

Multi-scale model inter-comparisons of CO₂ and H₂O fluxes over forested ecosystems

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Abstract:

Predictions from four process-based stand-level models of varying complexity (3-PG, PnET II, Biome-BGC, and SECRETS-3PG) and a newly proposed nested model are compared with 4 years of eddy-covariance measured water vapor (*LE*) and CO₂ (*F_c*) fluxes above a maturing loblolly pine forest. The nested model resolves the “fast” CO₂ and H₂O exchange processes using canopy turbulence theories, ecophysiological principles, and radiative transfer schemes while slowly evolving processes were resolved using standard biomass equations for carbon allocation modified to improve leaf phenology. This model captured most of the intra-annual variations in leaf area index (*LAI*), net ecosystem exchange (*NEE*) and *LE*. Our findings suggest that increasing model complexity, often justified for resolving faster processes, does not necessarily translate into improved predictive skills at all time scales. Additionally, none of the models tested here adequately captured the ‘drought memory’ effects on water and CO₂ fluxes.

Keywords: *LAI* dynamics, model nesting, *NEE*, gas exchange, model comparison.

Introduction

Ecosystem models are needed for developing relationships between anthropogenic CO₂ emissions and atmospheric CO₂ concentrations - a relationship required by policy makers to stabilize future atmospheric CO₂ (IPCC, 2001). Net ecosystem exchange of CO₂ (*NEE*) models represent the current state of understanding of ecosystem processes, and remain a central tool for predicting the response of ecosystems to disturbances and changing environments (Hanson *et al.*, 2004). For these reasons, modeling *NEE* is currently a central topic in ecology, hydrology and climate change research.

Key processes that are relevant to carbon transfer and storage in forested ecosystems can vary over multiple spatial and temporal scales. Across time scales, *NEE* is influenced by fast processes such as turbulent transport mechanics (often measured in seconds) and slow processes such as forest growth (often measured in years to decades). In space, photosynthesis varies at the leaf scale (often measured in millimeters) while stand level variables such as tree density often vary over hundreds of meters (Katul *et al.*, 2001). This wide scale separation in time and space is complemented with a broad range of process-based models that have emerged to simulate different aspects of ecosystem carbon function. At the ‘fast’ end, some multi-layer models, such as the CANVEG model (Baldocchi & Meyers, 1998), consider within-canopy physiological and radiative transfer processes starting from leaf-level equations and integrate these processes up to the stand level using turbulent dispersion theories. These models provide vertically explicit carbon and water flux estimates (as well as concentrations) within and above the canopy over the course of the day and they resolve all nonlinear interactions between intra-canopy radiative transfer processes, photosynthesis-light response, skin temperature and energy balance, and drag and attenuation of flow statistics. At the ‘slow’ end, zero-dimensional forest growth models such as 3-PG (Landsberg & Waring, 1997) utilize a species-specific potential carbon uptake rate without resource limitations, then modify this rate by a set of reduction functions imposed by

