CHAPTER 11

BOREAS
(BOREAL ECOSYSTEMS-ATMOSPHERE STUDY):
GLOBAL CHANGE AND BIOSPHERE-ATMOSPHERE INTERACTIONS IN THE BOREAL FOREST

BOREAS Science Steering Committee

INTRODUCTION

To a large extent, the Earth Sciences of meteorology, oceanography, atmospheric chemistry, bioclimatology and ecology grew up independently of each other. Observational methods, theories and numerical models were developed separately within each discipline. This situation began to change about 20 years ago as it become obvious that an interdisciplinary approach was required in order to understand the Earth System as a whole.

Two forces have favored the growth of the new interdiscipline called "Earth System Science". One is the unified perspective on Earth provided through satellite remote sensing that has been one of the most important cultural impacts of space technology. The second is a growing awareness of and/or apprehension about global change which encompasses the so-called greenhouse effect (Rotty, 1983; Trabalka, 1985; Ramanathan, 1988; Hansen et al., 1981); stratospheric ozone depletion (Antarctic Ozone Hole Special Issue,1987; WMO, 1989); deforestation and other anthropogenic changes to the Earth's surface (Mooney et al., 1987; McElroy and Wofsey, 1986); and, the possibility of second-order biospheric feedbacks resulting from the above stresses due to changes in photosynthesis, respiration, transpiration and trace gas exchange (NRC, 1988). The next few years should see the emergence of a research strategy to explore the causes, impacts and likely future developments in global change which will doubtless include a focus on biosphere-atmosphere interactions and their response to perturbation. The planned study, BOREAS, described in this paper represents a significant contribution to the broader effort concerned with global change.

The Boreal Forest biome (dominated by coniferous species, but containing deciduous species) is composed of upland forests, extensive wetlands and bogs, and many lakes. It is one of the largest biomes on the Earth's surface and is a major storehouse of organic carbon, mostly in its soils. Its sensitivity to changes in the physical climate system (PCS) and the nature and severity of the possible consequences of such changes, in terms of ecological perturbations and the release of organic emissions into the lower atmosphere, are the subjects of much scientific conjecture and debate (Tans et al., 1990).

Various modelling studies have indicated that changes in the climatology and ecological functioning of the biome could have significant implications for at least the circumpolar region. Consequently, the proposed study is aimed primarily at providing a research base for a range of related investigations into the biome's internal dynamics and its links to the global environment. Briefly, the goal of the Boreal Forest Study is to understand the interactions between the boreal forest biome and the atmosphere in order to clarify their roles in global change.

The scientific issues at stake are as follows.

> **Sensitivity of the Boreal Forest biome to changes in the physical climate** system: A number of simulation studies have been carried out to assess the climatic impact of increasing atmospheric CO_2: see the reviews of Schlesinger and Mitchell (1987) and Harrington (1987). Many of these studies indicate that the greatest warming engendered by increasing CO_2 will occur at higher (45°N-65°N) latitudes with the most marked effects within the continental interiors; for example, the

doubled-CO_2 experiment of Mitchell (1983) produced a difference of 3K to 10K in the mean winter surface temperature for much of the land surface area of this zone. If this, or anything like this, should actually come about, it would have a dramatic impact on the biophysical characteristics and ecological functioning of the biome (see Figure 11.1).

The Carbon Cycle and the boreal forest: The study of Tans et al. (1990) presents evidence for the existence of a large terrestrial sink of carbon in the temperate boreal zone. The exact mechanisms involved and the spatial contributions to this sink are as yet unknown, but the implication is that carbon is being stored in either living tissue or in the soil. However, any sustained increase in surface temperature, combined with changes in soil moisture climatology, could result in changes in the cycling of nutrients in the soil profile and bogs with associated releases of CO_2 and CH_4 from the surface. If this occurs on a large enough spatial scale, the oxidation capacity of the lower atmosphere could be significantly altered. As yet we do not know enough about important processes within the region to be able to predict or even simulate the carbon source/sink dynamics there.

