Evaluation of Atmosphere–Vegetation Interaction Models

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2025-07-16

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Understanding microclimatic and ecological processes at high spatial resolution requires integrated modeling approaches that couple atmospheric dynamics with plant and vegetation processes. The models compared here span a wide range of capabilities, from fluid dynamics solvers to ecophysiological simulators. This document introduces the evaluation criteria, explains the scoring approach, and provides literature references for further exploration.

Objective of the Evaluation

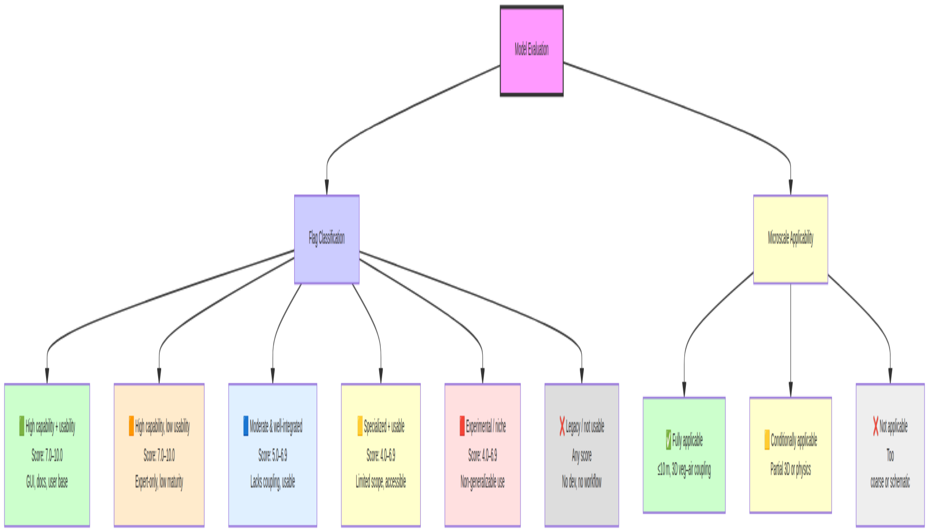
This model comparison aims to evaluate and categorize existing modeling platforms that simulate atmosphere-vegetation interactions, emphasizing realistic deployment, dimensional and structural detail, and biophysical relevance. While many models offer advanced features in isolation, such as turbulence modeling, vegetation physiology, or 3D structural input, only a few integrate these capabilities in a usable and accessible way. This evaluation considers not only modeling power but also technical complexity, scientific maturity, and practical deployability.

- Full 3D support with high spatial resolution

- Integration of real-world vegetation structure from TLS, QSM, or ALS
- Explicit representation of plant–atmosphere feedback (e.g., transpiration effects on local climate)
- Availability of user interfaces, documentation, licensing, and feasibility on common research workstations

Model Evaluation Structure

Scoring Criteria (Max Score: 10.0)



The Evaluation Framework

When selecting a suitable model for simulating interactions between the atmosphere and vegetation, more aspects than just scientific completeness must be taken into account in the context of operationalization. Models differ considerably in their structure, focus, technical maturity, and accessibility. What does this mean? Some models achieve excellent physical accuracy (e.g., LES-based turbulence and complete feedback between plants and the atmosphere) but require in-depth technical knowledge or high-performance computers. Other models, on the other hand, sacrifice physical completeness in favor of practicality and easy integration into planning or monitoring processes.

Our attempt is to enable this multi-criteria assessment and make it comprehensible by means of an evaluation framework in order to arrive at a pre-selection. This is done by combining quantitative assessments with a qualitative classification system, in particular:

- scientific completeness based on various categories
- operational usability

The evaluation is based on clearly defined criteria such as model physics, plant physiology, plant structure, model dimensionality and scales, and user-friendliness. However, the relative weights reflect value-based assessments – what is considered more important depends on the context (urban planning vs. ecohydrology vs. forest micrometeorology). In concrete terms, this means:

- In urban planning, user-friendliness and realistic 3D air flows may be paramount.

- In plant science, biophysics and physiology may be paramount.

