3 R’s of Terrestrial Ecosystem Modeling

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Review article | **Highlight paper** |

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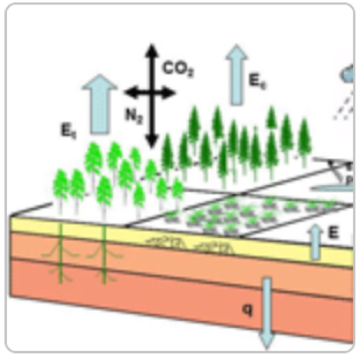


Reliable, robust and realistic: the three R's of next-generation land-surface modelling

I. C. Prentice, X. Liang, B. E. Medlyn, and Y.-P. Wang

Abstract. Land-surface models (LSMs) are increasingly called upon to represent not only the exchanges of energy, water and momentum across the land–atmosphere interface (their original purpose in climate models), but also how ecosystems and water resources respond to climate, atmospheric environment, land-use and land-use change, and how these responses in turn influence land–atmosphere fluxes of carbon dioxide (CO_2), trace gases and other species that affect the composition and chemistry of the atmosphere. However, the LSMs embedded in state-of-the-art climate models differ in how they represent fundamental aspects of the hydrological and carbon cycles, resulting in large inter-model differences and sometimes faulty predictions. These "third-generation" LSMs respect the close coupling of the carbon and water cycles through plants, but otherwise tend to be under-constrained, and have not taken full advantage of robust hydrological parameterizations that were independently developed in offline models. Benchmarking, combining multiple sources of atmospheric, biospheric and hydrological data, should be a required component of LSM development, but this field has been relatively poorly supported and intermittently pursued. Moreover, benchmarking alone is not sufficient to ensure that models improve. Increasing complexity may increase realism but decrease reliability and robustness, by increasing the number of poorly known model parameters. In contrast, simplifying the representation of complex processes by stochastic parameterization (the

History of LSMs

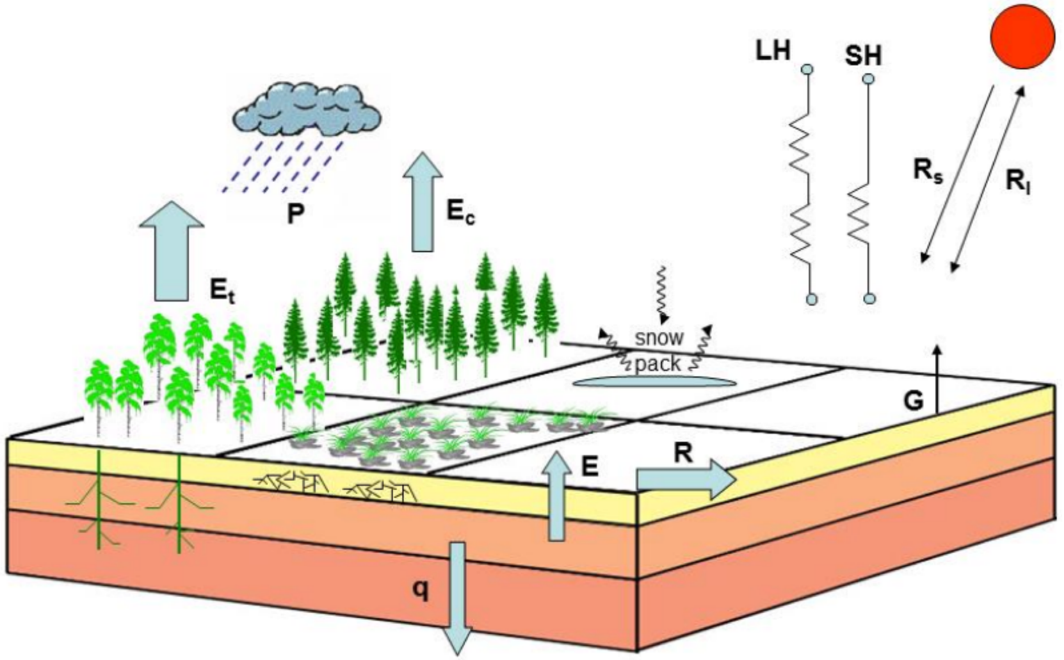


Figure 1. Schematic of "generation 2A" LSMs. The energy budget is represented by short-wave radiation (R_S), long-wave radiation (R_l), latent heat flux (LH), sensible heat flux (SH) and ground heat flux (G). The water budget is represented by P (precipitation), E (bare ground evaporation), E_t (transpiration), E_c (evaporation from canopy interception) and surface runoff (R). The water budget is coupled with the energy budget, but hydrological processes are represented very simply; for example, subsurface runoff is represented only by vertical drainage (q). Precipitation, vegetation type and soil properties are treated as constant within each grid cell.

