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Comparing simulated and measured water and carbon dioxide fluxes spatially over the 15 km by 15 km FIFE site

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Comparing Simulated and Measured H_2O and CO_2 Fluxes Spatially Over the 15 km by 15 km FIFE Site

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Chairperson: Dr. E.R. Hunt ERH

My objective was to determine whether the CO_2 and H_2O fluxes simulated by BIOME-BGC (a point scale ecosystem process model) may be extrapolated to landscape scales using remotely-sensed data. I used data from the FIFE Information System CD-ROM set to develop data layers (530 by 530, 30-m grid cells) for elevation, slope, aspect, soil depth, cover type, and LAI for the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) site near Manhattan, KS. Using these layers and a detailed climate file as input, I predicted evapotranspiration (ET) and net ecosystem exchange (NEE) for the summer of 1987, and compared the output with aircraft eddy-correlation measurements. Results showed that NEE was significantly correlated with measurements of carbon flux, whereas ET showed no correlation with measurements of latent heat flux. NEE and ET were visibly correlated with topography, soils, LAI, and cover type. All simulated data fell into the range of expected values for a tallgrass prairie ecosystem. The valley bottoms and upland plateaus had deeper soils and consequently more available water, thereby increasing ET and NEE. The R^2 for the simulated NEE vs. measured carbon flux was 0.27, which was encouraging because the model output was aggregated to fit the larger 4 by 8 grid cells (3.8 km by 1.8 km) of the aircraft data. The limited spatial and temporal resolution of the aircraft data may have failed to capture the heterogeneity of the landscape caused by small variations in topography and vegetation patterns.

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CHAPTER 1

INTRODUCTION

OVERVIEW

The field of landscape ecology has a clear need for information at a wide variety of spatial and temporal scales, a good deal of which may be obtained from remote sensing. Unfortunately, only a few of the variables of interest to ecologists are directly observable with remote sensors (Roughgarden et al. 1991). Mass exchange processes such as evaporation, transpiration, photosynthesis, and respiration; and soil processes such as litter accumulation, decomposition, and water storage are not visible to optical sensors. However, models that calculate these (and other) processes from remotely-sensed data are available, and are continuously being validated (Running 1994, Nemani and Running 1989).

Simulating terrestrial ecosystems at scales larger than a homogeneous plot requires generalized models of ecosystem processes that can be accurately applied to different landscapes through the use of data that is dynamic in terms of space and time. In order to simulate a system as complex as an ecosystem, models must simulate processes and states at spatial and temporal scales that parallel the system of interest. One such model is BIOME-BGC (for <u>B</u>io<u>G</u>eochemical <u>C</u>ycles), a generalized ecosystem process model that simulates the hydrologic, carbon, and nitrogen biogeochemical pathways of terrestrial ecosystems. The objectives of this work are to determine whether the flux logic within BIOME-BGC may be extrapolated spatially; and to develop methods to simulate data layers for key variables where spatial data do not exist.

It is extremely costly in terms of time and money to directly measure ecosystem processes for large areas in and accurate and timely manner. By simulating fluxes with a dynamic ecosystem model, and organizing the data spatially with a geographic information system (GIS), extrapolations to landscape scales are possible (Nemani et al. 1993, Running 1990, Running et al. 1989, Band et al. 1991). This allows for spatial representations of ecosystem processes through time under a wide range of possible landscape condition.

There are three main considerations when scaling ecosystem processes from small scales (leaves) to large scales (landscapes). First, the variables that determine ecosystem processes such as the exchange of H_2O and CO_2 may be completely different at different scales. Consider the energy budget of a leaf compared to the energy budget of the canopy. The energy budget of the leaf is determined in large part by its air temperature. The energy budget of the entire canopy, however, is dependant on the total radiation load. Of course, the integration of the energy budget for each leaf would give a true estimation of the canopy energy budget at any one point in time, but measurements at this scale are not feasible for landscapes. A second consideration for extrapolating from small to large scales is the effect that plant communities have on governing variables such as boundary layer conductance, vapor pressure deficit, temperature, and CO_2 concentration. The status of any of these variables in and above the canopy can be unrelated to the same variable at the leaf. Finally, the aggregation of fine scale, nonlinear ecosystem processes may lead to errors associated with the methods of aggregation. Aggregation of calculated values for ecosystem processes is necessary in order to represent data spatially (Rastetter et al. 1992).

These considerations lead to a practical approach to describing the exchange systems of vegetated surfaces at large scales (Baldocchi 1993). First, the mechanics of the system must be characterized at a micro-scale. The processes governing the exchange of H_2O and CO_2 from a leaf operate at a cellular scale, and involve subtle intracellular gradients, and rapid morphological responses by the leaf. Second, these processes must be integrated using a logical approach based on factors at a meso-scale, for example, vegetation type and distribution. Finally, the states and factors that control the processes at the meso-scale must be determined at the macro-scale in order to extrapolate the processes across a landscape. Soil water holding capacity, leaf area index (LAI), cover type, and topography are factors that govern ecosystem processes at the macro-scale (Hunt et al. submitted, Running and Hunt 1993, Band et al. 1991, Running et al. 1989).

The parameterization scheme of BIOME-BGC follows this logic. Physiological variables such as maximum photosynthetic rate, respiration coefficients, intracellular O_2 and CO_2 partial pressure, and leaf nitrogen concentration were estimated from micro-scale work. Climatic data (Table 2) and other site data such as soil texture, albedo, and latitude were instrumental in integrating flux processes in space and time. A digital elevation model (DEM) was used to describe topography (elevation, slope and aspect), and to simulate a spatial representation of soil depth. Remotely-sensed LAI and cover type (Figures 2, 3, and 4) were used to extrapolate these processes across the study area.

My objective is to determine whether the flux logic contained in BIOME-BGC may be extrapolated to two dimensions using data coverages for key input variables and differentially initializing states and parameters using a simple site classification. This work may be valuable for determining the patterns and distributions of ecosystem processes across landscapes, and for the development of new models that operate at landscape scales.

The methods and results of my work are presented in chapter two as a journal article. The remainder of this chapter provides background on FIFE, the estimation of LAI by remote sensing, the estimation of soil depth by a DEM, and eddy-correlation measurements.

DESCRIPTION OF FIFE

The FIFE (First International Land Surface Climatology Project (ISLSCP) Field Experiment) site is a 15 km by 15 km research area located in central Kansas. The site consists primarily of native tallgrass prairie mixed with gallery oak forests and croplands. Tallgrass species include big bluestem (Andropogon gerardii), little bluestem (Andropogon scoparious), and indian grass (Sorghastrum nutans) (Friedl et al. 1994, Bark 1987). The mean annual precipitation is 835 mm, with monthly mean temperature ranging from -2.7 °C in January to 26.6 °C in July (Bark 1987). The area is characterized by three relatively deep (for Kansas, 60 m relief) drainages and a central upland plateau. Areas within the Konza Prairie Long Term Ecological Research site (occupying the northwest quarter of the FIFE site) are under controlled treatment regimes that include grazing and burning over several annual cycles. Gallery oak forests (Quercus spp.) occupy the valley bottoms and steeper north-facing slopes. Uplands are used primarily for grazing, and some cereal crops and hay are grown in the valley bottoms.

The objectives of FIFE are to better understand the role of biology in controlling the interactions between the land and the atmosphere, and to determine the value of remotely-sensed data in estimating climatological parameters (Sellers et al. 1992, Sellers 1988). Progress toward these objectives requires a wide variety of measurements made at a variety of spatial and temporal scales. By necessity, FIFE was a coordinated, interdisciplinary effort by researchers in remote sensing, meteorology, and biology (Sellers et al. 1992, Sellers et al. 1988).

FIFE was initiated in 1983, and the majority of field work was done during the summers of 1987 and 1989. Now the project is nearing completion, with a large amount of data contained in: 1) a special issue of the Journal of Geophysical Research (vol. 97 1992), 2) a series of five CD-ROM volumes, and 3) a Distributed Active Archive Center (DAAC) administered at the Oak Ridge National Laboratory in Oak Ridge, Tennessee. The scientific framework for the project was outlined in the implementation plan for ISLSCP and reformulated by Piers Sellers (1988).

In studies involving the biophysical system of the earth it is important to consider the forcing of the atmosphere by the vegetated surface (Shukla et al. 1990, Sud et al. 1990). Until recently, little was known about the global distribution of energy, water, carbon, and intermediate sources and sinks. Even less was known about how these changed through time, how they affected general atmospheric circulation, or how they were related to landscape parameters such as topography, vegetation, or land use. On the other hand, there was a great deal known about how these factors behaved at small scales. For example, it is well documented that individual plants have highly correlated evapotranspiration and photosynthetic rates that insure maximum production for a given amount of water loss. There is also strong evidence that these fluxes are related to canopy chlorophyll density, quantifiable by remote sensing (Sellers et al. 1992, Tucker and Sellers 1986, Tucker 1979). However, there is an enormous information gap in scaling these fine scale systems up to the landscape scale. Up until FIFE, untenable assumptions about the vegetated surface were used as the premise for research exploring the interactions between the surface and the atmosphere. ISLSCP was initiated to address the problem of determining the usefulness of remotely-sensed data in describing landscape and climatological parameters. Another main goal of ISLSCP was the collection and organization of relevant large scale data sets that could be used for model initialization and validation. As ISLSCP evolved, it became apparent that these objectives could not be met unless the biological controls on surface/atmosphere interactions could be described qualitatively or quantitatively (Sellers 1988). By achieving these goals it would be possible to: 1) monitor large scale changes of the land surface caused by climate or humans; 2) develop models designed to simulate interactions between the surface and the atmosphere; and 3) make consistent, synoptic data available for diagnostic and empirical studies of the earth as a system.

In order to meet these objectives, satellite data, along with simultaneous measurements of biophysical processes such as energy budgets, radiation, and mass fluxes at a variety of scales were necessary. Until FIFE, no attempt to collect data at the scales required to capture the variation of biophysical processes in space and time, or to allow for inclusion of satellite data at several different scales had been made. The only larger scale work concerning interactions between the surface and the atmosphere had been conducted at scales less than a few hundred meters. The leaders of ISLSCP were faced with two main problems: 1) the integration of small-scale measurements of biological parameters to the large scales involved in atmospheric research and 2) the measurement of processes such as photosynthesis, evapotranspiration or associated states such as chlorophyll density, soil moisture, and vegetation type using remotely-sensed data. FIFE was proposed to be the pioneering effort in addressing these questions; it was also an opportunity to evaluate the different methods used to measure the same parameters.

Given the objectives of FIFE, three issues were identified that would frame the experimental design: the size of the site, the duration of data collection, and the location of the site (Sellers et al. 1992). The size of the site was based on a compromise between capturing the variation in processes at the surface, and including enough area to encompass a reasonable number of satellite pixels. The site also had to be large enough to allow for a sufficient footprint for intermediate aircraft eddy-correlation measurements. The surface measurement sites were distributed based on a stratified sampling method in order to capture the variation in land use and topography (Davis et al. 1992).

The duration of FIFE was set to capture the variation in surface conditions (vegetation, moisture status, climate) and account for constraints on the various measurement devices. A monitoring program from the spring of 1987 to October 1989 was initiated for continuous data collection from satellites and meteorologic, hydrological, and biometric stations. In 1987 the monitoring work was enhanced by four intensive field campaigns (IFCs 1-4) taking place at and around yearday 150, 190, 230, and 280, respectively. During these periods, researchers with specialized equipment were dedicated for periods from 12 to 20 days to collecting simultaneous data at a variety of scales. Each IFC was scheduled to capture a different phase of vegetative condition at the site (Sellers 1992). IFC-1 (May 26 - June 6) was conducted during the "green-up" period, before the peak vegetation biomass. IFC-2 (June 25 - July 15) was conducted at the peak vegetation biomass. IFC-3 (August 10 - August 25) was conducted as biomass decreased. And IFC-4 (October 5 - October 16) was conducted as vegetative biomass senesced (Sellers 1988). The specific goals of the IFCs were to simultaneously collect data at a variety of scales in order to rigorously test models and algorithms relating remotely-sensed data to observed biophysical processes and states.

