REMOTE SENSING OF FOREST ECOSYSTEM DYNAMICS: MEASUREMENTS AND MODELING

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ABSTRACT:

The Forest Ecosystem Dynamics Project at NASA Goddard Space Flight Center is developing an integrated approach to modeling of forest dynamics encompassing submodels of forest growth and succession, soil processes and radiation interactions. Remote sensing technology is a key element of this study in that it provides data for developing, initializing, updating, and validating the models. In this paper we review project objectives, discuss data collected and models in use, and describe a framework for studying interactions between the forest growth, soil process and energy interaction components. Remote sensing technology used in the study includes optical and microwave field, aircraft and satellite-borne instruments. The types of data collected during intensive field and aircraft campaigns included bidirectional reflectance, thermal emittance and multifrequency, multipolarization synthetic aperture radar backscatter. Synthetic imagery of derived products such as forest biomass and NDVI, and collections of ground data are being assembled in a georeferenced data base. We then use these data to drive or test multidiscipline simulations of forested ecosystems. Enhancements to our modeling environment permit considerable flexibility in configuring simulations and selecting results for reporting and graphical display.

INTRODUCTION

The Forest Ecosystem Dynamics (FED) project is being conducted by the Biospheric Sciences Branch within the Laboratory for Terrestrial Physics at Goddard Space Flight Center, the University of Virginia, and associated university investigators. The goal of this research is to use forest succession models, soil process models, and radiation scattering models, combined with ground-based and remotely sensed observations, to improve understanding of the dynamics of the northern forest ecosystem (Figure 1).

This research program concerns changes within forest ecosystems at local to regional spatial scales (10^2 to 10^5 meters) and temporal scales ranging from daily to decadal periods (10^{-2} to 10^2 years). Explanations for spatial patterns and dynamics are sought among mechanisms operating at scales ranging from those of physiological processes to long term ecological processes (10^{-4} to 10^3 years). The nature and impacts of these changes, as well as the feedbacks to global climate, are being addressed through the integration of mathematical models using an object-oriented simulation workbench (see Levine et al., 1993).

The initial focus of the FED project is the North American transition zone between northern hardwood forests and the boreal forest biome. The boreal forest is one of the earth's major vegetated ecosystems, accounting for nearly 20% of the terrestrial plant carbon and covering one-sixth of the Earth's land surface (Bolin, 1986). The northern and southern margins are especially sensitive to climate change as evidenced by the northward migration of boreal species since the end of the last Ice Age.

FED MULTISENSOR AIRCRAFT CAMPAIGN

Data to develop and verify models for the FED project come from several sources. The most important sources have been intensive field campaigns conducted in cooperation with the University of Maine at International Paper's Northern Experimental Forest at Howland, Maine, USA. Numerous investigators coordinated their research objectives and activities, and supporting aircraft flights in concentrated Multisensor Aircraft Campaigns (MACs). This approach not only made for more efficient use of aircraft hours, but it also fostered cross-collaboration of research activities between scientists of diverse interests and expertise. The research carried out under the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) and the Geological Remote Sensing Field Experiment (GRSFE) are two of the better known examples of NASA MAC activities. A 1994 special issue of Remote Sensing of Environment highlights results from research carried out under two NASA sponsored Multisensor Aircraft Campaigns focused on forest ecosystems: the FED MAC study, which focused on the research site near Howland, Maine and the Oregon Transect

