Fourth International Conference on Earth System Modelling
4ICESM-1, 2017

Representation of the terrestrial carbon cycle in Earth System models: problems and solutions

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It is no secret that current models of the land carbon cycle perform poorly against benchmarks, produce divergent results, and are not improving either in reliability or in consistency. After more than two decades of development, this situation amounts to a crisis. But the suggestions regularly offered to address the situation – the wider application of standard benchmarks, and the inclusion of more processes – are by no means sufficient to resolve it. Benchmarking is essential, and efforts are underway to make it routinely practicable. But far more can be achieved using the wealth of currently available data than simply an "end-of-pipe" comparison with the outputs of models. Data assimilation is valuable but offers no safeguard against incorrect model formulation. The inclusion of additional processes in a model is even more problematic, because of its enormous potential for misuse as a cryptic means of compensating for incorrect formulations of processes already present.

In science generally, models are used to translate theory into testable predictions, with observations providing the tests. The problem facing the first land model developers was that theory was lacking and relevant observations extremely sparse. Today, observations are abundant – but terrestrial ecosystem science still lacks a firm theoretical basis.

Many of the problems in current models have arise because of ad hoc assumptions (e.g. about the constancy of key parameters) that have been taken to be innocuous simplifications, but in fact violate the most fundamental law of biology – the law of natural selection, which rapidly eliminates uncompetitive trait combinations and thereby ensures that the space of possible biological parameter combinations is highly constrained. If natural selection is disregarded, models of ecosystems – as assemblages of organisms – are hopelessly underspecified, and no amount of data assimilation will endow them with useful predictive ability.

Fortunately, an alternative approach is possible, and is starting to prove its worth. Explicit optimality hypotheses have a long history in ecophysiology but only recently have they begun to penetrate Earth System models (ESMs). A well-known example is the Cowan-Farquhar criterion for optimal stomatal behaviour, which has led to many insights about the coupling of terrestrial carbon and water exchange. But this criterion is insufficient for predictive modelling because it requires specification of a parameter (λ) that varies spatially and temporally in unknown ways. An alternative criterion, the least-cost hypothesis, yields – by contrast – explicit, testable predictions of how the air-to-leaf carbon dioxide drawdown (regulated by stomata) should respond quantitatively to growth temperature, vapour pressure deficit and atmospheric pressure. These predictions account for several long-standing and otherwise puzzling observations, and can be shown to be consistent with data derived from stable carbon isotope measurements of leaves grown in different environments. The additional optimality criterion known as the co-ordination hypothesis then allows the prediction of the light-use efficiency of gross primary production (GPP) via the Farquhar model, with no free parameters to estimate (whether by imputation or by data assimilation), and no distinctions among plant types except for the basic difference between the C3 and C4 photosynthetic pathways. The so-called P model embodying these hypotheses is providing the basis for a new satellite-based GPP model which, unlike existing products, avoids discontinuities associated with biome boundaries, and includes a realistic representation of CO_2 effects on photosynthesis. This model also represents a crucial first step ¬– via data-informed carbon and nitrogen allocation modelling – towards the development of a "first principles" model of plant growth and ecosystem function for ESMs.