climatic, hydrologic, and resource constrains. Here, zero-dimensional models are models that do not include any spatial structure; they represent the biosphere by a big leaf or reservoir of known capacity or size. Multi-layer models are one-dimensional models that do resolve the vertical structure of the canopy, often via the leaf area density. Analogous to the spatial representation, the 3-PG model uses a coarse integration time step (i.e., monthly) to compute individual components of *NEE*. Although this time scale is too coarse for resolving diurnal cycles of light, temperature, vapor pressure deficit (*D*), or wetting fronts in soils, it may be sufficient to assess the long-term impact of forest management on forest production. Comparing models with different assumptions and simplifications in their formulation contributes to understanding the controls over ecosystem productivity and helps identify critical gaps in our knowledge. Model comparison is also timely for two data-related reasons: 1) Many FluxNet (a global network of eddy-covariance flux measurements) tower sites across a wide range of biomes have gathered long-term (e.g. more than four years) data for *NEE* and associated climatic and ecological measurements; and 2) satellite remote sensing is now providing global coverage of ecological variables at a spatial resolution comparable to the footprint of eddy-covariance flux measurements of *NEE*. Models are the primary tools for merging information from these data sets into terrestrial carbon exchange, and comparing model performances is important for assessing our ability to estimate ecosystem productivity. A recent study compared the output of 13 models against a 10-year data record that included *NEE* estimated over a hardwood forest in the southern U.S., assumed to be in equilibrium, i.e., leaf area no longer changed with age but mainly with climatic, hydrologic, and other disturbances (Hanson *et al.*, 2004). The study concluded that models that resolve the light/canopy structure performed better at short time scales than the standard coarse-grained (or zero-dimensional) models. However, their findings at longer time scales were surprisingly mixed, suggesting that the next step in model inter-comparisons must establish a framework to: 1) methodically investigate “across-scale” information flow for various models, and 2) use such information to construct hybrid models that can utilize “skills” from various model-components at appropriate time scales. Addressing the first point will advance understanding on how “sub-grid filtering”, which refers to the effect of the unresolved fine scale (in time and space) processes to model outputs, affects model performance at resolved scales. Addressing the second point invites the potential use of formal “nesting” schemes to link fast processes (e.g. diurnal variation of photosynthesis) to the slowly evolving ones (e.g. carbon allocation). The nesting approach should be useful because of the wide scale separation between variability at diurnal scales (important for radiative transfer) and monthly scales (important for carbon allocation).

We investigated the performance of a broad array of process-based models to assess their prognostic ability to reproduce variability in biosphere-atmosphere exchange of carbon and water for a maturing loblolly pine plantation that has a sub-canopy hardwood component in the Southern Piedmont region of North Carolina. We employed a spectral comparison because it enables identifying the time scales at which the model can reproduce measured flux variability correctly. Often, models with several parameters can be calibrated to reproduce the mean flux values at the desired scale (e.g. hourly or annual). However, model-generated relationships between internal variables (e.g. *LAI*), external forcing, and flux variability may not be sensitive to such calibration at other time scales (e.g. at seasonal or inter-annual time scales). We considered four existing models that vary in complexity, number of parameters, and spatio-temporal integration of the canopy processes. Formally, algorithmic complexity is connected with the number of rules needed to define the state dynamics in a model. These four models are:

- 1) Physiological Principles in Predicting Growth or *3-PG* (Landsberg & Waring, 1997),
- 2) Photosynthesis and EvapoTranspiration or *PnET II* (Aber & Federer, 1992),
- 3) BioGeochemical Cycles or *Biome-BGC* (Running & Coughlan, 1988), and
- 4) Stand to Ecosystem Carbon and EvapoTranspiration Simulator or *SECRETS-3PG* (Sampson *et al.*, 2001).

In addition to the above models, we developed a nested model, hereafter referred to as *CANVEG-A* that uses *CANVEG*, which is a coupled ecophysiological, biogeochemical, and atmospheric diffusion model later revised for realistic physiology and modified to include detailed second-order closure principles (Lai *et al.*, 2000), to resolve fast processes, along with a newly proposed simple allocation scheme similar to 3-PG for the slow processes. These five forest ecosystem models were chosen because they populate almost the entire domain of model complexity given their process algorithms and their space-time resolution. Currently, *Biome-BGC* and *PnET II* are used to scale-up carbon uptake on continental scales using remotely sensed LAI measurements (e.g. from MODIS). It is not our intent here to assess how well these models reproduce NEE when forced by LAI measurements because LAI must be one of the predicted variables when assessing how forested ecosystems respond to future disturbances or changing environments. We used a pine plantation as a case study because, in addition to their economic importance, they represent a “simple” system (in terms of dominant species) for which ample data is available. A four-year eddy-covariance data set (from 2000 to 2003) collected at the Duke Forest pine site along with ecological measurements was used in this model comparison. Based on the annual precipitation measurements, the selected four years include a mild drought at the beginning of the growing season (2001), a severe drought (2002, 5th most severe on record), and two wet years (2000 and 2003). Hence, a wide range of climatic and hydrologic conditions was sampled within the study period.

