BOREAS
Experiment Plan

Chapter 1
Science Background and Objectives

May 1994 Version 3.0

Executive Summary

The good of BOREAS is to improve our understanding of the interactions between the boreal forest biome and the atmosphere in order to clarify their roles in global change. This document, the BOREAS Experiment Plan (EXPLAN) is the core reference for the field phase of BOREAS. The contents of the plan are briefly summarized below.

Chapter 1: Science Background, Objectives

The scientific rationale for BOREAS is set out. The principle science issues at stake are the sensitivity of the boreal forest biome to changes in the physical climate system; the carbon cycle and biogeochemistry in the boreal forest; and biophysical feedbacks on the physical climate system. The main objectives of BOREAS are to:

(i) Improve the process models which describe the exchanges of energy, water, carbon and trace constituents between the boreal forest and the atmosphere.

(ii) Develop methods for applying the process models over large spatial scales using remote sensing and other integrative modeling techniques.

Some schematics of the different components of the project (Energy-Water fluxes, hydrology, carbon cycle, trace gas biogeochemistry and remote sensing science) are provided as a guide as to how different investigations support the science.

Chapter 2: Experiment Design and Project Organization

A multiscale approach using a hierarchy of nested spatial scales, and the basis for the overall experiment design: The experiment covers the following scales:

Region:	A 1000 x 1000 km area covering a large portion of Saskatchewan and Manitoba.
Study Areas:	Two large study areas are embedded in the region, each of around 10000 km^2. The Southern Study Area (SSA) located near Prince Albert, Saskatchewan will focus on processes which limit vegetation activity

	near the southern boundary of the boreal forest biome, principally soil moisture stress and fire; while the Northern Study Area (NSA) near Thompson, Manitoba will be used to study limiting processes near the northern boundary, which are mainly related to growing degree days. The NSA and SSA are about 500 km apart.
Transect:	Area connecting and including the NSA and SSA.
Modeling Sub-Areas:	Tenting ground for modeling activities and gridded data products. These areas have the highest priority for remote sensing studies and low-level airborne flux measurements.
Tower Flux Sites:	These are sites within the study areas where flux measurement towers operate. These TF sites are located in the center of areas of around 1 km^2 of homogeneous vegetation and are expected to measure fluxes (including CO_2) representative of the most important vegetation types in the biome. Nine TF sites will operate during 1994.
Auxiliary and Process Study Sites:	Around 80 auxiliary and process study sites are to be used for investigator studies or as correlative targets for remote sensing investigations.

Maps of the region and the study areas may be found in this chapter.

A monitoring program of meteorological measurements, satellite data acquisition and some other work started in 1993 and will continue through 1995 or 1996. Within the period August 1993 through September 1994, six field campaigns were scheduled, each of about 20 days duration, in which the bulk of the science teams will take field measurements. The twelve aircraft involved in BOREAS will be taking data over and between the study areas during this time. The field campaign objectives and dates are summarized in Table 2.1.2 and Figure 2.1.2.

Background information on the vegetation and soil at each TF site may be found in section 2.2.2. Section 2.3 outlines the project organization.

Chapter 3: Staff Support

BOREAS staff oversee the components of the project that require significant logistical effort, extended and/or routine monitoring work, or work that requires the particular expertise and resources of one of the participating agencies. The staff monitoring program (section 3.2) includes:

- Automatic Meteorological Station Network
- Upper Air Network
- Hydrology, snow and soil moisture
- Auxiliary site work
- Biometry and allometry
- Radiometric calibration
- Standard gasses and gas calibration
- Thermal radiance intercomparison
- Global and Positioning System (GPS) facilities

The satellite data and airborne remote sensing plans are summarized in section 3.2 -- note that this section covers airborne remote sensing instrument and data processing, not flight operations which are covered in chapter 5. Site logistics and infrastructure (including laboratory facilities) are covered in section 3.4 and the BOREAS Information System (BORIS) is reviewed in section 3.5.

Chapter 4: Science Teams

Some 85 science teams are participating in BOREAS. These have been divided into six disciplinary groups for easier organization doing the field phase. The objectives of these six science groups and the science goals of each investigator team are written up in this chapter. The science groups are are as follows:

Airborne Fluxes and Meteorology (AFM): Four aircraft will be used to measure turbulent fluxing, sounding lidars and radars will also be fielded. Several investigators will use mesoscale and global scale atmospheric models in their studies of surface-atmosphere interactions.

Tower Fluxes (TF): Nine TF towers will operate during the growing season of 1994, measuring radiation, heat, water, CO_2 and in some cases CH_4 and other trace gas fluxes. Two of the sites, one in the NSA and one in the SSA will operate continuously from the fall of 1993 onwards. The layout of each TF site is shown in Figures 4.2.3.2.

Terrestrial Ecology (TE): Over twenty teams will examine the biophysical controls on carbon, nutrient, water and energy fluxes for the major ecosystems in the boreal landscape and will develop logic and algorithms to scale chamber measurements to stand, landscape, and regional scales. An important focus for the TE group will be on measuring the components of the carbon cycle. A number of small towers will be installed in the study areas to facilitate access to the vegetation canopy for chamber measurements.

Trace Gas Biogeochemistry (TGB): The ten TGB teams will use chamber measurements and other techniques to characterize the flux of trace gases between the soil and the atmosphere, including CO_2, CH_4 and NMHC's. The B group will also measure the long-term accumulation of carbon in boreal soils.

Hydrology (HYD): The HYD group will focus on measurements of snow hydrology, components to support on remote sensing algorithm development initiative, and will also work on catchment hydrological processes in the SSA and NSA using precipitation gage networks, streamgages and a rain radar (SSA only). The HYD group will also support soil moisture measurements at the TF sites.

Remote Sensing Science (RSS): The RSS group will develop linkages between optical and microwave remote sensing and boreal zone biophysical parameters at scales that include leaf, canopy and regional levels using field, aircraft and satellite-borne sensors and a range of radiative transfer models.

Chapter 5: Experiment Execution: The activities planned for the monitoring program and field campaigns over the period August 1993 through October 1994 are reviewed. The procedures for making decisions and carrying them out are set out.

Section 5.1 covers the management of Experiment Operations. Section 5.2 covers aircraft mission plans: a large number of figures and tables describe the details of individual aircraft missions. Figures 5.2.4 show the coverage of the region by Landsat and SPOT satellites.

Section 5.3 gives details on planned experiment operations for the field campaigns. The objectives of each campaign are set out and the participating aircraft and science teams are listed. Chapter 5 serves as the day-to-day guide to BOREAS Mission managers and study area managers in the field.

Appendices: The titles of each appendix are listed below.

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Appendix L:	BOREAS Inter-IFC Survival Guides
Appendix M:	BOREAS Modeling Contributions
Appendix N:	BOREAS Auxiliary Site Directions
Appendix O:	AES Surface Weather Stations
Appendix P:	BOREAS Emergency Procedures and Guidelines for SSA and NSA

Participating Canadian agencies include the Canada Centre for Remote Sensing, Environment Canada, Natural Sciences and Engineering Council, Agriculture Canada, National Research Council, and Canadian Forest Service. For the United States, the effort is being led by the National Aeronautics and Space Administration's Mission to Planet Earth, with participation from the National Oceanic and Atmospheric Administration, the National Science Foundation, the United States Geological Survey and the Environmental Protection Agency. BOREAS contributes to both the U.S. and the Canadian Global Change Research Programs.

NOTE: BOREAS Investigators participating in field campaigns are required to read.

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1.0 SCIENCE BACKGROUND, OBJECTIVES

The goal of BOREAS is to improve our understanding of the interactions between the boreal forest biome and the atmosphere in order to clarify their roles in global change.

1.1 Scientific Issues

The scientific issues at stake are as follows.

