

# **FLUXNET-CANADA MEASUREMENT PROTOCOLS**

## **WORKING DRAFT VERSION 1.3**



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## Working Draft - NFI Ground Sampling Guidelines

**Fluxnet-Canada:**  
**Mandatory Continuous Measurements of Meteorology and Flux**

	<b>Mature forest and peatland sites</b>	<b>Disturbed sites</b>
<i>Eddy-covariance (EC) fluxes, above canopy</i>	<ul style="list-style-type: none"> <li>- Carbon dioxide flux</li> <li>- Latent heat flux</li> <li>- Sensible heat flux</li> <li>- Momentum flux</li> </ul>	<ul style="list-style-type: none"> <li>- Same as for mature forests and peatlands</li> </ul>
<i>Fluxes or storages below EC level</i>	<ul style="list-style-type: none"> <li>- CO<sub>2</sub> air column storage</li> <li>- Sensible and latent heat air column storage</li> <li>- Aboveground biomass heat storage</li> <li>- Soil heat flux at the soil surface</li> </ul>	<ul style="list-style-type: none"> <li>- Same as for mature forests and peatlands, where a canopy exists</li> </ul>
<i>Radiation</i>	<ul style="list-style-type: none"> <li>- Net above canopy (using a network standard 4-way net radiometer<sup>1)</sup>)</li> <li>- Down- and up-welling photosynthetically active radiation (PAR), above canopy</li> <li>- Diffuse PAR</li> <li>- Fraction of PAR absorbed by the vegetation (fPAR) using at least one ground-level PAR sensors where a significant canopy exists</li> </ul>	<ul style="list-style-type: none"> <li>- Net above canopy Down- and up-welling PAR, above canopy</li> <li>- fPAR using at least 1 ground-level PAR sensor</li> </ul>
<i>Meteorology, above canopy</i>	<ul style="list-style-type: none"> <li>- Air temperature and relative humidity (aspirated and shielded)</li> <li>- Wind speed and direction</li> </ul>	<ul style="list-style-type: none"> <li>- Air temperature and - relative humidity (shielded)</li> <li>- Wind speed and direction</li> </ul>
<i>Meteorology within canopy</i>	<ul style="list-style-type: none"> <li>- Air temperature and relative humidity (shielded)</li> </ul>	<ul style="list-style-type: none"> <li>- Air temperature and relative humidity (shielded), where a canopy exists</li> </ul>
<i>Meteorology, other</i>	<ul style="list-style-type: none"> <li>- Barometric pressure</li> <li>- Precipitation (all-weather accumulating gauge)</li> <li>- Rainfall</li> <li>- Snow depth</li> </ul>	<ul style="list-style-type: none"> <li>- Barometric pressure, not needed if &lt;5 km of mature stand</li> <li>- Rainfall</li> <li>- Snow depth</li> </ul>
<i>Soil</i>	<ul style="list-style-type: none"> <li>- Soil temperature profile (2, 5, 10, 20, 50, 100 cm, 2 replicate profiles)</li> <li>- Soil moisture profile (by depth to at least 50 cm, or, where the roots go deeper, to the rooting depth, 3-6 depths, 2 replicate profiles)</li> <li>- Water table depth (peatlands)</li> </ul>	<ul style="list-style-type: none"> <li>- Same as mature forests and peatlands.</li> </ul>

1. This instrument provides downwelling and upwelling shortwave radiation, and downwelling and upwelling longwave radiation as outputs.