History of LSMs

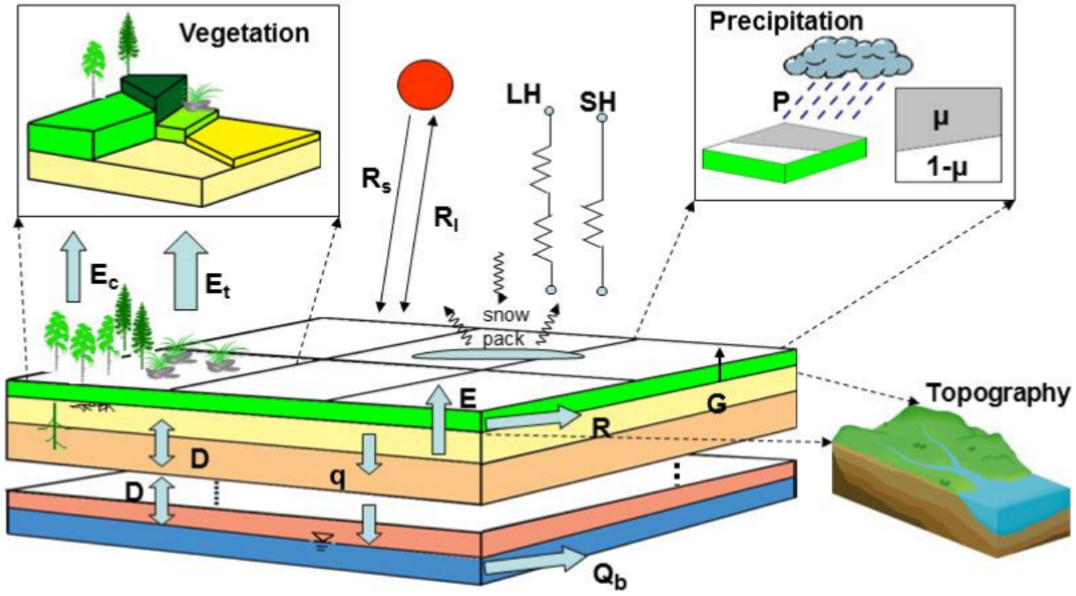


Figure 2. Schematic of "generation 2B" LSMs. See Fig. 1 for basic symbols. In addition, subgrid variabilities of precipitation, vegetation type, soil properties and topography are represented statistically (μ represents the variable precipitation-covered area) and hydrological processes are represented more explicitly. Thus surface and subsurface runoff (Q_b and q) are distinguished, and diffusion (D), lateral flow in the subsurface (Q_b), and groundwater table dynamics are also modelled.