Biophysical feedbacks on the physical climate system: Research work has indicated, above, that changes in the ecological functioning of the biome could be brought about by changes in the physical climate system. It is anticipated that these may be accompanied by alterations in the biophysical characteristics of the surface, namely albedo, surface roughness, and the biophysical control of evapotranspiration (surface resistance). Any such changes may have feedback effects on the near-surface climatology (temperature, humidity, precipitation and cloudiness fields) (see Sato et al., 1989).

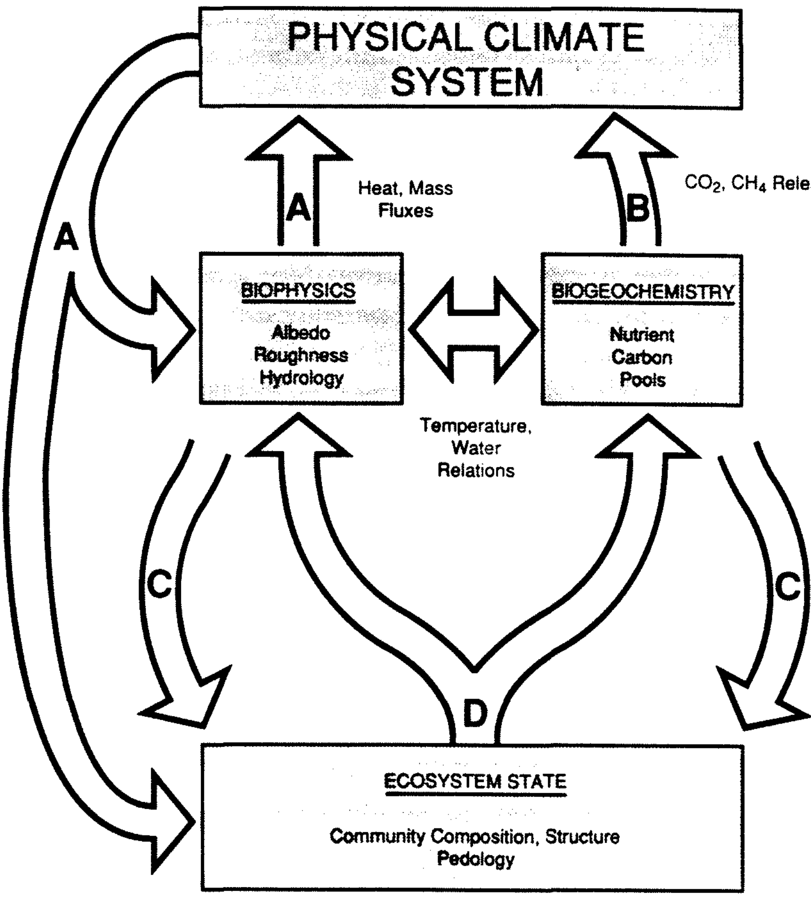

Figure 11.1: Important interactions between the Boreal Forest and the atmosphere with respect to global change: (a) Influence of changes in the Physical Climate System on the biophysical characteristics and ecology of the biome; (b) Changes in nutrient cycling rates; release of CO_2 and CH_4 from soil carbon pool back to the atmosphere; (c) Ecological change in species composition results in changes in land surface characteristics of albedo, roughness and soil moisture availability with possible feedbacks on near-surface climatology.

In addition to the above scientific issues, there are important social and practical considerations. The Boreal Forest is a large, relatively unperturbed biome which is almost contiguous in the circumpolar region. Its borders fall entirely within many of the world's developed nations (Canada, European and Scandinavian Communities, USA and USSR), so its fate has social and economic significance. On the practical side, a complex experiment should be relatively easy to execute in the boreal region of North America due to good logistical and institutional support.

The focus of the proposed study is a cooperative field experiment involving land-surface climatology (LSC), tropospheric chemistry (TC) and terrestrial ecology (TE) components, with remote sensing playing a strong integrating role. A coordinated approach to the experiment design and execution will be adopted from the outset to ensure the maximum benefit from each discipline's participation.

OBJECTIVES

The overall goal of the study is to understand the interactions between the Boreal Forest biome and the atmosphere in order to clarify their roles in global change. This goal leads directly to the specification of detailed objectives to move toward the goal, some of which address short timescale processes (LSC, TC, TE) and some of which address longer timescale processes (TE) (see Figure 11.1).