**Fluxnet-Canada:**  
**Mandatory Measurements of Site Characteristics**

	<b>Variable</b>	<b>Frequency</b>
<i>Carbon stocks<sup>1</sup></i>	<ul style="list-style-type: none"> <li>- Aboveground biomass by species, including overstory biomass (basal area, sapwood area, stem density) and understory biomass (shrubs, herbs, moss).</li> <li>- Root biomass</li> <li>- Surface detrital C including standing dead trees, coarse and fine woody debris, and forest floor organic layers</li> <li>- Mineral soil C</li> </ul>	<ul style="list-style-type: none"> <li>- At start and end of the experiment.</li> <li>- Once, at the start</li> </ul>
<i>Vegetation</i>	<ul style="list-style-type: none"> <li>- Site history</li> <li>- Species composition</li> <li>- Canopy height</li> <li>- Clumping index</li> <li>- Specific leaf area</li> <li>- Foliar element size</li> <li>- Spatial variability in fPAR</li> <li>- Leaf area index</li> <li>- Rooting depth</li> <li>- Date of budbreak</li> </ul>	<ul style="list-style-type: none"> <li>- Once</li> <li>- At least at the start and end of the experiment, but annually for disturbed sites</li> <li>- For mature sites at start and end of experiment, but perhaps more frequently for regrowth and deciduous.</li> <li>- Annually (coniferous) or seasonally (deciduous)</li> <li>- Once</li> <li>- Annually</li> </ul>
<i>Soil</i>	<ul style="list-style-type: none"> <li>- Profiles (sampled by depth to at least 50 cm, but where the roots go deeper, to the rooting depth) of:           <ul style="list-style-type: none"> <li>- soil texture</li> <li>- bulk density</li> <li>- soil coarse fragment fraction</li> <li>- water retention characteristics (field capacity, wilting point)</li> <li>- pH</li> <li>- Cation exchange capacity</li> <li>- N total, extractable P and K</li> <li>- % base saturation</li> <li>- C content</li> </ul> </li> <li>- <sup>13</sup>C and <sup>18</sup>O</li> <li>- Mineralizable N</li> </ul>	<ul style="list-style-type: none"> <li>- Once</li> <li>- Once per year</li> <li>- Annually</li> </ul>

1 Following National Forest Inventory Ground Plot protocols, but with modifications to augment estimation of root biomass and dead organic material and to sample within the flux footprint

**Fluxnet-Canada:**  
**Mandatory Measurements of Ecological Variables**

	<b>Variable</b>	<b>Frequency</b>
<i>Component Carbon Fluxes</i>	<ul style="list-style-type: none"> <li>- Soil carbon dioxide efflux (automated and portable chambers)</li> <li>- Aboveground growth increment (dendrometers or increment cores)</li> <li>- Fine root phenology/turnover<sup>2</sup></li> <li>- Litterfall</li> <li>- Overstory mortality</li>   <li>- Litter decomposition (bags)</li> <li>- <sup>13</sup>C, <sup>18</sup>O and <sup>2</sup>H in air</li> </ul>	<ul style="list-style-type: none"> <li>- Continuously (automated chambers) or occasionally (portable chambers)</li> <li>- Seasonally<sup>1</sup> with dendrometers or at end of experiment with increment cores</li> <li>- Seasonally</li> <li>- Seasonally for sites with canopy</li> <li>- Annually or from re-measurement of C stocks</li> <li>- Annually</li> <li>- 7 times per year</li> </ul>
<i>Vegetation</i>	Foliar nutrients (total N, P, K) <sup>13</sup> C & <sup>18</sup> O in leaves and wood	<ul style="list-style-type: none"> <li>- Annually in mid-summer</li> <li>- Annually in mid-summer<sup>3</sup></li> </ul>
<i>Ecophysiology</i>	<ul style="list-style-type: none"> <li>- Maximum stomatal conductance</li> <li>- <i>In situ</i> photosynthetic light response curves (i.e., quantum efficiency and V<sub>max</sub>).</li> <li>- <i>In situ</i> A/C<sub>i</sub> curves</li> <li>- Pre-dawn and/or mid-day water potential</li> </ul>	<ul style="list-style-type: none"> <li>- Once<sup>4</sup></li> <li>- Once<sup>4</sup></li> <li>- Once<sup>4</sup></li> <li>- During significant drought periods</li> </ul>

1. Seasonally refers to an attempt to capture at least some seasonal differences. Thus, there could be two, three or four sampling dates (e.g., early, middle and end of the growing season plus winter) depending on the variable and the equipment capabilities of the station.
2. Full network coverage will depend on the availability mini-rhizotrons.
3. See Cross-Transect Stable Isotopes plan.
4. Once is only the bare minimum requirement for all flux sites. Variation in leaf gas exchange parameters is an important Fluxnet-CA research question and we foresee more frequent measurements at most sites.

**FLUXNET-CANADA  
PROTOCOL FOR EDDY COVARIANCE (EC) FLUX  
MEASUREMENTS**

**The EC/Met Expert SubGroup  
of the Measurement Standardization Working Group**

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## BRIEF DESCRIPTION OF METHOD

The EC method is based on the concept that the vertical flux ( $F_x$ ) of an entity,  $x$ , is equal to the covariance of the vertical velocity ( $w$ ) and the concentration of  $x$ . This can be expressed as  $F_x = \overline{w'x'}$ , where the prime means difference from the mean and the overbar means time average – usually over a period of a half an hour. If  $F_x$  is positive, the flux is upward.