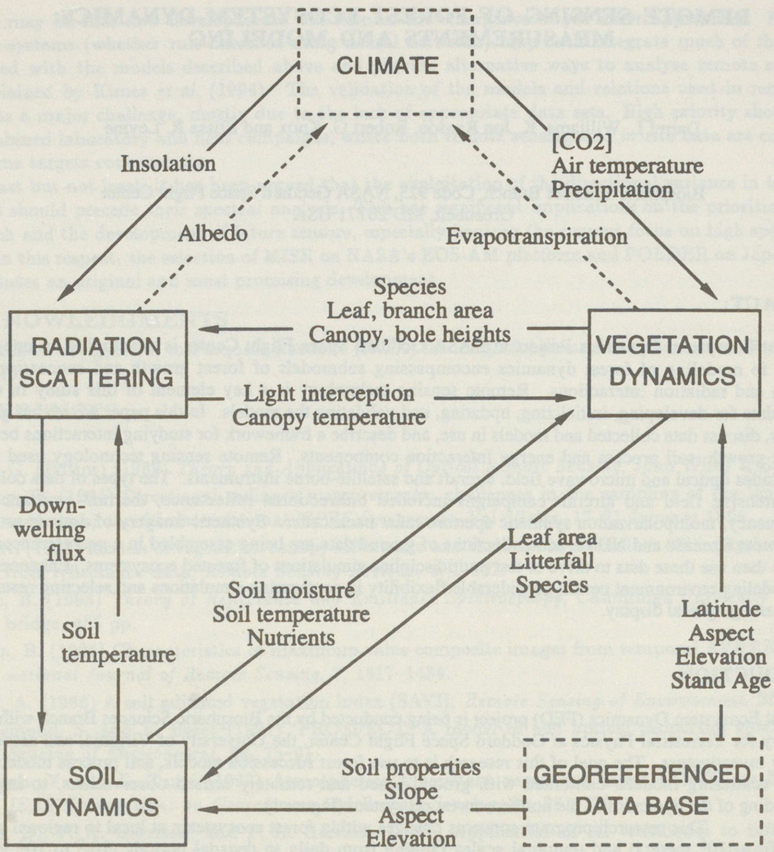

Figure 1. Major interactions among forest ecosystem processes, including soil dynamics, vegetation dynamics, and radiation scattering in coupled models of a forested ecosystem, with links to local or regional climate and georeferenced data.

Terrestrial Ecosystems Research (OTTER) study, which examined the vegetation gradient in western Oregon (Peterson and Waring, 1993).

The diversity of research represented in the FED MAC study is striking. Not only are wide portions of the electromagnetic(EM) spectrum considered, but the scales of analysis extend from leaves and plant cells to the landscape of a 10 by 10 km study site. The primary objective of NASA aircraft missions -- assessment of advanced remote sensing concepts -- provides the context for this diversity. Theoretical understanding of electromagnetic energy-matter interactions suggests that there is considerable information contained in EM measurements that is not exploited by existing spaceborne sensor systems. However, there are sufficient imponderables in the theoretical knowledge of terrestrial EM interactions to warrant collection of such empirical observations.

Data from the MAC's, from prior research at the Maine site, and from subsequent research funded by NASA and the US Forest Service and Environmental Protection Agency provide an integrated suite of field measurements, and optical and radar remote sensing observations (Tables 1 & 2). Participating NASA aircraft experimental sensor systems cover a considerable range of advanced remote sensing system concepts.

Table 1. Field Characterization at the FED Experimental Site at Howland, Maine.

Category	Type	Measurement	Unit
ATMOSPHERE	Meteorological	- air temperature	^oC
		- wind speed and direction	m/s
		- barometric pressure	mmHg
		- precipitation	cm
	Radiation	- shortwave irradiance	w/m^2
		- solar zenith angle	degrees
		- optical depth	ppm**
	Gas Flux	- methane	
		- carbon dioxide	
		- nitrous oxide	
CANOPY	Forest Stand	- density	stems/ha
		- height	m
		- diameter (breast height)	cm
		- age	years
		- species composition	%
		- crown shape, depth, diameter	m
		- cone angle	deg
		- trunk size and inclination	m, degrees
		- branch volume, size, angle distribution	
	Needle	- volume	
		- size	
		- density	num/stem cm
		- angle distribution	degrees
		- age (first or second)	years
		- reflectance	%
		- transmittance	%
		- absorptance	%
		- water potential	%
		- chlorophyll (a,b,total)	mg/g dry
		- anatomy (cell type, cell arrangement)	
		- moisture	%
		- leaf area index	m^2/m^2
SOIL	Classification	- drainage class	
		- taxonomy	series
	Properties	- dielectric	
		- roughness profileß	cm
		- moisture (gravimetric)	%
		- temperature	^oC
		- particle size (sand, silt, clay)	%
		- water potential (at 0.3 and 1.5 MPa)	%
	Chemistry	- pH (H_20, KCl, and $CaCl_2$)	-
		- exchangeable cations (Ca, Mg, Na, K)	cmol/kg
		- exchangeable acidity	cmol/kg
		- extractable exchangeable aluminum	mg/kg
		- cation exchange capacity (sum, effective)	cmol/kg
		- iron oxide (in pyrophosphate, oxatlate, CBD)	mg/kg
		- organic carbon	%
		- total nitrogen	%
		- heavy metals (Cu, Ni, Mn, Co, Zn, Pb, Cr)	mg/kg
		- sulfate adsorption isotherms	ppm SO_4

The AVIRIS (Airborne Visible Infrared Imaging Spectrometer) and ASAS (Advanced Solid-state Array Spectroradiometer) are both directed toward more fully exploiting the spectral reflectance properties of terrestrial materials in the solar irradiance portion of the spectrum. AVIRIS is primarily directed toward high spectral resolution measurements, whereas ASAS concentrates on the anisotropy of surface directional reflectance. The AIRSAR (Airborne Synthetic Aperture Radar) was designed to explore multiple frequency, multiple polarization active microwave remote sensing.