SCIENTIFIC BACKGROUND

Leaf Area Index

LAI is defined as the ratio of leaf area per unit ground area (Watson 1947), and is the most important variable in BIOME-BGC for describing vegetation density and quantifying energy and mass exchange from an ecosystem. LAI is used in the following BIOME-BGC calculations: canopy interception and evaporation, transpiration, canopy radiation attenuation, photosynthesis, and vegetative nitrogen content. One approach commonly used in estimating LAI from spectral measurements is to make use of the differential reflectances of soil and leaves (Figure 1).

An important distinction needs to be made between radiance and reflectance. Satellites measure radiance which includes radiation reflected by the surface (reflectance), radiation that is backscattered by the atmosphere (path radiance), and differential irradiances based on slope and aspect. When remotely-sensed data are used to describe vegetation some care must be take to correct the raw satellite data for the atmospheric transmissivity and the topography of the area being studied. After this radiometric correction has been made, the calculated reflectance data may be used to determine vegetation density or distribution.

Leaves absorb about 85% of the radiation between 0.3 and 0.7 μm (photosynthetically active radiation, PAR) and reflect about 85% of the radiation between 0.8 and 1.2 μm (near infrared, NIR). Soil, on the other hand, reflects more radiation in the 0.3 to 0.7 μm range and usually reflects less radiation in the 0.7 to 0.9 μm range. Sensors in the red ($\approx$0.65 μm) and NIR ($\approx$0.85 μm) may be used to accurately capture these differences with minimal radiometric correction due to the large differences in reflectance. A commonly used ratio is the normalized differential vegetation index (NDVI) defined as:

$$NDVI = (\rho_{nir} - \rho_{red}) / (\rho_{nir} + \rho_{red}) \qquad (1)$$

where ρ_{nir} and ρ_{red} are, respectively, the reflectances in the NIR and red intervals. In remote sensing, these intervals are referred to as bands, and are unique for each sensor.

For this work, radiometrically corrected data from the Landsat Thematic Mapper sensor were used, and the bands that correspond to the red and NIR intervals are band 3 (0.63-0.69 μm) and band 4 (0.76-0.90 μm), respectively. LAI has been found to be correlated with NDVI in a number of biomes (Tucker 1979, Running et al. 1989, Nemani et al. 1989). It is important to note, however, that the accuracy of estimations of LAI from NDVI are strongly dependant on local conditions such as vegetative composition, and bare soil reflectance.

Soil depth

Soil depth is an important factor determining site water balance, which affects carbon allocation, photosynthesis, plant-water relations, and nutrient cycling. It is a critical variable in ecosystem simulations (Running and Coughlan 1988, Running and Gower 1991, Hunt et al. submitted). Without a logical method of extrapolating known soil depths across a landscape, ecosystem simulations will have little significance. Many studies have determined the importance of topographic data in hydrologic and ecosystem studies (Beven and Kirkby 1979, Band et al 1991, Nemani 1993). Zheng et al. (in press) have developed a topographically-based methodology for determining available soil water across a landscape using a topographical index, $\ln(\alpha/\tan\beta)$ (Beven and Kirkby 1979), where α is upslope contributing area and β is slope, and using the mean and max soil water contents from available soil databases. This method will be described in detail in Chapter 2. It has been argued that site water status should be measured at the soil rather than at the leaf (Jones 1992, Hunt and Running 1990). There are a number of reasons that suggest soil water potential (Ψ_{soil}), rather than leaf water potential (Ψ_{leaf}), is a more appropriate measurement of plant water status. Ψ_{leaf} shows much short-term variability as a result of microclimatic conditions. Variable cloud cover in particular can alter the water potential of leaves by as much as two-fold in a manner of minutes (Jones 1992). On occasion, Ψ_{leaf} may be higher in plants with closed stomata under water stress. Stomatal closure, in this case, cannot be explained as a feedback control acting through Ψ_{leaf}, but may be explained by a response to Ψ_{soil} (Jones 1992). For these reasons, estimations of plant water status that are related to Ψ_{soil} are more relevant to plant processes than estimations based on Ψ_{leaf} at a single point in time. Unfortunately, soil moisture status is extremely variable across a landscape; thus, it is difficult to determine soil moisture status over a large area such as the FIFE site. Existing soil databases are at too coarse a scale to capture the heterogeneity in landscape soil depths (Zheng et al. in press). It is reasonable to assume that a soil depth model based on topography will provide spatial estimations that are more accurate than existing data because topographic data is available at a finer resolution than the majority of soil databases, and topography is readily measured by remote sensors, whereas soil depth or texture across landscapes are difficult to measure (Zheng et al. in press). Soil depth and texture tend to change with topography; with deep fine soils found in valley bottoms, shallow medium textured soils on slopes, and deeper, more coarse soils found on uplands. Soils will tend to accumulate in valley bottoms, convergent areas, and areas with low slopes and larger material supply zones (Zheng et al. in press). The movement of soil through a landscape is determined by gravity, consequently, $\ln(\alpha/\tan\beta)$ should be strongly correlated with soil depth (Zheng et al. in press).

Eddy Correlation Measurements

The most direct method of measuring the fluxes to and from a vegetated surface is the eddy-correlation method proposed by Swinbank (1951). Because of the heterogeneity of ecosystems, point measurements are not representative of processes involving energy and mass exchange from an area. The eddy-correlation method, when stationed on a platform such as an airplane, may give reasonable estimations of fluxes from an area in the format of a flight grid (vector data). A method was proposed by Schuepp et al. (1992) to extrapolate data from this grid to two dimensions based on data in adjacent flight lines. Eddy-correlation is based on the premise that at any given point above a surface, at any instant in time, air may be moving in any direction as a consequence of turbulent eddies. Over a small interval, net fluxes of CO_2 and H_2O may occur in any direction due to this turbulence, but over a longer period this turbulent transfer process must carry a quantity of CO_2 down that is sufficient to replace that lost by net photosynthesis (Field et al. 1991). The net flux of a compound such as H_2O or CO_2 vertically past a point is given by the integral over time of the upward and downward flows of the compound. During periods of high evapotranspiration, the concentration of water is greater in the upward eddies than in the downward eddies. Specifically, the net flux of a compound is equal to the mean covariance between the vertical velocity of the eddy, and in the concentration if the compound of interest. If the changes in concentration are not correlated with instantaneous vertical velocity, then there is no net flux of the compound, but if the vertical velocity and concentration changes are correlated, then there is a net flux. Negative correlation indicates a downward flux, and positive correlation indicates an upward flux. This technique requires that instantaneous vertical velocity and instantaneous concentration are measured accurately, rapidly, and simultaneously. On a rapidly moving aircraft this is no simple feat, and up until recently the instruments and computing power to assure simultaneous measurement were not available. At FIFE the aerial flux measurements were made using aircraft equipped with accelerometers, gust probes for measuring wind gusts in the *X*, *Y*, and *Z* directions, equipment for determining inertial velocity of the aircraft, and fast-response infrared gas analyzers. Data were recorded 16 times a second and then filtered to reduce machine error (MacPhearson 1992).

Chapter 2

COMPARING SIMULATED AND MEASURED H_2O AND CO_2 FLUXES SPATIALLY OVER THE 15 KM BY 15 KM FIFE SITE

INTRODUCTION

Simulations of mass exchange between the surface and the atmosphere have most often been conducted at one of two scales. The global scale (>20,000 km^2), where one cell is an aggregation of landforms, lifeforms, and meso-climates; and the single plant scale, where processes are determined my micro-climate and local site variables. Neither scale adequately captures the range of variation in landscape parameters such as topography, life form, vegetation density, or soil characteristics that are primary factors in governing the heterogeneity of mass fluxes between the surface and the atmosphere.

When moving from point-scale simulations to landscape-scale simulations it is imperative that key processes be defined, and the variables that are primarily responsible for these processes be logically extrapolated from existing data to provide coverage for the entire area of concern. Baldocchi (1993) suggests a three tiered approach to identifying mass flux processes that operate at adjacent space and time scales.

First, the mechanics must be defined at the micro-scale. CO_2 and water transfer in a single leaf depend on small-scale intracellular and microclimate gradients that define the rate of flux. Key factors at this level are Intracellular CO_2 and O_2 partial pressure, leaf water status, leaf nitrogen, and radiation load. Second, these micro-scale factors and processes must be integrated in order to quantify flux processes for the entire canopy. This involves determining differential radiation load through the canopy, and calculating rates based on this variable energy availability (Cihlar et al. 1992, Gao et al. 1992, Smith et al. 1992). Macro-scale factors such as vegetation type, elevation, slope, aspect, and soil depth may then be used to extrapolate from the meso-scale to the landscape.

It is beyond our capability to extrapolate all of the variables that operate on the micro-scale to the macro-scale. Baldocchi (1993) suggests there are two main guidelines for determining which criteria are used to extrapolate from micro to macro scales: 1) which factors are important throughout the continuum of scales, and 2) which factors may be spatially represented at the scale of the area of interest. A number of factors may be identified that are key in determining the rates of CO_2 and water exchange within a plant community; these include leaf morphology, leaf distribution, leaf chemistry, age of vegetation, and acclimation to local environment. Is it necessary to represent these all of these factors at the micro-scale in order to make accurate estimations of flux processes? The answer is elusive, but the cost in terms of time and money in achieving good spatial estimations from measurements made at the micro-scale is prohibitive, and the current thinking is that by classifying vegetation into broad categories, an adequate amount of the heterogeneity at the micro-scale may be represented. The "broadness" of each category should be determined based on the system being modelled, and the resources available to the researcher.

Previous efforts in validating BIOME-BGC involved testing point-scale simulations using detailed measurements for model drivers, state variables, and site and vegetation parameters. These simulations were compared with concurrent tower-based eddy-correlation data from FIFE station 16 (Verma et al. 1992). The simulated data fit the measurements well (Hunt, unpublished results). These correlations showed that when detailed site data are provided, the model predicts fluxes that agree well with measured values (Hunt, unpublished results).

Six variables were identified that influence flux processes from micro to macro scales. These variables were: elevation, slope, aspect, soil depth, leaf area index (LAI), and vegetation type. My objectives were to determine whether the flux logic in BIOME-BGC may be extrapolated to landscape scales using spatial data from the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE).

METHODS

Study Area

The FIFE site is a 15 km by 15 km NASA study area located 8km south of Manhattan, Kansas (Northwest corner: N 4333000 E 706000, UTM zone 14). It consists primarily of native tallgrass prairie, with deciduous oak woodlands in the valley bottoms and steeper slopes, and croplands scattered throughout. Topography is characterized by three relatively deep (60 m relief) drainages with a central upland plateau. Areas within the Konza Prairie Long Term Ecological Research (KPLTER) site, occupying the northwestern quarter of the FIFE site, are under a variety of land-use regimes, including burning and grazing in a number of annual rotations. Uplands are used for grazing and some cereal crops are grown in the valley bottoms.

The objectives of FIFE were to better understand the role of biology in determining the interactions between the biosphere and the atmosphere, and to determine the value of remotely-sensed data in determining climatological parameters.