The major objectives of BOREAS are as follows:

- develop an improved understanding of the processes and states governing the exchanges of energy, water, heat, carbon and trace gases between the Boreal Forest biome and the atmosphere with particular reference to those processes and states that may be sensitive to global change; and,

- develop the use of remote sensing techniques to transfer our understanding of the above processes from local scales to regional scales.

These objectives embrace contributions from all three disciplinary areas involved in BOREAS. A number of subsidiary objectives have also been specified:

- test the limits and sensitivity of different surface energy and mass (H_2O and CO_2) balance modelling approaches. (The models are to be forced by meteorological and remote sensing data). This involves the calculation of state variables (e.g. leaf area index, cover types, etc.) from remote sensing;
- quantify transfer processes between the land surface and the troposphere (includes use of planetary boundary layer studies for integration and scaling checks);
- define the trace gas climatology of the biome with reference to ecosystem state, diurnal and seasonal variability and long range transport;
- quantify the fluxes of radiatively important trace gases and those gases which could affect the oxidant balance of the atmosphere;
- investigate the relationship between trace gas fluxes and ecosystem nutrient dynamics, including the effects of possible feedbacks from the atmosphere to the surface; and,
- identify easily measured LSC and TE surrogates and remotely sensed variables which could be used to estimate trace gas fluxes.

EXPERIMENT DESIGN

Approach

The experimental approach is largely determined by the objectives as stated above. The most important characteristics are as follows.

Ecological Gradient: The overall goal of the project and some of the subsidiary objectives emphasize the need to study the biome's biophysical, chemical and ecological functioning under different conditions. The governing climatological variables determining these in the biome are temperature (associated with length of growing season, radiation budget, etc.) and moisture availability (associated with precipitation, snow hydrology and surface hydrological processes). Essentially, the northern ecotone of the forest is delineated by temperature (growing degree days) while the southern boundary is determined by moisture stress and fire frequency in central and western Canada, and by ecological competition with temperate forests to the east of the Great Lakes. A minimum of two sites is therefore required - one near the northern boundary and one near the southern boundary where moisture relations could play an important limiting role. Most global change scenarios predict warming and drying in the mid-continent. The proposed two-site strategy would therefore allow observations of processes associated with those limiting stress factors (temperature in the north, moisture in the south) that are most likely to undergo significant change within the biome as a whole.

Concentration of Effort: The measurement of fluxes at or near the surface and of radiances and emittances above the surface necessitates the use of sophisticated airborne and surface equipment. The operation of this equipment is expensive in terms of personpower and money and cannot be sustained for long periods. Additionally, there is a strong need to obtain contemporaneous observations of all the appropriate parameters. These facts favor concentrating the intensive observational effort at as few sites as possible and conducting a series of intensive field campaigns, each of about 20 days duration, with time in between for rest and for refurbishing equipment. These campaigns should be embedded in a longer term monitoring effort carried out using satellites and automatic instrumentation.

Scale: One of the objectives is to integrate models and observations of processes and states operating at small scales (<100 m^2) with scales appropriate to regional remote sensing and airborne flux measurement. These two factors argue for sites of roughly 20 x 20 km in size, with stratified sampling and measurements within their borders.

Experimental Framework

The size, duration and scope of the experiment are constrained by the experimental approach and some practical considerations.

Size: The objectives require an explicit study of the effects of temperature and moisture availability as they control ecosystem state and surface-atmosphere exchanges in the biome. At least two intensive sites are required to resolve these effects; their final selection will be predicated by the process rates (mass/energy exchange) associated with each site rather than just climatology. Each intensive site will be of 20 x 20 km dimension to allow the acquisition of useful airborne flux measurements and satellite observations while still allowing reasonable coverage with surface instruments. It is anticipated that almost all of the LSC and TC work will be conducted within these 20 x 20 km main sites. Spacing between these sites may have to be on the order of 500 km to resolve the ecological gradient. Ecological survey studies may also require some sampling within the whole domain along and normal to gradient isolines with particular concentration within and around the main sites. The definition and allocation of additional TE sampling sites should be directed at defining the heterogeneity of surface states and processes within and between the main sites.