I. **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^oN-65^oN) latitudes with the most marked effects within the continental interiors; for example, the doubled-CO_2 experiment of Mitchell (1983) produced differences of 3K to 10K in the mean winter surface temperature for much of the land surface area of this zone. Other studies have indicated that there may be significant warming and drying in the summer months in the same region. Studies by Davis and Botkin (1985) and Solomon and Webb (1985) suggest that this warming and drying could modify the composition and functioning of the boreal forest, see Figure 1.1

II. **The carbon cycle and biogeochemistry in the boreal forest**. The study of Tans et al. (1990) presents evidence for the existence of a large terrestrial sink for fossil fuel carbon in the mid latitudes of the Northern Hemisphere 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, could result in changes in the cycling of nutrients in the soils with associated releases of CO_2, CH_4 and other trace gases from the surface. If this occurs on a large enough spatial scale, the oxidative capacity of the lower atmosphere could be significantly altered. Additionally, changes in the temperature and moisture regime could alter the biomes exposure and response to discontinuous disturbance, i.e. fire frequency, which could substantially affect the carbon cycle within the biome. 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.

III. **Biophysical feedbacks on the physical climate system**. Research work has indicated (See I. 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 and internal resistance). Any changes in these may have feedback effects on the near-surface climatology (temperature, humidity, precipitation and cloudiness fields), see Sato et al. (1989).

Further discussion of the larger scientific issues framing BOREAS may be found in the BOREAS Science Plan (Sellers, et al; 1991).

The focus of BOREAS is a cooperative field experiment involving land surface climatology, biogeochemistry and terrestrial ecology components with remote sensing playing a strong integrating role. A coordinated approach to the experiment design and execution has been adopted from the outset to ensure the maximum benefit from each discipline's participation.

1.2 Objectives

The overall goal of BOREAS is to improve our understanding of the interactions between the boreal forest biome and the atmosphere in order to clarify their roles in global change.

The immediate experimental phase of BOREAS is planned to run for two to three years. Obviously, this is too short a period for us to observe the effects of global change directly but it will allow us to observe important processes under a wide range of conditions so that we can develop and test key process models. The strategy of the experiment is specifically directed toward this: first, measurements will be taken throughout the year at a variety of 'representative' sites to characterize the meteorological regimes and ecophysiological conditions to be found in the region. These measurements will be used initially to improve our process models. Second, remote sensing and integrative modelling techniques will be used to apply these process models over large areas to see how well we can describe the present situation. If this can be done convincingly over one or two annual cycles, then we will have more confidence in applying our models as predictive tools to address the issues listed in Section 1.1. In addition, the knowledge gained should enable us to design a better, more cost-effective long-term monitoring program to track future changes in the biome and subsequent interactions between the forest and the physical climate system. The governing objectives of BOREAS can therefore be stated as follows:

(I) **Improve the process models which describe the exchanges of energy, water, heat, carbon and trace constituents between the boreal forest and the atmosphere**.

This will be done by measuring fluxes over a wide range of spatial scales together with observations of the ecological, biogeochemical, and atmospheric conditions controlling them. The process models will be developed and thoroughly tested before they can be applied to the 'global change' issues described above.

The initial focus will be on validation and improvement of local-scale (site to landscape) energy balance, mass balance and biophysical process models that operate at relatively short time scales (seconds to seasons) and which are amenable to measurement within a two year field program. The results of this effort will also be useful for the study of ecosystem level dynamics and land surface/climate interactions at regional and local scales over longer time periods (years to decades).

The necessary field observations include measurements of fluxes of these quantities at the plot or leaf scale (chambers, porometers), the stand scale (tower mounted devices) and the mesoscale (airborne eddy correlation). These observations will be coordinated with a series of ecological, meteorological and edaphic measurements which will quantify the state variables controlling the fluxes.

(II) **Develop and test methods for applying the process models over large spatial scales using remote sensing and integrative modeling techniques**.

This objective will be addressed by ensuring close coordination of the process studies described in (I) above with remote sensing investigations using satellite, airborne and surface-based instruments. These focused remote sensing studies, combined with mesoscale meteorological studies, will allow us to scale-up and apply the process models at regional and ultimately global scales. There are some large-scale validation techniques at our disposal to test these scale-integration methods explicitly, including airborne eddy correlation and meteorological observations.

The two governing objectives described above provide the overall framework for the project. Figures 1.2a through 1.2j show schematically how measurements taken at different scales support the overall objectives in the areas of atmospheric energy-water fluxes, carbon cycle, surface hydrology, trace gas biogeochemistry, and remote sensing science. These studies are aimed at quantifying initial/boundary conditions and mechanisms associated with the important ecological processes (i.e. ecophysiological and edaphic) which govern the interactions between the boreal forest and the atmosphere.

Each pair of figures (e.g., 1.2a and 1.2b) shows how the measurements fit together at different scales and then how individual investigations contribute

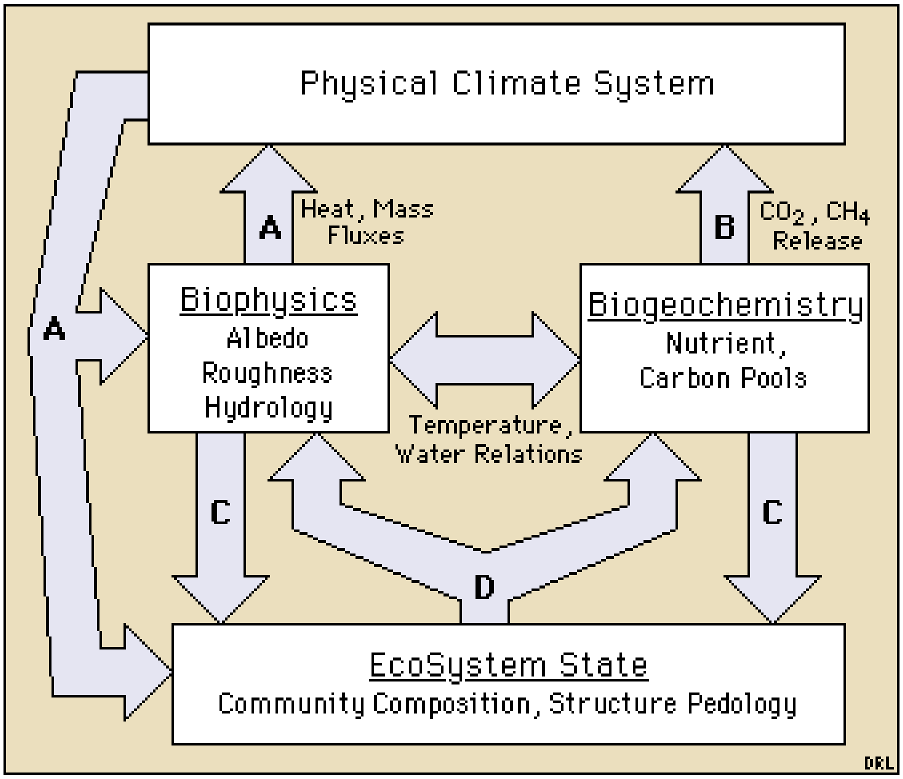

Figure 1.1 **Important interactions between the boreal forest and the atmosphere with respect to global change**

(A) **Influence of changes in the Physical Climate System on biophysical processes. These may feedback to the atmosphere through changes in energy, heat, water and CO_2 exchange.**

(B) **Changes in nutrient cycling rates; release of CO_2 and CH_4 from the soil carbon pool back to the atmosphere.**

(C) **Changes in biogeochemical processes and water and nutrient availability influence community composition and structure.**

(D) **Change in species composition results in changes in surface biophysical characteristics and biogeochemical process rates.**

to the work. Figures 1.2 are focused on the measurements aspects of BOREAS, but some of the modeling contributions are also shown where appropriate. More information on the investigations can be found in Chapter 4 and the Appendix.

