AN INTEGRATIVE APPROACH TO QUANTIFYING ECOSYSTEM RESPONSES TO CHANGES IN FOREST STRUCTURE: Time-varying parameter sensitivity analysis of the Two Source Balance Model clarifies model behavior over a gradient of canopy complexity

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Abstract—**Evapotranspiration (ET), which includes evaporation and vegetation transpiration, is an important component of the earth's energy balance that influences water availability and energy partitioning at the land surface. Two-source energy balance (TSEB) models are widely used for estimating ET, however selecting an appropriate modeling scheme often depends on the understanding of the system, data availability, and modeling objectives. Therefore, understanding how the development of TSEB models influences their process-level behavior is a necessary next step to advance the field. To this end, I developed a comprehensive exploration of the dominant parameters in the TSEB model structure. Model controls are isolated using time-varying Sobols Sensitivity analysis over time series data accounting for spatial and temporal variability environmental conditions in order to assess the time-dependent nature of parameter sensitivity. Sensitivity indices are visualized along gradients to identify key behavioral differences between TSEB models and to connect these back to the models underlying assumptions. The results highlight model differences in performance controls. Understanding the links between model formulation and behavior can be an important diagnostic approach in applications where dominate model controls change over time.**

I. INTRO

EVAPOTRANSPIRATION is the transfer of water from land to the atmosphere through evaporation from the surface and through transpiration from plants. It is a major component of the water cycle, and is affected by climate (temperature, humidity, wind speed, etc), soil type and water availability, plant type and condition, and other factors. The ability to predict evapotranspiration based on these weather and environmental factors is important to understand the water demands of plants, and has resulted in the widespread use of evapotranspiration models for agricultural and water managements purposes [1], [2]. It is also very valuable to understand forest water use, and may provide valuable insights into the response of forests to droughts or factors that influence water availability and use [3], [4].

Vegetation structure is a key ecosystem property influencing the atmosphere-land surface energy balance. The vertical structure of forest canopies can alter the movement of wind, heat, and moisture throughout the ecosystem. Forests are of particular interest as they are highly variable and complex compared to grasslands and agricultural systems. However, the variable nature of forest structure creates a challenge for incorporating structure into models focused on mapping energy fluxes across space and time. Current atmosphere-land energy balance models that incorporate vegetation structure generally do so by using look-up table parameters that are a function of land cover classification or spectrally-derived indices (e.g. MODIS/Landsat products). Characterizing the interactions between vegetation structure parameters and model drivers is important for understanding model performance over diverse vegetation composition and structure.

Generally, the TSEB model partitions incoming thermal radiation to two-sources: (1) the canopy, and (2) the soil [5]. The model inputs include meteorological variables typically acquired via eddy-covariance flux towers, as well as several canopy structure parameters from vegetation class look-up tables (e.g. canopy height and leaf clumping index) or multi-spectral remote sensing data (e.g. LAI and fractional cover; Landsat/MODIS products). The combined effect of the meteorological variables (specifically relationships between air, canopy, soil, and air-in-canopy temperatures) and canopy structure determine the how the incoming radiation is partitioned between the canopy and the soil. The Latent Heat Flux (LE) is calculated as a residual of the energy balance. TSEB runs until convergence using canopy temperature and sensible heat as convergence tracers. The advantage of using thermal remote sensing to model surface flux and temperature gradients is that inferences about water-availability can be determined without the need for detailed soil moisture and precipitation data [6].

Sensitivity analysis is the study of how uncertainty in model outputs can be attributed to uncertainty in model inputs and parameters. The objective of a sensitivity analysis is to identify the most important parameters, that if optimized, would result in the largest reduction of variance of the output of interest. In this instance, TSEB was chosen as it has been shown to displace variable behavior across different types of vegetation structure. By using a time-varying sensitivity analysis, we can model processes across a range of conditions match the dominant real-world processes [7]. This allows us to explore process-level model behavior across spatial and temporal variability in surface conditions. Typical performance-based approaches for model optimization focus solely on flux prediction, however optimal performance does not necessarily indicate that the model structure accurately represents the underlying physical process being modeled. The Sobol' method works well with nonlinear models with complex parameter interactions [8]. Using the Sobol' method for the sensitivity analysis of TSEB allows for quantitative ranking of first order parameter sensitivity and parameter interactions. The objective of this study was to characterize the time-varying sensitivity of TSEB model parameters related to vegetation structure.

