Section 1

Project Overview

Objectives

- Develop an understanding of the environmental and ecological controls on leaf area index (LAI), total net primary production (NPP), and carbon allocation within and among biomes
- Examine relationships between NPP and net ecosystem exchange (NEE) and how to translate between them using ecological models
- Develop algorithms to scale vegetation cover, LAI, fraction absorbed photosynthetic active radiation (f_{APAR}) and NPP from point measurements to larger regions (several square kilometers)
- Quantify errors and uncertainties that exist when scaling vegetation characteristics from small plots to large areas

Methods

- At a given site, measure land cover, LAI, f_{APAR}, and NPP (aboveground and belowground components) for a 5 x 5 km area
- Extrapolate field measurements to high-resolution grids (cover, LAI, f_{APAR}, and NPP) using Landsat imagery and statistical and ecological models
- Characterize errors in these grids using independent field observations
- Compare field-verified high-resolution grids to Moderate Resolution Imaging Spectrometer (MODIS) product grids
- Isolate effects of land-cover generalization, image grain size, and ecological modeling parameters on MODIS NPP estimates
- In the field, examine spatial autocorrelation of cover, LAI /f_{APAR}, and NPP, and use this information to guide scaling algorithms

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Background and Summary

The objective of BigFoot is provide ground validation of MODLand (MODIS Land Discipline Group) land cover, leaf area index (LAI), f_{APAR}, and net primary production (NPP) products. The name BigFoot was selected to describe the multiple scales, or footprints, of ground validation that the project will undertake (Figure 1.1). The current BigFoot study plan covers measurement, mapping, and modeling activities at four sites, each equipped with a meteorological flux tower that makes continuous measurements of energy, water, and carbon fluxes for a roughly 1-km^2 footprint. Ground validation measurements will be conducted both within the 1-km^2 eddy flux tower footprint and in an outlying area covering 25 km^2.

The core BigFoot products will be 25-km^2 surfaces at 25-m spatial resolution for land cover, LAI, f_{APAR}, and NPP. Land cover and LAI will be based on land satellite (LANDSAT) ETM+ (i.e., passive-sensor) imagery, and NPP will be based on spatially distributed, process-based biogeochemistry models. The models will be initialized with the land cover and LAI surfaces and driven by time-series meteorological data. Validation of BigFoot land cover and LAI surfaces will be based on ground sampling of land cover and LAI, which is not used in development of the original surfaces. Validation of BigFoot carbon and water flux estimates will be made over the flux tower footprints at a daily time step, based on flux tower measurements, and for the 5 x 5 km study area (henceforth referred to as the MODLand footprint) based on a sample of new aboveground NPP (NPP_A) measurements. Belowground NPP (NPP_B) will be measured mostly in the immediate vicinity of the flux towers.

For comparisons to MODLand NPP products, the BigFoot 25-m^2 grid at each site will be overlain with the 1-km^2 MODLand grid that is spatially consistent with the MODIS imagery. NPP models will be run for calendar years 1999 and 2000 for the Northern Old Black Spruce (NOBS) boreal forest and agricultural cropland (AGRO) study area and compared with MODLand NPP products produced at 8-day and annual time steps (Figure 1.2). Similar analyses will be conducted for

Figure 1.1. Conceptual model illustrating the use of field measurements and remote sensing to characterize the vegetation cover, f_{APAR}, LAI, and NPP for the BigFoot sites.