Methods

Experimental Site

The study site is located at the Blackwood division of Duke Forest near Durham, North Carolina, USA (35°58'N, 79°05'W, elevation = 163m above sea level) and is part of the *AmeriFlux* network (Baldocchi *et al.*, 2001). The site was uniformly planted with loblolly pine (*Pinus taeda* L.) in 1982; the current density is ~1733 trees per hectare. The momentum, CO₂ (*F_c*), latent (*LE*) and sensible (*H*) heat fluxes were measured by a standard eddy-covariance (EC) system comprised of a CO₂/H₂O infrared gas analyzer and a triaxial sonic anemometer (CSAT3, Campbell Scientific, Logan, UT, USA) positioned at 20.2 m. A 10 Hz sampling rate was used and real time processing of the fluxes and flow statistics was performed (CR23X, Campbell Scientific, Logan, Utah, USA). The Webb-Pearman-Leuning (Webb *et al.*, 1980) correction was applied to *F_c* and *LE* to account for the density variation effects on eddy covariance flux measurements. A footprint analysis (Hsieh *et al.*, 2000) showed that under near neutral atmospheric stability conditions, the maximum fetch rarely exceeded 450 m.

Temporal dynamics of leaf area index (*LAI*) were generated using leaf litterfall mass and specific leaf area, needle elongation rates, fascicle, flush and branch counts, allometry, and optical gap fraction measurements (Heather McCarthy, personal communication). Allometric relations were used to estimate net primary productivity (*NPP*). Biomass estimates and above- and belowground respiration rates, described elsewhere (Hamilton *et al.*, 2002), were used to quantify respiration. The maximum rate of ribulose-1,5-bisphosphate-carboxylase-oxygenase (Rubisco) activity ($V_{c,max}$) was available from leaf-level gas-exchange measurements.

Models

To investigate the predictive skills of the five process-based models at various time scales, we evaluated their ability to reproduce the measured spectral properties of *NEE* and *LE*. Unlike previous comparisons that assess how well models reproduce annual, monthly, or diurnal *NEE* or *LE*, spectral analysis permits us to assess how well these models reproduce the variability (activity or energy) at these time scales. Hence, this approach has the added advantage of being

able to assess how well these models reproduce the temporal autocorrelations in the *NEE* (or *LE*) time series as well as the excursion from long-term averages at a wide range of time scales. We employed Fourier spectral comparison because we can interpret the squared Fourier coefficient (representing the spectral energy) for each frequency as the portion of the variance explained by that frequency. So it determines the time scales best reproduced by each model for each variable. Spectral analysis also permits us to assess whether resolving short-term dynamics with CANVEG-A improves long-term flux predictions. For this purpose, we used Fourier transformation averaged to the relevant time scales for biosphere-atmosphere gas exchange to discern model performance in reproducing the EC measured spectral variability.

CANVEG with carbon Allocation - CANVEG-A

We used a formulation that couples conservation equations for heat and mean scalars (CO_2 and water vapor), leaf energy and radiation budgets, with biophysical and physiological mechanisms responsible for carbon assimilation (i.e., the Farquhar model) nested within a carbon allocation routine that distributes carbon into four different pools. To resolve the effect of turbulent transport processes (i.e., representing the effects of turbulent eddies with a time scale of seconds on 30 minute averaging time scales), CANVEG uses second order closure principles (Siqueira & Katul, 2002) integrated to half-hourly time steps. Models that use second-order closure principles solve for the mean wind speed and all six components of the turbulent Reynolds stresses needed for linking vertical scalar source (or sink) distribution to mean concentration (e.g. water vapor and atmospheric CO_2) or temperature inside canopies. Conversely, the carbon allocation was set to vary on a monthly time step. This time step was deemed sufficiently short to resolve foliage growth, the most dynamic of the four carbon pools (Stoy *et al.*, 2005). In the current implementation of CANVEG, we used a light model (Stenberg, 1998) that resolves penumbral effects, a Eulerian closure model for scalar transfer including local thermal stratification inside the canopy, and a more physiologically sound Leuning conductance model (Katul *et al.*, 2000, Stoy *et al.*, 2005) in lieu of the original Ball-Berry model (Collatz *et al.*, 1991). Hence, CANVEG does not assume “well-mixed conditions” inside the canopies and actually solves for the vertical distribution of mean temperature, CO_2 , and H_2O concentration profiles (unlike the remaining four models). Since CANVEG resolves the vertical structure of the scalar sources within the canopy we were able to separate the forest into overstory pine and an understory hardwood within the nested scheme. This multi-species approach enabled us to account for differences in both seasonal dynamics and physiology of these two distinct vegetation components. Maintenance respiration rates of different tissues of both pines and hardwoods, needed in *NPP* estimations, were computed as functions of temperature using the Q_{10} formulation. Foliage temperature was calculated as part of the energy budget, root temperature was assumed to be at soil temperature and stem/branch temperature was a weighted average of air (with a delay) and soil temperatures to account for wood heat capacity and sap flow cooling. CANVEG-A explicitly considers four carbon pools for each vegetation component: foliage, stem, roots and a labile pool. Similar to 3-PG, belowground allocation assumes that the more nutrient limited the soil environment, the greater the fraction of *NPP* allocated to the root system (Landsberg & Waring, 1997). As in 3-PG, environmental condition modifiers are defined as functions of air humidity deficit, site fertility and stand age. Even though these modifiers were primarily developed in 3-PG to constrain light use efficiency, they were also used for partitioning *NPP* between below and above ground components.