Table 2. FED Field Experiment Sensor Deployment

Band	Sensor	Specifications	Data
	ALPS	Airborne Laser Polarimeter System	
		Mode 1: 1060 nm quad-polarization	
		Mode 2: 5350 nm quad-polarization	
	ASAS	Advanced Solid State Array Spectroradiometer	16 total flights
		29 15nm bands within 465nm to 871nm	5 sites
	AVHRR	Advanced Very High Resolution Radiometer	archival
		Band 1 : 580 nm to 680 nm	
		Band 2 : 725 nm to 1100 nm	
		Band 3 : 3550 nm to 3930 nm	
		Band 4 : 10300 nm to 11300 nm	
O		Band 5 : 11500 nm to 12500 nm	
P	AVIRIS	Airborne Visible / Infrared Imaging Spectrometer	2 total flights
T		220 9.8 nm bands within 400.0nm to 2448.2nm	entire region
I		Instr 1: 400.0 nm to 703.8 nm	
C		Instr 2: 713.6 nm to 1331.0 nm	
A		Instr 3: 1340.8 nm to 1958.2 nm	
L		Instr 4: 1968.0 nm to 2448.2 nm	
	GOES	Geostationary Operational Environmental Satellite	
	PARABOLA	Portable Apparatus for Rapid Acquisition of Bidirectional Observations of the Land and Atmosphere	
		Band 1: 650 nm to 670 nm	
		Band 2: 810 nm to 840 nm	
		Band 3: 1620 nm to 1690 nm	
	photography	Camera 1: 35 mm	
		Camera 2: 22.86 cm square	
	SE-590	Spectron Engineering Radiometer	1500 scans
		121, 5nm bandwidths between 400nm to 1000nm	7 sites
	SPOT HRV-MS	Satellite Probatoire d'Observation de la Terre - High Resolution	archival
	video	color	
		Beta II	
	Landsat TM	Landsat Thematic Mapper	archival
		Band 1: 450 nm to 520 nm	
		Band 2: 520 nm to 600 nm	
		Band 3: 630 nm to 690 nm	
		Band 4: 760 nm to 900 nm	
		Band 5: 1000 nm to 1300 nm	
T		Band 6: 1550 nm to 1750 nm	
H		Band 7: 2080 nm to 2350 nm	
E		Band 8: 10400 nm to 12500 nm	
R	MMR	Barnes Modular Multiband Radiometer	1500 scans
M		same as Landsat TM	17 sites
A		+ 1150nm - 1300nm	
L	TMS	Thematic Mapper Simulator	16 overflights
		same as Landsat TM	5 sites
		+	
M	AIRSAR	Airborne - Synthetic Aperture Radar	Howland
I			(25°, 35°, 45°)
C		L-Band: 0.2398 m quad-polarization	Old Town
R		C-Band: 0.05656 m quad-polarization	(25°)
O		P-Band: 0.6813 m quad-polarization	

The reports contained in the OTTER -- FED special issue can be considered building blocks for future applications of these advanced sensor systems. Relative to active microwave or RADAR remote sensing, Salas et al. (1994) explored the variations in tree dielectric properties as a function of species and time. Weishampel et al. (1994) considered the nature of backscatter signals as a function of spatial scale and Lang et al. (1994) assessed the causes of strong backscatter signals from red pine plantations. Ranson and Sun (1994) employed multitemporal SAR images to conduct forest land cover classification in Maine. Smith and Goltz (1994) presented a new modeling approach to the simulation of forest canopy thermal patterns which should be of considerable value in thermal infrared remote sensing.