Model

BIOME-BGC (for BioGeochemical Cycles) is an ecosystem process model that calculates the carbon, nitrogen, and hydrologic cycles of an ecosystem. Input for BIOME-BGC falls into three main categories: 1) state variables and parameters (Table 1), 2) meteorologic variables (Table 2), and 3) spatial inputs (Figures 2-4). These variables are responsible for describing the ecosystems of the FIFE site throughout the study period. The model has a dual time-step with the hydrologic and carbon budgets calculated daily as a function of LAI, and the nitrogen cycle, leaf and root turnover, and allocation calculated annually. Only the daily processes are calculated for this study.

The hydrologic cycle starts with an initial soil water reservoir. Precipitation is intercepted (based on LAI) and evaporated if radiation is sufficient, or it falls through the canopy and is added to the soil water reservoir. Canopy conductance is calculated based on average daytime temperature, vapor pressure deficit, incident photosynthetically active radiation (PAR), and available soil water (Hunt and Running 1992, Running and Hunt 1993). Soil water holding capacity is a function of soil texture and depth. Bare soil evaporation and transpiration (ET) are then calculated using the Penman-Monteith equation, accounting for incident solar radiation absorbed by the soil and canopy.

The carbon cycle is simulated based on maximum photosynthetic and respiration rates adjusted for daylength and daytime average air temperature. Net photosynthesis is based on LAI, quantum efficiency, the rate of leaf maintenance respiration (based on a Q_{10} of 2.0), and incident PAR. Net primary productivity (NPP) is the difference between net photosynthesis and autotrophic respiration, and net ecosystem exchange (NEE) is calculated by subtracting heterotrophic respiration from daily NPP.

Meteorological data used for driving variables are: yearday, daily solar radiation (S_o, kJ m^{-2} day^{-1}), daily minimum/maximum air temperature (T_{min}, T_{max}, °C), daily precipitation (mm H_2O), average daily soil temperature (T_{soil}, °C) at a depth of 0.1 m, and incident PAR (μmol m^{-2} s^{-1}) at noon (Table 2) (Hunt et al. submitted). Daylength, average daily temperature, vapor pressure deficit, nighttime average temperature, absorbed radiation, and transmitted radiation are all calculated from these inputs (Hunt submitted).

State variables describe initial conditions and parameters for calculation of the carbon and hydrologic cycles (Table 1). These include leaf carbon, stem carbon, root carbon, litter carbon, and soil carbon to describe the initial conditions for the carbon cycle; and soil water content and soil texture to initialize the calculations for the hydrologic cycle. Parameters such as stem and leaf respiration at 0 °C; maximum respiration for leaves, stems, and roots; maintenance respiration coefficients; maximum photosynthetic rates; optimum temperature for photosynthesis; and maximum stomatal conductance govern the equations for photosynthesis and respiration.

Six site variables were identified that could be represented spatially for the FIFE site using standard remote sensing and GIS techniques. These variables were: elevation, aspect, slope, soil depth, cover type, and LAI. These variables were chosen based on the fact that they represent the main sources for heterogeneity in mass exchange processes across the landscape (Cihlar 1992, Gao 1992, Smith 1992, Stewart 1992). In many cases where spatial data are used to describe ecosystems, data are aggregated into relatively large grid cells or classified into polygons. This may lead to an incomplete representation of landscape heterogeneity resulting in underestimations of flux processes. By averaging a process for an area (grid cell or polygon), and using the mean as an estimate of that process, the nonlinearity of the process is not accounted for (Rastetter et al 1992, Pierce and Running submitted). To reduce this bias, 530 by 530 (30 m grid cell) data coverages for each of the six variables were developed and used for extrapolating calculations of carbon flux and evapotranspiration. This resolution corresponds with the resolution of the digital elevation model (DEM) for the FIFE site, as well as Landsat-Thematic Mapper data (Strebel et al. 1993, Davis 1992, Dozier et al. 1989).

Simulations and Eddy-Correlation Data

BIOME-BGC was run for each 30 m grid cell, using the data coverages along with a detailed climate file (see Appendix 1; Alan Betts and Joseph Berry, personal communication) as input, from yearday 146 (May 26, 1987) to yearday 289 (October 16, 1987). Daily integrated output coverages for ET and NEE were generated at yearday 163 (June 12), 195 (July 14), and 227 (August 15). These dates corresponded with the dates of the Landsat-TM images used for determination of LAI. A summary of the model runs is displayed in Figure 5.

Aircraft eddy-correlation measurements of instantaneous latent heat and CO_2 fluxes across the FIFE site were available from Desjardins et al. (1992). These data were collected by the Canadian NAE twin otter aircraft and were aggregated into a four by eight grid (3.8 km by 1.9 km grid cells) using the methods of Schuepp et al. (1992), providing complete coverage for the FIFE site for August 15, 1987 between the hours of 11:00 am and 4:00 pm. The ET and NEE output coverages for August 15 were aggregated by arithmetic mean up to the larger scale of the aircraft data, and the comparisons between measured and simulated daily values were evaluated using ordinary least-squares linear regression. I hypothesized the correlations would be positive due to the relationships between instantaneous latent heat and CO_2 fluxes with daily ET and NEE respectively.

SPATIAL DATA

Elevation (Figure 2), slope, and aspect are important variables that determine net radiation through the Lambert Cosine Law in BIOME-BGC. Data for these coverages were available on the FIFE CD-ROM set, Volume 5 (Strebel et al. 1992). All coverages were registered to the UTM grid using known ground coordinates, and resampled to the 530 by 530 (30 m grid cells) study grid. Slope and aspect were derived by taking local derivatives in the x and y direction (Dozier 1992, Davis et al. 1992).

Soil Depth

Soil depth (Figure 3) for the FIFE site was determined using the logic of Zheng et al. (in press) where a topographic index defined as: $\ln(\alpha/\tan\beta)$ (Beven and Kirkby 1979, Famigletti et al. 1992, Zheng et al. in press), for which α is the upslopes contributing area for any given cell on the DEM and β is the local slope of the cell, is used to determine soil depth from elevation data. It has been shown that a linear correlation exists between this ratio and soil water holding capacity (Zheng et al. in press), which is directly affected by soil depth and texture (Hillel 1982). For this work I assumed that soil texture was fairly homogeneous for the FIFE site (Schimel et al. 1992, Knapp et al. 1992).

In order to calculate soil depth (S) from $\ln(\alpha/\tan\beta)$ estimates of mean and maximum soil depths were used in combination with summary statistics of the distribution of $\ln(\alpha/\tan\beta)$ for the FIFE site. Mean depth was assumed to be 40 cm while maximum depth was assumed to be 180 cm (Knapp et al. 1992). Soil depth was calculated using two multipliers, M_1 and M_2; one of which was calculated for each grid cell, based on the value of $\ln(\alpha/\tan\beta)$ (Zheng et al. in press). If $\ln(\alpha/\tan\beta)$ was less than or equal to the mean $\ln(\alpha/\tan\beta)$ value for the area then M_1 was given by:

$$M_1 = S_{mean} / 0.5(LN_{mo} + LN_{me})) \quad (1)$$

where LN_{mo} and LN_{me} are the mode and mean $\ln(\alpha/\tan\beta)$ values for the area and S_{mean} is the estimated mean soil depth. If $\ln(\alpha/\tan\beta)$ was greater than LN_{mean}, then M_2 was given by:

$$M_2 = S_{max} / LN_{max} \quad (2)$$

Finally, soil depth was determined by multiplying the value of $\ln(\alpha/\tan\beta)$ by the appropriate M coefficient. It has been suggested by Zheng et al. (in press) that this method for determining soil depth for an area is more accurate than using existing data because of a finer resolution and a logic that parallels the movement of soil through a landscape. Existing soil data contain unknown errors due to economic, technical, political, and physical constraints. This was the case with FIFE, as the only soils data available did not provide sufficient physical data, and were not edge-matched across county lines.

Cover Type

The cover type data layer (Figure 3) was responsible for setting the states and parameters for the calculation of flux processes for different vegetation types. For this work I stratified the FIFE site into three main categories: C_4-tallgrass ecosystems, C_3-crop ecosystems, and C_3-deciduous forest ecosystems. Different maximum photosynthetic rates, respiration coefficients, temperature responses, morphologies, and conductances were all represented by differentially setting the states and parameters according to cover type.

Leaf Area Index

LAI coverages for three dates (Figure 4) through the summer of 1987 (June 12, July 14, and August 15) were derived from images of NDVI using the SAIL model (K.F. Huemmrich, personal communication). These dates corresponded with three of the intensive field campaigns carried out during FIFE, and spatially represented eddy-correlation data for evapotranspiration and CO_2 exchange were available for August 15 from Desjardins et al. (1992). LAI describes the density and distribution of vegetation in BIOME-BGC and is used to calculate interception, canopy carbon and nitrogen concentrations, canopy conductances, photosynthesis, maintenance and growth respiration, and canopy lignin concentration. LAI, in addition to climate, is the only variable in BIOME-BGC that represents changes in the site through the study period.

The SAIL model assumes an exponential relationship between NDVI and LAI:

$$LAI = -\ln\left(\left(NDVI_x - NDVI\right) / NDVI_d\right) / k \qquad (3)$$

where $NDVI_x$ is the NDVI value for an infinitely thick canopy, measured to be 0.877 for a tallgrass prairie, and $NDVI_d$ is the difference between $NDVI_x$ and the NDVI of the background, equal to 0.454, and k, the extinction coefficient, is 0.834 (K.F. Huemmrich, personal communication).

RESULTS AND DISCUSSION

Soil Depth

Figure 3 shows soil depth for the FIFE site. Values range from 0 to 180 cm, with deeper soils in the valleys and flat uplands. The most shallow soils were found on the steepest slopes.

The soil depth data layer appeared to be properly distributed with high values in the uplands and valley bottoms. This distribution is consistent with the description of the soils of the FIFE site found in Schimel et al, (1992) and Knapp et al. (1992). In order to simulate soil depth more accurately with this method, it would be necessary to measure depths at several different sites in order to make a more accurate estimation of the mean and maximum soil depths for this area. These data could also be obtained from various other sources depending on the scale of the study. It has been suggested that this method is more applicable to areas with relatively higher relief because a higher correlation between soil characteristics and $\ln(\alpha/\tan\beta)$ is expected (Zheng et al. in press). If this method were used along with existing data, a more accurate spatial representation of soil depth could possibly be derived. Seamless soil data for the FIFE site between counties was a problem.

Leaf Area Index

Figure 4 shows the three images of LAI for the FIFE site. The June 12th image shows the higher values in the oak woodlands and upland tallgrass ecosystems, with the lack of LAI for crops at this date evident in the valley bottoms. The July 14 LAI coverage shows an increase in the tallgrass prairie systems, and a few crop fields with high

LAIs compared to June 12. Bare soil is evident in all three drainages. The August 15 image shows a dramatic increase in LAI in croplands with a decrease in LAI for the tallgrass prairie systems.

The data coverages for LAI were consistent with expected values for oak woodlands and tallgrass prairie ecosystems (Jones 1992, Dyer et al. 1992, and Redelfs et al. 1987). Any errors associated with these methods for determination of LAI are most likely due to the fact that the SAIL model was configured for tallgrass ecosystems which were not applicable to croplands or woodlands. Without NDVI/LAI relationships for crops or woodlands, a true spatial estimate of LAI from satellite data for the FIFE site was difficult. Friedl et al. (1994) have estimated LAI for the FIFE site using ground data, satellite imagery, and a complex stratification scheme based on topography and land-use. Their research showed more accurate estimates of LAI from satellite indices may be made by combining ground measurements and topography with linear models.

Evapotranspiration and Net Ecosystem Exchange

Output images for ET and NEE are displayed for June 12, July 14, and August 15, 1987 (Figures 7 and 8). Evapotranspiration varies from 0 mm/day to 8.5 mm/day with the largest range (0 mm/day - 8.5 mm/day) seen in June.