To develop the detailed design of the experiment, objectives I and II were translated into a set of specific supporting sub-objectives.

(i) **Test the limits and sensitivity of different surface energy and mass (H_2O and CO_2) balance modeling approaches. The models are to be forced by meteorological and remote sensing data. This involves the calculation of state variables from remote sensing and the in-situ measurement of heat, mass and energy fluxes for model validation**.

A specific goal is to construct models and collect data which will allow the estimation of the principal terms in the carbon budget for a number of sites at spatial scales of meters to a few kilometers and time scales out to a year or so, see figures 1.2a through 1.2f, 1.2h and 1.2j.

The essential observational components for this include:

- Measurement of radiation budget terms.

- Measurement of the turbulent fluxes of sensible heat, water vapor, CO_2 and momentum using chambers or enclosures (where appropriate), towers and airborne instrumentation combined within a nested, multiscale sampling strategy.

- Measurement of important state variables (e.g. surface cover type, fraction of PAR absorbed by the canopy, leaf area index, soil moisture, etc.) in such a way as to allow direct comparison with the radiation and flux measurements described above and the appropriate remote sensing measurements described below.

- Measurement of meteorological variables (temperature, humidity, precipitation, wind speed, cloud cover, etc.) using a coarse mesoscale network of surface stations and profilers grouped around and between the intensive study sites.

- Measurement (if possible) of key hydrological variables (soil moisture, stream flow, snow water equivalent, above and below canopy precipitation, evapotranspiration) with the aim of closing the water balance of gauged catchments within or including the study areas.

- Remote sensing of atmospheric and surface state variables associated with the above using surface and airborne instruments (for direct correlative studies) and satellite sensors.

The modeling component of this effort may include the construction, validation and application of the following types of models.

- Biophysical models (soil-plant-atmosphere models) which describe the absorption and partition of energy by the surface on the spatial scale of the flux measurements.

- Models of the carbon budget, ranging from short time scale, small space scale photosynthetic models; out to landscape scale models of carbon flow which address gains from photosynthesis and losses by respiration, fire and runoff.

- Mesoscale meteorological models, which may have elements of the above two classes of models embedded within them, to (i) synthesize the regional-scale fields of surface - atmosphere fluxes for comparison with remote sensing and airborne eddy correlation data, (ii) provide a regional context for the detailed site studies and (iii) explore the impact of the spatial arrangement of regional-scale flux fields on the physical climate system.

- Hydrological models, operating over the entire range of spatial scales addressed by BOREAS (meters to tens of kilometers), to (i) provide an independent check on the water budget over a longer time scale and (ii) contribute to the 'scaling up' procedure in concert with the remote sensing and mesoscale modeling efforts.

(ii) **Study the exchange and the processes governing the exchange of trace gases between the boreal forest and the atmosphere with reference to the diurnal and seasonal variability of the energy and moisture fluxes to the ecosystem, see Figures 1.2e through 1.2h.**

The following particular issues will be addressed:

- Carbon dynamics, emphasizing the role of environmental controls on carbon storage and fluxes. This will involve direct measurements of CO_2, CH_4, and CO fluxes over a 1 to 2 year period with the aim of describing the annual carbon budget of selected sites. This work will be coordinated with studies of moisture and energy fluxes and with studies of carbon storage in the soils.

- Methane (CH_4) dynamics, based on the recognition that the boreal forest can be both a source and a sink of CH_4.

- Seasonal differences in the chemistry of the boreal troposphere, particularly to determine whether the winter troposphere accumulates reactive nitrogen and to contrast seasonal pollutant loadings.

- The dynamics of short-lived gases, such as O_3, NO_x, CO and NMHC.

- The dynamics of biogenic hydrocarbons: factors controlling the emission and degradation of isoprene, terpenes and oxygenated hydrocarbons and their role (in combination with other gases) in the oxidation cycles of the lower troposphere.

- The role of fires in determining tropospheric chemistry.

- Direct quantification of the fluxes of radiatively important trace gases and those gases which could affect the oxidant balance of the troposphere.

- Direct quantification of the fluxes of radiatively important trace gases and those gases which could affect the oxidant balance of the troposphere.

(iii) **Investigate the relationship between the fluxes of energy, heat, mass, momentum and trace gases on the one hand and ecosystem successional state and nutrient dynamics on the other hand, including the effects of possible feedbacks from the atmosphere to the surface, see Figures 1.2e through 1.2h.**

This will require a number of intensive ecological studies coordinated with the flux and state variable measurement efforts described above. The aim is to produce ecological models that may be partly driven by remote sensing and meteorological/climatological data and which explore (a) the fate of assimilated carbon, (b) the limits on assimilation, allocation and respiration imposed by climate and nutrient cycling controls, and (c) the expression of (a) and (b) in the growth and development of different vegetation - soil complexes. Measurements include:

- State variables (cover type, biomass, leaf area index, canopy and soil chemistry, age class distribution, etc.).

- Nutrient status and cycling rates using in-situ observations and perhaps small scale (less than 100 x 100 m) manipulation experiments.

- Ecophysiological measurements (leaf photosynthesis, stomatal conductance, canopy FPAR, leaf water potential, etc.).

- Studies of the fate of assimilated carbon, including allocation and respiration by vegetation, soil fauna and macrofauna. The impact of key species on nutrient and carbon cycling rates should be studied.

(iv) **Develop and evaluate remote sensing algorithms that relate parameter drivers associated with all of the above models to spectral, spatial and temporal patterns of surface radiance fields, see Figures 1.2i and 1.2j.**

Remote sensing will contribute to BOREAS in two principal ways:

(a) Upscale integration of models and parameter fields: If links between remotely-sensed signatures and key atmospheric and surface state/process variables and parameters can be established and validated at the intensive study sites, a combination of remote sensing, mesoscale meteorological modeling and other spatial integration/interpolation techniques should allow an extension of the knowledge gained at the experimental site scale out to regional scales.

(b) Landscape characterization and dynamics: The distribution, characteristics, and temporal dynamics of the boreal vegetation cover types can be established through archived and newly acquired satellite data. The historical record of Landsat data, to give one example, extends back for over twenty years. The temporal and spatial scope of satellite data provides us with a unique classification tool that can be used to study the dynamics of vegetation communities (growth, senescence, succession, fire, etc.) over a wide range of scales. Again, these data will help to place the intensive study sites in their correct context in relation to the biome as a whole.

Goals and methods of the remote sensing element of BOREAS are reviewed in more detail in Hall et al. (1993).

To make the best use of satellite data, the following studies need to be conducted:

- Correlative remote sensing measurements linked to the principal process/state variable studies described above, using surface, airborne and satellite sensors (active and passive).

- Measurements of the atmospheric state, to allow correction of the remotely sensed data.

- Modeling studies, to establish the physical links between observed radiances/emittances and surface or atmospheric states and processes (e.g. construction of radiative transfer models to explore how visible and near-infrared reflectances can be used to calculate canopy FPAR).

- Evaluation studies, to determine the limits of accuracy with which important parameters can be estimated for a range of different surface and atmospheric conditions and a range of spatial scales.

A full year of data acquisition is scheduled for 1994. Also in 1994, some preliminary modeling intercomparison work will be carried out. Modelers from a number of different groups will run Soil Vegetation Atmosphere Transfer models on the same test data set to learn more about behavior and sensitivity, see Appendix J. During 1995, data reduction, analyses, and modeling work will move ahead in parallel with a reduced set of field observations. If necessary, there may be a return to the field in 1996.