The net ecosystem exchange of CO<sub>2</sub> (NEE) is calculated by adding the rate of change of CO<sub>2</sub> storage in the air column below the EC sensor level ( $\Delta S_c/\Delta t$ ) to the EC flux of CO<sub>2</sub>,  $F_c$ . NEE is positive for CO<sub>2</sub> loss to the atmosphere and negative for CO<sub>2</sub> uptake (sequestration) by the ecosystem. To a good approximation, net ecosystem productivity (NEP) is equal to -NEE. Baldocchi et al. (1988) provide an overview of the method. Aubinet et al. (2000) describe the eddy covariance methodology used in the European flux network (EUROFLUX). Here we will focus on the measurement of the fluxes of CO<sub>2</sub> and water vapour.

## REQUIRED EQUIPMENT

Equipment required are a three-dimensional sonic anemometer-thermometer (SAT), a fast response infrared gas analyzer (IRGA) and a data acquisition system capable of measuring and recording high frequency signals.

In Fluxnet-Canada, two SATs are recommended: the model R3 or R3-50 (Gill Instruments Ltd.) and the model CSAT3 (Campbell Scientific Inc. (CSI)). Both instruments have a 10-cm path length between sonic transducers and are capable of operating at temperatures as low as -40°C. The CSAT3, however, does not make measurements during rain or immediately after rain. The UBC group has compared the two SATs on a number of occasions and found they agree very well in good weather. Where dew, rain or hoar frost are common, it is recommended that the R3 or R3-50 be used to minimize data loss during wet periods in the growing season and snow and frost periods in the winter.

Two types of gas analyzers can be used to make high frequency CO<sub>2</sub> and water vapour concentration measurements: (i) closed-path and (ii) open-path. The first has a temperature-controlled cell (optical bench) through which sampled air must be drawn, while the second has an array open to the atmosphere consisting of a light source and a detector. Models LI-6262 and LI-7000 (LI-COR Inc.) are examples of the first and model LI-7500 (LI-COR Inc.) is an example of the second. The LI-7000 is a much-improved version of the LI-6262. The LI-7000 has a much higher frequency response than the LI-6262, has high frequency digital (serial) output as well as analogue output, and operates in differential mode. Both instruments should be enclosed in a temperature-controlled environment. The LI-7500 has the advantage of an excellent high frequency response but does not operate during or for several hours after rain. Snow, hoarfrost and dew also cause the instrument to fail. Furthermore, its environmental specifications (-25 to +50°C) are more limiting than those of the above sonic anemometers.

### *Closed-path IRGA arrangement*

In Fluxnet-Canada, only closed-path IRGAs should be used for year round flux monitoring at main (mature stand) sites. The LI-7000 is recommended. It should be housed in an enclosure in

which the air temperature is maintained within  $\pm 2^{\circ}\text{C}$ . This temperature should be at least  $5^{\circ}\text{C}$  above ambient air temperature to allow heat loss to the environment for temperature regulation. The LI-6262 can be used for EC measurements above tall forest stands where low frequency response ( $< 1 \text{ Hz}$ ) is adequate. It is not recommended for use in recent clearcuts, which are aerodynamically smooth. The sampling tube should be no longer than 4.5 m. This allows the box containing the IRGA to be placed 2.5-3 m below the SAT and the entrance to the sampling tube, which ensures that the IRGA box causes minimal aerodynamic disturbance of the air flow through the SAT array. An internal pressure transducer should be installed in the IRGA.