Means for June, July, and August were 2.0 mm/day, 3.8 mm/day and 4.1 mm/day respectively. Values for ET in June were highest in the woodlands and lowlands, where soils are well-watered. In July, ET showed a dramatic increase with woodlands showing the highest values, but with relatively little difference between well-drained upland or well-watered lowland areas. August 15 ET was again highest in the forested areas, with high values for the croplands occupying the valley bottoms.

Values for NEE ranged from the negative to 16 g m^{-2} day^{-1} with high values seen in the valley bottoms and lower values in the well-drained uplands. June 12 showed the least overall NEE with a mean of 2.8 g m^{-2} day^{-1}. A fair amount of the June image (≈15%) showed negative values for NEE. High values appeared to correspond with deeper soils and high values of LAI. Although some negative values for NEE were associated with areas of high LAI. In July, mean NEE was 3.0 g m^{-2} day^{-1} with less of the image showing negative values. Mean August NEE was 3.4 g m^{-2} day^{-1} with increases seen primarily in the wooded areas.

Output coverages for ET and NEE were well within expected values for tallgrass, forest, and cropland ecosystems such as the ones found at FIFE (Verma 1992, Desjardins 1992, Cihlar 1992, Gao 1992, Smith 1992, Stewart 1992). When examining these output images it is important to view them from the perspective of the climatic conditions preceding that specific day. Figures 8 and 9 show minimum and maximum temperature and precipitation throughout the summer of 1987 and Appendix 1 contains a subset of the raw data from the climate file used to drive the simulations.

June 12 was preceded by several dry days (RH 58-67%, no precipitation) with high values of incident radiation (30-32 kJ m^{-2} day^{-1}) this drying down period may have resulted in a drying of upland, south-facing soils. This is evident in the ET output for June 12 (Figure 6). The valley bottoms, on the other hand, still may have been well-watered due to a storm at the end of May, which could be the reason for the higher values of ET seen in the valley bottoms. ET on July 14 (Figure 6) was higher across the image, perhaps due to a larger amount of available soil water (2.93 cm precipitation in the preceding week) or less heterogeneity in LAI (Figure 4). ET on August 15 (Figure 6) was affected by a large storm on August 14, and ET was higher across the image, except for areas without vegetation. I expected lower values for unvegetated areas, but this was not evident on July 14 when water conditions were similar. I suspect this has something to do with errors in the calculations for bare soil evaporation within BIOME-BGC.

Negative and low values for NEE on June 12 (Figure 7) corresponded with areas of low ET. These may be the result of a lack of soil water in the upland areas. Some of the steeper, forested areas also showed low values, perhaps indicating low soil water. NEE on July 14 (Figure 7) was less variable across the image, perhaps caused by less variable water status and LAI. August 15 NEE (Figure 7) showed the least negative values, with the highest values in the forests. On August 15 NEE was higher in the uplands than in other images, probably due to the recent rain recharging the soil water.

Comparison to Aircraft Flux Data

Linear regression between the aggregated NEE output and aircraft flux measurements for August 15, 1987 yielded an R^2 of only 0.27, indicating that we have not captured the range in variation of NEE at the FIFE site for this date. The simulated ET and aircraft latent heat data were not correlated.

Low correlation between simulated and measured ET and NEE could result from a number of reasons. Desjardins et al. (1992) found no correlations between greeness index (which is highly correlated with NDVI) and CO_2 and H_2O fluxes for August 15, 1987. This indicates that fluxes were unrelated to LAI for this day. Furthermore, Desjardins et al. (1992) have suggested that these measurements are to be taken with a varying degree of confidence based on location over the site, and variable atmospheric conditions during the measurement period.

Measurements made near the downwind (northern) edge of the FIFE site had the lowest level of confidence due to a source strength estimate used for extrapolating the data from the flight lines to the entire site (Desjardins et al. 1992, Schuepp et al. 1992). All airborne flux estimates are subject to bias due to intermittent turbulent events that may not be accounted for in the final filtering of the data. The aircraft flux measurements for July 11, 1987 and August 15, 1987 showed comparable spatial heterogeneity. On August 15 this may have been due to relatively homogeneous net radiation (Desjardins et al 1992). This was evident in the fluxes simulated by BIOME-BGC. Unfortunately, no aircraft flux data were available for the site for June, so no estimates of relative heterogeneity could be made.

No daily integrated flux data from aircraft were available for the FIFE site. The output from BIOME-BGC, however, is integrated over the day, and instantaneous output is not currently possible. Nevertheless, I did expect to see correlations between the simulated data and the measured data based on the control of flux processes (at the macro scale) by the six data coverages. Unfortunately this was not the case. This may have been due to the following four reasons. First, convective upwelling over the site during the aircraft measurements may have resulted in an unrepresentative sample of fluxes for the entire day (Anthony W. King personal communication). Second, the footprint (resolution) for the flux measurements may not have been sufficient to capture the range of variation in flux processes over the site. The larger scale of the aircraft data caused single grid cells to encompass fluxes from valley bottoms as well as ridge tops. The cells also represented an aggregation of vegetation types and densities. Third, the stratification scheme I used to differentially parameterize the vegetation (C_3-croplands, C_3-forest, and C4-grasslands) may have been inadequate to capture the range of variation in vegetation structure and land use. For example, areas that I characterized as purely C_4 grasslands were made up of a combination of C_3 and C_4 grass with the relative percentages changing over the study period (Knapp et al. 1993). Next, the images for LAI may not have adequately represented vegetation density for the site. The relationship between LAI and NDVI is affected by a number of factors including topography, vegetation composition and morphology, and background (soil) reflectance. These factors conspire to make the relationship different under every circumstance. The problem is a "near-flat" response of NIR reflectance over a range of LAIs (Nemani 1993), this results from morphologically complex, multilayer canopies. Finally and perhaps most importantly, ample precipitation prior to August 15 recharged soil water and in combination with uniform net radiation could have led to more or less the same ET over the site (Desjardins 1992).

CONCLUSIONS

Simulations of this nature could be extremely valuable for determining the proper footprints for aerial measurements of ecosystem processes. By simulating the heterogeneity of these processes for an area, a reasonable estimate of the resolution needed to capture the range of variation of the area may be developed. This, in addition to the need for spatially extrapolated representations of ecosystem processes, provides a basis for the development of models like BIOME-BGC. New technologies are needed to increase our ability to measure ecosystem processes across landscapes in order to properly validate and parameterize models. Although I acknowledge the shortcomings of the use of extrapolated data for input to ecosystem process models, I see no other current alternative for moving from micro-scale physiological models to landscape-scale biogeochemical models.

In conclusion, the extrapolation of ecosystem process simulations to the landscape scale is dependant on accurate spatial representations of key input variables as well as good spatial measurements of ecosystem processes in order to validate these models. In spite of the lack of correlation with aircraft flux data, this work shows that BIOME-BGC is capable of accepting spatial data as input and mapping evapotranspiration and carbon flux for an area.

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Figure 1 - Bare soil vs leaf reflectance

Bare soil reflects more radiation in the red (0.3 - 0.7 μm) wavelengths than vegetation. Vegetation absorbs about 85% of the radiation in the red wavelengths and reflects about 85% of the radiation in the near infra-red (0.8 - 1.2 μm) wavelengths. This is the basis for many methods of describing vegetation from satellite data.

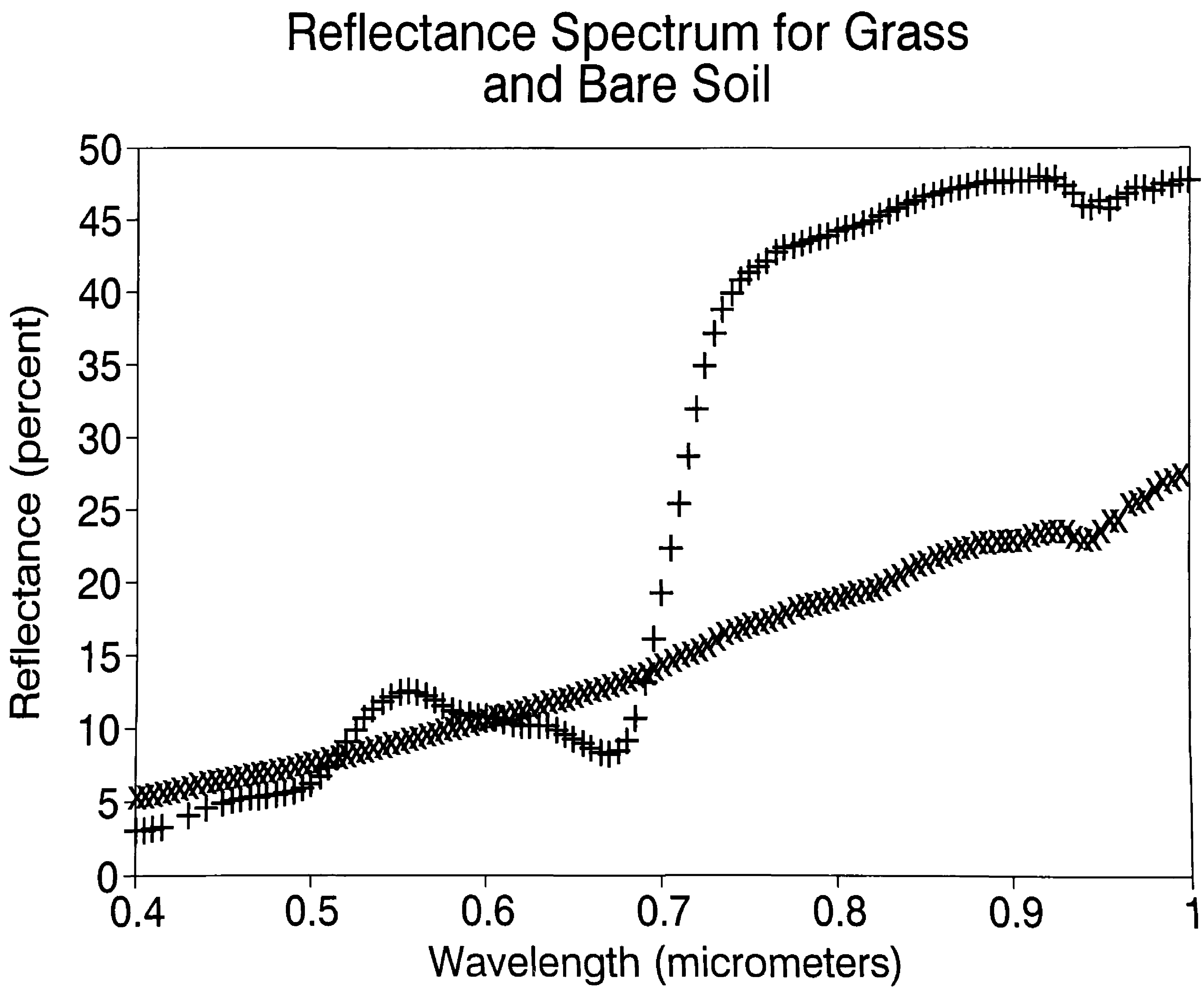

Reflectance Spectrum for Grass
and Bare Soil
Reflectance (percent)
50
45
40
35
30
25
20
15
10
5
0
0.4
0.5
0.6
0.7
0.8
0.9
1
Wavelength (micrometers)

Figure 2 - Digital elevation model (DEM) for the FIFE site

This is a 530 by 530 grid cell image where every cell has three values. An x and a y value denoting geographic location, and a z value denoting elevation. The DEM was used to determine the slope, aspect, and soil depth data coverages for input to BIOME-BGC.