- In forestry, compatibility with TLS or QSM inputs may be required.

This is not a weakness, but a strength, as it allows adaptation to the user's goals – as long as the weighting and criteria are transparent.

Integrated Criteria Table for Atmosphere–Vegetation Model Evaluation (Max Score = 10.0)

Criterion	Weight	Sub-Capabilities / Description	Scoring Guidelines
Atmosphere	3.0	LES/RANS, radiative transfer, soil–vegetation coupling	**1.5–3.0**: Full LES or RANS / radiation / soil **0.6–1.4**: Partial (e.g., radiation only) < **0.6**: Basic or missing physics
Structure	1.0	Realistic vegetation structure (e.g., QSM/	**0.8–1.0**: Full 3D voxel/QSM/tree geometry **0.4–0.7**: Schematic trees

Criterion	Weight	Sub-Capabilities / Description	Scoring Guidelines
		LAD, voxel, TLS-derived)	< **0.4**: No or empirical structure
Feedback	1.0	Biophysical feedback transpiration ↔ air	**0.8–1.0**: Full coupling **0.4–0.7**: Drag or partial interaction < **0.4**: One-way/ static
Physiology	1.0	Transpiration, photosynthesis, stomata, water flow	**0.8–1.0**: Full physiology **0.4–0.7**: Simplified < **0.4**: None
Usability	2.0	GUI/CLI, documentation, install, license, hardware	**1.5–2.0**: Documented, user-friendly **0.6–1.4**: CLI/ complex < **0.6**: Legacy/ unusable
3D	2.0	Full 3D resolution and within-canopy gradients	**1.0–1.9**: Full 3D **0.6–0.9**: Pseudo-3D **0.3–0.5**: Layered < **0.3**: None

The flags “microscale applicable” and “experimental or outdated”

Microscale applicable models can resolve processes on spatial scales of ≤ 10 m. At this scale, air flows, radiation, and microclimate dynamics become relevant at the tree level. These models are typically characterized by the following features:

- They work with high-resolution 3D grids.
- Vegetation is explicitly represented (e.g., voxel- or TLS-based).

- Localized simulations of plots, tree groups, or urban areas are possible.

Microscale capability is essential for LiDAR-based modeling, urban forestry, and the investigation of microclimates in tree canopies.

Symbol	Microscale Capability Description
✅	**Fully applicable**: Designed for a resolution of $\leq 10\,\mathrm{m}$ with 3D vegetation–atmosphere coupling.
🟨	**Conditionally applicable**: Partial support for high resolutions, but limited physics or geometry.
❌	**Not applicable**: Coarse resolution or missing spatial details.

The following characteristics are flagged with an ❌ for experimental or obsolete models:

- no longer maintained or widely used.
- they were developed for niche applications or obsolete use cases.
- there is a complete lack of user-friendly workflows or adequate documentation.

This leads to the following classification scheme:

Flag	Label	Implied Score	Explanation of the Classification
🟩	High capability, high usability	7.0–10.0	Fully featured and deployable with reasonable effort (GUI, docs, user base)
🟧	High capability, low usability	7.0–10.0	Powerful but difficult to use; expert-only setup, low maturity
🟦	Moderate capability, well-integrated	5.0–6.9	Solid for many tasks; lacks advanced coupling but usable and balanced
🟨	Specialized model, high usability	4.0–6.9	Limited scope (e.g. radiation only), but very accessible and documented
🟥	Experimental or niche	4.0–6.9	Limited audience or non-generalizable application

Flag	Label	Implied Score	Explanation of the Classification
❌	Legacy/ unmaintained/ not usable	any	No active development or practical use case today

Note: This classification does not always correspond to the ranking by score, which is intentional. For example, a model with a high score may still be marked with 🟧 or ❌ if it is technically difficult to implement, is not documented or maintained, or is simply no longer available. This helps to put the pure scoring performance into perspective, which would otherwise lead to the selection of models that prove to be unusable in practice.