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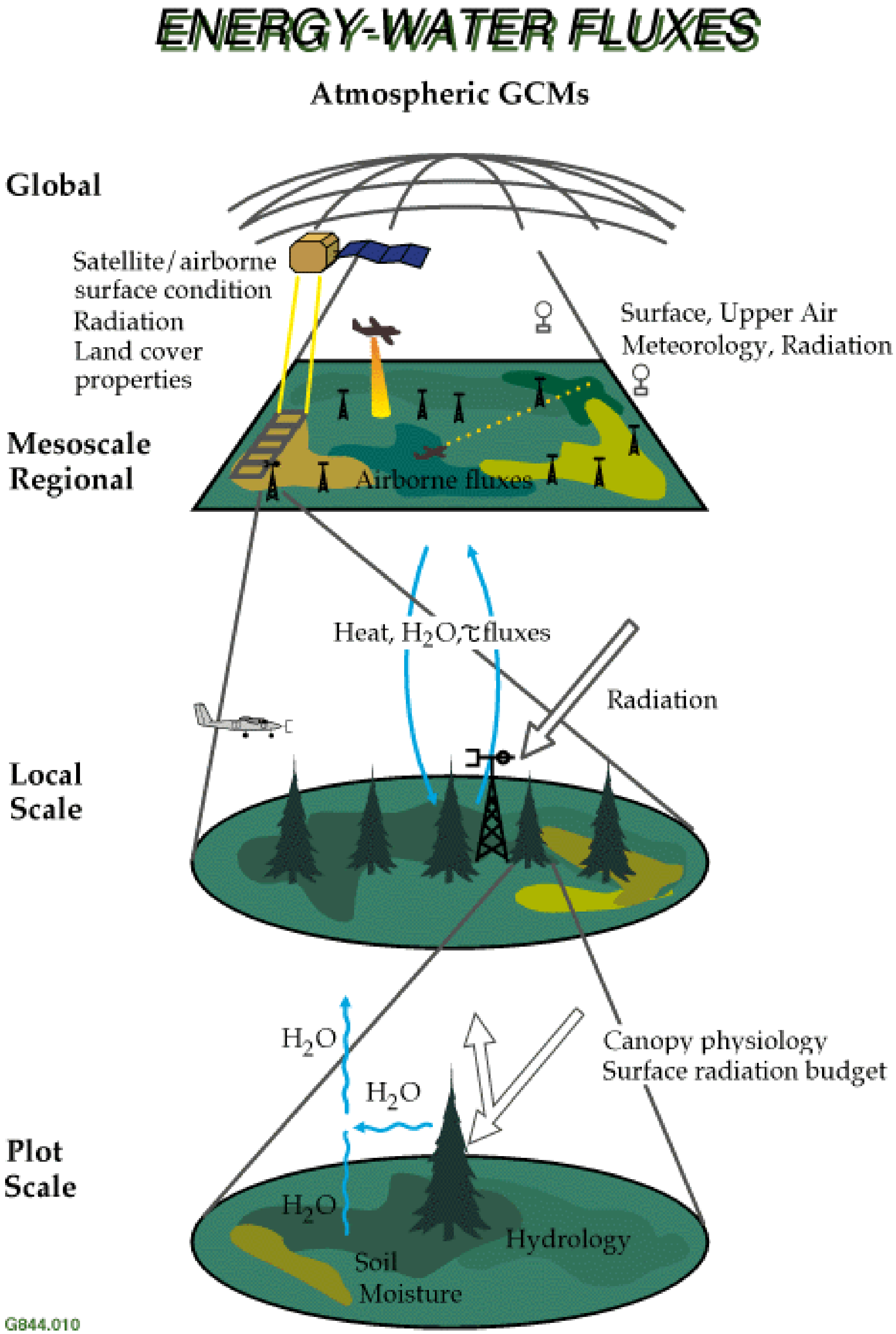
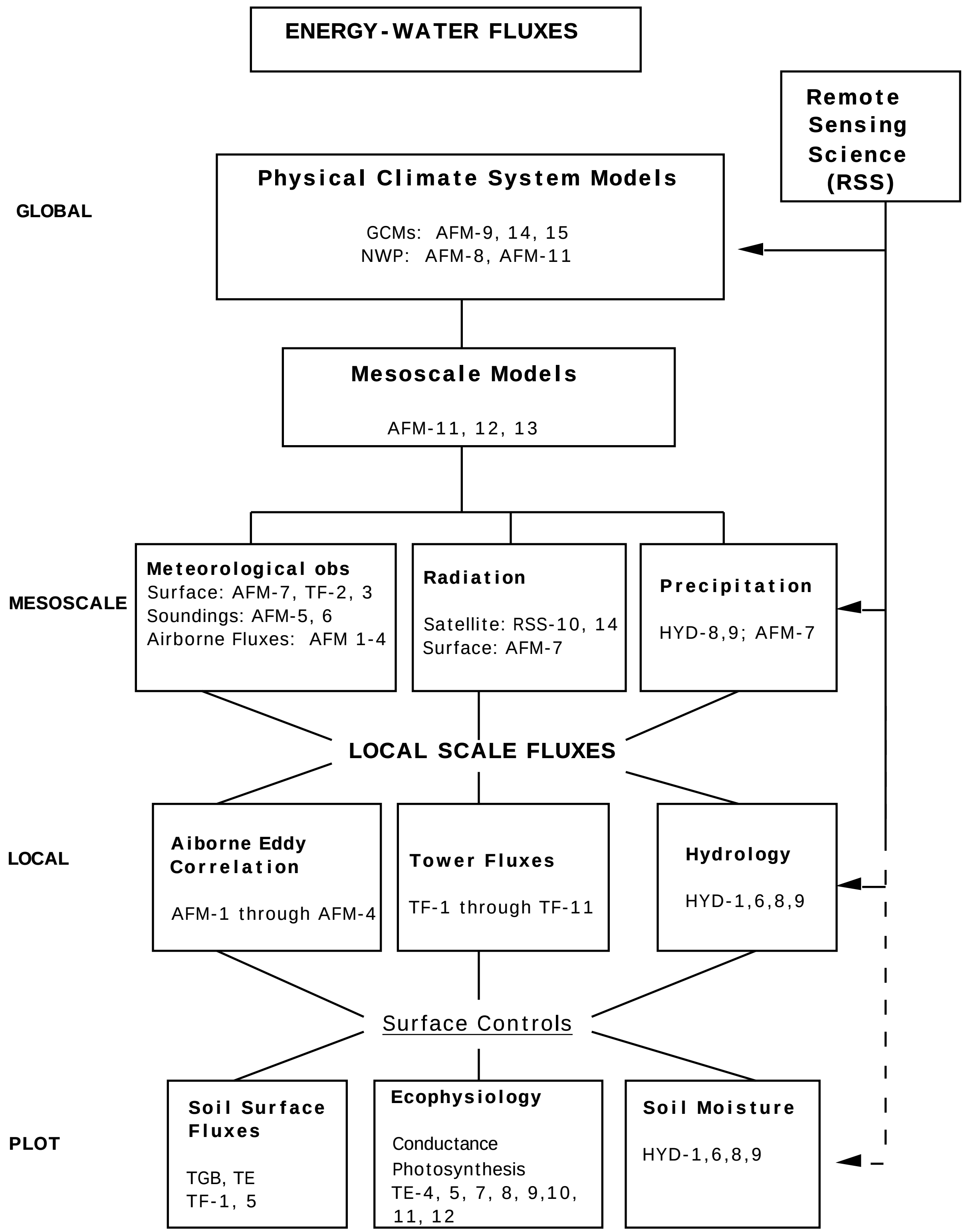
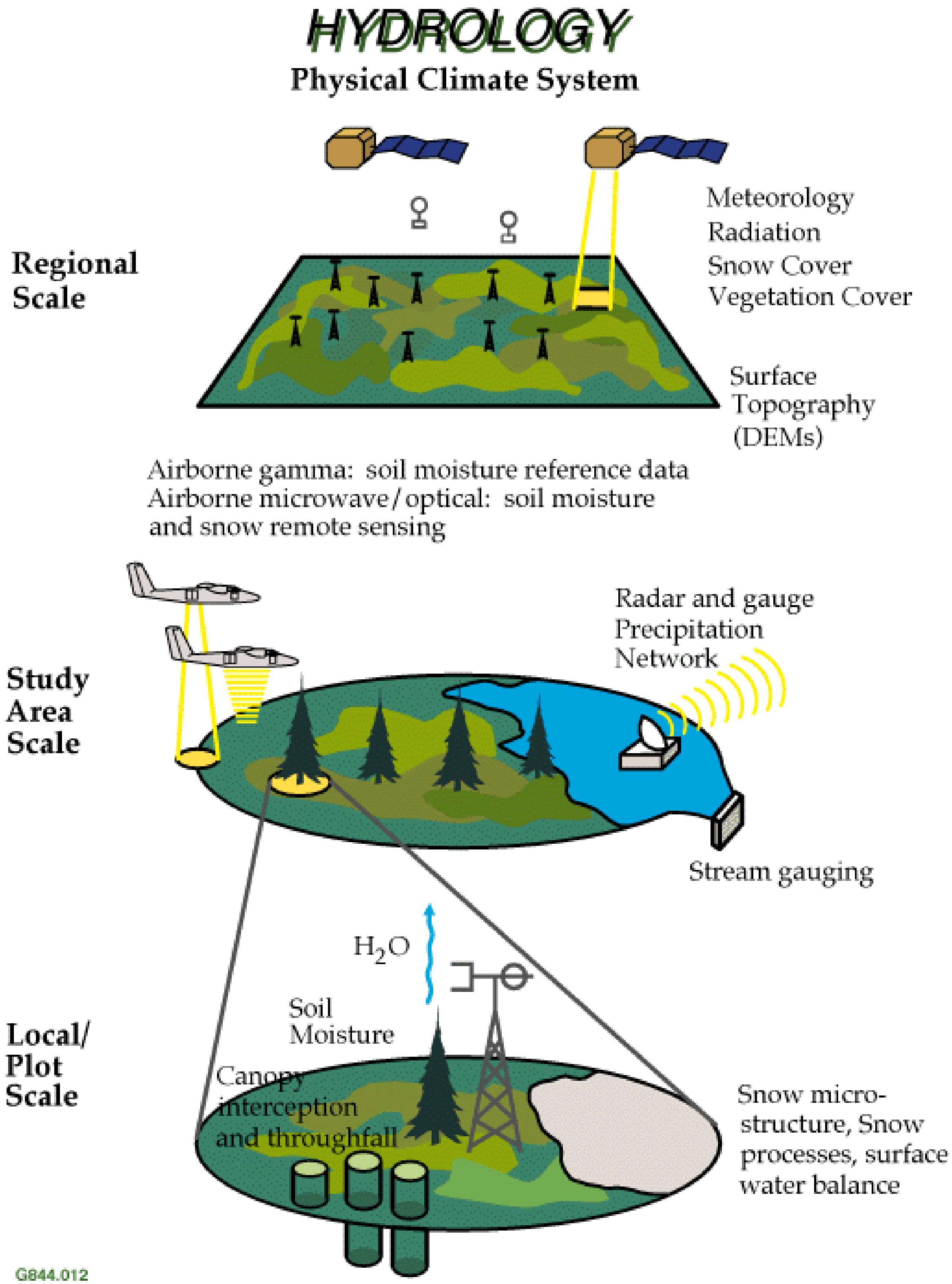