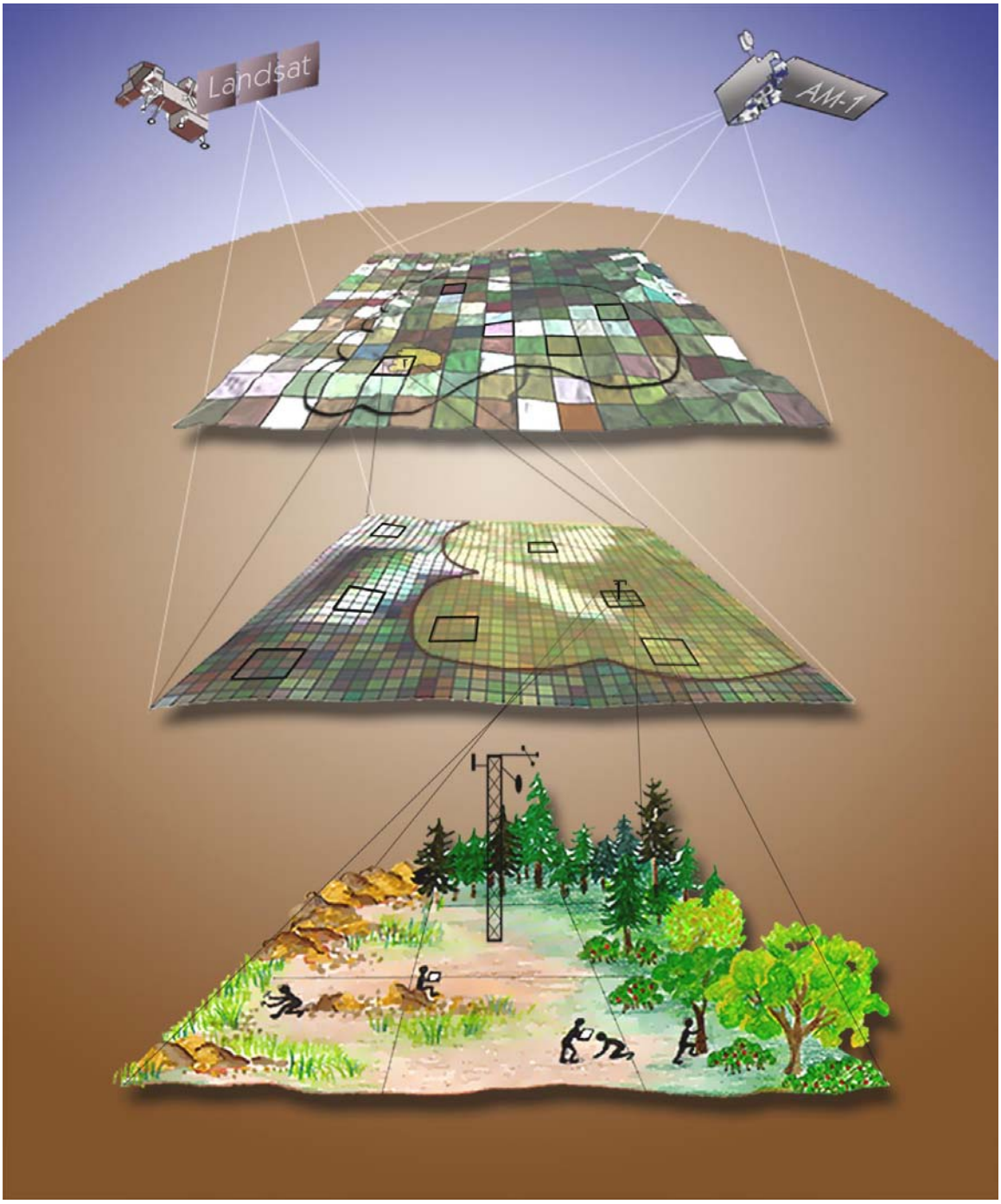
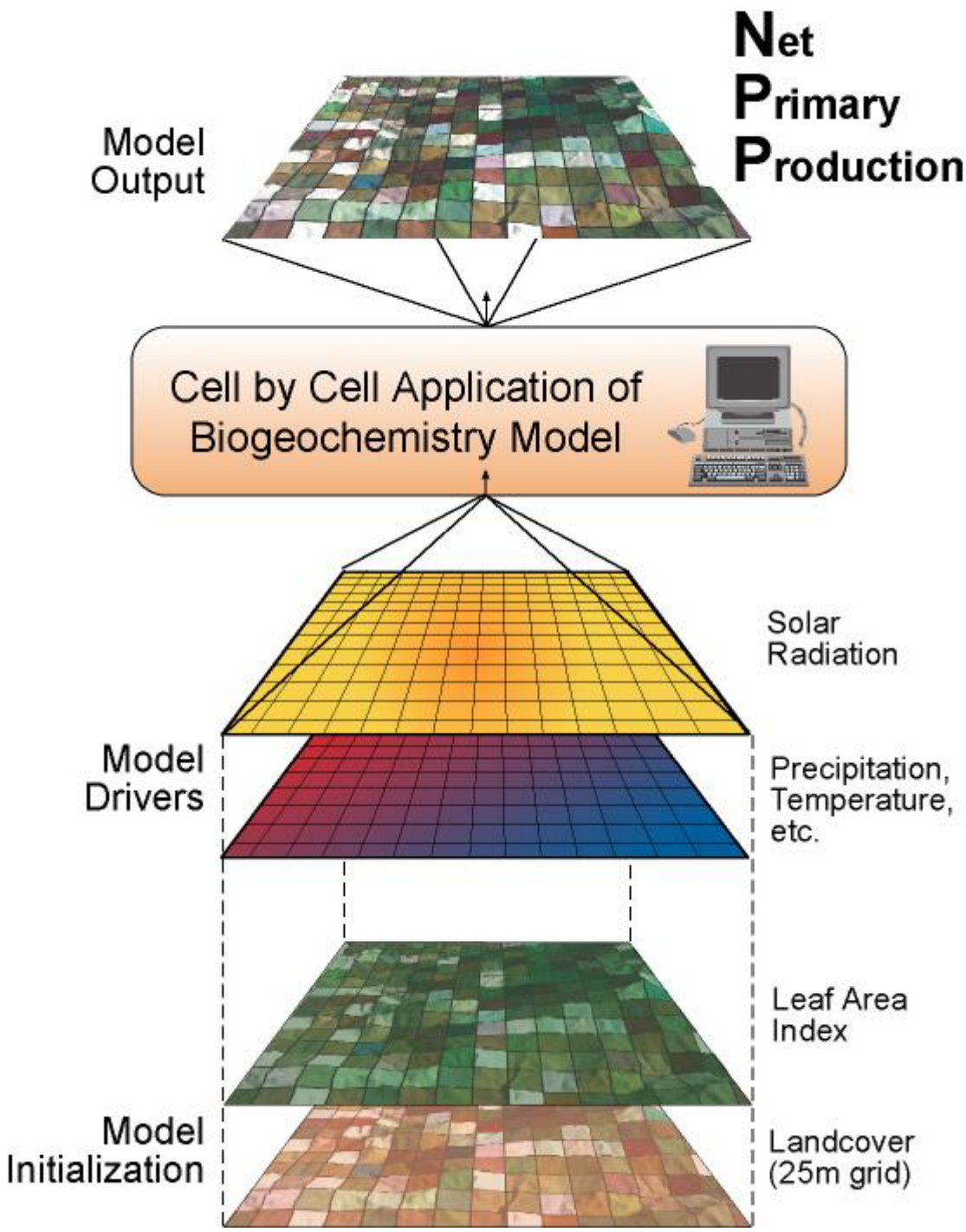