II. Study Area

The Parker Tract study site is located near Plymouth in Eastern North Carolina. The site is largely a commercially-managed loblolly pine plantation (*Pinus taeda*) with some stands of mixed composition containing native broadleaf species. The site contains a broad range of even-aged pine stands with distinct differences in forest structure. One segment of the site is retained as natural forest while the rest have experienced some degree of logging. Within the study area, Weyerhaeuser Corporation, NC State University, the US Forest Service, and the FLEX-US 2013 Airborne Campaign (collaboration between NASA, ESA, and the FLuorescence Explorer Mission) collected extensive field data at the site (e.g. forest inventory, structural attributes, leaf chemistry). Two AmeriFlux eddy covariance towers are located at the study site (NC-2 and NC-3) and continuously measure CO2, heat, and water vapour fluxes within a loblolly stand and loblolly clear-cut. The following analysis focuses on the loblolly forested stand (NC-2).

III. TSEB

Generally, the TSEB model partitions incoming thermal radiation to two-sources: (1) the canopy, and (2) the soil. The model inputs include meteorological variables typically acquired via eddy-covariance flux towers, as well as several canopy structure parameters from vegetation class look-up tables (e.g. canopy height and leaf clumping index) or multi-spectral remote sensing data (e.g. LAI and fractional cover; Landsat/MODIS products). The combined effect of the meteorological variables (specifically relationships between air, canopy, soil, and air-in-canopy temperatures) and canopy structure determine the how the incoming radiation is partitioned between the canopy and the soil. The Latent Heat Flux (LE) is calculated as a residual of the energy balance [9]–[12].The TSEB model partitions the energy available at the land surfaces into turbulent fluxes of sensible and latent heat:

$$RN - G = H + \lambda E \tag{1}$$

where RN is net radiation (Wm^{-2}), G is the soil head conduction flux (Wm^{-2}), λ is the latent heat of vaporization (J kg^{-1}), and E is evapotranspiration (kg s^{-1} m^{-2} or mm s^{-1}). TSEB represents the land-surface interface as a series of resistances between the soil and vegetation canopy which allow for interactions between soil and vegetation. In order to analyze TSEB sensitivity over various temporal resolutions, radiometric temperature ($TRAD$) was approximated using Ameriflux tower outgoing long wave radiation (LW_{out}) by solving equation (2) for temperature.

$$LW_{out} = \varepsilon\sigma T^{1/4} \tag{2}$$

Radiometric temperature is then partitioned into soil (T_S) and canopy temperature (T_C) using fractional cover (f_C) (Eqn. 3).

$$TRAD \approx [f_C(\theta)T_C^4 + (1 - f_C(\theta))T_S^4]^{1/4} \tag{3}$$

Fractional cover is estimated using a modified Beer's-Lambert relationship (Eqn. 4) where $\Omega(\theta)$ is the vegetation clumping index at sensor zentith angle θ and F is an estimate of LAI.

$$f_C(\phi) = 1 - exp\left(\frac{-0.5\Omega(\theta)F}{cos(\theta)}\right) \tag{4}$$

The fluxes are calculated as flowed. Subscripts with S represent soil estimates, subscripts with C represent canopy estimates. Resistances are additionally subscripted with A for air and X for within canopy resistance.

$$RN_S = H_S + \lambda E_S + G \tag{5}$$

$$RN_C = H_C + \lambda E_C \tag{6}$$

$$H_C = \rho C_P \frac{T_C - T_{AC}}{R_X} \tag{7}$$

$$H_S = \rho C_P \frac{T_S - T_{AC}}{R_S} \tag{8}$$

$$H = \rho C_P \frac{T_{AC} - T_A}{R_A} \tag{9}$$

$$\lambda E_S = RN_S - G - H_S \tag{10}$$

$$G = c_G RN_S \tag{11}$$

$$\lambda E_C = \alpha_{PTC} f_G \frac{\Delta}{\Delta + \gamma} RN_C \tag{12}$$

IV. SOBOL' SENSITIVITY ANALYSIS

Sobol' method [8] is a variance-based global sensitivity analysis that attributes variances in the model output to each model parameter and its interactions. Sobol' Sensitivity analysis is intended to determine how much of the variability in model output is dependent on each of the input parameters. [7] The Sobol' method decomposes the total model output variance into its component parameters and their interactions which can be written as:

$$D(f) = \sum_i D_i + \sum_{i<j} D_{ij} + \sum_{i<j<k} D_{ijk} + ... + D_{1,2,...n}, \tag{13}$$

where $D(f)$ represents the total variance of the model output f; D_i is the first order variance attributed to the ith parameter, D_{ij} is the second order variance attributed to ithe interaction between parameters i and j, and $D_{1,2,...n}$ contains all interactions higher than the third order, up to n total parameters. The parameter ranges used for the analysis are summarized in Table 1.

TABLE I
SUMMARY OF TSEB PARAMETERS AND RANGES.

Parameter	**Description**	**Range**
LAI	Leaf Area Index	1.0 - 4.0
h_C	Canopy height	0.01 - 40.0
f_C	Fractional cover	0.0 - 1.0
w_C	Canopy width:height	0.1 - 5.0
f_g	Green fraction	0.0 - 1.0
$leaf_{width}$	Leaf width	0.5 - 1.0
$emis_C$	Canopy emissivity	0.97 - 0.99
$emis_S$	Soil emissivity	0.94 - 0.96
x_{LAD}	Leaf Angle Distribution Chi parameter	0.9 - 1.0
$\rho_{vis_{soil}}$	Soil Visible Reflectance	0.04 - 0.05
$\rho_{vis_{canopy}}$	Canopy Visible Reflectance	0.005 - 0.01
$\rho_{nir_{soil}}$	Soil NIR Reflectance	0.04 - 0.05
$\rho_{nir_{canopy}}$	Canopy NIR Reflectance	0.005 - 0.05
$\tau_{vis_{canopy}}$	Canopy Visible Transmission	0.005 - 0.01
$\tau_{nir_{canopy}}$	Canopy NIR Transmission	0.005 - 0.15
$z0_{soil}$	Bare soil roughness length	0.01 - 0.02

V. MODEL PERFORMANCE METRICS

In order to analyze the controls of the performance of the model, the RMSE was used as the model output metric. The RMSE represents the sum of the squared residuals over a given time period:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(F_{s,i} - F_{o,i}\right)^2} \tag{14}$$

where F_s and F_o are the simulated and observed fluxes, respectively.

VI. Results

TSEB vegetation parameters showed variation in sensitivity over the course of a year when analyzed at weekly (Fig. 2) and monthly (Fig. 1) time-scales. The model was most sensitive to fractional cover which retained consistently high sensitivity over the course of the year. Canopy Width:Height was highly sensitive at lower values of ET towards the tails of the growing season. LAI exhibited a similar pattern to Canopy Width:Height where sensitivity was lowest during the peak growing season and higher at the ends.

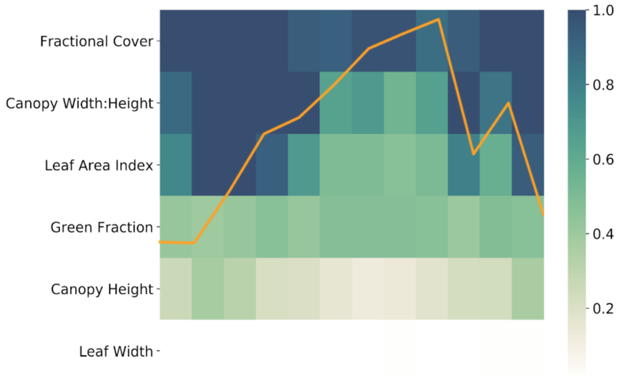

Fig. 1. Total Sensitivity Index of TSEB vegetation parameters re-sampled to monthly averages over the course of one year. The orange line is the re-sampled latent heat flux from the tower.