Duration: A one-year concentrated observational effort is currently planned for 1994, sandwiched between monitoring, pilot and planning activities (before) and by monitoring activities and limited revisits (after). Observational efforts may follow the First ISCLSP Field Experiment (FIFE) (Sellers et al., 1988) strategy of 2 or 3 intensive field campaigns (IFCs), each of about 3 weeks duration, during the growing season, to capture a range of conditions. Additionally, some hydrological work should be conducted during the winter. The analysis phase of the project would continue for at least 2 years after the main experimental effort.

Scope: The scientific issues and environmental conditions make the project a challenging one. The environmental conditions (cloudiness, lake, wetland, forest mixtures, logistical problems) and other complicating factors will make the technical design and execution of the experiment moderately difficult (see below).

Complicating Factors

Meteorological: The boreal region is typified by extended periods of cloudiness and relatively low solar angles throughout the year. This limits the opportunities for optical and thermal remote sensing.

Structural: The shape and arrangement of trees in forest canopies give rise to fundamentally different observational problems than in grasslands. Specifically:

Optical properties: At least two scales of phytoelement clustering have to be considered: needles to shoots, in the case of conifers; and, shoots to crowns. Both have severe effects on the radiative transfer properties of the surface; anisotropy, shadowing and ambiguous surface-cover contributions to the total radiation field are particularly difficult problems to resolve. Ground cover optical properties also have to be considered: moss, lichens, litter, etc.

Exchange characteristics: The height and spatial heterogeneity of tree crowns ensure efficient exchange between foliage and atmosphere. Unlike grasslands, aerodynamic resistance (r_a) is not a major control on evaporation and photosynthesis; the bulk stomatal resistance, r_s, is typically one order of magnitude greater than ra (see Figure 11.2). Because of this, gradients above the forest are shallow (due to efficient mixing), so foliage-air temperature differences are small. These factors discourage the use of Bowen ratio techniques for flux measurement and the application of the (T_s - T_a) remote sensing method of estimating heat fluxes. The use of eddy correlation systems (the only accepted measurement alternative) requires fairly level sites with large fetch; this is also a requirement for flux aircraft measurements. Flows below the canopy are complex, which poses severe problems for eddy correlation measurements of soil respiration/understory photosynthesis.

Geographical: The sites will undoubtedly contain a mixture of surface types: forests, lakes, bare rock, slopes, etc.

Logistical: Each site must be close to (<100 km) a small airfield (4,000 feet, hard runway) and reasonable accommodation. One site must be near (<350 km) an airfield with a 7,000 feet, hard runway and hangar, and with access to remote communication facilities: satellite downlink, etc.