Studies in the solar reflective region considered both detailed spectral structure and bi-directional reflectance patterns. Rock et al. (1994) measured detailed spectra of leaf optical properties and sample branch stacks for selected species and age classes from the FED MAC site. Lawrence et al. (1994) compared remotely sensed reflectance spectra from three airborne spectroradiometers (AVIRIS, ASAS and SE-590). Levine et al. (1994) considered possible relations between underlying soil properties and variations in spectral vegetation index measurements at the Howland, Maine site. Deering et al. (1994) presented detailed ground measurements of canopy spectral, bi-directional reflectance properties. Ranson et al. (1994) explored the information content of ASAS measurements for well-characterized subsites.

Although this research indicates progress accomplished with a range of possible alternate sensor systems, it is also evident that the field is becoming more specialized and complex. For example, in primary reports to date from the FED MACs, there is no consideration of possible synergies in combining observations from the solar reflective, thermal infrared and/or microwave regions. Given the difficulties in exploring within any one of these EM regions, it is not surprising that such interactions are not yet considered. We anticipate that, with the preservation and publication of these observations on floppy disks or public on-line data sets, there will be many opportunities for new discoveries in remote sensing. Ongoing work at the Goddard Space Flight Center includes developing a data base (Geographic Information System - GIS) of georeferenced and registered image products and field data from the FED MAC study area. In addition to supporting our research and that or our collaborators with this data base, we hope to shortly make data in a subset GIS available for remote access over the Internet. These spatial data should complement the browse data base and smaller data sets being distributed on diskettes for personal computers. They will be suitable for testing ecosystem process models, model integration approaches, and remote sensing algorithms, and examining scaling questions and ideas for sensor fusion.

ONGOING ANALYSIS AND MODELING

Data from the FED MAC and other research at the same study site are being used as checks on model predictions of potentially observable attributes (e.g., above-ground biomass, thermal profiles, species composition), and as potential sources for extracting biophysical properties of forest canopies, soils, and hydrologic parameters used for model inputs. Point to point variation in natural and managed landscapes complicates direct comparisons of remote sensing data with results of models of radiation scattering. Effects of soil and management history on vegetation can account for much of the variation between large patches (e.g., Levine et al. 1994), whereas a dynamic model of the forest population can approximate variability seen within patches (Knox et al., in preparation).

Component Models

The FED model framework integrates existing models of forest growth and succession (e.g., ZELIG - Smith and Urban, 1988; HYBRID - Friend et al. 1992), soil processes (e.g., Levine and Ciolkosz, 1988; GAPS - Riha and Rossiter, 1993; RESIDUE - Bidlake et al., 1992), and radiation scattering (e.g., thermal - Smith and Goltz, 1994; reflective - Verhoef, 1984; microwave - Sun et al., 1991). The forest succession submodel (ZELIG) is a spatially explicit individual tree simulator or "gap model." The model simulates the establishment, annual diameter growth, and mortality of each tree in a ca. 0.10 ha plot. Simulations can start and stop at any point within the life cycle of a forest and reflect changes that are caused by gradual or catastrophic events. In addition, the HYBRID model calculates individual short-term photosynthesis and transpiration in a population of trees. This makes it suitable for coupling to canopy thermal models and for predicting stand-level gas flux and energy exchange. HYBRID is less suitable for long-term simulations of forest structure because of its heavy computational demands. The soil process submodel is based on mechanisms operating during the genesis of a soil. Included in the submodel are short term processes such as water flux, gas flux, ion concentrations and decomposition. Longer term processes such as sesquioxide formation, organic matter, cation exchange capacity, water holding capacity, bulk density and soil structure are also considered. We are implementing it as a set of parallel models, each focusing on one cluster of soil processes. The radiation interaction models consider the energy environment within and external to the canopy and include solar radiation as a modifier to plant growth and energy (optical and microwave) as remote sensing signal. The forest succession and soil process models require initial information on available species, and characterization of soil horizons. Radiation scattering models require inputs that are specific to each species and canopy layer (e.g., LAI, spectral and dielectric properties, canopy architecture). Also each model requires some representation of processes or properties simulated by the others.

Modeling Framework

Although scientists from a wide range of disciplines have studied forested ecosystems, it has been difficult to relate and contrast models of forested ecosystems from such disparate fields as biogeochemistry, ecophysiology, land surface climatology, pedology, plant demography, remote sensing science, and soil physics. Integrated approaches spanning more than two or three of these disciplines have proved unsatisfactory to specialists, yet questions of how forested ecosystems respond to global change require integrated approaches. Our approach is to develop the modeling tools and data to construct a virtual workbench or laboratory (Figure 2) for collaborative modeling and testing ideas that cross disciplines, using the spatial context provided by data from remote sensing. Key differences from previous integrated models stem from our efforts to keep critical elements accessible to specialists in the various disciplines and from providing the type of graphical interface previously associated with applied science and engineering models or teaching environments.