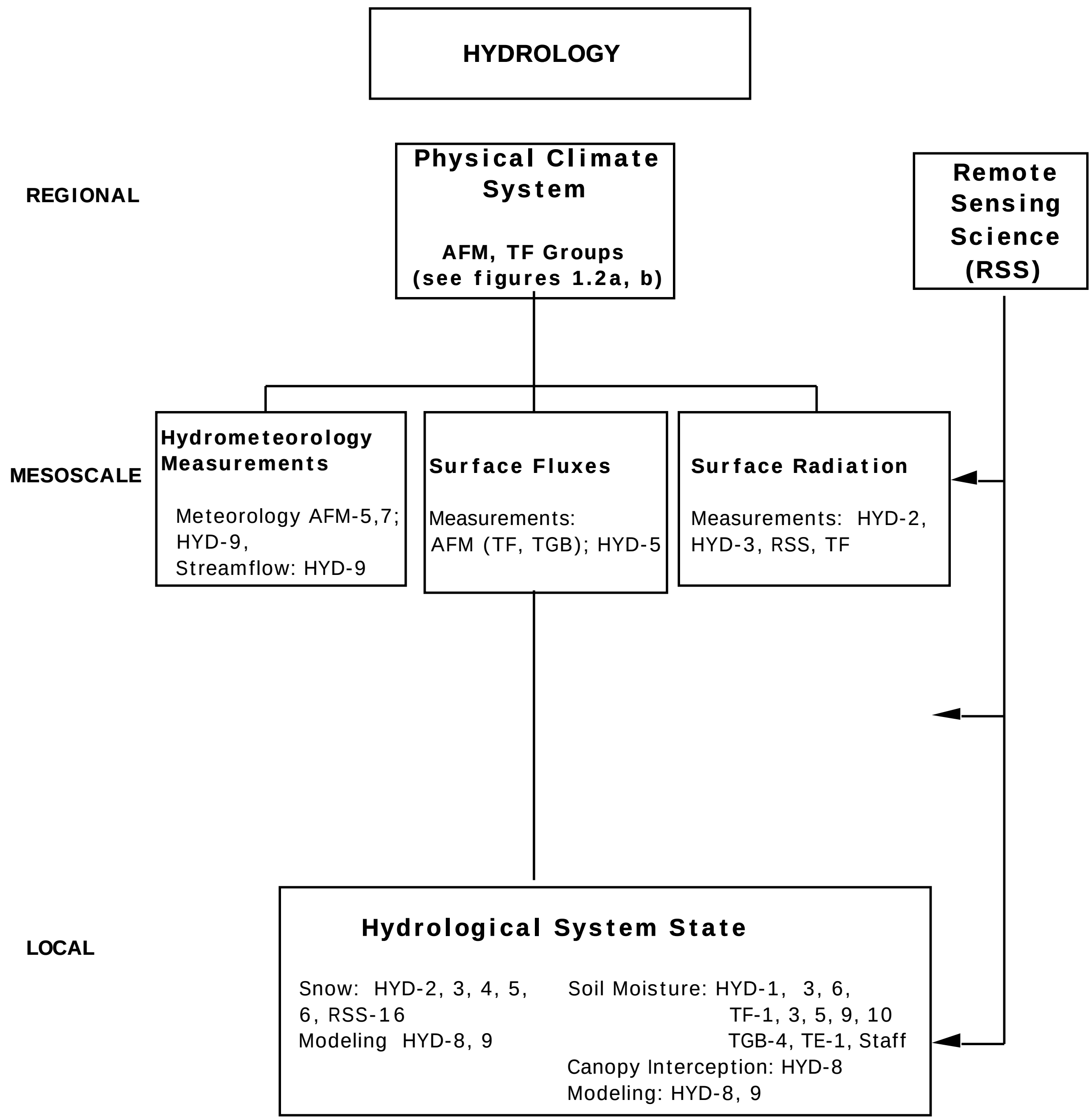
1.2.a Schematic of processes associated with energy and water fluxes in the boreal forest.