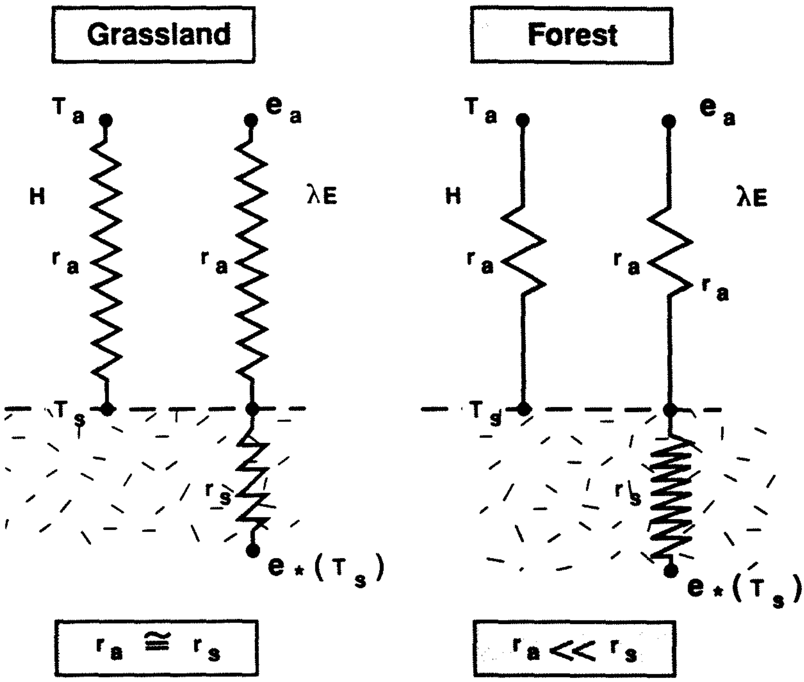

Figure 11.2: Roles of surface (r_s) and aerodynamic resistance (r_a) in energy/mass exchange over forests and grasslands. In grasslands, (r_a) (r_s), so that the T_s - T_a difference may be used to estimate the sensible heat flux, H. In forests $r_a < r_s$ so that T_s and T_a are nearly equal in which case accurate heat flux estimation must be based on a calculation of r_s, the dominant resistance term.

Site Selection

The main study sites were selected in the fall of 1990.

The essential characteristics of the BOREAS sites are as follows.

Site location: Two principal sites, each 20 x 20 km are arranged roughly north-south on the climatic temperature/moisture gradient. The sites may be up to 600 km apart. These sites will be the foci of almost all the LSC and TC work; TE studies will be centered on and around them.

Atmospheric influence: Sites should not be located in areas of even moderate pollution. Although exact criteria are hard to specify, it should be possible to separate the 'natural' trace gas signal from anthropogenic influences.

Landscape characteristics, patch size and terrain: The main sites should not be atypical of the surrounding region in terms of vegetation composition, soils and hydrology. The vegetation within the site should occur in patch sizes of less than 5 km dimension with three or four 'typical' elements with patch sizes of greater than 1 km. The former constraint is to reduce the complexity of the airborne flux measurement task (low-level mesoscale flows, etc.) while the latter is to allow sustainable surface flux measurements. The surface slopes in the flux measurement 'patches' should not exceed 1:20. There should be no large lakes in the sites and an upwind fetch of similar terrain and vegetation should be adequate.

Hydrology: It must be feasible to gauge the outflow of a reasonable proportion of the site area for hydrological and chemical studies.

Control: Acquire control or knowledge of near- and mid-term land use plans.

Logistics: Each site must be close (<100 km) to a small airfield with a 4,000 feet hard runway and reasonable accommodation. One site should be located within 350 km of a 7,000 feet hard runway and hangar, with access to remote communication facilities: satellite downlink, etc. Road access to the sites is essential.

Cloud climatology: The cloud climatology of the area should allow for a few clear days per month for optical remote sensing work.

Methodologies

The complicating factors discussed above mean that the optical remote sensing component of the study will be challenging (cloudiness, low solar angles, surface anisotropy, etc.) and that thermal remote sensing may be of limited value in calculating the surface energy budget (T_s - T_a). Additionally, surface validation efforts (flux measurement, biomass and leaf area index estimates, etc.) will be complex and labor intensive. These factors will probably impel us towards modelling and observing the physiological controls on energy/mass exchange instead of applying thermo/aerodynamic methods appropriate to short vegetation. This effort will necessitate investigations into methods for quantifying biological limits (photosynthetic capacity, minimum stomatal resistance) and stresses (soil moisture stress, saturation, soil nutrient status, constraints on mineralization, etc.) on surface-atmosphere exchanges and nutrient cycling within the biome. There is obviously some potential for adapting existing methodologies to the science tasks but in some cases we will have to explore novel approaches. Additionally, the investigation of processes over a large spatial domain should be coupled with a mesoscale modelling effort at some level; as far as possible, this should make use of existing observational networks. The following methodological approaches will be explored within the experiment design.

Multiangle optical remote sensing: The surface anisotropy of forests dictates a multi-angle observational approach to allow effective interpretation of the existing satellite data and to explore future sensor designs.

Radar: Satellite and airborne radar remote sensing may offer opportunities to investigate canopy structure (which will help with optical data interpretation) and to conduct surveys of community composition and structure (CCS) under cloudy conditions.

Multispectral remote sensing: The requirement for better definition of the physiological state of the vegetation needs to be addressed, especially as thermal methods are less likely to be effective. The potential of high spectral resolution data for quantifying changes in leaf chemistry, and therefore photosynthetic capacity, etc., must be explored.