Atmosphere–Vegetation Model Comparison of Models

Fifteen models were systematically evaluated based on the assessment framework presented above. The models were selected on an exploratory basis using Google searches, specialist literature (e.g., GMD Geoscientific Model Development, ScienceDirect), well-known model comparisons, and open-source repositories. The selection is therefore well-founded but not entirely systematic. The following tables shows the results of this evaluation. It not only shows the weighted overall score, but also differentiates between the underlying individual criteria. In addition, the applicability in the microscale range is indicated and each model is classified using a color-coded classification system. This makes the performance of a model in terms of the atmosphere-vegetation coupling transparent and shows the extent to which a model can be realistically integrated into scientific or operational processes.

Atmosphere–Vegetation Model Evaluation (Criterion-Level Justification)

	Model	Score	Atmosphere Physics	Structure	Feedback	Physiology	Usability	3D	Microscale Capabilities	All	Micro Scale
1	**PALM-4U**	**7.6**	**1.0** Full LES and radiative transfer; no soil–water coupling	**0.8** Static 3D vegetation model	**0.7** Air–vegetation	**0.3** No explicit physiology	**0.4** Complex install, Linux	**1.0** Fully resolved CFD	LES solver at meter-scale; used in urban microclimate studies <10 m; limited	🟧	🟩

	Model	Score	Atmosphere Physics	Structure	Feedback	Physiology	Usability	3D	Microscale Capabilities	All	Micro Scale
					drag interaction		only; well documented		physiology, strong flow–structure resolution		
2	**MuSICA**	**7.4**	**0.8** Soil–plant-atmosphere exchange; no LES or radiative transfer	**0.6** Layered cohort model, not voxel-based	**1.0** Detailed biophysical feedback	**1.0** Includes transpiration, photosynthesis, stomata, water dynamics	**0.3** Legacy Fortran, hard to install	**1.0** 1D canopy model	etailed canopy and physiology; vertical 1D, not voxel; grid spacing cohort-based	🟥❌	🟨
3	**OpenFOAM**	**7.3**	**2.5** LES/RANS CFD; partial radiation support	**1.0** Porosity/drag approach for tree structure	**0.5** Customizable feedback via coding	**0.0** No vegetation physiology	**0.2** Expert use only, CLI	**1.9** Full 3D CFD	CFD model with <1 m resolution; porosity drag; physiology via coding	🟧	🟩
4	**ENVI-met**	**6.9**	**0.8** RANS turbulence and radiation; no soil coupling	**0.6** Blocky trees, parametric structure	**0.4** Basic one-way coupling	**0.3** Simplified energy–water exchange	**0.6** GUI, documented, PC-compatible	**1.0** Pseudo-3D (layered)	Grid 0.5–2 m; urban canopy focus; simplified structure	🟩	🟩
5	**WRF-Urban**	**6.5**	**0.9** Urban-scale RANS + radiation; coarse resolution	**0.7** Urban and vegetation layering	**0.6** Bulk vegetation–atmosphere interactions	**0.2** No individual physiology model	**0.3** HPC-heavy, complex setup	**1.0** Grid-based, some canopy effects	Urban RANS, VEGE3D coupling; no true <10 m flow+veg	🟧	🟨
6	**ForestED**	**6.1**	**0.9** Radiation balance only	**0.8** TLS-derived trees, but limited structural detail	**0.5** Weak air interaction	**0.3** No detailed physiology	**0.4** Prototype, no GUI	**1.0** Real 3D from TLS	Full 3D via TLS; radiation only, no flow coupling	🟥❌	🟩
7	**DART**	**5.7**	**0.6** Radiative transfer simulation, no air dynamics	**1.0** Voxel-based structural import	**0.0** No air–plant feedback	**0.2** No physiology	**0.3** Complex setup, technical barrier	**1.0** Radiative 3D	Radiative voxel model <1 m; no airflow or feedback	🟥❌	🟩
8	**ED2**	**5.6**	**0.7** Surface energy and hydrology; no LES	**0.5** Functional cohort-based	**0.6** Partial feedback, not dynamic	**1.0** Rich physiology,	**0.4** Command-line only, heavy model	**0.5** Vertical layers, no 3D	Cohort-based; no individual trees or microclimate	🟦	❌