The sampling tube should be Dekoron, Teflon or stainless steel. These materials have acceptably low water vapour and  $\text{CO}_2$  adsorption if kept clean and above dew-point temperature (see below). Dekoron is robust and convenient to work with in the field, and is recommended for EC measurement in Fluxnet-Canada. A convenient size of the sample tubing is 3.9 mm internal diameter (ID) (this is the ID of  $\frac{1}{4}$ " outer-diameter Dekoron tubing). It is imperative to maintain the air flow in the sampling tube turbulent to insure maximum frequency response of the gas analysis system. Generally, a Reynold's number ( $\text{Re}$ ) exceeding 2300 ( $6.5 \text{ L min}^{-1}$  for the above ID) results in turbulent flow in a tube. In practice, however, frequency response continues to improve with increasing flow rate. In Fluxnet-Canada, a flow rate of 8.5 to  $9.0 \text{ L min}^{-1}$  ( $\text{Re} = 3000$  to 3,500) is recommended. It should be noted that the flow rate through the LI-6262 should not exceed  $10 \text{ L min}^{-1}$ . Also it is important to avoid using high flow rates because they can disturb the airflow around the sonic transducer array. It is important that the walls of the sampling tube stay above the dew point temperature of the air. This is usually the case during the daytime with the tubing being warmed by solar radiation. At night, however, net loss of longwave radiation by the tubing can result in cooling of the walls below dewpoint temperature. It is, therefore, recommended to warm the tubing electrically. The tubing should be enclosed in thermal insulation (e.g.,  $\frac{3}{4}$ " OD x  $\frac{1}{2}$ " thick hot water pipe insulation) and 2-4 W/m of heat applied beneath the insulation (e.g., using nichrome heater wire wound around the tubing). The insulated tube should be wrapped with aluminum foil tape to keep out moisture and reduce radiative cooling at night.

The entrance to the sampling tube should be positioned about 35 cm from the centre of the sonic transducer array and level with the lower transducers. The position should be downwind of the array for the main wind directions at the site so that there is minimum disturbance of the airflow through the array by the sampling tube. Disturbance should also be minimized by having the sampling tube extend vertically from beneath the sonic array and by using a small conical "roof" (4 cm diameter x 4 cm high) to prevent precipitation from entering the sampling tube. Mosquito screen (or a 10  $\mu\text{m}$  Nupro filter) should be used to prevent insects and large air borne particles from entering the sampling tube.

The sampling tube must be replaced or cleaned every 6-8 months or more often. The filter (1  $\mu\text{m}$  Gelman Co., placed at the sample input to the IRGA) must be replaced every 2 months or more frequently during the pollen or forest fire season.

The flow rate of the nitrogen gas that passes through the reference cell of the IRGA should be maintained at 80 to  $300 \text{ mL min}^{-1}$ , but should be kept consistent. It should be scrubbed using soda lime and manganese perchlorate to remove trace quantities of  $\text{CO}_2$  and water vapour.

### *Open-path IRGA arrangement*

The open-path IRGA (LI-7500) can be used at satellite sites especially where monitoring may not be year round. It is useful for clearcuts where high frequency response is desirable. It is valuable in tests assessing the high frequency losses in closed-path IRGA systems.

It should be mounted following the recommendations for positioning the entrance of the sampling tube in the closed-path IRGA arrangement (see above). Orienting the main axis of the instrument 15°-30° with respect to the horizontal helps drain water from rain or dew off the light-source (lower) window. It is not recommended to use the LI-7500 as a long-term flux-monitoring instrument, particularly at sites with significant rainfall events.

### *Fine wire thermocouples*

It is recommended to use 25 µm chromel-constantan (Type E) thermocouples to check on sonic temperature measurement. These should be mounted 35 cm from the centre of the SAT array in a down wind direction. It is convenient to use at least two because they frequently break in strong wind and rain or wet snow. The thermocouples are used to check the air temperature obtained from the speed of sound measurement by the SAT. More important, however, is the comparison of the sensible heat flux values obtained from the covariance of  $w$  and sonic temperature with the covariance of  $w$  and thermocouple temperature. Good agreement between these two covariances indicates that the SAT is making a good sensible heat flux measurement thus indirectly indicating that the CO<sub>2</sub> and water vapour fluxes are reliable.

## **DATA ACQUISITION EQUIPMENT AND PROCESSING**

### *Quality of power to data acquisition equipment*

An uninterruptible power supply (UPS) must be used at all sites using line power or electric generators. A UPS provides a clean AC signal for the data acquisition system that is free of spikes that frequently occur in line power during bad weather. The batteries in the UPS enable it to continue to supply power for up to 45 minutes (depending on demand) when there is a power failure, which enables the system to be shut down safely.

### *Signal measurement frequency*

It is recommended that EC signals are measured at a frequency of 20 Hz; however, a minimum of 10 Hz is acceptable for tall stands. At aerodynamically smooth sites (e.g., clearcuts), it is desirable to measure at 20 Hz; to ensure that there is no loss of high frequency contributions. This also increases the statistical precision of approaching the true covariance for some quantities, reduces aliasing, offers additional high-frequency information for spectra, and provides more flexibility in correlating lags.