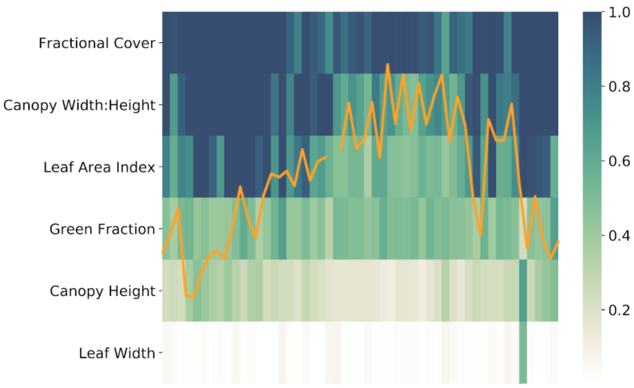

Fig. 2. Total Sensitivity Index of TSEB vegetation parameters re-sampled to weekly averages over the course of one year. The orange line is the re-sampled latent heat flux from the tower.

The first-order sensitivities of the the vegetation parameters were low for all parameters, with Green Fraction and Canopy Width:Height showing slightly higher first-order sensitivity (Fig. 3). Low first-order sensitivity indicates that the model sensitivity to variation in individual parameters is low.

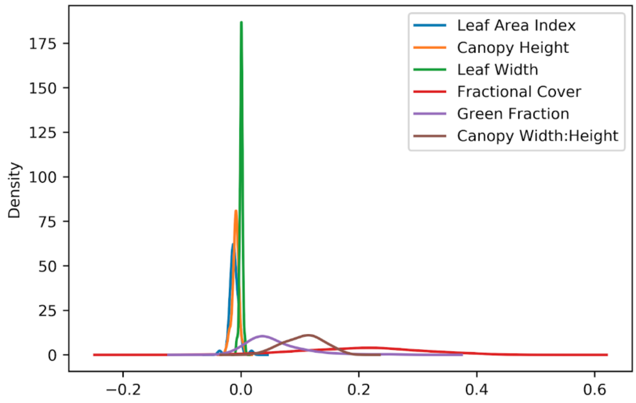

Fig. 3. Density plot showing the distribution of the first-order sensitivity indices for the TSEB vegetation parameters.

The total sensitivity index which represents the sensitivity of the model to the parameter and the parameter's interactions showed large differences in sensitivity among the vegetation parameters(Fig. 4). The clear bi-modality of LAI and Canopy Width:Height highlight the strong temporal variation seen across time with higher sensitivity at the ends of the growing season and lower sensitivity in the mid-season.

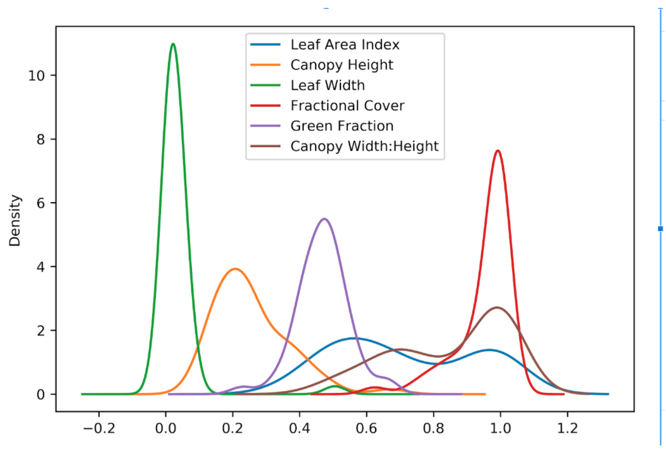

Fig. 4. Density plot showing the distribution of the total sensitivity indices for the TSEB vegetation parameters.

VII. Conclusions

Understanding how the development of TSEB models influences their process-level behavior is a necessary next step to advance the field. To this end, I conducted a comprehensive exploration of the dominant parameters in the TSEB model structure. Model controls were isolated using time-varying Sobols Sensitivity analysis over time series data accounting for spatial and temporal variability in vegetation structure in order to asses the time-dependent nature of parameter sensitivity. Sensitivity indices were visualized across time to identify key differences in parameter sensitivity. The results highlight. Understanding the links between model formulation and behavior can be an important diagnostic approach in applications where dominate model controls change over time. My sensitivity analyses shows that vegetation characterization is important in the TSEB model and that there is room for parameter optimization to in order to improve the model. Such optimizations will help to connect changes in vegetation structure to changes in surface energy fluxes. My research examines how modeled ecosystem processes respond to changes in forest structure while enhancing our ability to scale ecosystem response from the canopy to landscape levels.

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