Supplement

OPEN MODELING FOUNDATION

This supplement provides additional information related to the definition of **OMF's ODD** as a standard for describing mechanistic models.

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1 Template for Model Descriptions following OMF's ODD protocol

This template provides the document structure and guiding questions to describe and document models following OMF's ODD[1] protocol, version 1.0, of the Open Modeling Foundation.

To use it, fill in the corresponding information and use the template's questions as a **checklist**. Make sure to read the description of the standard first (doi), and check examples and the guidance document.

If you go for the **base level of OMF's ODD**, use the template's O-Part. If the resulting description is too long for be included in the main text of an article or report, put it to the Supplement, and use the template for summary ODDs instead.

[1] In the following sometimes we sometimes refer briefly to „ODD" instead of „OMF's ODD".

If you go for the **full level of OMF's ODD**, use the entire template. If it the resulting description is too long for be included in the main text of an article or report, put it to the Supplement, and use only the O-part or the summary ODDs for the main text.

We recommend for ODDs **in the supplement to keep the guiding questions**, as this will help readers yet unfamiliar with the protocol, and, in general, help checking for compliance with the standard.

When using this document, refer to it, in the main text:

> **"The model description follows the <base/full level> of OMF's ODD protocol, a standard format or lingua franca for describing models (doi:<.. >; <publication announcing OMF's ODD protocol>)."**

This will allow the OMF to check how compliance, and the standard itself, can be improved.

We recommend **keeping the simplistic formatting** of this template so that ODDs produced by different authors not only use the same structure and terminology, but also look similar, making it easier for model users to perceive OMF's ODD as a standard format.

After producing your ODD, delete these explanations.

Model description following OMF's ODD protocol

This model description follows the <base/full level> of OMF's ODD protocol, a standard format for describing models (DOI: ; <publication announcing OMF's ODD protocol>). It is comprised of seven elements. The first three provide an **Overview** of the model's purpose, questions, validation criteria, state variables, processes, and scales. The 4th element, **Design Concepts**, lists important concepts underlying the model's design; it is meant to make sure these concepts are addressed explicitly. The remaining three elements include the **Details** about the model's initialization, input data representing external drivers, and the details of the submodels implementing the model's processes; they are meant to provide full transparency and enable replicability.

If this document includes **hyperlinks**, navigation back and forth along previously chosen links works via "ALT" + "←" or "ALT" + "→".

1. Purpose and patterns

The ODD text for this element should describe:

- **The model's overall purpose** (e.g., demonstration, understanding, prediction)
- **The specific research questions**
- **The patterns or data used as criteria for evaluating the model's suitability for its purpose.**

<…>

2. Entities, state variables, and scale

Describe:

- **The kinds of entities in the model and what they represent.**
- **Why those entities were included and, if relevant, why other entities were not included.**
- **The state variables of each kind of entity, usually in a** table**. For each state variable, describe exactly what it represents, its units, whether it is dynamic or static, its type, and its range.**

- **Whether the model represents time and, if so, whether time is represented via discrete time steps, as continuous, or both. If time steps are used, define their length (the temporal resolution). Describe how much time is represented in a simulation (the temporal extent).**
- **Whether the model represents space and, if so, whether space is represented as discrete spatial units, as continuous, or as both. If discrete spatial units are used, describe their shape and size (the spatial resolution). Describe how much total space is represented (the spatial extent).**
- **Whether any other dimensions are represented, and how.**
- **Why the spatial and temporal scales were chosen.**

<…>

3. Process overview and scheduling

Provide:

- **A complete but concise model schedule that defines exactly what happens each time step. The schedule should be presented as a hierarchy of "actions" that each describe which entity or entities execute which process or submodel under which conditions, which state variables are updated, and (for actions executed by multiple entities such as all agents or spatial cells) the order in which the entities execute it.**
- **A separate discussion, if needed, that summarizes how actions executed in continuous time instead of discrete time steps are scheduled.**
- **A discussion providing the rationale for why the model includes the processes it does.**
- **Do not include here elements of the model's initialization.**
- **A discussion providing the rationale for how the actions are scheduled. Why are the actions executed in the given order? For those actions executed by multiple entities, why did you choose the order in which the entities execute?**

<…>

4. Design concepts

This element is not needed to describe exactly what the model does or to replicate it, but instead is intended to place the model within a common conceptual framework and to show how its developers thought about its design. Examples are „Interaction" (How to the model's entities interact?), „Stochasticity" (Where is it included in the model, how and why?), or „Observation" (Which output variables are used to observe and analyze the model's behavior?). For agent-based models, 10 design concepts are suggested (Section 2 of this Supplement). For other model types, a list of the generally most important concepts will emerge and lead to model-type specific standards.