Figure 1.2. Conceptual model illustrating the approach used by BigFoot scientists to model vegetation characteristics for the validation of MODLand products.



the tallgrass prairie [Konza Prairie (KONZ)] and temperate forest [Harvard Forest (HARV)] study areas in 2000 and 2001. Differences between BigFoot and MODLand NPP products will be evaluated in terms of the differences in spatial resolution of the analysis, the differences in vegetation classification system, and the differences in epsilon, the light use efficiency factor, as used in the MODLand NPP algorithm and as derived from BigFoot NPP simulations.

Sites

The primary goal of BigFoot is MODIS product validation. To that end, we will compare fine-grained gridded surfaces developed within our project to MODIS coarse-grained surfaces. We want to know under what sets of conditions these surfaces both correspond and diverge. In particular, the effect of fine-grained cover type heterogeneity, the generalization of land cover classes, and the derivation of production efficiency factors will be evaluated. Comparisons of co-located grid cells within each site are one level of validation, whereas a comparison of grid cell summaries across sites is another. Theoretically, it is possible that not a single MODIS cell estimates land cover, LAI, and NPP accurately, but that at the multi-cell level within a site, MODIS does accurately represent these variables. This latter level of validation is critical as a first determination of how well MODIS products provide accurate estimates across sites (e.g., globally).