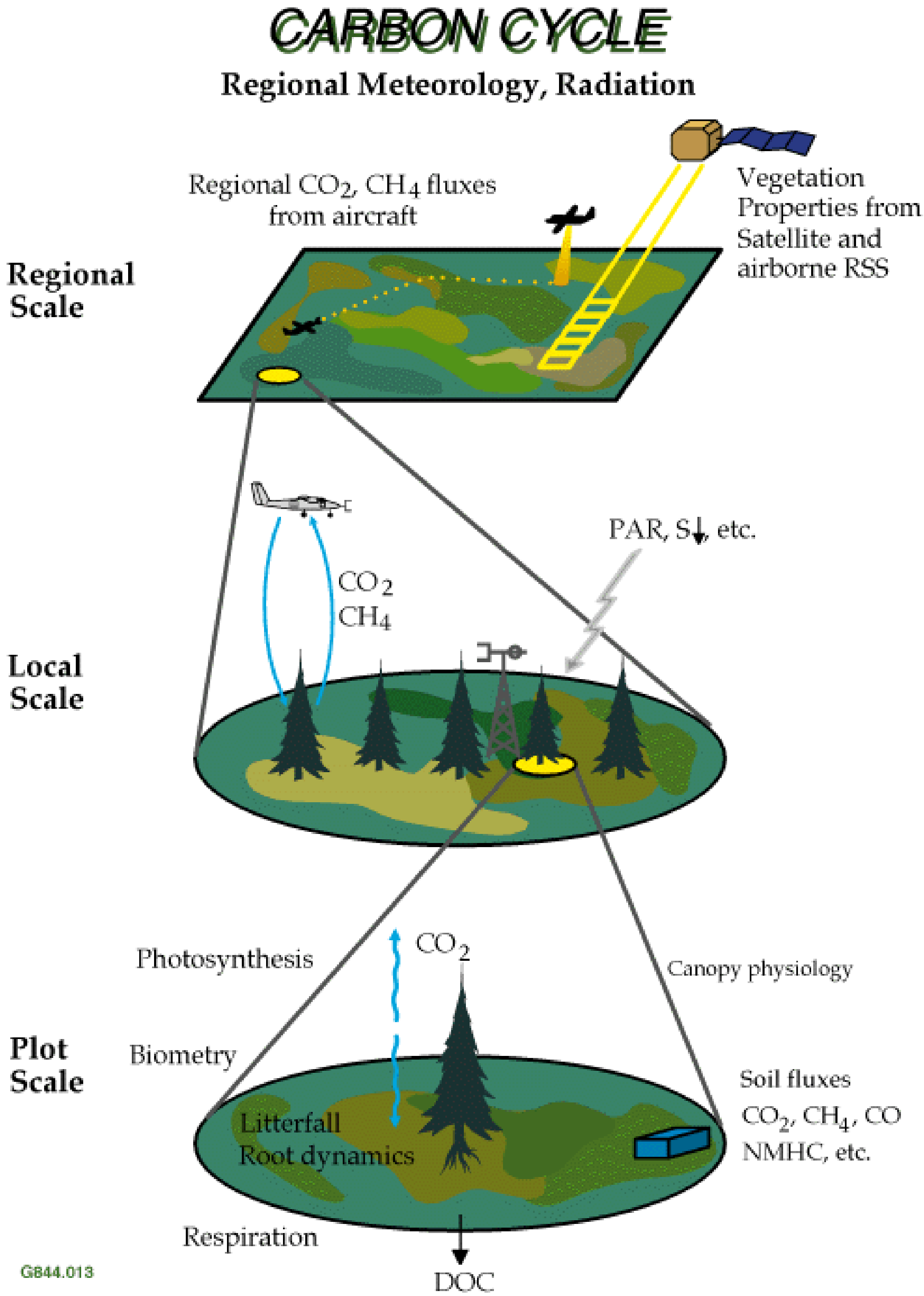
1.2.b Flow chart corresponding to 1.2.a, showing roles of BOREAS investigators.



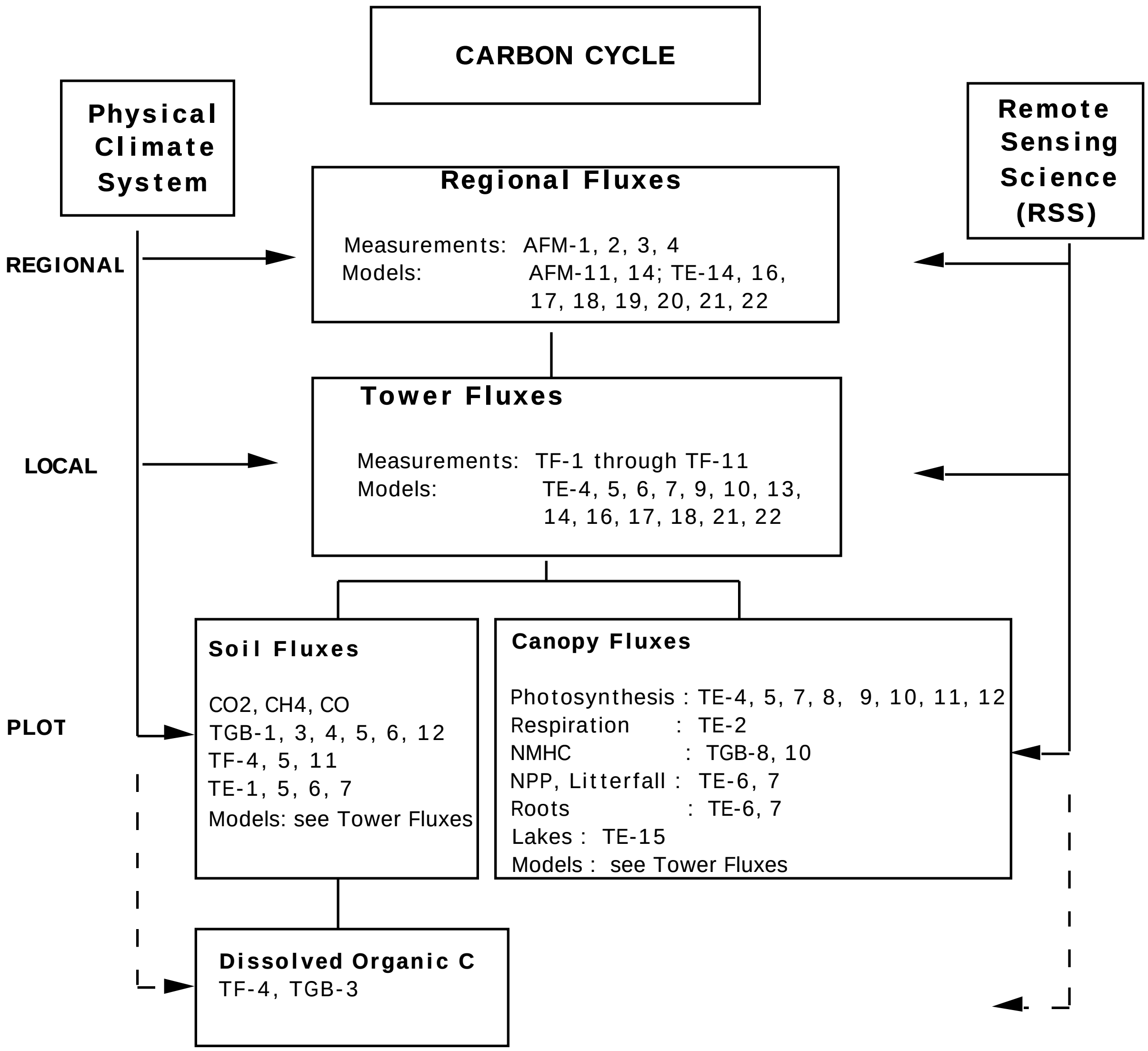
1.2.c Schematic of processes associated with hydrology in the boreal forest.