## *High frequency data storage*

### **Main sites:**

At these (mature forest) sites in Fluxnet-Canada, all high frequency EC data must be stored throughout the year. These data must include the following raw measurements from the EC system, which can be either in mV or engineering units:

*Primary signals:* Variables used in the flux calculations; three components of wind speed ( $u$ ,  $v$ ,  $w$ ), sonic temperature or speed of sound, fine wire thermocouple temperatures (at least two), CO<sub>2</sub> and water vapour.

*Auxiliary signals:* Variables used to convert the primary signals to useful units (IRGA optical bench temperature and pressure) and high frequency quantum flux density (i.e. PAR) to assess stationarity of radiation.

At the main sites, the data acquisition system must be either a PC or a CSI CR5000. For example, with 8 EC signals, this requires a daily storage of 27 MB by the PC (2-byte integers) or twice this by the CR5000 with 4-byte integers. With the PC, a minimum of 3 months of data can be stored on a 5GB hard disc, while about 3 weeks of data can be stored on a 1 GB Compact Flash card used by the CR5000. If there is limited storage space (e.g., during the winter), data can be stored at a minimum of 5 Hz provided it is properly down sampled to avoid aliasing. The advantage of the CR5000 is that it has a low power requirement (<1W) compared to the PC (8-12 W). One of the advantages of the pc is that it can accept digital data directly from measuring instruments (see below) and can operate many other measurement or control systems at the site (e.g., a CO<sub>2</sub> profile system, an understory EC system, and a soil chamber system).

### **Satellite sites:**

At these sites where high frequency data are not stored routinely, the CSI 23X data logger is acceptable. It can measure at 7-10 Hz for EC flux measurements. It is recommended to use the logger's burst software with a laptop computer (or invoke a program that retains high frequency data on a storage module) to record high frequency data for periods of several hours in different meteorological conditions to examine the EC power spectra and cospectra at the site. The accuracy of the 23X-based EC system should be evaluated by operating it next to the EC system at the Flux Station's main site for a period of a several days (see below).

## *Digital versus analogue signals*

Digital input doesn't require an analogue to digital converter so these signals can go directly into the PC. Digital signals are easier to protect and isolate, there is no noise pickup, and there is more information (diagnostics) transmitted. Signal wires can be much longer than analogue signal wires. Digital input takes advantage of linearization already done by the measuring instrument. Care must be taken, however, when synchronizing data from multiple measuring instruments. With analogue signals, 16 bit resolution is necessary, anti-aliasing filters should be used, and signal wires must be less than 100 m. Noise pick up and ground loops are common problems. It is easier to synchronize the analogue signals from multiple instruments than the digital signals. **It is recommended to use digital input when possible**, e.g. with a PC-based system when using the LI-7000, LI-7500, R3 and CSAT3. The LI-6262 can not output digital data faster than 5 Hz so it's preferable to use its analogue output. With the CR5000, it is necessary to use analogue signals from these instruments.

## *Data processing programs*

For all flux stations, there will be only one set of EC data processing (i.e., data acquisition and flux calculation) programs used for each of the three data acquisition systems, i.e., those based on the PC, the CR5000 and the 23X. Each set of programs will be developed jointly by the researchers involved. In some cases, an existing set of programs will be used initially. For example, the UBC programs will be used for the PC-based system. This will standardize flux calculations across the network and permit valid inter-site CO<sub>2</sub>, water vapour and sensible heat flux comparisons. Differences between site EC systems will then be attributable to only sensor calibration or response differences, which will be identified by the cross-site EC inter-comparison procedure.

All high frequency EC data processing must be done using the MATLAB programming language. This includes the on-site flux calculations with the PC-based system, as well as the post-processing of the high frequency data recorded by the CR5000 and PC-based systems. The on-site MATLAB program used in the PC-based system will be identical to that used in post-processing all recorded high frequency data.

## *Flux calculations*

Flux calculations must be done on a half-hour basis, which is the interval currently recommended by Ameriflux.