Several factors were considered in site selection, including BigFoot objectives, representation across the range of biomes, budgetary and logistical constraints, and relative cost of potential sites within the overall budget. BigFoot is attempting to be as consistent as possible with Earth Observing System (EOS) validation goals and objectives; thus, an additional criterion was that the sites have an active eddy flux tower.

A total of four sites were selected for the BigFoot study: a boreal forest (NOBS), a temperate hardwood forest (HARV), a midwestern cropland (AGRO), and tallgrass prairie grassland (KONZ). The boreal evergreen conifer forest site is the Boreal Ecosystem-Atmosphere Study (BOREAS) Northern Study Area (NSA) old black spruce site (NOBS) near Thompson, Manitoba, Canada. Drs. S. Wofsy, Harvard University, and Mike Goulden, University of California—Irvine, oversee the operation of the flux tower at the site. The temperate crop site has alternate crops of corn and soybean; it is located near Champaign-Urbana, Illinois. Dr. Tilden Meyers, National Oceanic and Atmospheric Administration (NOAA), oversees the flux tower at the site. The site is also used for Global Energy and Water Cycle Experiment (GEWEX) validation. The tallgrass prairie site is located at Konza Prairie near Manhattan, Kansas. The site is part of the U.S. Long-Term Ecological Research (LTER) network. Dr. Jay Ham, Kansas State University, oversees the flux tower at the site. The temperate hardwood forest site is located at the Harvard Forest, near Petersham, Massachusetts, and

is also part of the U.S. LTER network. Dr. Steve Wofsy, Harvard University, oversees the operation of the flux tower.

Field LAI and NPP Measurements

At each site a 25-km^2 area has been identified using ETM+ imagery. The general sample design is a nested approach that provides a greater number of sample locations for easily measured characteristics (i.e., vegetation cover and LAI) and fewer sample locations for more laborious measurements (i.e., NPP_A and NPP_B). The sampling design is primarily an irregular spatial series, sometimes referred to as a systematic spatial-cluster design (Figure 1.3). The design is a spatial application of a time series, with the tessellation unit defined as the number of sample points over a predetermined distance. Using the vegetation cover, LAI, f_{APAR}, or NPP data from this sampling design, a variogram (a plot of autocorrelation coefficient values in ordinate versus distance) can be constructed to determine the following: autocorrelation intensity, the size of the zone of influence, and the type of spatial pattern. The shape of the variogram provides insight into spatial pattern and underlying processes that influence vegetation cover, LAI, and NPP. This complex sampling design is an efficient sampling design (Fortin et al. 1989), but it requires a pair of real-time, differential processing Global Positioning System (GPS) units to accurately locate the plots in the field. Plots will be located in all vegetation cover classes within the 25-km^2 grid to ensure adequate coverage (Figure 1.3).

We will make direct and indirect estimates of LAI at each site. Direct measurement approaches will include periodic area harvest for the crop and prairie ecosystems or application of allometric equations to tree diameter data for the forest sites. LAI will be estimated indirectly using optical approaches (Gower and Norman 1991, Fassnacht et al. 1994, Chen et al. 1997). Gower and Campbell (or colleagues) will visit each site a minimum of three times each year and determine LAI for the major land cover types using Li-Cor LAI-2000 Plant Canopy Analyzers. LAI will be calculated at all sites as