<…>

5. Initialization

Describe:

- **What entities are created upon initialization, and how all their state variables are given initial values.**
- **How the initial locations of entities are set, if relevant.**
- **How any initial collectives, networks, or other intermediate structures are created.**
- **Any site-specific data used to initialize the model: the data types, their sources, how they were processed, any known biases or uncertainties, and how they were used in initialization.**
- **Whether simulation experiments will typically use scenarios that differ in initialization methods; if so, say how initialization will vary.**
- **The rationale for key initialization methods. For example, explain why entities vary among each other in the way they do.**
- **Do not include here elements that are repeated every time step.**

<…>

6. Input data

Describe:

- **Whether the model uses any input data from external files to represent variables that change over time or events that occur during a simulation.**
- **The input data: what it represents, its units, and its source.**
- **Any nontrivial methods used to collect or prepare the input.**
- **If input is from another model, how that model was used to generate the input.**
- **"Input" here does not refer to user input on the models Graphical User Interface**

<…>

7. Submodels

Describe:

- **All of the submodels list in the Process overview (element 3), in a separate subsection for each. Use the same names for the processes here.**
- **For each submodel, its equations, algorithms, and parameters.**
- **A table with all model parameter, the name, definition, unit, default value and range, and how parameter values were selected.**
- **The analyses used to test, calibrate, and understand submodels by themselves.**

<…>

2 Design concepts for agent-based models

For details, see Supplement S1 of Grimm, V., Railsback, S. F., Vincenot, C. E., Berger, U., Gallagher, C., DeAngelis, D. L., ... & Ayllón, D. (2020). The ODD protocol for describing agent-based and other simulation models: A second update to improve clarity, replication, and structural realism. Journal of Artificial Societies and Social Simulation, 23(2).

The concepts which are likely to be relevant for all model types are underlined.

Basic Principles: What are the general concepts and theories underlying the model's design?

Emergence: Is a certain behavior of an agent imposed via fixed parameters (e.g., growth rate, mortality), or does it the result (emerge) from the agent's adaptive decisions?

Adaptation: How do the agents adapt (behave) in response to changes in their environment and themselves?

Objectives (Fitness): What objective functions do agents use in their adaptive behaviors?

Learning: Do individuals change their behavior as a consequence of their experience?

Prediction: In adaptive behaviors, do agents predict the consequences of their decisions? How?

Sensing: What are agents assumed to know or perceive when making decisions? Is the sensing process itself explicitly modelled?

Interaction: What forms of interaction (direct and indirect) among agents are there? How do agents interact with their environment?

Stochasticity: How are random numbers used? Why?

Collectives: Does the model represent any aggregations of individuals that affect the individuals? How?

Observation: What displays and (file) outputs are provided to understand and analyze the model?

3 Template for summary ODDs

This is a template for a narrative summary of the Overview part. Text that should be used as is is in bold, ODD's key terms are in italics. Journals do not use bold fonts, so please make sure to start paragraphs with the sentences used here at the begin of each paragraph – this will increase the recognition factor of this standard's elements and structure.

A complete, detailed model description, following OMF's ODD (Overview, Design concepts, Details) protocol (Reference) is provided at <Insert link to web repository where you uploaded your ODD>**.**

<Optional: start with a free-form summary: > **The basic idea underlying the model is ...** < …>

The overall *purpose* of our model is … <summarize the corresponding part of the full ODD>. **Specifically, we are addressing the following questions: …** <summarize the corresponding part of the full ODD>. **To consider our model realistic enough for its purpose, we use the following *patterns* …** <summarize the corresponding part of the full ODD>.

The model includes the following *entities* … <list entities>**. They are characterized by the following *state variables*/The *state variables* characterizing these entities are listed in Table X: ...** <Ideally, present a Table with model entities and their state variables (see Supplement S1 for further guidance). For experienced modelers, such a table provides a good overview of the model's structure and scope>. **The *spatial* and *temporal* resolution and extent are …**

The most important *processes* of the model, which are repeated every *time step*, are ... <Use the sequence of the model's schedule. If possible, use the same self-explaining names, or similar, of the full ODD. Here, in contrast to the full ODD, you would also describe the essentials of these key processes. Exception: for complex submodels, it might be better to present them in some more detail at the end of the summary ODD>.

THE FOLLOWING APPLIES IF THE MODEL DESCRIPTION AIMS AT THE FULL LEVEL OF OMF's ODD

The most important *design concepts* of the model are ... <List and briefly explain those design concepts, which are essential, most characteristic, and most sophisticated of your model>.

<Optional: list aspects of Initialization and Input data, if they are essential: > **The model is initialized with ...** <Specific initial conditions>. **Model dynamics are driven by *input data* representing ...** <What kind of data, and what processes are they driving? What is the source of the data?>.