History of LSMs

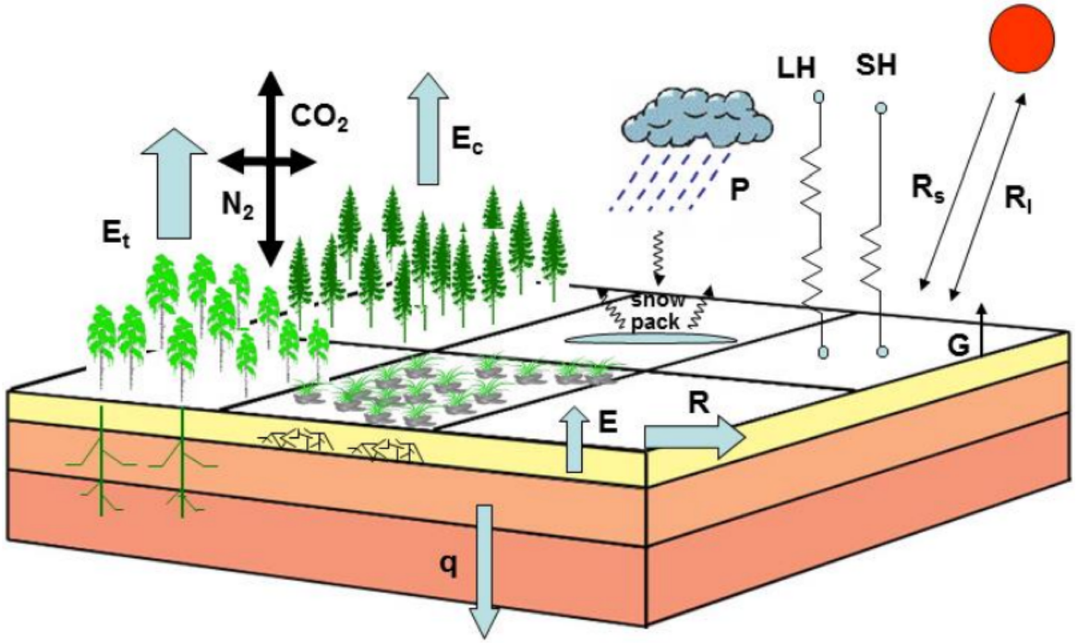


Figure 3. Schematic of "third-generation" LSMs, which are similar to generation 2A (Fig. 1) except that now the carbon budget is coupled to the calculation of the water and energy budgets through parameterizations of stomatal behaviour. However, these models do not incorporate the improved treatments of subgrid spatial variability and hydrological processes developed in generation 2B (Fig. 2).

Despite parallel development, LSMs still vary a lot…

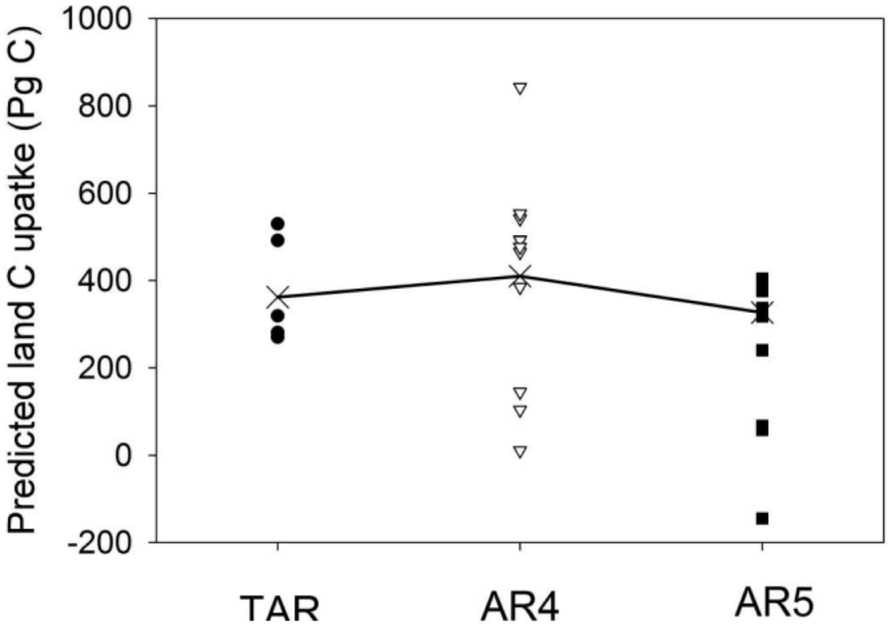


Figure 4. Simulated land carbon uptake to 2100 under a "high-end" global warming scenario, as projected by global models in the IPCC Third Assessment Report (TAR), Fourth Assessment Report (AR4) and Fifth Assessment Report (AR5). The cross represents the mean of the models included in each assessment.

…and none are correct!