Flux measurement: Flux measurements of momentum, sensible heat, and mass (moisture, trace gases) will be carried out at the main sites. Surface and airborne eddy correlation, combined with light direction and ranging equipment (LIDAR), are the primary methods of choice for this study. Separation of the net CO_2 flux into photosynthetic and respiration components will probably require combined CO_2 surface flux/vertical divergence measurements conducted at night. (Horizontal flows may be a problem.) During the day, some of the airborne methods will rely on the grid/double-stack methods developed at FIFE, as simpler (one-level) methods are deemed unreliable.

Profiling: The need for semi-continuous atmospheric profiling represents a problem. Flux aircraft can be used up to a point; other non-labor intensive techniques should be investigated (radiosondes). LIDAR may be used during Intensive Field Campaigns.

Monitoring: As far as possible, automatic equipment should be used to monitor micrometeorological and soil moisture conditions.

Hydrology: Catchment water balance and sub-canopy raingauge methods (see Shuttleworth et al., 1984) should be used as additional means to determine the water balance, specifically the interception loss term. Snow interception and melt are clearly important to the hydrological processes within the biome and need special attention.

Data System: A data system with a central archive and active field nodes should be available to provide near real-time interactive access to data sets and in the field, quick-look analyses.

Simulation Modelling: A range of simulation models should be developed and run prior to the execution of the experiment. These should focus on the relationships between the forest ecosystem states/process rates and those parameters amenable to remote sensing. The requirement for model validation will help with the detailed design of the measurement network.

Climatology: Climatological data and synoptic meteorological data will be required for the region surrounding the sites.

EXPERIMENT EXECUTION

Schedule: 1990-1996

1990: Reconnaissance for sites using satellite, map data and airborne/surface surveys was performed. A list of strong candidates for the principal sites which satisfy the essential criteria listed above were provided at the end of 1990. During this year, preparatory work was initiated to resolve issues crucial to final site selection and detailed experimental planning.

1991: Candidate sites were instrumented with Portable Automatic Mesonet (PAM) devices. There were a preliminary satellite data collection effort, exploratory visits by flux teams and test runs with flux aircraft. The Experiment Information System were initiated.

1992-1993: Final site selection. Pilot efforts with flux measurement and airborne remote sensing and the monitoring effort will be intensified: soil moisture, stream gauging, satellite observations, etc are expected. The information system, investigator network and field nodes will be installed and tested. All preliminary monitoring data will be on-line.

1994: Main experiment execution (see next section).

1994-1996: Data analysis and monitoring work will continue.

1994 Experiment Execution

Timing:

The monitoring effort should continue throughout the year if practicable. The timing of Intensive Field Campaigns (2 to 3 during the year, each roughly 3 to 4 weeks long) may be set by the following events (Figure 11.3):

<u>IFC-1 Thaw</u>: Trace gas emission and anaerobic activity will probably peak with warming wet soil conditions. Wet soil may exert stress on trees. Recovery from winter state. (Second priority).

<u>IFC-2 Growing season peak</u>: This will be mid summer, with maximum radiation load and higher temperatures. (First priority).

<u>IFC-3 Growing season decline</u>: Effects of soil moisture and nutrient stress should be more apparent. (Third Priority).

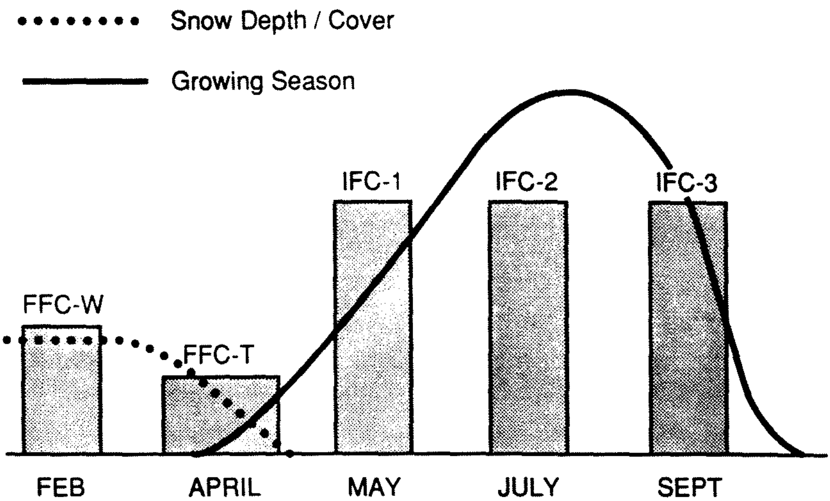

Figure 11.3: Timing of monitoring period and the Intensive Field Campaigns (IFC) in the experiment.