	Model	Score	Atmosphere Physics	Structure	Feedback	Physiology	Usability	3D	Microscale Capabilities	All	Micro Scale
						plant hydraulics					
9	**MAESPA**	**5.3**	**0.4** No LES or full RANS	**0.5** Elliptic crown geometries	**0.5** Simple coupling (transpiration ↔ air temp)	**1.0** Includes water and stomatal response	**0.4** CLI, old Fortran	**0.8** Layered or semi-3D	Tree-level radiation, no fluid; stand-scale design	🟦	❌
10	**PyDOM**	**5.0**	**0.5** Solar irradiance modeling using discrete ordinates method; no fluid dynamics	**0.6** Uses simplified canopy layers or volumes; structure inferred	**0.0** No biophysical feedback	**0.3** No physiology model	**0.5** Script-based usage; moderately usable	**1.0** Volumetric but low-resolution	Voxelized solar DOM; no air coupling	🟨 ❌	🟨
11	**COMOKIT**	**4.9**	**0.4** No atmosphere simulation; only agent-level heat/ energy accounting	**0.3** Simplified static vegetation	**0.5** Agent-based feedback loops via scenario definition	**0.5** No continuous transpiration or photosynthesis, only thermal behavior	**0.7** Accessible GUI, easy scenario logic, extensive documentation	**0.5** Visual pseudo-3D, no physical gradients	Agent-based; no physical coupling; coarse graphics	🟨	❌
12	**LPJ-GUESS**	**4.4**	**0.7** Energy and gas exchange with climate integration; no internal 3D resolution or LES	**0.4** Functional PFTs with vertical profiles, no explicit geometry	**0.4** Climate–vegetation coupling, but coarse	**0.9** Complex physiology model with stomatal control, photosynthesis	**0.3** CLI-based ecosystem model, config-heavy	**0.0** No 3D, grid-cell aggregated PFT composition	DGVM, no 3D, coarse PFT representation	🟦 ❌	❌
13	**Microclimc**	**4.2**	**0.6** Radiative energy balance and temperature with simple terrain effects; no CFD or LES	**0.3** Schematic trees only, no voxel or lidar structure	**0.4** One-way: vegetation affects energy balance, no feedback from air	**0.4** Simple transpiration and energy fluxes only	**0.8** R-based, documented, GUI-like interface	**0.5** Layered canopy modules, semi-3D	1–5 m radiation/temp; schematic trees; no LES	🟨	🟨
14	**iTREETools**	**3.1**	**0.3** No atmosphere model; static inventory system	**0.2** Tree inventory tables	**0.2** None; no feedback, no fluxes	**0.0** No physiology modeling	**0.9** Very accessible GUI, well supported	**0.0** No 3D; inventory only	Empirical inventory; no spatial simulation	🟨 ❌	❌

	Model	Score	Atmosphere Physics	Structure	Feedback	Physiology	Usability	3D	Microscale Capabilities	All	Micro Scale
				only; no geometry							
15	**Fluspect**	1.9	**0.1** Leaf-scale radiative simulation; no atmosphere	**0.0** No spatial structure	**0.0** None	**1.0** Detailed leaf spectral and biochemical simulation	**0.3** Niche tool, standalone use; requires integration	**0.0** No 3D; single-leaf model	Leaf-level only; no domain or airflow	🟥 ❌	❌

Based on the upper table, the below graph helps visualize the trade-off between model capability and usability, making the multi-dimensional classification system intuitively accessible at a glance.

Model usability vs. total score across classified microclimate models. The inverse relationship reflects a common trade-off: high-performing models (right) often require expert-level setup (low usability, bottom), while user-friendly models (top) tend to be simplified. Colored points reflect model classification: 🟩 usable and capable, 🟧 powerful but complex, 🟦 balanced, 🟨 specialized, and 🟥 experimental. Models above the trend line (e.g., ENVI-met) offer better usability than expected for their score; those below (e.g., MuSICA) require disproportionately high effort.