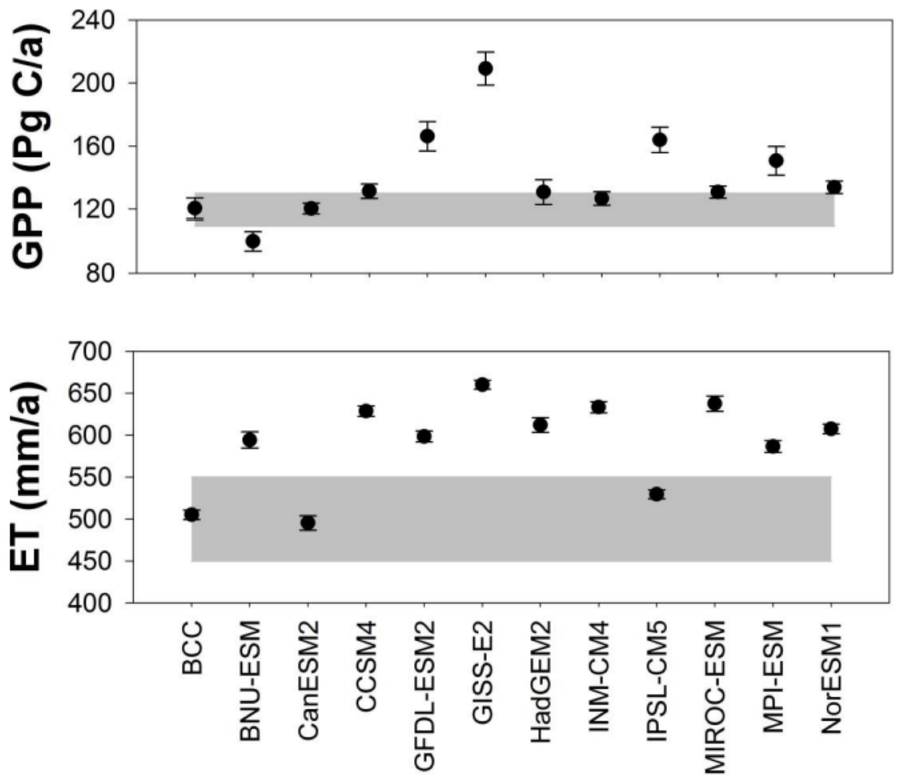


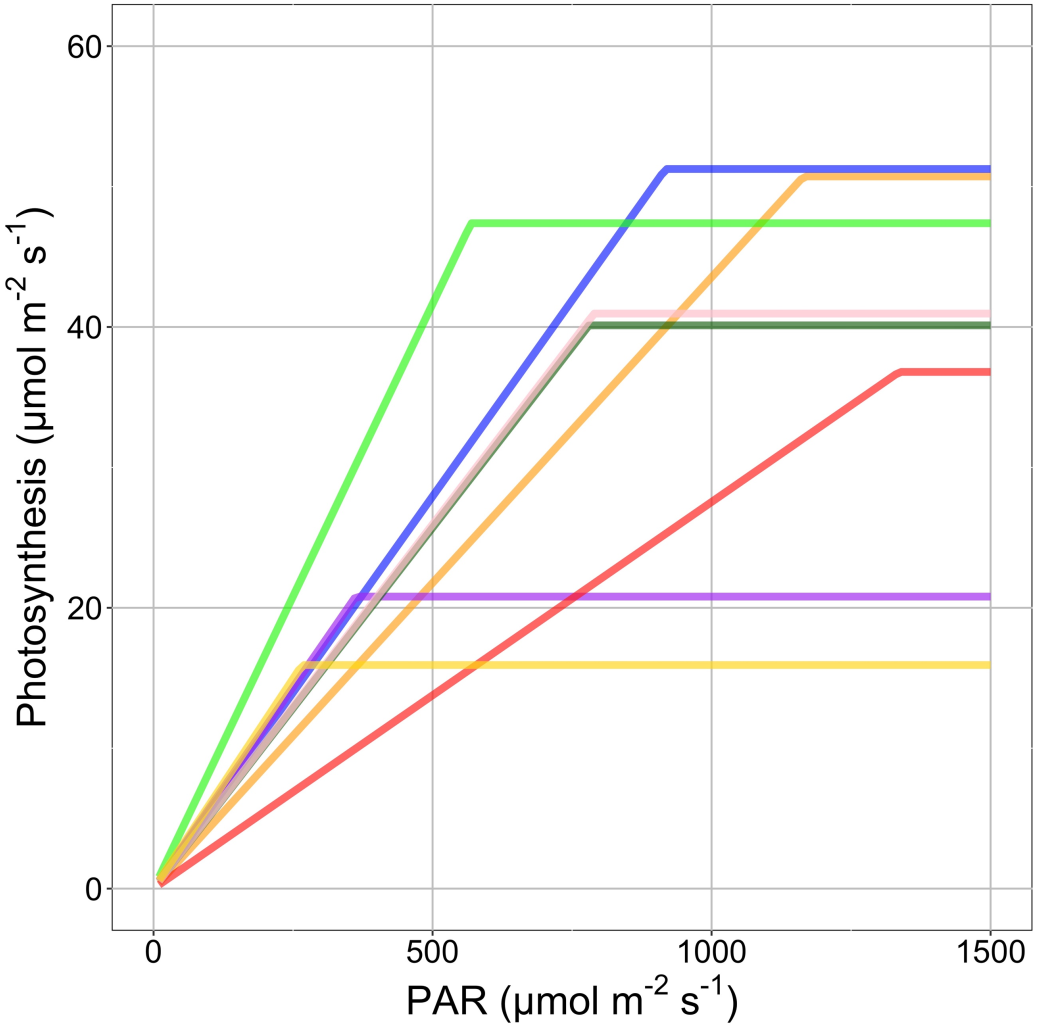
Figure 5. Mean annual gross primary production ($Pg\,C\,a^{-1}$) and evapotranspiration ($mm\,a^{-1}$) from the global land surface during 1901–2010, as simulated by 12 Earth system models in the IPCC Fifth Assessment Report. The grey lines represent upper and lower limits based on observations.