<Optional: explain here in more detail submodels that are too complex to be described with one or two sentences in the process overview above: > ***Key processes* in the model are ...**
<Refer to each of the processes you want to describe here by the name you used in the overview above, set in italics. Give a verbal **summary** description, but also include equations if they are essential for understanding.>

4 Examples of summary ODDs

The following four example summary ODDs cover different model types, and in one case even a modular modelling system. Note that despite these differences, the summary model descriptions always follow the same structure and use the same phrases. Readers thus learn that independent of model type, system, domain, etc., they can always expect the same structure and terminology, which helps them to understand what a model is and does, and how it is related to data and observed patterns. Accordingly, model developers will learn that readers expect this structure and terminology. All this supports introducing and following OMF's ODD, both base and full level.

1 Tiger model by Carter al. 2015

Volker Grimm

A complete, detailed model description, following the ODD (Overview, Design concepts, Details) protocol (Grimm et al. 2006, 2010, 2019) is provided in Carter et al. (2015).

The overall *purpose* of our model is to predict tiger population dynamics to support tiger conservation. **Specifically, we are addressing the following question:** How does the number, location, and size of tiger territories change in response to habitat quality and tiger density? **To consider our model realistic enough for its purpose, we use *patterns*** in mortality, age structure, and female territory tenure and overlap of male territories with female territories.

The model includes the following *entities*: tigers, square grid cells of 250x250 m², and territories. **The state *variables* characterizing these entities are listed in Table 1.** Female territories consist of a set of habitat cells, which the females add to their territory based on prey availability and presence and rank of other females. Male territories consist of a set of up to six female territories, which the males add to their territory based on their spatial proximity and absence or rank of other males. **As for the *spatial* and *temporal* resolution and extent:** A time step in the model represents one month and simulations are run for 1-20 years. Test simulations were run on landscape of 40x40 and 128x128 cells, while the Chitwan national park required 157x345 cells. Landscape structure in terms of prey availability is assumed to be constant in this model version, but will change in response to human land use in future model applications.

The most important *processes* of the model, which are repeated every *time step*, are the acquisition of territories by dispersing young tigers, and the maintenance of territories by established tigers. Female tigers add grid cells to their territory until they can satisfy their monthly prey requirement. Grid cells can be won from or lost to other females. Male tigers do not strive to add space based on prey availability, but on the availability and location of female territories. They try to overlap up to six female territories, but compete for these with each other, depending on their relative age and rank; the latter depends on the outcome of previous contests.

If a female territory is won from another male, infanticide can occur, which can add substantially to juvenile mortality.

The most important *design concept* of the model is the way in which we represented territorial dynamics, in particular the response of females to prey availability, and of males to the distribution of both female and male residents. Thereby we let population structure and dynamics emerge from the prey distribution in the landscape and from overall tiger density.

Table 1. Entities and state variables of the tiger model by Carter et al. (2015)[2] .

Entity	Variable	Description	Possible Values	Units
Female	Age	Age in months	1 - 180	Months
	fertile?	Indicates whether female is fertile	True/False	--
	gestating?	Indicates whether female is gestating	True/False	--
	males-in-my-territory	Identities of males overlapping female territory	Set of male identities	--
	my-mom	Identity of mom	Identity of female tiger	--
	my-offspring	Number of offspring in current litter	1 - 5	Individual cubs
	natal-origin	Patch where female was initialized at or the centroid patch of mother's territory	0 - max X, 0 - max Y	Patch units
	num-litters	Total number of litters the female has had up until current time	0 - max number of litters over lifetime	--
	age-class	Indicates development stage of female	Cub, Juvenile, Transient, or Breeder	--
	territory	Set of patches belonging to territory	Set of patch coordinates	--
	terr-orig	Patch that female was initialized at or first patch of territory	0 - max X, 0 - max Y	Patch units
	t-gestation	Indicates how long female has gestated	0 - 3 or 4	Months
	t-parenting	Indicates how long female has been a parent of current litter	0 - 24	Months
Male	Age	Age in months	1 - 180	Months
	dominant-males	Identities of males that have beaten male in challenges	Set of male identities	--
	females-in-my-territory	Identities of females overlapping female territory	Set of female identities	--
	initial-male?	Indicates whether male was created at beginning of simulation	True/False	--
	lost-territory?	Indicates if male lost a territory to a challenger	True/False	--
	male-land-tenure	Total time that male held onto territory	0 - entire breeding phase until death	Months
	my-mom	Identity of mom	Identity of female tiger	--
	natal-origin	Patch where male was initialized at or the centroid patch of mother's territory	0 - max X, 0 - max Y	Patch units
	age-class	Indicates development stage of male	Cub, Juvenile, Transient, or Breeder	--
	territory	Set of patches belonging to territory	Set of patch coordinates	--
Cell	owner-fem	Identity of female with patch in her territory	Identity of female tiger	--
	owner-male	Identity of male with patch in his territory	Identity of male tiger	--
	Prey	Prey produced at patch	0 - max prey production	kg/month
	is-churia?	Indicates whether patch falls within churia hill boundary (Chitwan landscape only)	True/false	--

[2] If space allows, a table with all state variables should be included, or otherwise made available in an Appendix or Supplement.

	is-park?	Indicates whether patch falls within national park boundary (Chitwan landscape only)	True/false	--

References

Carter, N., Levin, S., Barlow, A., & Grimm, V. (2015). Modeling tiger population and territory dynamics using an agent-based approach. Ecological Modelling, 312, 347-362.