Digital Elevation Model for the FIFE Site

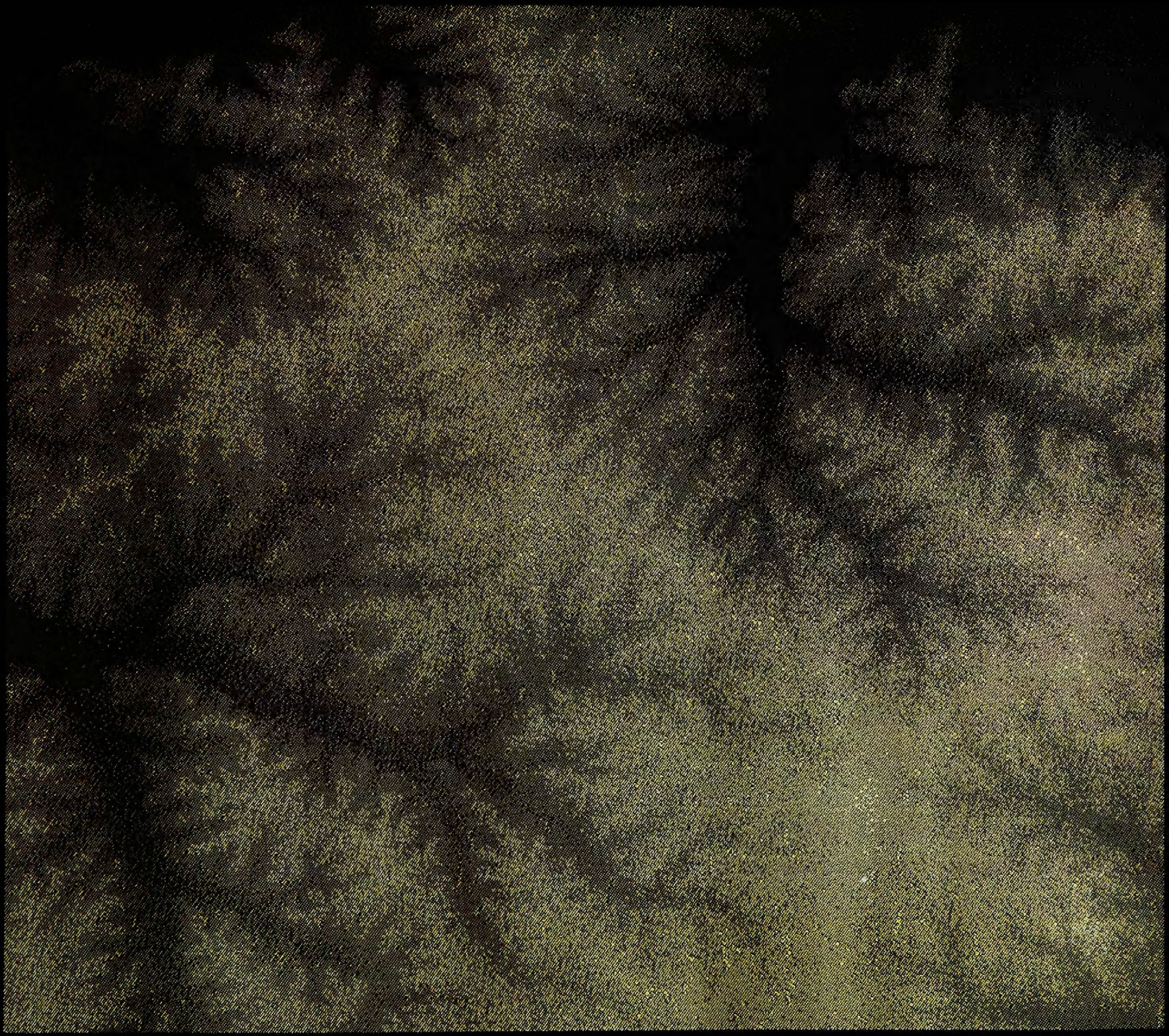
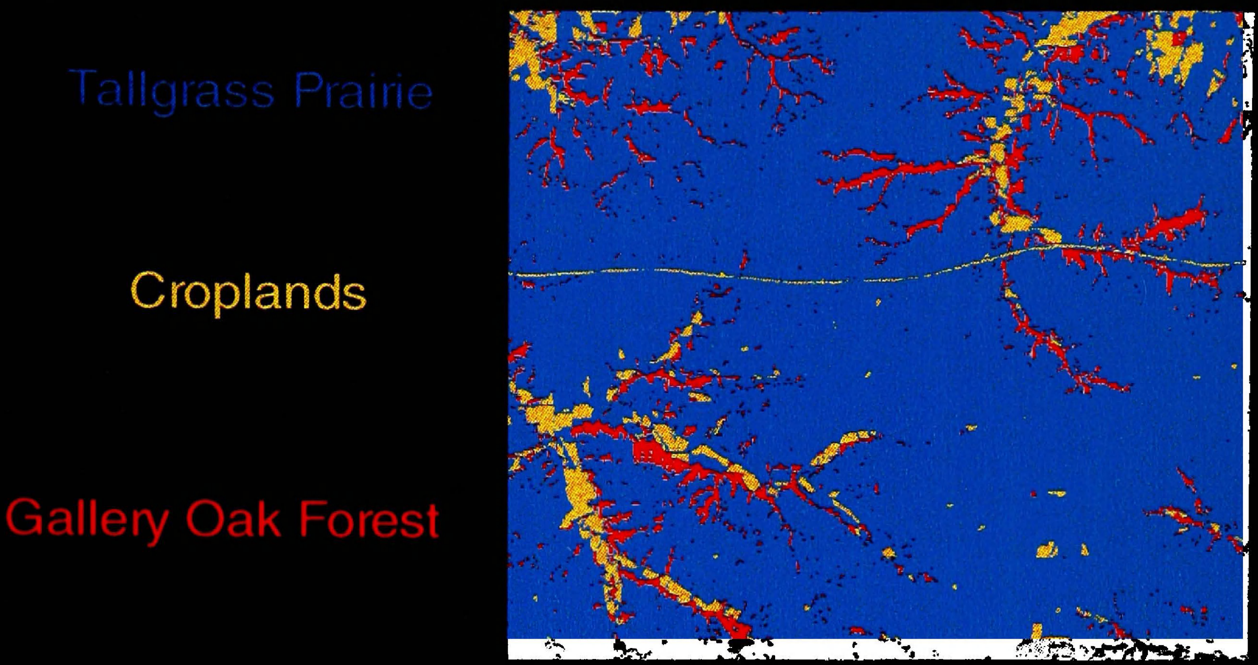


Figure 3 - Soil depth and cover type

Soil depth was determined from the DEM for the FIFE site using the methods of Zheng et al. (in press) Where a topographic index is used to distribute soil depth based on known mean and maximum depths, slope, and contributing area.

Cover type was compiled from data available on the FIFE CD-ROM set (Strebal 1992). Cover type determined how vegetation would be differentially parameterized for the model runs.

Cover Types for the FIFE Site



Simulated Soil Depth for the FIFE Site

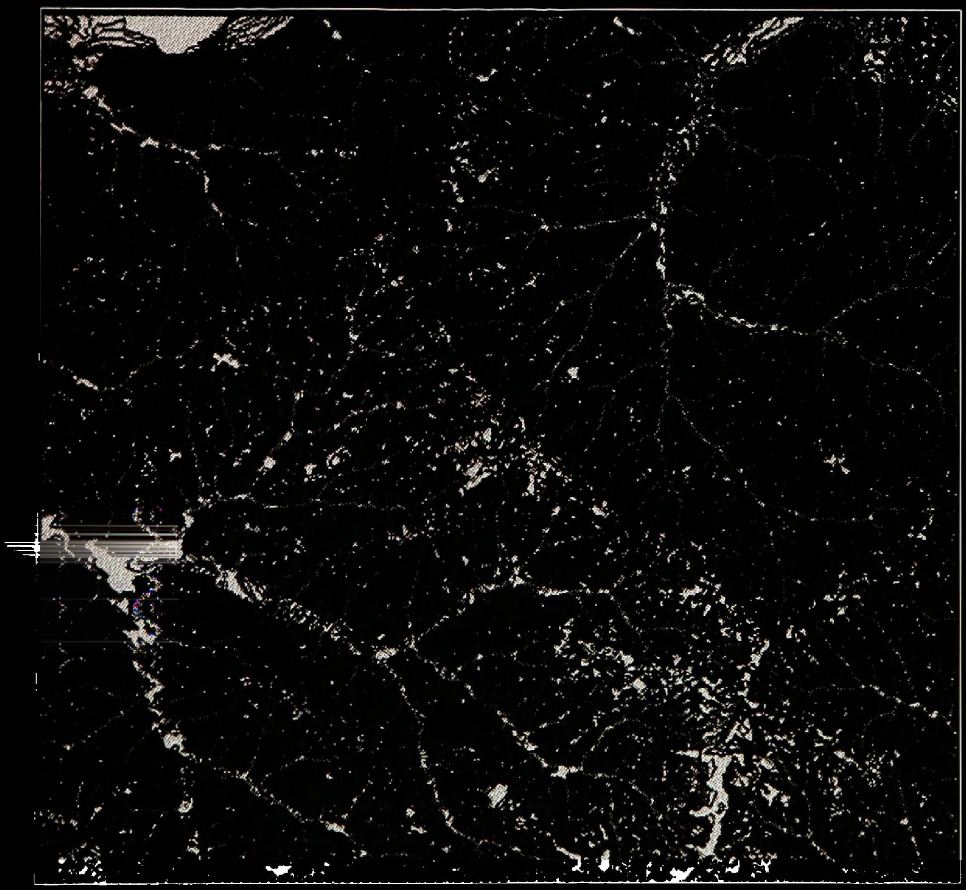


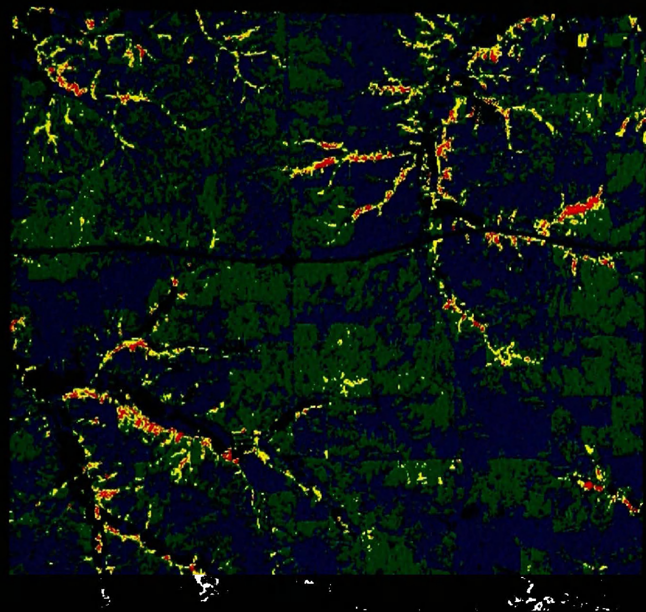
Figure 4 - LAI for the FIFE site

LAI was determined using the SAIL model developed for FIFE by Fred Huemmrich. LAI was derived for June 12, 1987; July 14, 1987; and August 15, 1987 from NDVI products available on the FIFE CD-ROM set, volume 5. The color scheme follows:

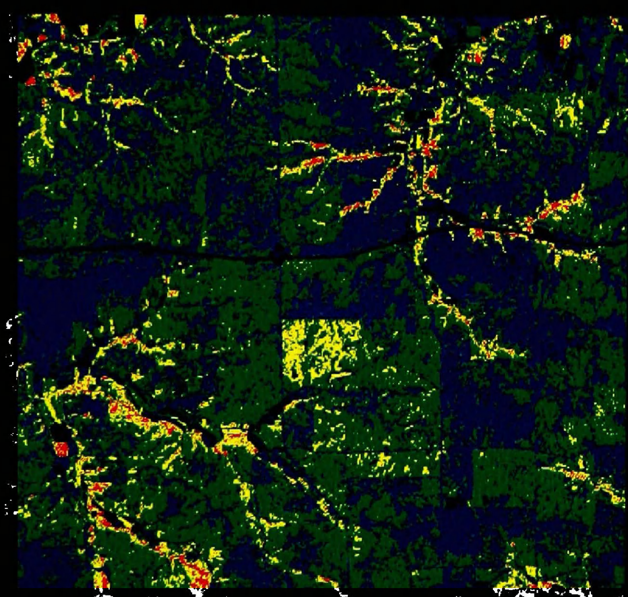
0	Black
0.1 - 1.0	Blue
1.1 - 2.0	Green
2.1 - 3.0	Yellow
3.1 - 4.0	Orange
4.1 - 5.0	Red

Values for LAI were highest for the Oak forests found in valley bottoms and some of the steeper slopes. LAI was a primary variable in extrapolating calculations of ET and NEE across the FIFE site.