$$LAI = (1-\alpha)\ Le\ \gamma_E / \Omega_E,$$

where

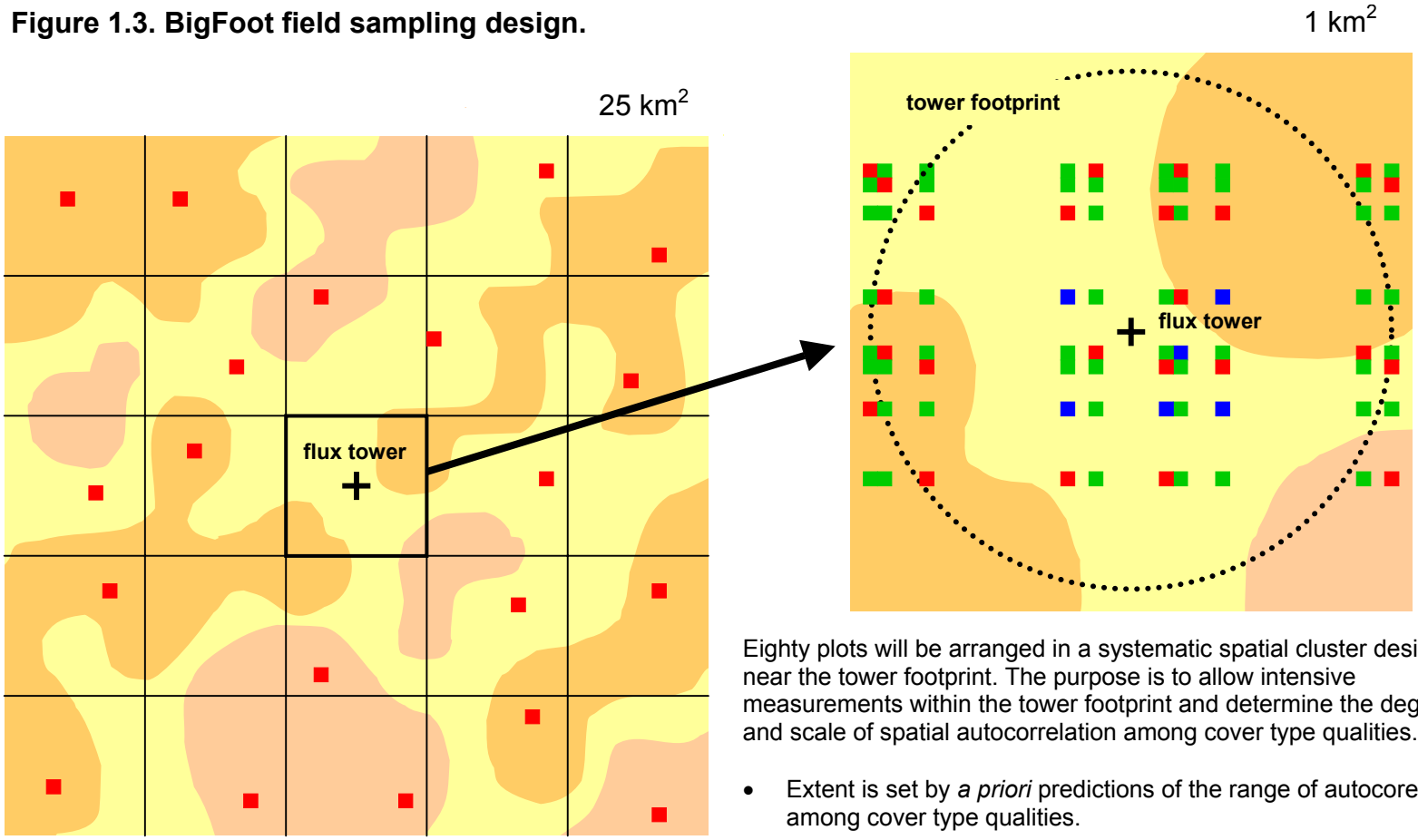
α = ratio of wood area to total plant area (wood + foliage area) and can be determined in forests from allometric relationships or using a multiband image analyzer (Gower et al. 1999);

Le = effective leaf area index, which is commonly measured by instruments like the Li-Cor LAI 2000;

γ_E = needle-to-shoot area ratio, which quantifies clumping at the shoot level and increases as clumping increases. $\gamma_E = A_n/A_s$, where A_n is the ratio of one half the total area (all sides) of needles in a shoot and A_s is one half the total shoot area.

Ω_E = clumping correction factor for clumping at the branch-to-tree level.

Figure 1.3. BigFoot field sampling design.



Twenty plots (25 x 25 m in size) will be placed outside the tower footprint and within a 25-km^2 grid. The plots will be arranged in a deliberate fashion such that each of the major cover types is represented (i.e., stratified by cover type). The purpose is to verify that cover type-specific qualities hold over multi-kilometer distances and to address surface features that influence the 25-km^2 MODIS surface but are not necessarily present within the tower footprint.

Eighty plots will be arranged in a systematic spatial cluster design near the tower footprint. The purpose is to allow intensive measurements within the tower footprint and determine the degree and scale of spatial autocorrelation among cover type qualities.