2 Spatially Explicit Integrated Modeling System (SEIMS)

Liang-Jun Zhu

3Introduced by Zhu et al. (EM&S, 2019), which built-in parallel computing strategies proposed by Liu et al. (EM&S, 2014; EM&S, 2016).

A complete, detailed model description, is provided in Zhu et al. (2019) and https://github.com/lreis2415/SEIMS. <Zhu, L.-J., Liu, J., Qin, C.-Z., & Zhu, A.-X. (2019). A modular and parallelized watershed modeling framework. Environmental Modelling & Software, 122, 104526. https://doi.org/10.1016/j.envsoft.2019.104526>

SEIMS (Spatially Explicit Integrated Modeling System) is an open-source, process-based, modular, parallelized, distributed watershed modeling framework. SEIMS allows users to add modeling algorithms of single or multiple watershed processes (belonging to hydrology, erosion, ecology, etc.) as modules in a nearly serial programming way. SEIMS provides a flexible way to combine user-specific modules to construct parallelized watershed models for long-term or storm-event simulations. SEIMS supports inside-model and model-level parallel computation for efficiently executing applications that need numerous model runs, such as scenario analysis of BMPs (best management practices).

The basic idea underlying the model is that a process-based watershed model consists of hillslope processes and channel routing processes that are simulated on different scales of spatial units with hierarchical relationships and upstream-downstream relationships, such as hillslope processes on grid cells or other fine-scale spatial units and channel routing processes on channels that belong to subbasins. Subbasins can be regarded as relatively independent geographic objects connected by the channel network with upstream-downstream relationships and contain grid cells with topography-based flow directions.

The overall *purpose* of our model is to flexibly customize process-based distributed watershed models and efficiently execute on common parallel computing platforms such as personal computers with multi-core CPU and symmetrical multiprocessing (SMP) clusters for understanding the watershed processes of the study area and predicting watershed responses to designed BMP scenarios. **Specifically, we are addressing the following questions:** how can we design a flexible modular structure and efficient parallel computing middleware to facilitate researchers in building their own watershed models effectively and efficiently?

To consider our model realistic enough for its purpose, we use the following *patterns* of 1) spatial hierarchical units delineated based on geographic processes, management requirements, and available data, and 2) physical processes occurred in the watershed. The spatial hierarchical

[3] This summary does not describe a specific model, but a modelling system. Still, using the summary ODD template can help readers to quickly get an idea of the bigger picture.

units of a watershed from coarse to fine levels could include subbasins, hillslopes, landforms, and basic simulation units (e.g., grid cells, Voronoi polygon, or hydrologic response units), as well as channel lines. The physical processes of the real watershed can be modeled by a combination of separated processes and simulated on various types of spatial units. For example, the hillslope processes consisting of interception, infiltration, percolation, surface runoff routing, and so on are simulated on grid cells, and the channel routing processes of water, sediment, and nutrients are simulated on channel lines. Some types of spatial units can be assigned topography-based flow directions and thus simulation dependencies exist among such spatial units, i.e., the simulation on downstream units can only be started after finishing the simulation on upstream units in the same time step.

The model includes the following *entities*: basic simulation units (e.g., grid cells), channel lines, subbasins, management units. **The *state variables* characterizing these entities are listed in Table 1:** the basic simulation units consist of a set of state variables used for simulating various hillslope processes, which can be extended according to the user's added modeling module of specific processes, such as climate variables, topographic variables, land use/cover variables, and soil variables; the channel lines consist of geometry variables, content variables of water, sediment, and nutrient, and hydrological and erosion modeling variables; the subbasin contains many basic simulation units and one channel line, each subbasin mainly consists of spatial relationship variables; the management unit contain one or many basic simulation units, each management units consists of BMP-specific variables such as operation variables of irrigation, fertilizer, harvest, etc. for plant management BMPs. **The *spatial* and *temporal* resolution and extent** depend on the input data and model configuration. The input spatial data (e.g., the DEM) determines the spatial resolution (e.g., 30 m) and extent (e.g., 90 km2) of watershed modeling. The model configuration of the modeling algorithm of watershed processes and the input climate data (e.g., the precipitation) determine the temporal resolution (e.g., daily or 5 minutes) and extent (e.g., ten years or one storm event).