There currently seems to be no critical requirement for a substantial winter IFC although snow hydrology work should continue throughout the preceding winter. Some radiation measurements and remote sensing work might also be conducted during the winter.

Surface Observations:

Monitoring: The monitoring effort will include the soil moisture and catchment water balance studies, productivity measurements, biomass/species surveys, nutrient assays and micrometeorological observations.

Intensive Field Campaigns: A wide range of measurements will be executed in a coordinated fashion (see Figure 11.4).

Profiling: If possible, atmospheric soundings should be carried out at each site.

Surface fluxes: Two or three flux stations per site should be considered the minimum. CO_2 flux measurement is highly desirable. One tall (50 m) and two short (25 m) towers should provide a good range of sampling coverage.

Physiological: Leaf physiological properties should be measured: photosynthesis, stomatal conductance, leaf water potential, chlorophyll density, lignin/nitrogen, carboxylase, etc. Respiration components should be identified, if possible, using chambers, porometers, etc. Leaf optical properties should be measured and leaf extension data should be taken throughout the growing season. In general, a significant preparatory effort is required to improve our methods of making such *in situ* measurements.

Biogeochemical cycling and gas flux studies: Soil nutrient turnover rates and flux measurements of selected trace gases (N_2O, NO, CH_4, and CO_2) should be