- Extent is set by *a priori* predictions of the range of autocorelation among cover type qualities.
- Resolution (plot size) is set at 25 x 25 m by LANDSAT pixel size.
- Pattern and plot number is set by the number of cover types present and *a priori* predictions of their spatial arrangement.

Plots will be sampled at three levels of intensity:

- 3rd order plot: species comp, aboveground biomass, LAI, and f_{APAR}
- 2nd order plot: above plus aboveground productivity (NPP_A)
- 1st order plot: above plus below ground productivity (NPP_B)

Measurement of these parameters will be done following the protocol described in Fassnacht et al. (1994) and Chen et al. (1997). Results of all data analysis shoot architecture measurements and indirect estimates of LAI will be provided to site investigators. Estimates from these standard, well-established methods will be correlated to other LAI estimates obtained from either direct or indirect methods by site investigators. This approach has been used successfully in BOREAS (Chen et al. 1997). Average values by land cover class of specific leaf area and percent N in foliage will also be determined.

Net primary production is defined as the sum of the annual biomass production of each tissue (e.g., wood, foliage, roots). Various methods are used to estimate NPP_A and NPP_B, with some more suitable for small-stature vegetation communities (i.e., grasslands, tundra, agriculture crops) than for large-stature forests. We will estimate NPP using the following equation:

$$NPP = NPP_W + NPP_F + NPP_{CR} + NPP_{FR} + NPP_U + NPP_{GC} \quad , \qquad (1)$$

where

W = aboveground wood (e.g., stem + branches),
F = foliage,
CR = coarse roots,
FR = fine roots,
U = understory,
GC = ground cover (e.g., mosses and sphagnum).

Herbivory generally constitutes <10% NPP in forest ecosystems (Schowalter et al. 1986) and will be ignored in this study, but losses of NPP to herbivory and harvest must also be accounted for in the prairie and agriculture ecosystems. Aboveground woody biomass (e.g., stem and branch) and coarse root biomass will be estimated from allometric equations that correlate component biomass to an independent variable, usually diameter or basal area at breast height (1.3 m). Woody biomass increment is determined from radial growth, measured using increment cores. Numerous abiotic and biotic factors have been shown to influence the allometric coefficients for new foliage biomass; therefore, we will estimate new foliage production from annual leaf litterfall detritus production for forests where site- and species-specific allometric equations are not available (Gower et al. 1999). This approach assumes the canopy biomass is in steady state. In the case of the agroecosystems and prairie we will use clip plots throughout the growing season to quantify biomass production.

Total foliage biomass and leaf area equations will be from the literature (e.g., Gower et al. 1999). Where appropriate, biomass and leaf area data for harvested trees of the same species, but from different sites, will be composited and a generalized regression equation will be used. NPP_A of the shrub and herbaceous layers will be quantified using clip plots. NPP_A of bryophytes at the NOBS site will be estimated using crank wires for sphagnum and ingrowth mesh plots (MPs) for

feathermoss; these methods were used successfully in BOREAS (Gower et al. 1997, K. Bisbee unpublished data).

Fine root NPP and mortality will be estimated using minirhizotrons (Steele et al. 1997). Because of the large costs associated with obtaining and processing these data to calculate NPP_B, we will restrict our analysis to a maximum of the two dominant vegetation cover types at each site. Twenty-five minirhizotrons will be installed in each ecosystem, and fine root growth will be measured for 2 years. Coarse root NPP will be estimated from allometric equations (Steele et al. 1997).

Land Cover and LAI Surfaces

The goal of this part of the research is to develop high-quality surfaces of land cover and LAI for use both for initializing the fine-grained NPP models and for comparison with MODLand surfaces that have the same two variables. To develop these two surfaces, we expect to use ETM+ data but will use Thematic Mapper (TM) data if no ETM+ data are available in a timely manner. Gower's field observations of land cover types and of LAI will be used to develop the surfaces. Independent field observations of cover and LAI will be used to characterize mapping errors associated with the generated cover and LAI surfaces.