The most important *processes* of the model, which are repeated every *time step*, are listed in the user-defined configuration file to construct the SEIMS-based watershed model. For example, the SEIMS-based model used in Qin et al. (2018) consists of hillslope processes simulated on the grid cells (i.e., canopy interception, surface depression storage, surface runoff, water erosion, plant growth processes, potential evapotranspiration, percolation, and interflow), groundwater flow process simulated on the subbasin, and channel routing processes of water, sediment, and nutrient simulated on the channel lines.

The model is initialized with a list of module names in a plain text file, which will be parsed by the SEIMS main program to assemble the corresponding modules. **Model dynamics are driven by *input data* representing** the climate dynamics and watershed characteristics. The climate dynamics, such as temperature, wind speed, and precipitation, drive various watershed processes, such as surface runoff. The watershed characteristics, represented by spatial data (i.e., a gridded DEM, a soil type map, and a land-use type map), also affect the modeling of watershed processes.

The most important *design concept* of the model is that watershed processes can be reasonably modeled by combining simulation units and modeling modules of interested processes, whose computation characteristics can guide the full use of the parallelizability at both the subbasin level and the basic simulation unit level (e.g., grid cell) to achieve high computing efficiency.

Table 1. Entities and state variables of the SEIMS model by Zhu et al. (2019).

Entity	Variable	Description
Basic simulation units (e.g., grid cells)	Climate variables	Driver factor of watershed processes, e.g., temperature, solar radiation, wind speed, relative moisture, and precipitation
	Topographic variables	Topographic properties derived from preprocessing of input spatial data (e.g., DEM), such as area, slope, flow direction, and flow length.
	Land use/cover variables	Land use/cover related properties such as landuse type, land cover status, initial leaf area index, and initial canopy height.
	Soil variables	Physical properties (e.g., clay, silt, and sand content) and chemical properties (e.g., concentration of nitrate, organic nitrogen, and organic phosphorus)
Channel lines	Geometry variables	Geometry properties such as length, width, depth, area, and side slope.
	Content variables of water, sediment, and nutrient	Storage of water, sediment, and various nutrient such as nitrogen and phosphorus.
	Hydrological modeling variables	Hydrological variables such as manning factor, bed hydraulic conductivity.
	Erosion modeling variables	Channel erosion variables such as bulk density of channel bed and bank sediment, erodibility of bed and bank sediment.
Subbasins	Spatial relationship variables	Each subbasin contains many basic simulation units and one channel line, and connects with other upstream and downstream subbasins.
Management units	Spatial relationship variables	Each management unit contains one or many basic simulation units
	BMP (best management practices)-specific variables	For example, plant management BMP often consist of operation variables of irrigation, fertilizer, harvest, etc.

References

Liu, J., Zhu, A.-X., Liu, Y., Zhu, T., & Qin, C.-Z. (2014). A layered approach to parallel computing for spatially distributed hydrological modeling. Environmental Modelling & Software, 51, 221–227.

Liu, J., Zhu, A.-X., Qin, C.-Z., Wu, H., & Jiang, J. (2016). A two-level parallelization method for distributed hydrological models. Environmental Modelling & Software, 80, 175–184.

Qin, C.-Z., Gao, H.-R., Zhu, L.-J., Zhu, A.-X., Liu, J.-Z., & Wu, H. (2018). Spatial optimization of watershed best management practices based on slope position units. Journal of Soil and Water Conservation, 73(5), 504–517.

Zhu, L.-J., Liu, J., Qin, C.-Z., & Zhu, A.-X. (2019). A modular and parallelized watershed modeling framework. Environmental Modelling & Software, 122, 104526.

3 Simulation of the evolution of root water foraging strategies in dry and shallow soils

Hugo Salinas, Michael Renton

A complete, detailed model description is being prepared for publication. This model is an updated version of the model provided at Renton and Poot (2014).

The basic idea underlying the model is that plant root morphology emerges from a set of basic traits that can be under natural selection, and soil conditions should drive selection of traits.

The overall *purpose* of our model is to simulate plant root architecture in the context of evolution and selection under different levels of resource heterogeneity. Specifically, we are addressing the following questions: Does selection of root traits differs across soil heterogeneity levels? And what strategies/root morphology emerge in each? To consider our model realistic enough for its purpose, we use the following **patterns**: The model can simulate

a wide variety of root types that can be visually realistic. Varying architecture parameter values results in different root morphology, and this in part results in different plant biomass. More favorable soil conditions (higher resource availability) result in higher plant biomass. In the simulation of evolution, the fitness of plants increased across generations, and the resulting morphology was consistent with those of real species from similar habitats.

The model includes the following entities (1) at the individual plant level: root branch, plant (composed of root branches), and soil. (2) at the evolutionary level: genotypes, and population (composed of genotypes).