The labile pool is a representation of the substrate reserve stored by the tree and receives second priority after the root system in terms of carbon allocation. To avoid negative values of this pool, its amount is kept at a level that will be enough to completely replace the foliage. The foliage carbon pool is divided into “new” and “old” leaf cohorts and the transition from “new” to “old” cohort occurs at a user specified month of the year. Litterfall is estimated as a proportion of the “old” leaf cohort immediately after the time of the “new to old” foliage transition. A look-up

table for each vegetation type gives a monthly proportionality factor. Foliage production removes carbon from the labile pool to build a “new” leaf cohort with the timing for foliage emergence determined by heat sums (growing degree days to start and end foliage production) analogous to PnET II. The actual amount of foliage produced is constrained by environmental conditions, for which the D modifier is used as a surrogate along with a species-specific sensitivity. The allometric relationship between foliage and stem mass as function of diameter at breast height (DBH) bounds the amount of foliage to be produced. CANVEG is used to solve for canopy photosynthesis, respiration, and ET every 30 minutes. The monthly-integrated values are transferred to carbon allocation modules, which then predict foliage dynamics and forest growth. The resulting changes in the carbon pools in the form of LAD and respiring biomass are then re-mapped back into CANVEG. This approach takes maximum advantage of the scale separation between the slowly evolving growth and allocation processes and the rapid (and nonlinear) response of photosynthesis, ET , and respiration to diurnal variations in light, D , wind speed, and T_a . The choice of monthly time step for biomass pool updates allowed us to develop efficient algorithms for the model calculations that take advantage of optimized fast matrix operations. It has been shown that at this pine plantation, the spectral energy of LAI, the most dynamic of the biomass pools, at daily time scale is almost an order of magnitude smaller than its monthly counterpart and at least 2 orders of magnitude less than its seasonal counterpart (Stoy *et al.*, 2005), making this time step choice optimal in terms of maximizing computational efficiency while retaining the key modes of variability in the ‘fast pools’. This allocation scheme proposed here provides several desirable features for pine forests. First, the model ensures that a reserve pool provides the carbon needed to produce foliage; hence, leaf display dynamics is decoupled from production on short time scales. Also, litterfall is no longer synchronous with leaf standing biomass (as is the case in 3-PG).

Results and Discussion

We begin by assessing the performance of the CANVEG-A scheme, concentrating on biosphere-atmosphere carbon and water exchange rates. Parameters required to run the models were obtained from direct eco-physiological measurements at the site or, when those were not available, from default values of each model.