To generate the land cover surfaces for each site, Cohen will conduct a field survey of cover types. For a given site, aerial photos, existing satellite imagery, and extant cover and ancillary data obtained from various sources will be examined in the lab prior to the field survey. This will familiarize Cohen with the sites and will result in a preliminary set of georeferenced points that will be visited in the field. This set will consist of a representative number of each important cover type and examples of apparent anomalies to the general set of cover types present. Consultation with site-level collaborators will ensure that Cohen has a good sense of the conditions at each site before visiting the sites. In the field, Cohen will use a borrowed real-time GPS instrument to record the locations of all points visited.

The ETM+ data will be atmospherically corrected and georeferenced in accordance with the methods, and with the assistance of software and expertise, of the MODLand Science Team. For each site, we plan to use multiseasonal imagery if it is available. First, an unsupervised classification of image data will be conducted to separate a vegetation/soil class from other classes, such as open water, rock outcrops, and non-biomass-producing anthropogenic features (Cohen et al. 1995). This single vegetation/soil cover class will be stratified into a series of classes consistent with a given site's characteristics, using a combination of statistical methods as appropriate to derive either class-level or continuous estimates (Cohen et al. unpublished data). One important land cover variable to be derived for all sites is (growing season) maximum percent vegetation cover. An additional, related characterization will be the percent

vegetation cover before commencement of the local growing season. For forested classes we will model percent hardwood versus conifer and a structural variable, such as dominant and co-dominant tree size or stand age (Cohen and Spies 1992, Cohen et al. 1995, Maiersperger et al. in review, Thomlinson et al. in review). Similar stratification logic will be used for the cropland and grassland sites, as relevant for those sites. To test the effect of land-cover generalization on NPP estimates, we will also generate a separate cover map for each site, based on MODIS land cover classes [e.g., International Geosphere-Biosphere Programme (GBP)].

At least two different maximum LAI maps will be created for each site. The first will be based on regression modeling to relate LAI to spectral vegetation indices (SVIs) (e.g., Fassnacht et al. 1997), and the second on a “paint-by-numbers” approach that involves assignment of LAI mean and variance values to class labels for individual map cells (S. Goetz et al. unpublished data). SVIs are notorious for their asymptotic nature in relation to LAI (above about 3; e.g., Chen and Cihlar 1996, Goetz 1997), and as several of the sites have LAIs in excess of 3, these relationships will be weak for higher LAI values. The paint-by-numbers approach is designed to avoid this limitation of spectral vegetation indices. Spatial statistics will also be used to examine correlations between LAI and other environmental variables; this information may also be used to create spatial LAI maps. If feasible, a third LAI map will be created for each site. This map would be based on a stratification of low and high LAI values, and then the derivation of two separate SVI-LAI relationships, one for each range of LAI values. One-half of the field measurements of LAI will be used to develop the LAI surfaces; the other half will be used to evaluate errors in the surfaces.

A thorough characterization of errors will be conducted for each LAI and land cover surface generated. For land cover, all points observed by Gower in the field will be used. For LAI, only one-half of the field data is available, as the other half was used to develop the surfaces.

NPP Surfaces

Two process-based NPP models (PnET and Biome-BGC) will be run in a spatially distributed mode over a 25-m grid for the 25-km^2 study area at each site (Figure 1.2). Georeferencing will be done in the coordination with the MODLand Science Team. The models will be implemented in the C programming language with an interface to the spatial data using Image Processing Workbench (IPW) code. IPW is Unix-based public domain software supported by the U.S. Geological Survey.

The most critical spatially varying model inputs are land cover type, LAI, climate variables, and soil water-holding capacity (WHC). The LAI maps will provide the seasonal maximum LAI for each cell. LAI will be used to derive maximum fine root biomass and sapwood biomass (in the case of forests) using allometric relationships (Ryan et al. 1991, Hunt et al. 1996). The seasonal trend

in LAI and fine root biomass will be determined by the phenology component of the models. For WHC, an initial average value for each site will be obtained from the WHC surface generated by the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) (Kittell et al. 1995). Where local digital maps of soil texture and depth to bedrock are available at a finer spatial resolution, this information will be used to create an alternative WHC surface.