We encapsulate existing models to be more "object like" so they can collaborate in an object oriented environment. (See Figure 2.) The environment supports a standard protocol for passing information among models and for responding to interactive requests for information or graphical display of intermediate results. Time is incremented by a single clock process, but models executing the same time step may run concurrently. The user selects which models to use for a particular simulation, configures them, and may create multiple instances of a single type of model. Models need not run on the same computer as the graphical interface or other models. This extends the framework described by Levine et al. (1993) by allowing greater flexibility in selecting which models participate in any single simulation and requiring fewer changes to the simulation code of existing models. The combination of an assortment of encapsulated models, a common graphical interface, and tools for scheduling and interprocess communication, establishes a framework for model integration. Rather than building a single integrated model of a particular ecosystem, we plan to extend and improve the framework as understanding improves and new data become available.

CONCLUSION

Our approach in the second phase of the FED Project has been to develop a modeling workbench that can link individual submodels of forest physiology, growth and succession, soil processes, and the radiation regime within and external to the forest-soil complex. These linked models are to be used in combination with ground-based, airborne and satellite observations, to better understand the dynamics of forest ecosystem evolution. By the end of Phase II, we will be able to predict multi-spectral response (optical and microwave) from simulated forest ecosystems for a variety of conditions, and as such, have a sensitive indicator of both direction and magnitude of ecosystem change. The approach allows us to test hypotheses about process interactions, spatial and temporal scaling, related to global change. This hypothesis testing occurs as we: (a) complete the logical and functional integration of the various process sub-models using an object oriented approach; (b) analyze the extensive ground-based, airborne, and satellite data sets which have been acquired in order to derive the products that are needed as inputs to the models and are useful in improving our understanding of ecosystem processes; and (c) rigorously validate both the sub-models and integrated models by comparing model-derived results with ground-based and remote observations.

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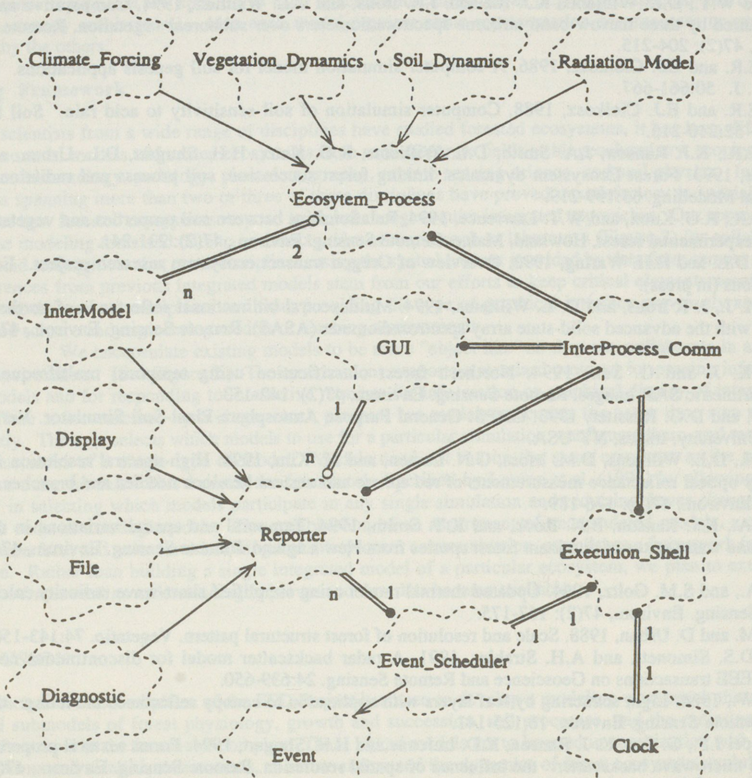

Figure 2. Class Interaction Diagram for an Object-Oriented Modeling Framework. Arrows point from more specialized subclasses to their more general parent classes. Double lines show where members of class marked with solid circle contain members of another class, or members of a class marked with an open circle use members of another class to provide part of their behavior. Cardinality labels indicate whether a relationship is one-to-one, one-to-many, many-to-many, and so on.