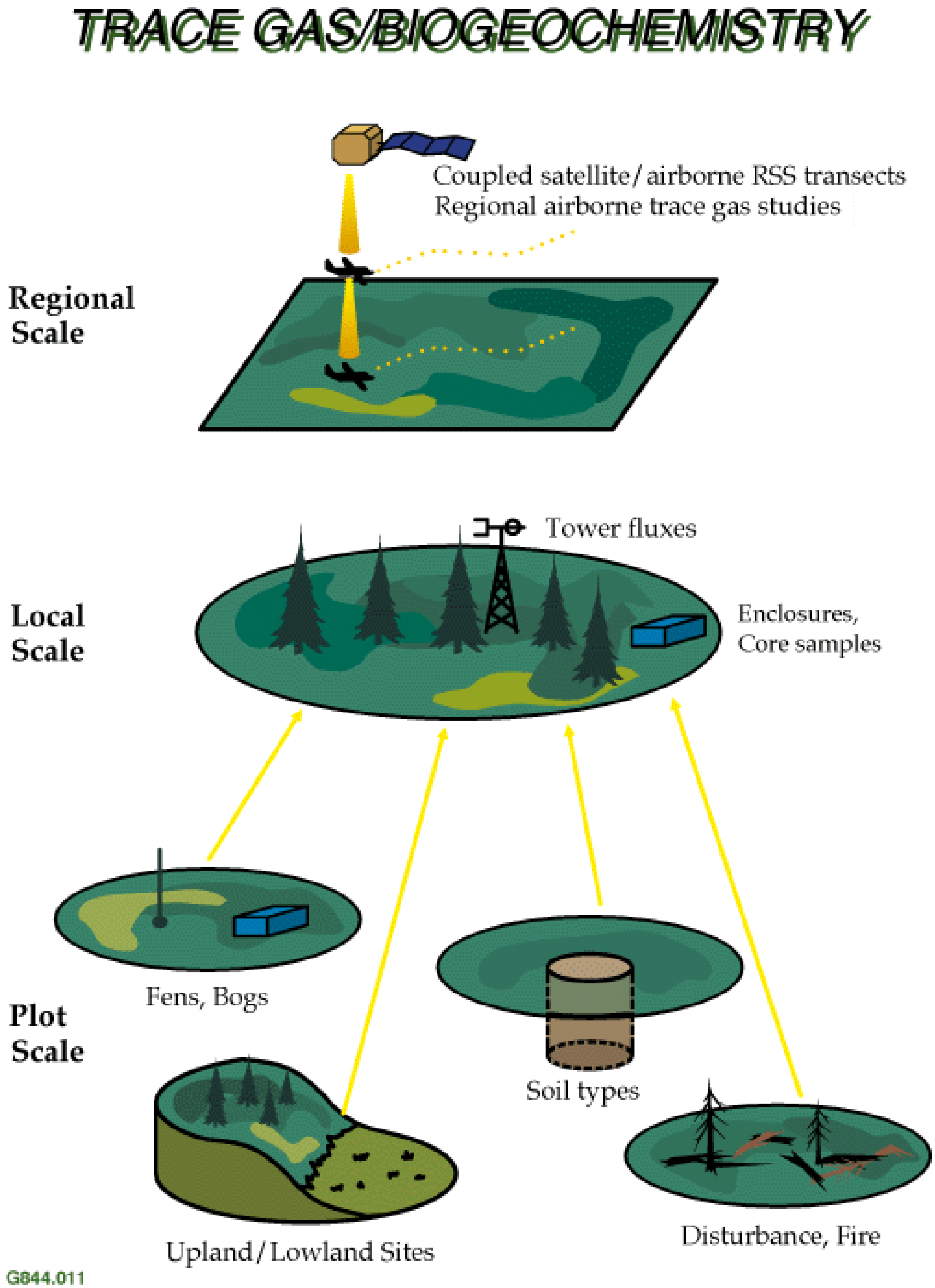
1.2.d Flow chart corresponding to 1.2.c, showing roles of BOREAS investigators.



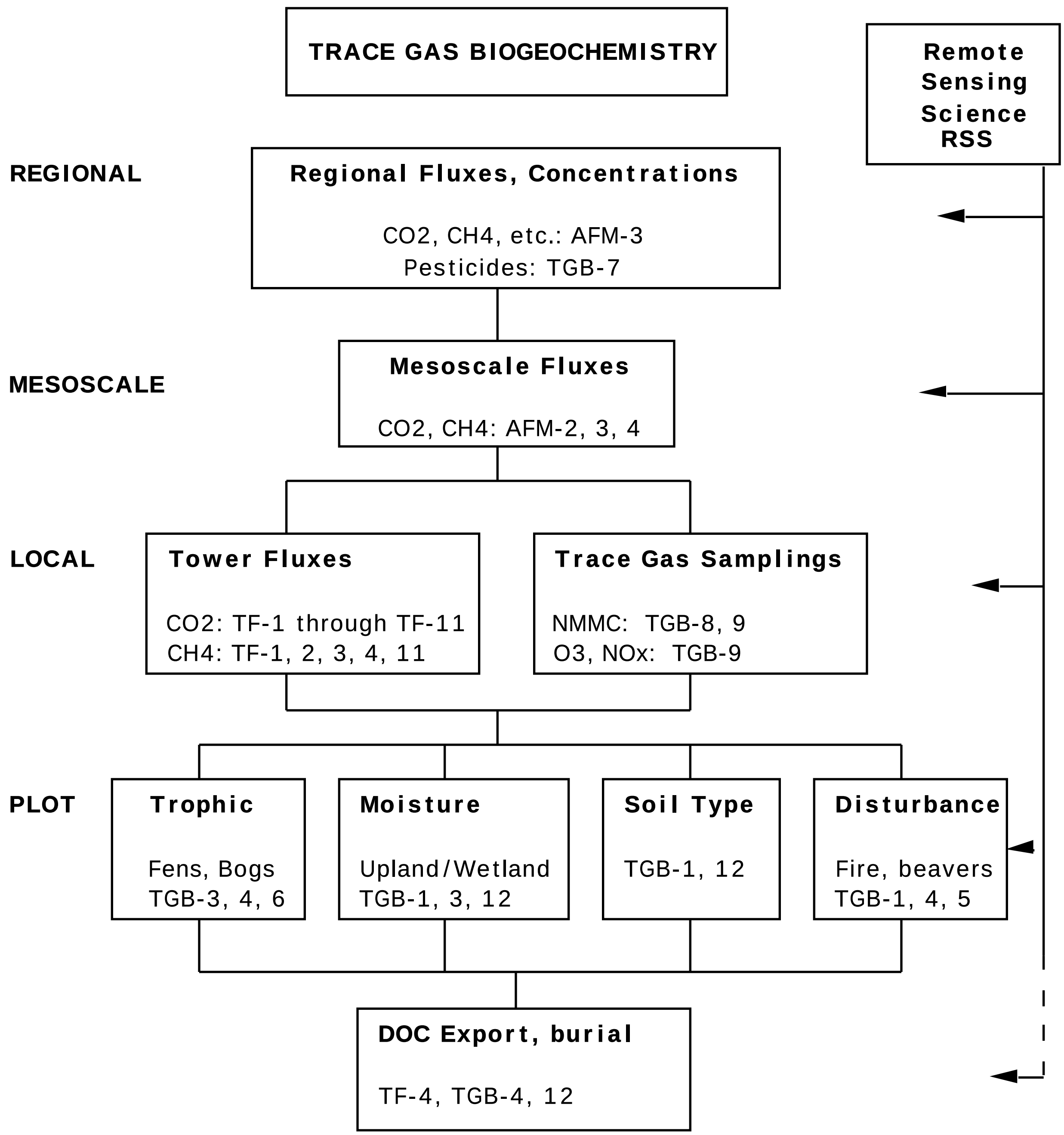
1.2.e Schematic of processes associated with the carbon cycle in the boreal forest.