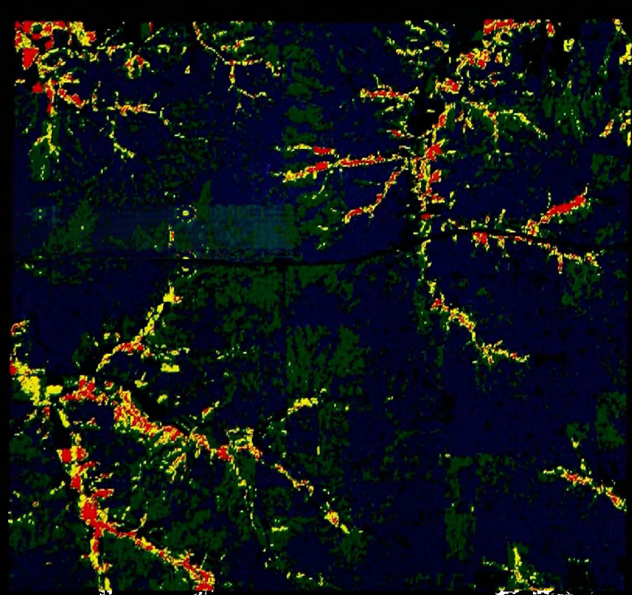
LAI for the FIFE Site



June 12, 1987



July 14, 1987

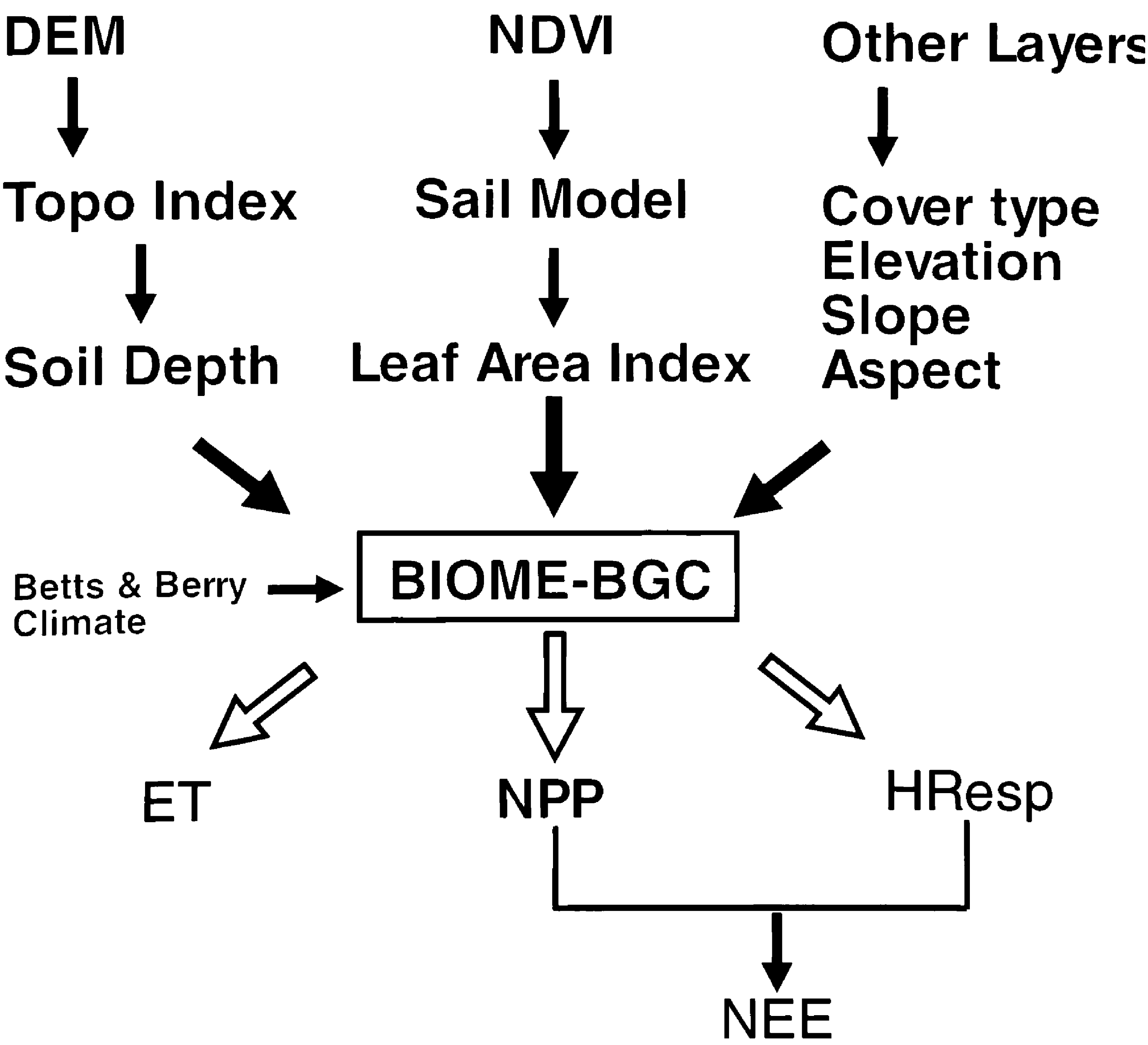


August 15, 1987

Figure 5 - Summary of model operation

This simple flowchart describes how the spatial input layers were used in combination with a climate file and BIOME-BGC to output coverages for evapotranspiration and net ecosystem exchange.

Summary of BIOME-BGC Simulations



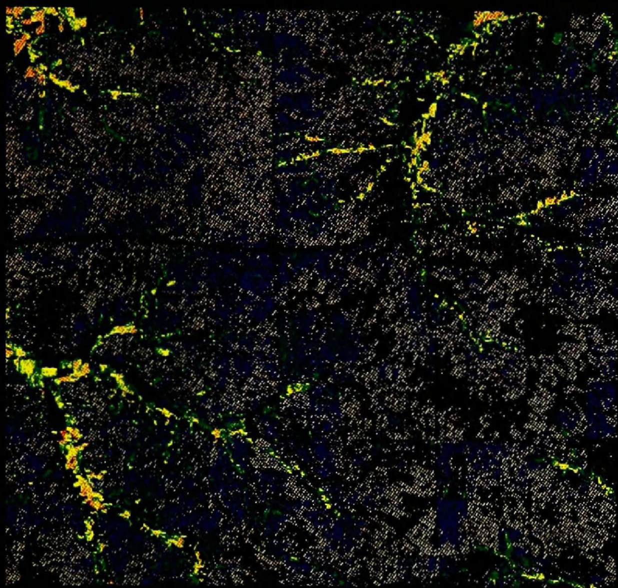
530 x 530 Seperate Simulations

Figure 6 - Simulated evapotranspiration for the FIFE site.

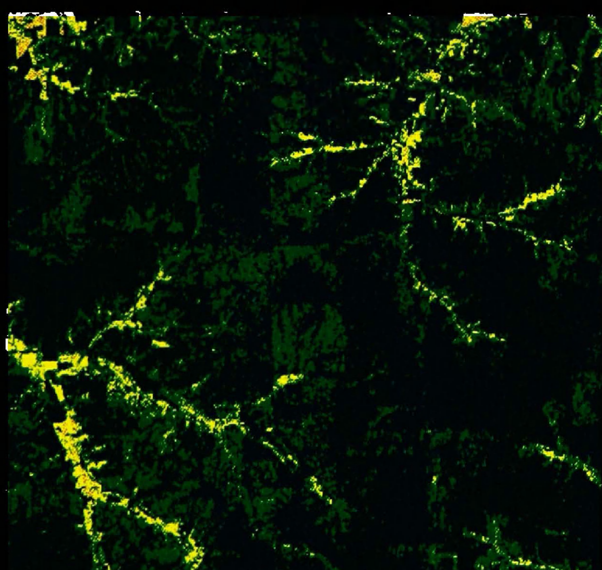
Evapotranspiration (ET) was mapped by BIOME-BGC for the three dates corresponding with the three LAI images. ET was affected by topography, LAI, soil characteristics, and cover type. The extreme differences between the June image and the July and August images were probably due to differences in available soil water. The color scheme follows:

0 - 1.0	mm	Black
1.1 - 2.0	mm	Gray
2.1 - 3.0	mm	Blue
3.1 - 4.0	mm	Blue/green
4.1 - 5.0	mm	Green
5.1 - 6.0	mm	Yellow/green
6.1 - 7.0	mm	Yellow
7.1 - 8.0	mm	Yellow/orange
8.1 - 9.0	mm	Orange
9.1 - 10.0	mm	Red/orange
10.1 - 11.0	mm	Red

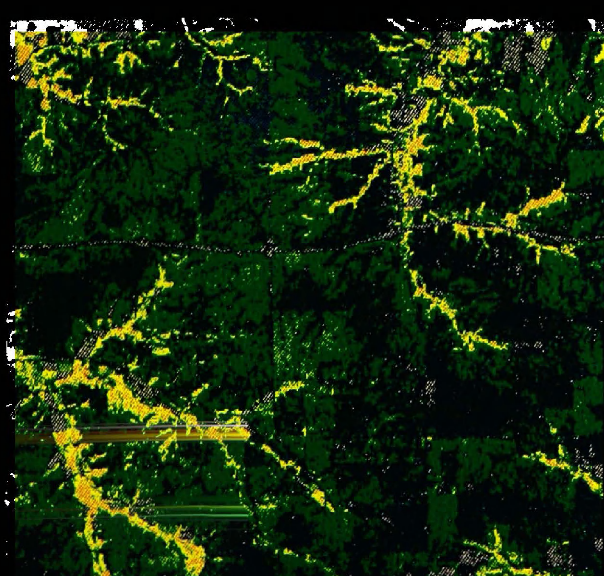
Simulated Evapotranspiration for the FIFE Site