“Moreover, complexity can conceal lack of rigour, because it becomes progressively easier to fit observations as more parameters are introduced. Thus, increasing complexity can mask a lack of understanding, resulting in a situation whereby models are tuned to perform well at standard tests but produce widely divergent results when projected beyond the domain of calibration.”

Variability impacts on non-linear models

Example on board

Fixed versus continuous parameters



Next generation models

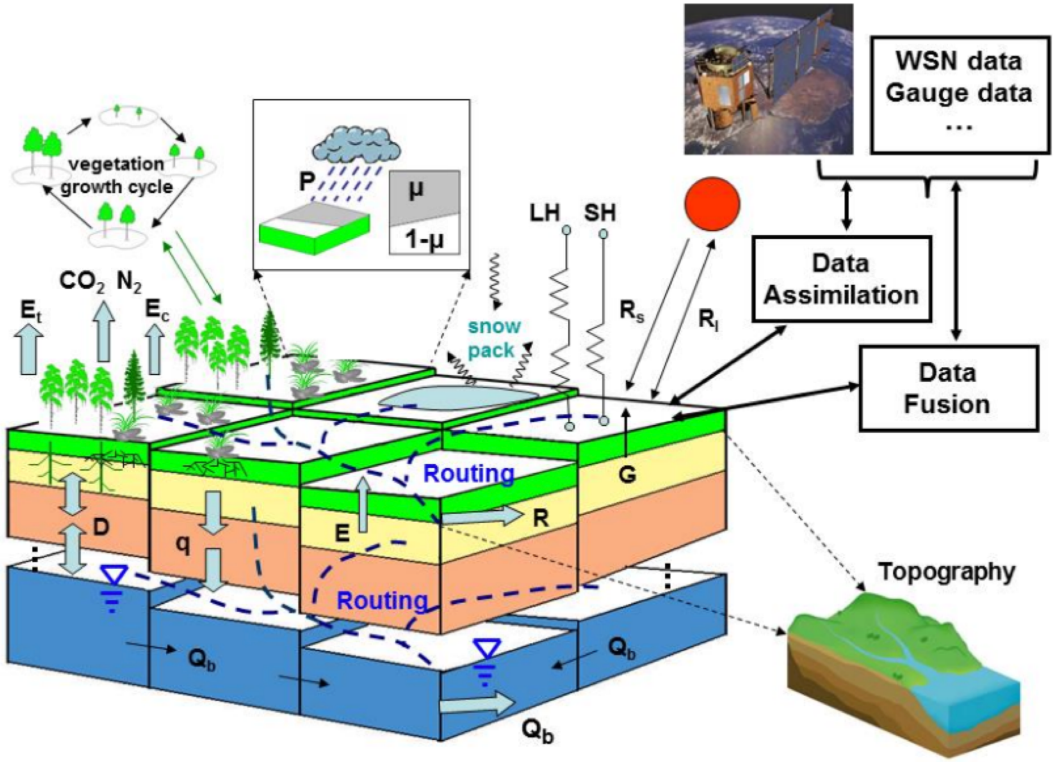
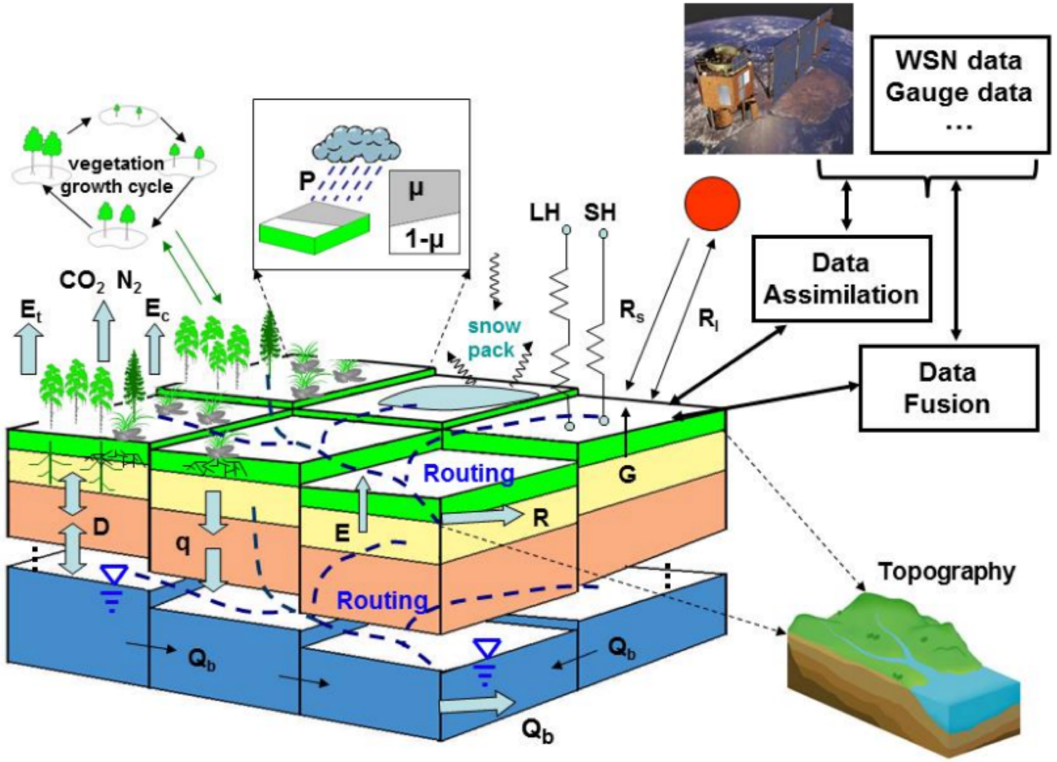


Figure 6. Hypothetical schematic of "next-generation" LSMs that will combine the desirable features of previous models, with the addition of surface and subsurface hydrological routing schemes and representations of vegetation dynamics. Model–data fusion and data assimilation will allow effective use of observations from different platforms. Experience suggests that it will be a major challenge to achieve such a complex, realistic representation of land-surface biology and hydrology without loss of reliability and robustness. The application of multiple physical and biological constraints, and the judicious use of stochastic parameterization for subgrid-scale processes, are advocated here as important tools for next-generation model development.



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Looks pretty complex?!

Bounding complexity: the use of multiple constraints

- Models are becoming increasingly complex
- Biological and physical constraints are needed
  - Reduce parameters
  - Include physically necessary relationships
  - Connect processes and parameters in more continuous manner
  - And compare to data!

Data assimilation

- Estimate optimal parameter values
- But can sometimes lead to errors
  - Uncertainty in both model and data!
  - Need to maintain mass and energy balance (thanks a lot Newton!)
  - Need big, fancy computers