CANVEG-A validation

CANVEG-A accurately reproduced the measured F_c and LE (Figures 1a and 1c, respectively) at times without water-stress. Statistical measures such as near-unity of the regression slope, the small regression intercept, the low root mean square error (RMSE) (about 10% of the highest measured value), and the high correlation coefficient ($r > 0.85$) provides the quantitative support for the apparent good agreement (not shown here). On the other hand, the model performance for F_c and especially LE deteriorated during the drought period. The modeled F_c was lowered due to constraints on conductance predicted by the Leuning model (Leuning, 1995) following a larger than average D experienced during the summer drought period of 2002 (see Figure 1b). However, this reduction was less than the reduction in the measured F_c and degraded statistics, especially the slope and RMSE, and indicates model bias during drought (not shown here). The model overestimated LE during the drought (see Figure 1c). The large driving force experienced in the summer of 2002 more than compensated for the reduction in leaf conductance induced by D . This suggests that plant-soil hydraulic system, not included in the model, plays a major role in controlling biosphere-atmosphere gas exchange at this site and only models that account for it can be expected to perform well under limiting moisture conditions.

Model comparison of Fluxes – Spectral analysis

The Fourier analysis revealed distinct divergence in the correspondence between modeled

and measured *NEE* and *ET* (represented by the power spectra of scalar fluxes, Figure 2a and 2b) across the time scales examined. The scalar flux time series variances (areas under the power spectra) indicate that CANVEG-A captured the spectral energy of both net carbon and water fluxes at intermediate scales, but not at hourly nor inter-annual time scales. Some mechanisms, known to produce significant hourly variability on eddy-covariance measurements, are not resolved by CANVEG-A. During the day, hourly flux variability is dominated by shifts in footprint size and direction. At night, passage of clouds and intermittent turbulence are important contributors to the variance at this time scale (Cava *et al.*, 2004). These mechanisms are more related to the intermittent and dynamic nature of the eddy-covariance measurements (footprint and night-time storage flushing) and less to physiological processes relevant to forest carbon transfer and storage. The fact that the CANVEG-A model resolved *NEE* at the daily time scales suggests that the effects of dynamic eddy-covariance footprint and storage flushing average out over a day. This is consistent with other studies that specifically focused on footprint averaging and storage dynamics (Lai *et al.*, 2000).

At time scales ranging from days to months, CANVEG-A and SECRETS-3PG were able to reproduce the observed variance in *NEE* while Biome-BGC underestimated this variability greatly (Figure 2). The good performance of SECRETS-3PG and the CANVEG-A, and the underestimation by Biome-BGC is related to the ability of the former models to resolve the vertical structure of *LAD* and the inability of the latter model to do so. This point will be explored further in the *LAI* comparisons.

CANVEG-A is the only model that reproduced the variability in *NEE* at seasonal time scales in addition to the daily time scales. Note that the daily and seasonal scales are spectrally the most “energetic” in this record. All other models underestimated the intra-annual variability in *NEE*, and only PnET II was able to capture the seasonal variability in *ET*, though, as we show later, this may be explained by an artifact related to *LAI* dynamics. Thus, CANVEG-A, and to lesser extent SECRETS-3PG, were able to reproduce much of the flux variability at scales shorter than annual. The reason both models performed well at these time scales are obvious – they resolve all non-linearities in their response functions (e.g. photosynthetic response to light) at the leaf scale and correctly integrate this response vertically to the canopy scale. Hence, changes in leaf area density for each species and its nonlinear effect on light attenuation and photosynthesis were explicitly resolved.

Surprisingly, beyond annual time scales, the spectral performance of these models were inconsistent or “mixed”, as has been found for the mean flux values in another model comparison study (Hanson *et al.*, 2004). While the CANVEG-A (and also Biome-BGC) underestimated inter-annual variability, PnET II, 3-PG and SECRETS-3PG showed reasonable agreement with the measured value. However, this integration is performed on intra-annual variability that was consistently underestimated for both *LE* and *NEE* in all models except for CANVEG-A. This spectral inconsistency or “mixed” results suggests that good performance of some models on inter-annual times may be attributed to error cancellations. For *LE*, the contributors to observed pattern in variability may be attributed to *LAI* dynamics, the effects of drought, and averaging of the forcing variables. For *NEE*, additional contributors include estimates of carbon input (*GPP*), and the partitioning of carbon to *NPP*.