June 12, 1987



July 14, 1987



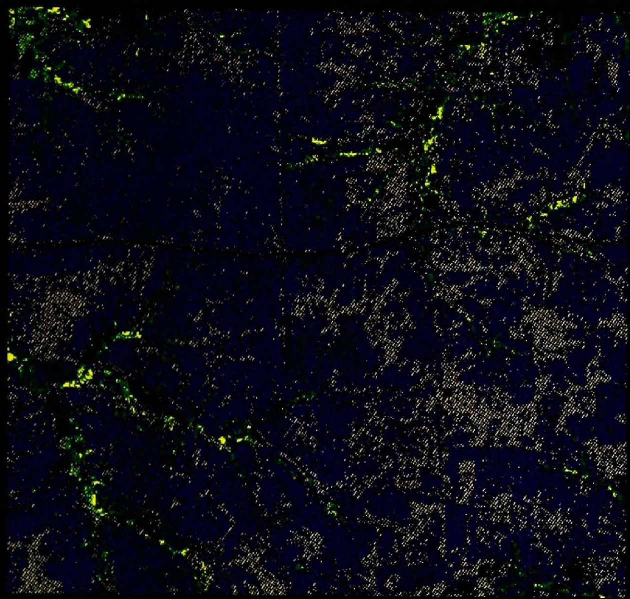
August 15, 1987

Figure 7 - Simulated net ecosystem exchange for the FIFE site

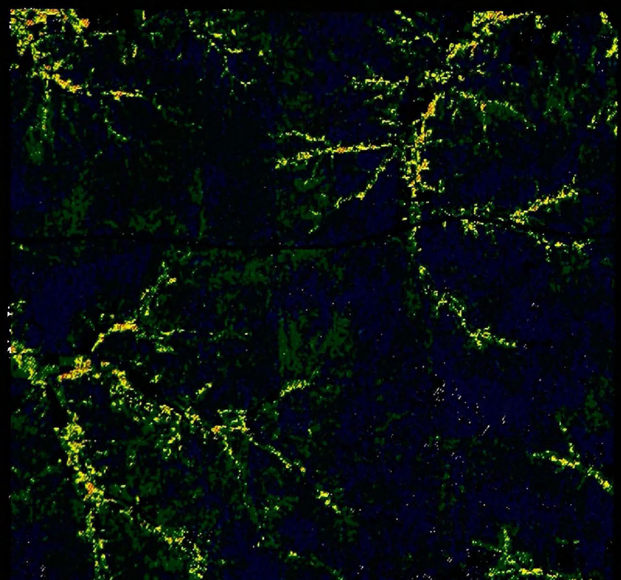
Net ecosystem exchange (NEE) for the FIFE site was mapped by BIOME-BGC for the days corresponding with the three LAI images. Values for NEE ranged from the negative to 16 g m^{-2} day $^{-1}$. The color scheme follows:

< -10.0	g m^{-2} day^{-1}	Black
-10.0 - 0.0	g m^{-2} day^{-1}	Gray
0.1 - 1.2	g m^{-2} day^{-1}	Blue
1.3 - 2.4	g m^{-2} day^{-1}	Blue/green
2.5 - 3.6	g m^{-2} day^{-1}	Green
3.7 - 4.8	g m^{-2} day^{-1}	Yellow/green
4.9 - 6.0	g m^{-2} day^{-1}	Yellow
6.1 - 7.2	g m^{-2} day^{-1}	Yellow/Orange
7.3 - 9.6	g m^{-2} day^{-1}	Orange
9.7 - 12.0	g m^{-2} day^{-1}	Red/orange
12.1 - 14.4	g m^{-2} day^{-1}	Red
> 14.4	g m^{-2} day^{-1}	Magenta

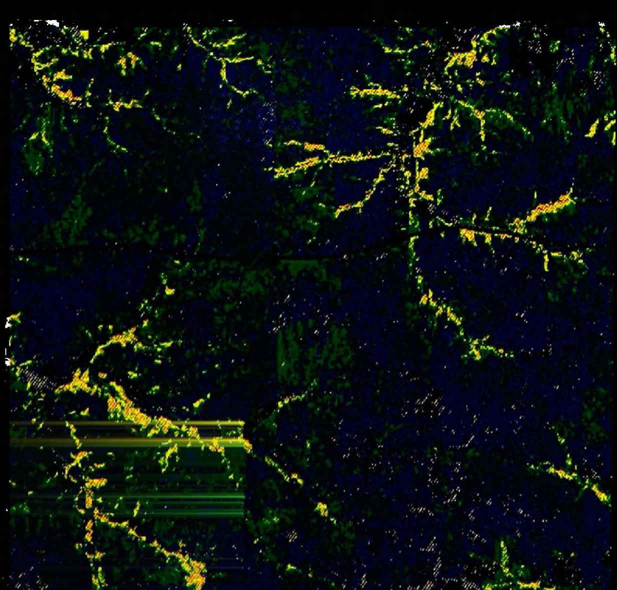
Simulated Net Ecosystem Exchange For the FIFE Site



June 12, 1987



July 14, 1987



August 15, 1987

Figure 8 - Minimum and Maximum temperatures for the FIFE site from yearday 146 to yearday 289.

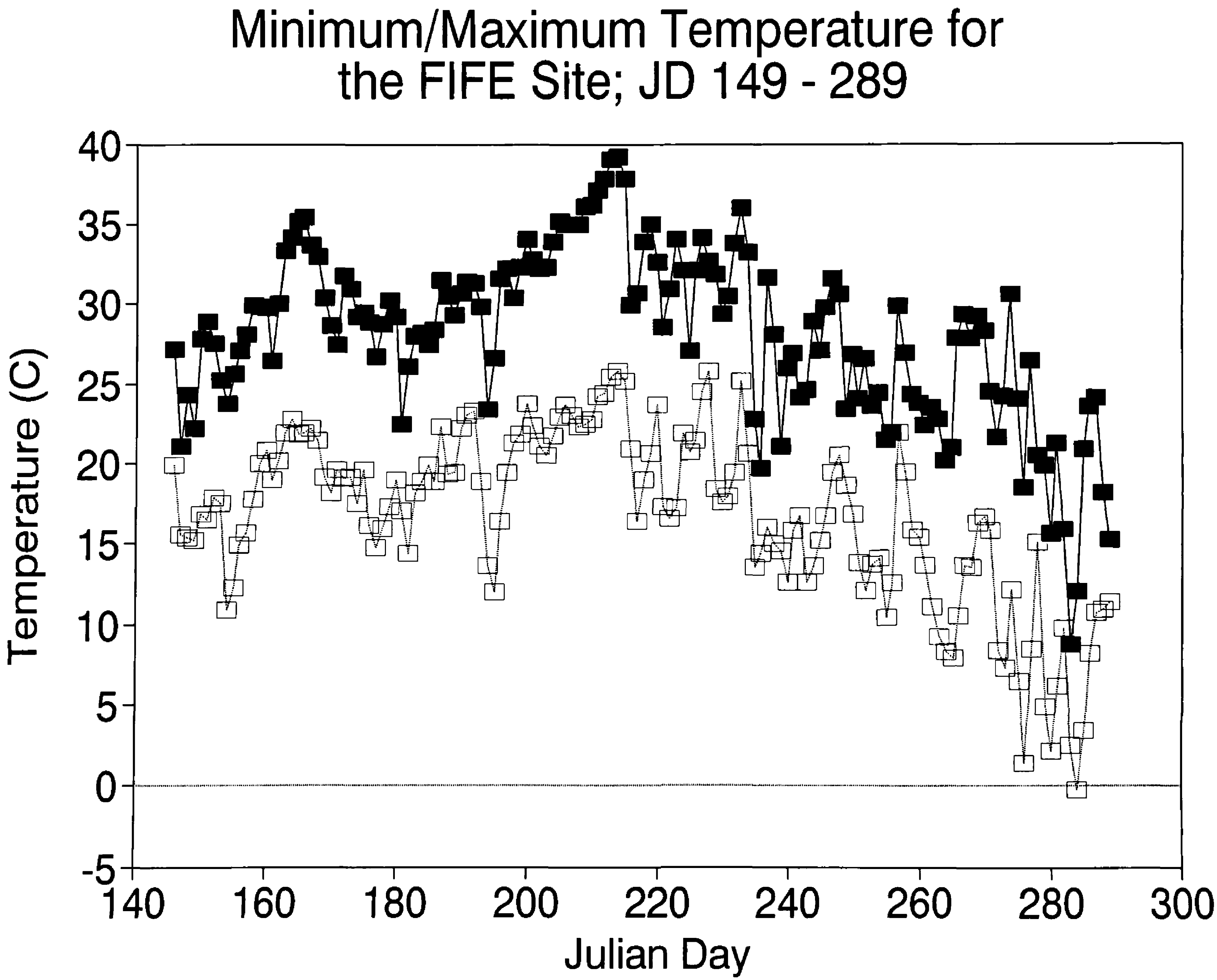
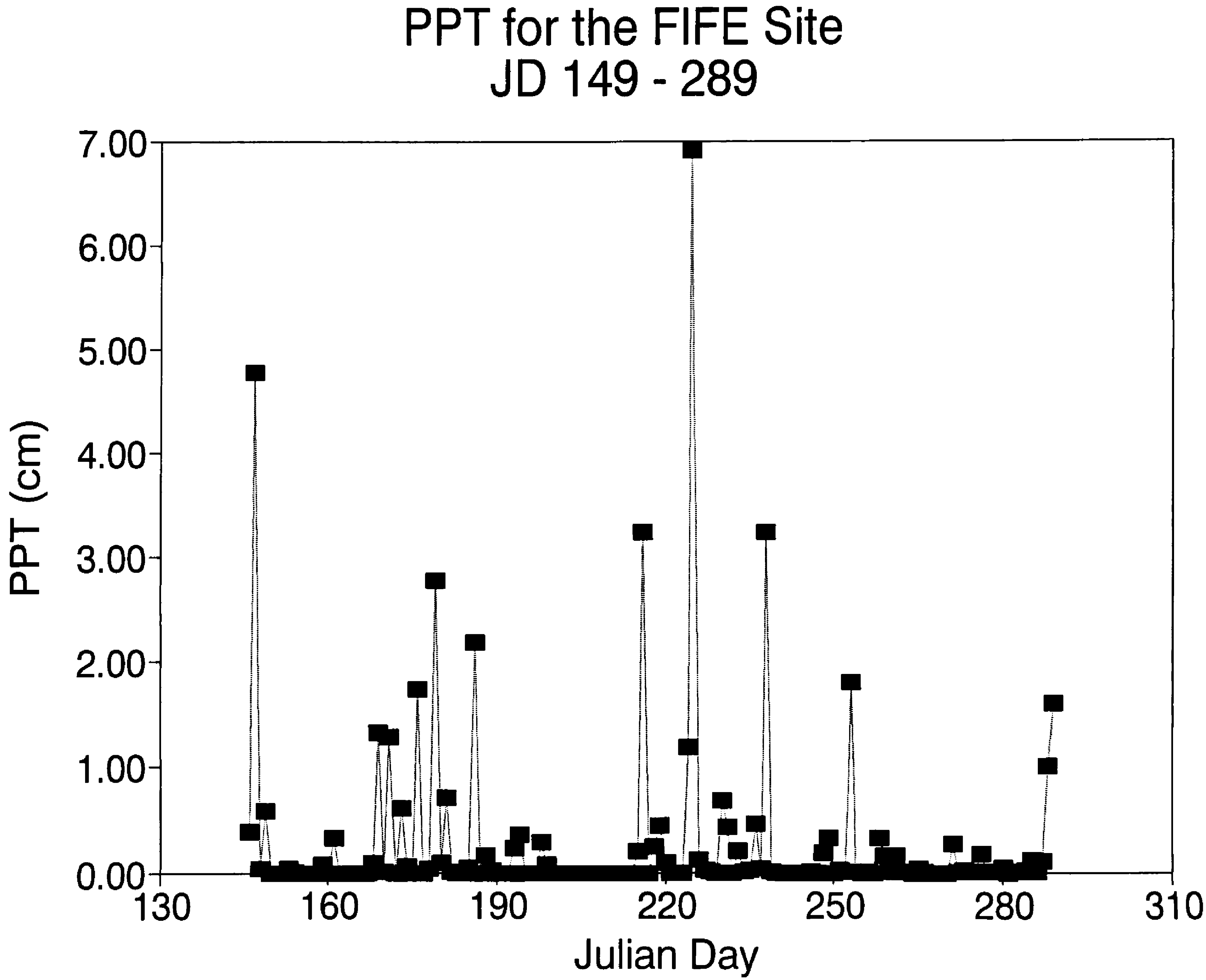

Minimum/Maximum Temperature for
the FIFE Site; JD 149 - 289
Temperature (C)
40
35
30
25
20
15
10
5
0
-5
140
160
180
200
220
240
260
280
300
Julian Day

Figure 9 - Precipitation for FIFE from yearday 146 to yearday 289.