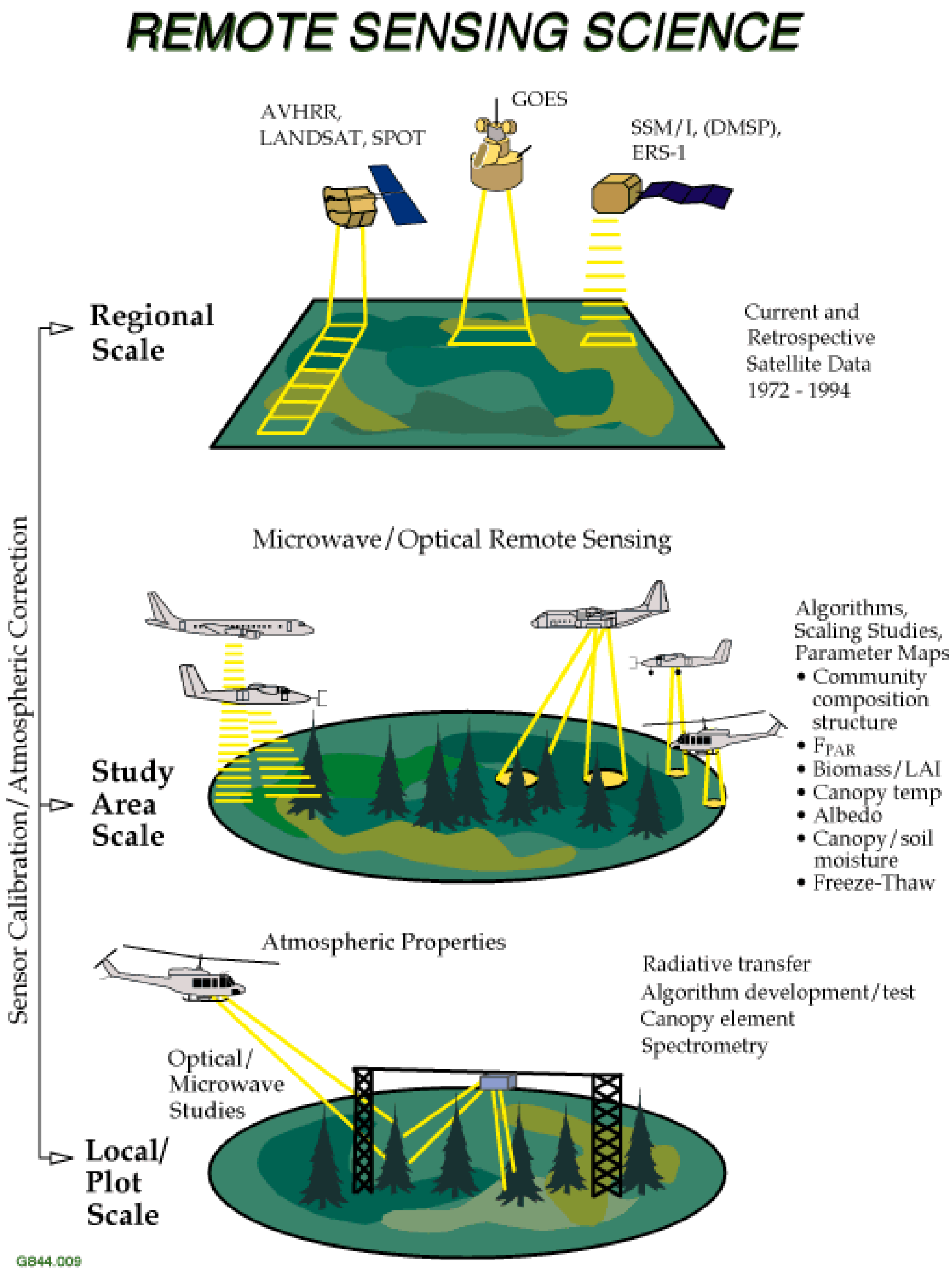
1.2.f Flow chart corresponding to 1.2.e showing roles of BOREAS investigators.



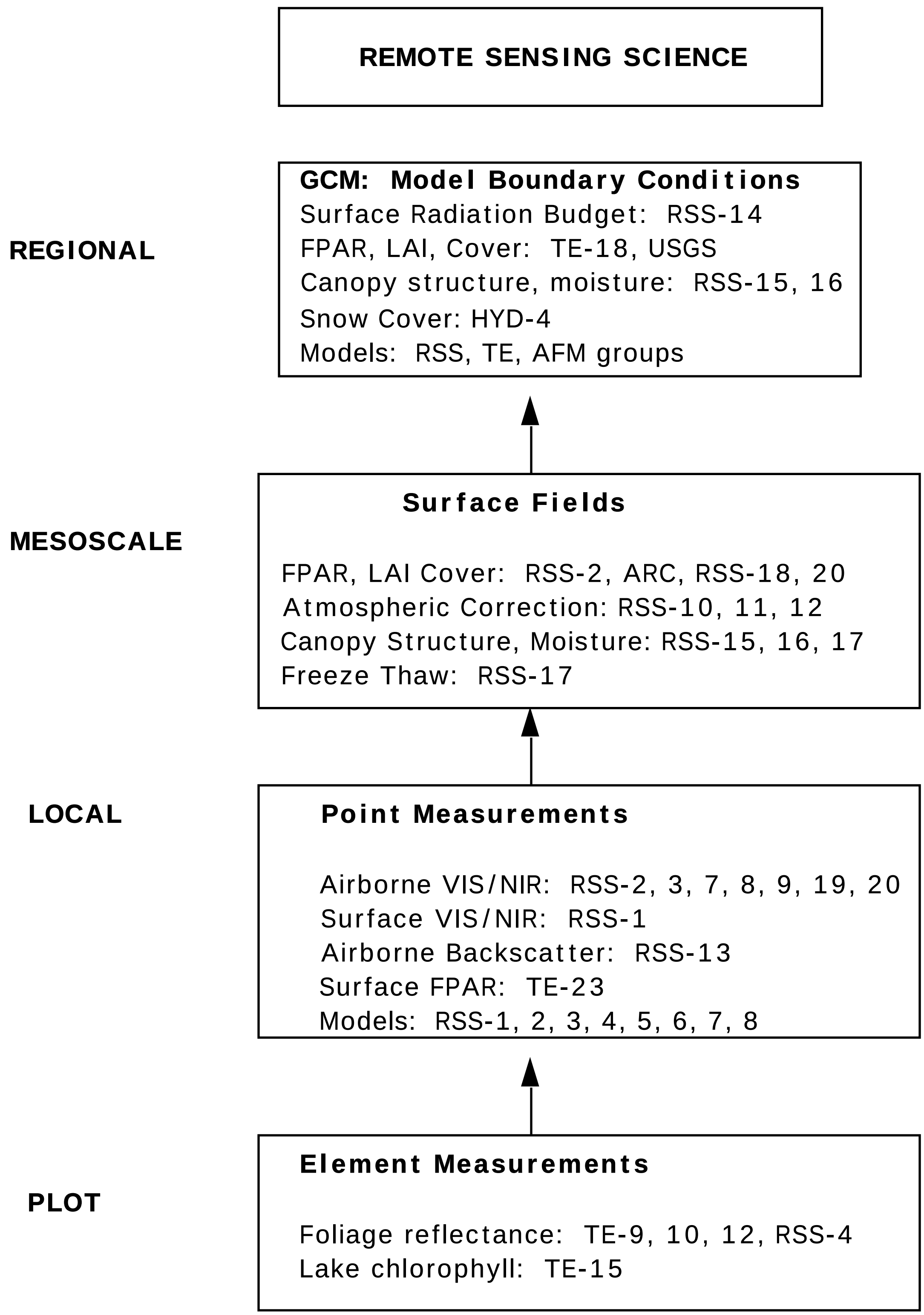
1.2.g Schematic of processes associated with trace gas biogeochemistry in the boreal forest.



1.2.h Flow chart corresponding to 1.2.f showing roles of BOREAS investigators.



1.2.i Schematic of tasks associated with remote sensing science in BOREAS.



1.2.j Flow chart corresponding to 1.2.i showing roles of BOREAS investigators.