The state variables characterizing these entities and model parameters are listed in Table 1 and 2.

The spatial and temporal resolution and extent are (1) at the individual plant level: plant growth is simulated in daily time-steps over 150 days, within a soil of size 40 × 40 × 140 cm (longitude, latitude, depth). (2) at the evolutionary level: generations.

The most important processes of the model, which are repeated every time step, are (1) at the individual plant level: water evaporation from the soil, water diffusion across the soil, rain, plants gathering water from the soil, root branches grow in length, root branching. (2) at the evolutionary level: genotypes in the population reproduce with mutations, fitness of each is measured, the fittest plants are selected.

The model is initialized with the following conditions (1) at the individual plant level: a plant has a single root branch with a single root segment. (2) at the evolutionary level: the population is initialized with identical genotypes that are not optimal.

Model dynamics are driven by input data representing (1) at the individual plant level: Architecture parameters. (2) at the evolutionary level: Population size, initial genotype (s), soil conditions.

Parameter	Description	Value range/Value
waterToBiomass (g mm^{-1})	Water to biomass conversion efficiency	0.00001
biomassPerVolume (g)	Biomass per unit of volume	0.001
waterTransEfficiency	Water transport efficiency	0.002
waterUptakePerRootLength (mm^3)	Water uptake per root length	10
maxElongationRate (mm day^{-1})	Maximum elongation rate	5
SegmentLength (mm)	Root segment length	2
soilvoxelsize (mm)	Side length of soil voxel	20
Whc	Maximum water holding capacity as fraction of voxel volume	0.1
ppatch	Proportion of soil in patches	[0, 0.1]
patchsize (mm)	Side length of rich patches	100
whcpatch	Maximum water holding capacity as fraction of voxel volume in rich patches	0.2
wobblesize	Random variation in root direction	[0, 0]
branchsupp	Controls average branching frequency	[-0.001, -0.0003]
rotang (radians)	Rotation angle	[0, 1.5]
branchang (radians)	Branching angle	[0, 1.5]
gravitrop	Gravitropism	[0, 0.3]
basezonelength	Length of base zone	[5, 30]
basezonep	Controls average branching frequency in the base zone	[0, 1]
maxorder	Maximum root order	[2, 8]
orderweightings	Growth priority weighting for roots of increasing order	[0.5 , 2]
kshoot1	Controls proportion of biomass allocation to shoot	[-5, 5]
kshoot2	Controls proportion of biomass allocation to shoot	[-0.1, 0.03]
Psize	Population size	30
ngen	Number of generations	500

Table 1: Model parameters and constants

Entity	Variable	Description
Plant	Root biomass (g)	Biomass in roots
Plant	Shoot biomass (g)	Biomass in shoot
Plant	Root structure	3D coordinates describing the structure of the root system
Plant	Water uptake (mm^3)	Water in plant
Soil	Soil moisture content (mm^3)	Water in a soil voxel
Population	Genotype	Set of parameter values

Table 2: Model state variables

References

Renton, M., Poot, P., 2014. Simulation of the evolution of root water foraging strategies in dry and shallow soils. Annals of Botany 114, 763–778. doi:10.1093/aob/mcu018.

4 A functional–structural plant model

Ming Wang

A complete, detailed model description, is provided in Wang et al. (2018).

The basic idea underlying the model is that the development of plants is driven dynamically by external and internal factors, and the occurrence of photosynthesis and adaptive carbon allocation at the organ level. Carbon allocation in a plant can be modelled as being dependent on current organ biomass and sink strength of each organ type (Marcelis, 1996; Lacointe, 2000; Marcelis and Heuvelink, 2007).

The overall *purpose* of our model is to simulate the development of architecture and growth patterns of an annual growth module (AGM) in the absence of fruit set for a young 'Hass' avocado tree in Australian orchards. The AGM in the model is formed from an indeterminate compound inflorescence (thyrse) that does not set fruit over an annual growing period, which comprises one mixed reproductive and vegetative (spring) and two vegetative (summer and autumn) growth flushes (Thorp and Sedgley, 1993a).

Specifically, we are focusing on gaining insights into the development of an AGM, and reproducing and predicting not only the architecture but also growth patterns that were observed empirically at various scales.