PPT for the FIFE Site
JD 149 - 289
PPT (cm)
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
130
160
190
220
250
280
310
Julian Day

TABLE 1. Variables and Parameters for BIOME-BGC Involving the Hydrologic and Carbon Cycles for the FIFE Study Area

<u>Variables</u>	
Soil water content	(m^3/ha)
Leaf carbon	(kg C/ha)
Stem carbon	(kg C/ha)
Coarse root carbon	(kg C/ha)
Fine root carbon	(kg C/ha)
Soil carbon	(kg C/ha)
<u>Parameters</u>	
Percent clay	(%)
Percent silt	(%)
Percent sand	(%)
Initial soil temperature	(°C)
Maximum volumetric water content	(m^3/m^3)
Minimum volumetric water content	(m^3/m^3)
Latitude	(°)
<u>Parameters Based on Cover Type</u>	
Ψ_{leaf} at stomatal closure	(-MPa)
Minimum Ψ_{leaf}	(-MPa)
VPD at stomatal closure	(-MPa)
Specific Leaf Area	(m^3/kg C)
Interception coefficient	(m/LAI/day)
Light extinction coefficient	
Maximum leaf conductance	(m/s)
Leaf respiration	(kg C/(kg C/ha)^1/day @ 0°C)
Stem respiration	(kg C/(kg C/ha)^2/day @ 0°C)
Root respiration	(kg C/(kg C/ha)^3/day @ 0°C)
Maintenance respiration coeff.	(@ Q_{10}=2.0)
Maximum PSN rate	($\mu mol/m^2/s$)
Optimum PSN temperature	(°C)
Maximum PSN temperature	(°C)

Table 2 - Climatic Driving Variables

Required Inputs	
Yearday	
Maximum air temperature	(°C)
Minimum air temperature	(°C)
Precipitation	(cm)
Calculated or Optional Inputs	
Daylength	(s)
Daily solar radiation	(kJ/m^2/day)
Photosynthetically active radiation	(kJ/m^2/day)
Average daytime relative humidity	(%)
Atmospheric CO_2	(ppm)
Soil temperature	(°C)

Appendix 1 - Site-averaged Meteorological Data for the FIFE Experiment Compiled by Alan Betts and Joseph Berry

JD	solrad	tmax	tmin	rh	ppt
146.00	16938.70	27.20	19.90	83.00	0.39
147.00	3966.50	21.10	15.60	92.90	4.77
148.00	19218.50	24.30	15.40	82.40	0.04
149.00	22695.30	22.20	15.20	88.20	0.58
150.00	27161.70	27.80	16.90	84.10	0.00
151.00	27600.60	28.90	16.50	73.20	0.00
152.00	29217.90	27.50	17.90	79.10	0.00
153.00	10438.60	25.20	17.50	85.20	0.04
154.00	30638.30	23.80	10.90	64.10	0.01
155.00	31652.50	25.60	12.30	62.20	0.00
156.00	30824.70	27.10	14.90	65.30	0.00
157.00	32076.00	28.10	15.70	62.70	0.00
158.00	30790.70	29.90	17.80	58.70	0.00
159.00	25285.80	29.80	20.00	67.70	0.08
160.00	23398.90	29.70	20.80	73.50	0.00
161.00	12196.90	26.40	19.00	88.90	0.33
162.00	23716.20	30.00	20.20	83.70	0.00
163.00	31868.30	33.30	21.90	79.10	0.00
164.00	32489.50	34.20	22.70	78.30	0.00
165.00	32422.80	35.20	21.80	72.90	0.00
166.00	28723.20	35.40	21.90	67.40	0.00
167.00	32287.90	33.70	22.20	73.50	0.00
168.00	23909.60	33.00	21.50	76.60	0.09
169.00	15876.50	30.40	19.20	74.40	1.33
170.00	28906.20	28.60	18.10	88.20	0.00
171.00	18578.30	27.40	19.60	84.80	1.29
172.00	29985.00	31.80	19.10	80.50	0.00
173.00	18320.90	30.90	19.20	80.90	0.61
174.00	30749.60	29.20	17.50	89.40	0.07
175.00	24646.20	29.50	19.60	83.00	0.00
176.00	28696.80	28.80	16.10	87.90	1.74
177.00	27324.40	26.70	14.70	68.00	0.00
178.00	27873.20	28.70	15.90	71.40	0.03
179.00	25027.30	30.20	17.30	79.70	2.78
180.00	12710.00	29.20	19.00	81.20	0.10
181.00	8872.10	22.50	17.00	91.80	0.70
182.00	26092.20	26.10	14.40	81.20	0.00
183.00	25161.10	28.00	18.10	81.50	0.00
184.00	20739.00	28.20	18.90	83.10	0.00
185.00	11445.40	27.40	19.90	91.60	0.05
186.00	22207.90	28.40	18.90	90.90	2.19
187.00	28379.70	31.50	22.30	86.20	0.00
188.00	12680.10	30.50	19.30	88.50	0.17
189.00	26066.90	29.30	19.40	78.20	0.03
190.00	21935.60	30.70	22.20	83.70	0.00
191.00	27412.60	31.40	23.00	79.70	0.00

192.00	27673.30	31.30	23.30	74.40	0.00
193.00	18158.50	29.80	18.90	79.90	0.23
194.00	27018.50	23.40	13.60	79.40	0.36
195.00	29145.10	26.60	12.00	64.80	0.00
196.00	30380.00	31.60	16.40	65.20	0.00
197.00	29720.60	32.20	19.40	74.10	0.00
198.00	17202.40	30.40	21.30	79.00	0.29
199.00	28414.20	32.30	21.80	78.40	0.07
200.00	28908.10	34.10	23.80	73.00	0.00
201.00	28884.80	32.80	22.40	73.40	0.00
202.00	27583.10	32.20	21.10	70.80	0.00
203.00	27289.90	32.30	20.50	67.00	0.00
204.00	27577.90	33.90	21.70	70.10	0.00
205.00	28328.20	35.20	22.90	67.80	0.00
206.00	26913.30	35.00	23.70	65.20	0.00
207.00	28192.20	35.00	23.00	67.30	0.00
208.00	27676.20	35.00	22.30	63.50	0.00
209.00	28657.40	36.10	22.50	60.10	0.00
210.00	26707.10	36.20	22.70	57.70	0.00
211.00	28564.40	37.10	24.20	53.80	0.00
212.00	28652.70	37.80	24.40	53.00	0.00
213.00	29222.40	39.00	25.40	52.00	0.00
214.00	28400.40	39.20	25.80	49.00	0.00
215.00	19501.50	37.80	25.10	51.20	0.21
216.00	21927.10	29.90	20.90	89.90	3.24
217.00	28992.30	30.70	16.40	73.10	0.00
218.00	22196.60	33.90	19.00	65.70	0.24
219.00	25148.50	35.00	20.60	72.80	0.44
220.00	10553.00	32.60	23.70	71.20	0.09
221.00	26135.20	28.50	17.30	81.80	0.00
222.00	28517.70	30.90	16.60	75.30	0.00
223.00	28200.10	34.10	17.20	71.80	0.00
224.00	9273.70	32.10	21.90	87.10	1.18
225.00	12009.50	27.10	20.70	94.10	6.90
226.00	24961.90	32.10	21.50	90.10	0.12
227.00	28085.10	34.20	24.50	71.20	0.03
228.00	27558.90	32.70	25.80	67.10	0.01
229.00	28275.70	31.90	18.40	59.60	0.00
230.00	21876.20	29.40	17.60	75.40	0.68
231.00	23817.90	30.50	18.00	83.90	0.44
232.00	26426.90	33.80	19.40	72.80	0.00
233.00	27128.90	36.00	25.10	51.90	0.20
234.00	21886.20	33.20	20.60	72.60	0.00
235.00	18693.80	22.70	13.50	78.70	0.02
236.00	4348.20	19.70	14.40	88.40	0.45
237.00	21989.40	31.70	16.00	81.80	0.04
238.00	5763.10	28.10	15.00	96.50	3.24
239.00	12133.00	21.10	14.60	88.40	0.01
240.00	25788.00	26.00	12.60	80.70	0.00
241.00	25986.30	26.90	15.80	69.50	0.00
242.00	23385.10	24.10	16.80	76.70	0.00
243.00	26572.40	24.60	12.60	75.90	0.00

244.00	24938.50	28.90	13.60	65.00	0.00
245.00	24781.30	27.10	15.20	75.20	0.00
246.00	18106.60	29.70	16.80	73.00	0.00
247.00	23980.20	31.60	19.40	60.80	0.00
248.00	16734.50	30.60	20.50	65.80	0.18
249.00	4449.60	23.40	18.60	89.70	0.34
250.00	18813.40	26.80	16.90	88.20	0.00
251.00	23499.70	24.00	13.80	85.30	0.02
252.00	19439.30	26.50	12.10	64.90	0.00
253.00	21957.30	23.60	13.70	88.80	1.81
254.00	20601.20	24.40	14.10	82.20	0.01
255.00	21960.50	21.50	10.40	80.80	0.00
256.00	24449.20	21.90	12.50	82.10	0.00
257.00	19436.80	29.80	21.90	65.80	0.00
258.00	15634.30	26.90	19.40	89.00	0.33
259.00	13651.80	24.30	15.80	88.60	0.16
260.00	21475.10	23.80	15.40	82.80	0.00
261.00	19101.60	22.40	13.60	80.90	0.17
262.00	23267.90	23.50	11.10	62.30	0.01
263.00	22163.80	22.70	9.20	67.50	0.01
264.00	19950.60	20.20	8.30	73.90	0.00
265.00	20062.20	21.00	7.90	81.00	0.03
266.00	21855.80	27.80	10.50	66.30	0.01
267.00	21841.50	29.30	13.60	68.30	0.00
268.00	20596.30	27.80	13.50	74.30	0.00
269.00	18726.30	29.20	16.30	61.60	0.00
270.00	19964.30	28.30	16.70	69.60	0.00
271.00	16673.90	24.50	15.80	80.00	0.28
272.00	21197.50	21.60	8.40	66.00	0.01
273.00	19628.00	24.20	7.30	62.80	0.02
274.00	19808.90	30.60	12.20	50.50	0.01
275.00	19545.90	24.00	6.50	43.30	0.01
276.00	24373.30	18.50	1.40	55.40	0.18
277.00	20878.00	26.40	8.50	46.30	0.00
278.00	19583.90	20.50	15.10	44.70	0.00
279.00	18712.80	19.90	4.90	44.10	0.00
280.00	18409.10	15.70	2.10	61.90	0.05
281.00	16160.70	21.30	6.20	47.10	0.00
282.00	15987.90	15.90	9.80	47.30	0.01
283.00	6981.10	8.80	2.50	63.90	0.01
284.00	17579.70	12.10	-0.30	67.70	0.02
285.00	17413.00	20.90	3.40	69.80	0.12
286.00	15560.50	23.60	8.20	51.80	0.01
287.00	9825.40	24.10	10.80	57.60	0.11
288.00	4936.20	18.20	11.00	50.50	1.01
289.00	7822.50	15.30	11.40	92.00	1.60