Final Selection of Models

If we narrow the selection by removing models that are either **classified as legacy systems (❌)** or that **lack both microscale applicability (❌) and fully resolved 3D spatial representation (<1.0)**, the set of viable modeling platforms is drastically reduced. This filtering excludes tools that are either outdated, lack dimensional realism, or are designed for coarse-scale applications incompatible with high-resolution vegetation–atmosphere modeling. What remains is a focused set of platforms that combine **scientific robustness** with **operational feasibility** for modeling processes at the tree or plot level. These remaining models offer realistic support for implementation in **urban microclimate design**, **LiDAR-informed ecological studies**, and **vegetation-based climate adaptation strategies** where 3D feedbacks and spatial structure matter.

Rank	Model	Score	Atmosphere	Structure	Feedback	Physiology	Usability	3D	All	Micro Scale
1	PALM-4U	7.6	1.0 – Full LES, radiation, no soil	0.8 – Static vegetation models	0.7 – Basic interaction	0.3 – No physiology	0.4 – Complex setup, Linux only, docs	1.0 – True 3D	🟧	🟩
2	OpenFOAM	7.3	2.5 – Full LES/RANS, partial radiation	1.0 – Porosity/drag approach	0.5 – Feedback via coding	0.0 – None	0.2 – CLI, expert only	1.9 – Full CFD	🟧	🟩
3	ENVI-met	6.9	0.8 – RANS, radiation	0.6 – Block trees only	0.4 – Weak one-way coupling	0.3 – Simplified transpiration	0.6 – GUI, docs, runs on PC	1.0 – Pseudo-3D layering	🟩	🟩
4	WRF-Urban	6.5	0.9 – RANS, radiation	0.7 – Layered urban/vegetation	0.6 – Bulk interaction	0.2 – None	0.3 – HPC, not easily usable	1.0 – Grid-based	🟧	🟨
5	Microclimc	4.2	0.6 – Radiation and temp model, no LES	0.3 – Schematic trees	0.4 – Indirect surface coupling	0.4 – Empirical transpiration	0.8 – GUI, documentation, R integration	0.5 – Semi-3D canopy layer	🟨	🟨

Sorting applied:

Primary: Microscale applicability (✅ > 🟨 > ❌)

Secondary: Total Score (descending)

Literature and Sources by Model

to be completed

ENVI-met

- Bruse, M., & Fleer, H. (1998). Simulating surface–plant–air interactions inside urban environments with a three-dimensional numerical model. *Environmental Modelling & Software*, 13(3–4), 373–384.
- ENVI-met Documentation: https://envi-met.info/

PALM-4U

- Maronga, B., et al. (2020). Overview of the PALM model system 6.0. *Geoscientific Model Development*, 13, 1335–1372. https://doi.org/10.5194/gmd-13-1335-2020
- https://palm-model.org/

MuSICA

- Ogée, J., et al. (2003). MuSICA, a CO2, water and energy multilayer, multileaf model for the analysis of function of vegetation at the canopy scale. *Ecological Modelling*, 156(2–3), 181–204.

OpenFOAM (custom vegetation)

- Gromke, C., & Blocken, B. (2015). CFD simulation of near-field pollutant dispersion including vegetation effects. *Atmospheric Environment*, 100, 238–249.
- The OpenFOAM Foundation Hom

WRF-Urban

- Chen, F., Yu, B., Wu, M., Yang, X., et al. (2021). Improved urban finescale forecasting during a heat wave by using high-resolution urban canopy parameters. Frontiers in Climate, 3, 771441. https://doi.org/10.3389/fclim.2021.771441
- Martilli, A., Nazarian, N., Krayenhoff, E. S., Lachapelle, J., Lu, J., Rivas, E., Rodriguez-Sanchez, A., Sanchez, B., & Santiago, J. L. (2024). **WRF-Comfort: Simulating microscale variability in outdoor heat stress at the city scale with a mesoscale model**. *Geoscientific Model Development*, 17, 5023–5039. https://doi.org/10.5194/gmd-17-5023-2024