To consider our model realistic enough for its purpose, we use the following *patterns*:
Quantitative patterns:
The number of sylleptic shoots on the primary growth axis (PGA) (Thorp and Sedgley, 1993a)

1. The number of proleptic shoots on the PGA (Thorp and Sedgley, 1993a)
2. The number of growth units (GUs) (Thorp and Sedgley, 1993a)
3. The number of terminal GUs (Thorp and Sedgley, 1993a)
4. The number of GUs per axillary shoot (Thorp and Sedgley, 1993a)
5. The number of flushes per year (Thorp and Sedgley, 1993a)
6. Flush growth timing (Thorp and Sedgley, 1993a)
7. The mean length (mm) of spring growth flush on the primary growth axis (PGA) on non-fruit-bearing shoots in south-east Queensland, Australia (Wolstenholme et al., 1990, p. 318)

8. The mean length (mm) of summer growth flush on the PGA on non-fruit-bearing shoots in south-east Queensland, Australia (Whiley et al., 1991, p. 594)
9. The mean length (mm) of autumn growth flush on the PGA on non-fruiting shoots in a commercial orchard in South Australia, Australia (Thorp and Sedgley, 1993b, p. 152)
10. The mean length (mm) of the PGA over a 1-year growing period on non-fruiting shoots on 2-year-old 'Hass' trees in south-east Queensland, Australia (Thorp and Sedgley, 1993a, p. 92)
11. The mean leaf area (mm^2) per shoot on non-fruit-bearing shoots in south-east Queensland, Australia (Wolstenholme et al., 1990, p. 318)
12. The mean number of nodes (leaf nodes only) per growth unit on non-fruit-bearing shoots found on 4-year-old 'Hass' trees in a commercial orchard in central Queensland, Australia (DAF, unpubl. res.)

Qualitative patterns:

13. The leaf sink–source transition occurred at approx. 35 % of final leaf length in Florida, USA (Finazzo et al., 1994, p. 162)
14. The leaf expansion duration (day) was about 30–40 d in Nelspruit, South Africa and Irvine, CA, USA (Liu et al., 1999a, p. 53; Whiley, 1990)
15. The peak vegetative flush growth duration observed in commercial orchards in central Queensland, Australia was about 6 weeks (DAF, unpubl. res.)

The model includes the following *entities*: the environment and the individual organs [apices (terminal buds), leaves, internodes, axillary buds, and compound inflorescence]; **They are characterized by the following *state variables* in Table 1.**

The *spatial* and *temporal* resolution and extent: The model is not spatially explicit as it does not contain spatial state variables. However, the given state variables are translated into a spatially explicit visualization of the module's architecture via L-studio (Karwowski and Prusinkiewicz, 2004; Prusinkiewicz et al.,2000). The model runs with daily time steps for 364 days in total to represent an annual growth cycle. The time represents the period of three growth flushes – spring flush (1 September to 30 November), summer flush (1 December to 28 February) and autumn flush (1 March to 31 May) – as a simplification of flush patterns experienced in Australia, plus winter, during which there is no growth flush.

The most important *processes* of the model, which are repeated every *time step*: Day-length calculation, Radiation conversion, Degree-days calculation, Photosynthetic production rate calculation, Internode production: growth of an internode (stem), Inflorescence production, Leaf production, Axillary bud production, Apex production, Carbon allocation, Observer updates. In L-systems (Prusinkiewicz et al., 1997), the biological component (organ type) 'productions' are conceptually applied in parallel in each time step, which corresponds to synchronous updating of state variables; this creates no artefacts as the productions of the different organs are independent of each other.

The model is initialized with an apex pre-formed in the previous growing season and its initial development is supported by a carbon allocation of 10,000 mg that is assumed to be available from carbon storage or current photosynthesis elsewhere in the tree (Scholefield et al., 1985; Whiley et al., 1996; Liu et al., 1999b). The model reads the environmental input file to retrieve climatic data of the first simulation day (1 September 1987). The number of pre-formed nodes and newformed nodes for each biological component is generated by the normal distribution function using the mean value and its standard deviation based on model parameters.

Model dynamics are driven by *input data* representing the environmental variables: daily maximum and minimum temperature and radiation.

Table 1. Overview of the entities' state variables

Entities	State variables	Description	Possible values	Units
Environment				
	Daily maximum temperature	Daily maximum temperature for calculating thermal time – degree-days in a day	Based on the day of year from the input data	°C
	Daily minimum temperature	Daily minimum temperature for calculating thermal time – degree-days in a day	Based on the day of year from the input data	°C
	Daily radiation	Daily total short-wave radiation for calculating the photosynthetic production rate	Based on the day of year from the input data	MJ m^{-2} d^{-1}
Apex				
	Location	The node number on the growth axis (mean ± s.d.)	1 to 9.2 ± 2.56 (excluding nodes for bud scales or inflorescences) for primary growth axis in the spring flush; 1 to 14.1 ± 2.16 for the primary growth axis in summer or autumn flushes; 1 to 11.9 ± 1.44 for the second- and third-order growth axes including proleptic shoots and extension shoot axes in summer or autumn flushes; 1 to 5.9 ± 6.49 for sylleptic shoots in spring, summer or autumn flushes	
	Order	The growth axis order: primary growth axis (0), second-order growth axis (1) and third-order growth axis (2)	0–2	
	Age	Age in thermal time using degree-days to track the age	Based on cumulative degree-days since inception	°C d
	Shoot type	Located on proleptic type (0) or sylleptic type (1)	0/1	
	Growth demand	Carbon required for the purpose of growth	Based on initial internode and leaf biomass	mg
Axillary bud				
	Location	The node number on the parent growth axis (subtending growth axis)	Based on the parent growth axis	
	Order	The growth axis order: primary growth axis (0), second-order growth axis (1) and third-order growth axis (2)	0–2	
	Age	Age in thermal time using degree-days to track the age	Based on cumulative degree-days since inception	°C d
	Season	Indicates season of flush growth to identify potential locations on the parent growth axis where sylleptic or proleptic shoots will develop from: spring (1), summer (2) and autumn (3)	1–3	
	Shoot type	Located on proleptic type (0) or sylleptic type (1)	0/1	
Internode				
	Biomass*	Biomass of the internode	Based on allocated carbon for growth	mg