The daily climate variables required to run the models are maximum temperature, minimum temperature, solar radiation (total short-wave and photosynthetically active), precipitation, and daytime average vapor pressure. The meteorological data to generate these climate surfaces will be based on measurements at the flux towers. FLUXNET is planning to maintain a website with filled-in time series climate data for each FLUXNET site. For sites with significant terrain, the Mountain Climate Simulator (MTCLM) model (Running et al. 1987) will be used with a 30-m digital elevation model to simulate the climate across the landscape. Model runs will be made for calendar years 1999, 2000, and 2001, depending on the timing of the NPP measurements.

Validation at the daily and weekly time step will be made using the tower flux estimates for gross primary production (GPP) (GPP = daytime net ecosystem exchange – daytime ecosystem respiration). The BigFoot GPP estimates will be spatially averaged over the tower footprint [up to several square kilometers (km^2)]. If pertinent information about daily shifts in the position and size of the footprint are provided by FLUXNET micrometeorologists, an effort will be made to use that information in the 2-D modeling scheme to refine the relevant C flux estimates. Validation (error assessment) at the annual time step for NPP_A will be made by comparing model-simulated NPP_A with measured NPP_A at 40 locations. In some cases, additional NPP_A measurements are being made at these sites by other researchers, and these plots will be used for validation purposes as well. Modeled NPP will be separated by leaf litter production, fine root production, and wood production. The estimate for fine root production will be validated only for the grid cell containing the flux tower.

Validation at the daily and weekly time steps for modeled evapotranspiration (ET) will be made in parallel with the daily and weekly C flux estimates. Where streamflow data are available, the monthly and annual simulated streamflow will be compared with field measurements. An additional opportunity for validation of site water balance will be available at the BOREAS and crop sites, where soil moisture is being monitored using time domain reflectometry.

BigFoot/MODLand

The MODLand land cover product will be at a spatial resolution of 1 km and follow the IGBP classification system. BigFoot will produce 25-m land cover maps also based on the IGBP classification and 25-m land cover maps using site-specific classification schemes. Differences between the MODLand land cover products and the BigFoot IGBP-based land cover maps will be evaluated in

terms of the proportional estimation error for each land cover class (Moody and Woodcock 1995) and the overall percentage difference at each site. For each site, evaluation of the BigFoot site-specific land cover map and the MODLand IGBP-based map will be in terms of the frequency distribution of the BigFoot cover types within each MODLand cover type. For LAI and NPP comparisons, there will be a direct overlay of the BigFoot and MODLand surfaces, and the differences will be determined for each 25 x 25 m grid cell.

Several scaling exercises will be performed to investigate causes of observed differences between BigFoot and MODLand NPP surfaces. To evaluate the role of spatial resolution, the BigFoot 25-m grids for input variables will be aggregated to resolutions of 250, 500, and 1000 m^2. Model runs will then be made at each spatial resolution, and comparisons of simulated NPP at the different resolutions (including 25 m^2) will be made with each other and with the MODLand 1-km NPP products. We hypothesize that there may be a fundamental grain size for each study site, above which error rates for NPP predictions accelerate. To evaluate the effect of the difference in land cover classification scheme (IGBP vs. site-specific), the models will be run at the 25-m resolution with only the land cover map varying. Results of model runs using the two land cover classification schemes will then be compared. To evaluate the differences between light-use-efficiency factors (epsilons) employed in the MODLand NPP algorithm and the corresponding epsilons from the climate data [incident photosynthetically active radiation (PAR)] and the BigFoot NPP models, the epsilon surfaces from each NPP model will be overlain with the MODLand epsilon surface.

Project Management

Cohen is the overall project leader, and as such, is responsible for making certain the project is effectively integrated. Cohen will supervise one Oregon State University research assistant, and together they will conduct the image processing and related analytical and scaling activities associated with land-cover and LAI surfaces. Gower is responsible for collection and analyses of ground data and for supervision of the University of Wisconsin personnel. Reich is responsible for 1-D modeling at each of the field points where NPP data are collected and for supervision of University of Minnesota personnel. Turner will conduct the 2-D spatial modeling and scaling-related activities associated with NPP and will supervise other Oregon State University research assistants. Although the comparison of gridded surfaces with MODIS surfaces will be led by Cohen, the integrative nature of this activity will require close interaction between the full BigFoot group and relevant MODLand scientists.

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