Summary and Conclusions

The nesting framework used would likely reproduce the entire spectrum of flux variability if realistic plant hydrodynamics can be included. Porous media models for the autotrophic system combined with measured vulnerability curves are a logical first step (Chuang *et al.*, 2005). Progress on this issue means that processes at time scales relevant to inter-storm periods and soil moisture redistribution must be adequately resolved. It is conceivable that rapid wetting is accompanied by other complex processes such as rapid increase in CO_2 production because of enhanced microbial activity (and hence a concomitant increase in forest floor respiration);

however, preliminary investigations suggest that this effect may be small on annual time scales for stands such as in our case study. Coupling precipitation, ET , and gas-phase CO_2 transfer in the soil to water redistribution following storms using variants on Richards's equation is computationally demanding, and may pose problems that are difficult to overcome. Currently this approach is being implemented and will be subject of future research.

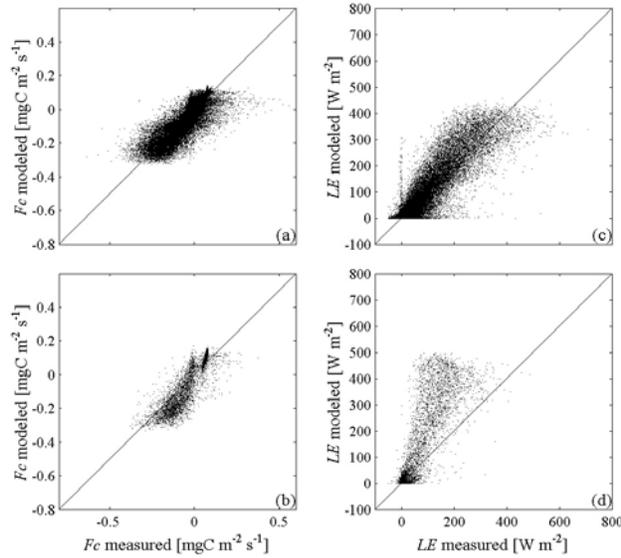


Figure 1: Comparison of half-hourly CO_2 flux (F_c) and latent heat flux (LE) measured by the eddy-covariance system and modeled by the CANVEG-A. Panels (a) and (c) show no water stress runs in the four-year period and panels (b) and (d) show runs during the drought period [April-September 2002]. The 1:1 line is shown for reference.

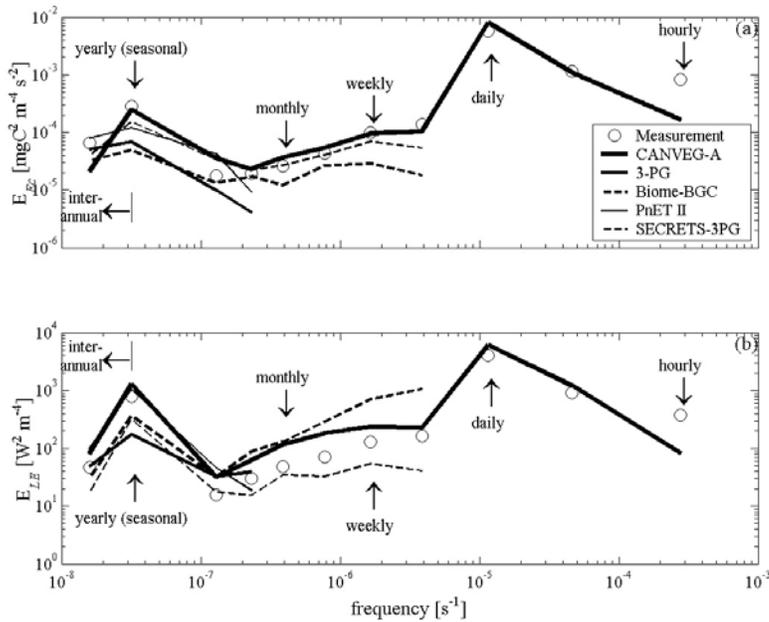


Figure 2: Measured and modeled power spectra for the CO_2 flux F_c [panel (a)] and latent heat flux LE [panel (b)].

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