	Age	Age in thermal time using degree-days to track the age	Based on cumulative degree-days since inception	°C d
	Season*	Indicates season of flush growth to show the detailed architecture and growth patterns with different colors for each flush: spring (1), summer (2) and autumn (3)	1–3	
	Maintenance demand	Carbon required for the purpose of maintenance	Based on internode biomass and maintenance coefficient	mg
	Growth demand	Carbon required for the purpose of growth	Based on internode biomass, internode potential relative growth rate and daily degree-day value	mg
Leaf				
	Biomass*	Biomass of the leaf	Based on allocated carbon for growth	mg
	Age	Age in thermal time using degree-days to track the age	Based on cumulative degree-days since inception	°C d
	Maintenance demand	Carbon required for the purpose of maintenance	Based on leaf biomass and maintenance coefficient	mg
	Growth demand	Carbon required for the purpose of growth	Based on leaf biomass, leaf potential relative growth rate and daily degree-day value	mg

* State variables used for visualization by L-studio.

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5 Example of how to follow reporting checklists

When writing a new model description from scratch, the questions of the checklists in each of the seven elements of OMF's ODD need to be answered. If a new study is based on an existing model, as is or modified, rewriting the existing model description might require substantial effort. Therefore, a summary ODD with full level ODD where for each checklist question is specified where to find, in the existing model description, the corresponding answer. This is the rationale of reporting guidelines in medical research, which has also been used for PRISMA, a reporting guideline for systematic reviews:

Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71

The example below is from Delos, M. C., Johnson, C. G., Weiskopf, S. R., & Cushing, J. A. (2025). Climate change effects on ecosystem services: Disentangling drivers of mixed responses. Plos one, 20(2), e0306017

Corresponding examples do not yet exist for OMF's ODD, but will be provided once the standard has been approved and finalized.

Table S2: PRISMA 2020 CHECKLIST (from the supplement of Delos et al., 2025).

Section and Topic	Item #	Checklist item	Location where item is reported (pg #)
TITLE			
Title	1	Identify the report as a systematic review.	2 (Abstract)
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	N/A
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	3
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	3
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	4-5

Section and Topic	Item #	Checklist item	Location where item is reported (pg #)
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	4
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	4
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	4-5, S1 Tables
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	4-5, S1 Tables
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	4-5
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	S1 Tables
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	4-5
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	N/A
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	4-5, S1 Tables
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	5
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	5
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	5
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	N/A
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	N/A
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	N/A
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	N/A
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in	5, Fig 1

Section and Topic	Item #	Checklist item	Location where item is reported (pg #)
		the review, ideally using a flow diagram.	
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	6
Study characteristics	17	Cite each included study and present its characteristics.	S3 Table
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	N/A
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	5-8
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	N/A
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	5-8
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	N/A
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	N/A
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	N/A
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	N/A
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	8-14
	23b	Discuss any limitations of the evidence included in the review.	8-14
	23c	Discuss any limitations of the review processes used.	14
	23d	Discuss implications of the results for practice, policy, and future research.	12-14
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	4
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	4
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	N/A
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	N/A
Competing interests	26	Declare any competing interests of review authors.	N/A

Section and Topic	Item #	Checklist item	Location where item is reported (pg #)
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	4, Data Availability Statement

6 ODD guidance for agent-based models

For agent-based models, ODD has been used since 2006 in more than 4000 publications. This original ODD did not work with explicit checklists like that for PRISMA (Section 5). Instead, it was described, using running text, what authors were supposed to do. In 2020, the detailed guidance was published, as supplement S1 to Grimm et al. 2020. This guidance is based on the experience of the authors with hundreds of ODDs, both of their own models, those they read, and those they dealt with as reviewers. Such experience does not yet exist of OMF's ODD, which is for all model types, but similar guidance will develop over time, assisted by mark-down templates, LLM-assisted compliance tests, etc.

The S1 supplement can be found here. https://www.jasss.org/23/2/7/S1-ODD.pdf

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