases, only the stem section of the tree was considered. For the two unsteady cases that we considered, the mass balance error was calculated as the total water that entered at the bottom of the tree minus the total transpiration and the change in water storage during the simulation. We expressed the mass balance error as a percentage of the total water that entered the bottom of the tree. For the two unsteady cases, the water mass error was 0.05% of the total mass of water that entered the tree, for a simulation period of 2 days.

For the steady case, the flux entering at the bottom of the tree and the transpiration rate are expected to be equal, with no changes in storage. We checked that in the numerical calculations, at steady state, the flux of water entering at the bottom of the tree and the transpiration rates were close to each other, and changes in storage were approximately null. At steady state, transpiration was equal to 99.97% of the total flux entering the tree, and the difference in storage between time steps was equal to $-2.77 \cdot 10^{-18}$ m^3.

For the case study, we expressed the mass balance error in the tree as the sum of storages in the tree (in the root and stem xylem) plus the root water uptake minus transpiration. We expressed this error as a percentage of the total amount of water that infiltrated the soil during the simulation. The water mass balance error in the tree was equal to 0.16% of the infiltration over a period of approximately 5 months (1st January to 4th June). In the soil, the mass balance error was calculated as the total soil water storage plus the sum of total water flux at the bottom of the soil (since the boundary condition at the soil bottom is a constant water potential) and infiltration, minus the root water uptake. This difference was equal to 0.30% of the total infiltration over the simulation period.

We included the following additions in the manuscript. For the unsteady state solution with the sink term depending only on time:

"The error followed the pattern of transpiration, reaching its peak during day time and corresponding to a maximum error of 0.09% of the exact solution. The mass balance error equalled 0.05% of the total water entering the tree during the simulated 2 days."

For the unsteady state solution, with a sink term depending on both time and vertical coordinate (z):

“The error for this case is higher than for the previous case, with a maximum value that is about 0.2% of the exact solution, with a mass balance error equal to 0.05% of the total water entering the tree during the simulated 2 days.”

For the steady state solution:

“For a 6-meter-high tree, the error of the numerical solution increases with elevation reaching approximately 0.4 $\cdot 10^{-3}$ MPa at the tree top, being 0.4% of the exact value. According to the steady-state condition, the differences in storage between the last two consecutive model time steps approached zero and were equal to -2.77e-18 m^3, with transpiration equalling 99.97% of the total flux entering the tree.”

For the case study:

“The model predictions for sap-flux during the day compared well with the observations during the entire measurement period (Fig.5a), reaching a R^2 value of 0.74. The total mass balance error in the soil represented -0.30% of total infiltration, and it was calculated as the change in soil water storage minus the difference between the flux entering (bottom boundary condition and infiltration) and exiting the soil (root water uptake). In the tree (root and stem xylem), the water mass error was -0.16% of the total infiltration, and was calculated as the change in water storage (in the stem and root xylem) minus the difference between the fluxes entering (root water uptake) and exiting (transpiration) the tree.”

R1C6: A discussion point that might need to be better addressed is the added benefit of the vertically distributed, computationally expensive solution. Many ecosystem models lump tree hydraulics with a small number of resistances (commonly soil to root, root to leaf and leaf to atmosphere) or a combination of a small number of resistors and capacitors (e.g., ED2 model – Trugman, Anna T., et al. “Leveraging plant hydraulics to yield predictive and dynamic plant leaf allocation in vegetation models with climate change.” Global change biology12 (2019): 4008-4021.). This approach is definitely more computationally parsimonious, and less data demanding as all plant hydraulic traits are lumped. A discussion of pros/cons would benefit the paper.

We have included in the revised manuscript a section between the Introduction and the Model Description to discuss the literature on plant hydraulic modelling, and the differences between the modelling approaches. This new section will clarify the pros and cons of each approach.

R1C7: In page 3 lines 64 and 73, I would advise the authors to rephrase the term “lumped” as it might lead to confusion as the model is at least in 1D distributed.

We thank the reviewer for the suggestion. We re-phrased these parts:

“Similarly to FETCH and FETCH2, FETCH3 assumes that the water movement in the xylem resembles flow in porous media; as in FETCH2, a macroscopic approach is used to simulate the water fluxes across the soil, roots, and stems with the fluxes being described in one dimension along the vertical direction (Fig. 1).”

“The 3D root architecture is **scaled** along the vertical dimension using a vertical mass distribution of the roots and an index that summarizes the extent of lateral root area per unit of ground area (Quijano and Kumar, 2015).”

R1C8: Looking at the Python code, I noticed that object orientation was hardly ever used, that would be great for a modular model design that can be used to “plug-in” additional modules in the future (e.g., radiative transfer schemes, photosynthesis, phloem transport etc). The authors might consider in the future reconstruction of the code.

We thank the reviewer for this suggestion. This is certainly something to be further developed and implemented. At this stage, our focus was to provide an open access code with a verified and tested solution of the system of Richardson-Richards equations. An updated version of the model will be provided with a more modular structure and with a vertically detailed transpiration function in an easy to replace function. This will highlight the importance of including multiple vertical layers, with a structure that allows for interactions between radiation and atmospheric conditions within the canopy and different storage and stomata restrictions at different vertical levels.