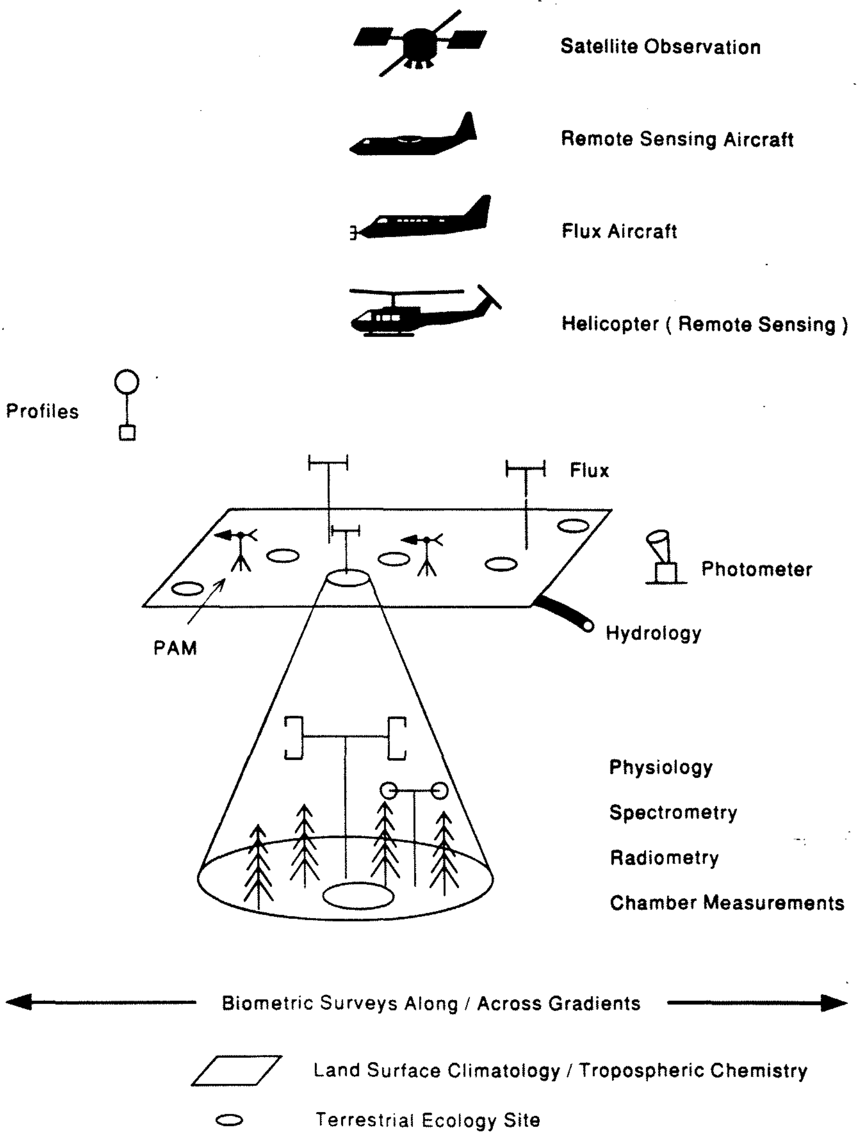

Figure 11.4: Surface Observations at the 20 X 20 km sites.

measured and related to site and climatic conditions. The tropospheric chemistry equipment should be located at the upwind end of the site to prevent interference from the other experiment components.

Photometry: The optical state of the atmosphere should be monitored using photometers during aircraft and satellite overpasses.

Spectral properties: The spectral properties of phytoelements and ground surface should be surveyed and correlated with the physiological measurements.

Biometric surveys: More intensive assessments of biometric properties should be executed during IFC; some of these will be conducted outside the main sites. Overstory, understory, species mix, crown density, diameter at breast height (DBH), core samples (for net primary production), and branch and leaf angles, among others, should all be measured.

Calibration: Intercalibration of the experiment instruments should be built into the experiment design.

Airborne Observations

The airborne operations will be confined to IFCs for practical reasons. A number of aircraft equipped with remote sensing and airborne eddy correlation devices will be used in coordinated studies over and around the two main sites. These studies will provide data that will be used to bridge the gap between the surface measurements and the larger scale satellite and meteorological observations.

Airborne Remote Sensing: The reliance on physiological models rather than thermo/aerodynamic models displaces emphasis from a 'tracking' of the diurnal surface temperature wave, as was done in FIFE. An assessment of this approach will be made if possible, but it will not be the primary (energy balance) remote sensing hypothesis for the LSC component of the study. More effort will be dedicated to the remote sensing of canopy structural, biochemical and biophysical properties and surface soil moisture conditions.

Airborne Flux and gas concentration measurements: The requirement for understanding controls on surface-atmosphere exchanges in a one-dimensional framework defines our minimum size 20 X 20 km site design. The requirement for understanding the relationship between climate and ecosystem state implies more extensive surveys. It is anticipated that the main sites will be used as the foci for cross- and along-gradient airborne surveys of biophysical states coordinated with selected ground sampling efforts. Some of the airborne TC studies will also consist of regional transects or budget studies.

It is expected that several remote sensing aircraft equipped with optical, thermal, passive microwave and radar sensors will be committed to the experiment in addition to one or two helicopters equipped with radiometers and/or spectrometers. Two flux measurement aircraft should be available to measure the turbulent fluxes of water, heat, CO_2, momentum and some specified trace gases. One other aircraft may be used for extensive surveys of trace gas concentrations and gradients. The field campaign will be supported by ongoing monitoring for both sites from several satellite platforms.

SUMMARY

The Boreal Ecosystem-Atmosphere Study (BOREAS) has the goal of understanding the interactions between the boreal forest biome and the atmosphere in order to clarify their roles in global change. The field component of the experiment will consist of coordinated surface, airborne and satellite measurements over two 20 X 20 km study sites located near the northern and southern ecotones of the biome. The main experiment execution is planned for 1994, sandwiched between monitoring work and preliminary studies (before) and monitoring and analysis (after). The experiment will be an international collaborative effort involving scientists from the U.S., Canada and other countries and will consist of contributions from the fields of land surface climatology, terrestrial ecology, tropospheric chemistry and remote sensing.

BOREAS Science Steering Committee consists of: M. Apps, J. Cihlar, B. Goodison, F. Hall, B. Harriss, D. Leckie, E. LeDrew, P. Matson, S. Running, P. Sellers

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