The following processing steps must be applied to calculate fluxes:

1. **Unit conversion:** Change units from the raw data to m/s for wind speeds, °C for temperatures, and mixing ratios (mol mol<sup>-1</sup> dry air) for CO<sub>2</sub> and H<sub>2</sub>O. Unit conversion of the high frequency data avoids the need to apply the WPL terms to calculated fluxes.
2. **Spike removal:** Find single data points whose deviation from a running mean is above a threshold value and replace with a running mean value. This eliminates faulty data due to electronic noise as well as raindrops blocking the sonic path and indicates flawed data when too many spikes occur.
3. **Lag removal:** Shift data from closed path sensors forward with respect to sonic output to account for travel time of the air in the sample tube. The lag used here should be predetermined by the investigator using covariance maximization when the sample tube is clean and the fluxes are high.
4. **Calculation of Statistics:** Means, standard deviations, minima and maxima (hereafter referred to as statistics), and the covariances between variables must be calculated. No filter is to be applied before these calculations. This is equivalent to a block averaging, which is the procedure currently recommended by Fluxnet. Fluxes are calculated from these covariances.
5. **Coordinate rotation:** Express statistics, covariances, and fluxes with respect to a reference frame where  $\bar{v} = 0$ ,  $\bar{w} = 0$ , and  $w'v' = 0$ . This is equivalent to calculating the fluxes normal to the half-hourly streamline above the forest at the tower.
6. **Calculation of Diagnostics:** These are the statistics of the raw data and of the auxiliary channels, the number of spikes removed from each variable, the lag and covariances after covariance maximization, and the rotation angles.

## *Quality control*

To allow checking of the EC system status, a quality control data set must be assembled from the on-site calculations. This data set includes the final statistics and fluxes, mean wind speed components and their standard deviations before rotation, the number of spikes for all channels, the lags calculated for CO<sub>2</sub> and H<sub>2</sub>O, and statistics of the auxiliary channels.

It is essential to obtain this minimum data set from the main sites daily. **Each of the main sites must have a phone (land line or cellular) or satellite internet connection.** These data sets must be examined immediately after they are received to see if all instruments are working properly. If an instrument appears to be broken action should be taken as soon as possible to replace or repair it. This is essential to ensure that flux and climate data gaps are kept to a minimum.

## *Standard gap filling procedure*

Gaps as short as 5 days are difficult to fill reliably using mean diurnal variation or other methods (Falge et al. 2001). Such gaps can be serious losses during short-duration phenological stages, e.g., senescence or leaf emergence. Frequent lengthy gaps will jeopardize our estimates of annual carbon sequestration. **A standard gap filling procedure for all Fluxnet-Canada sites should be established to ensure comparison of fluxes between sites. (Further work required on this section)**

## *Supplemental Measurements*

*Barometric pressure* measured by a sensor mounted in the instrument hut.

*CO<sub>2</sub> concentration profile* in order to calculate air column CO<sub>2</sub> storage change to calculate NEE from  $F_c$ .

*Operational diagnostics and control:* Zero and calibration gas tank pressures, enclosure/hut temperatures, sample tube temperatures.

A CR10 data logger must be dedicated to storing half-hourly average values of these variables. It should also be used to monitor the PC and reboot it when it fails to respond to a query from the logger.

## *Calibration Procedures*

### **IRGA calibration**

Table 1 summarizes the options available for the calibration of the closed and open path IRGAs. Calibration can be manual (M) or automatic (A).

Table 1. Calibration options for open and closed path IRGAs

		Open		Closed	
		CO <sub>2</sub>	H <sub>2</sub> O	CO <sub>2</sub>	H <sub>2</sub> O
Zero	On tower	M	M	A/M	A/M
	Off tower	M	M	M	M
Span	On tower	M	-	A/M	-
	Off tower	M	M	M	M

### *On tower calibrations of closed path IRGAs*

For CO<sub>2</sub>, it is necessary to calibrate by injecting zero and calibration (360 to 380 ppmv CO<sub>2</sub> in dry air, secondary standards) at the sampling tube entrance at a rate exceeding the sampling flow rate by 20-30% or about 2-3 L min<sup>-1</sup>. This ensures that no ambient air is drawn in during this procedure. For automatic calibration, it is recommended to run the calibration gases for 30-60 s each, depending on the flow rate of the system. Slower flow rates need longer calibration runs. For example, at 10 L min<sup>-1</sup> of sample flow, the calibration flow should be 12-13 L min<sup>-1</sup> and last for about 40 s, while at 8 L min<sup>-1</sup> of sample flow, the calibration flow should be only 9.5–10.5 L min<sup>-1</sup>, but it should last for more than 60 s. The calibration values should be obtained by averaging the last 3-5 seconds of the zero and calibration measurements. These are guidelines. The exact flow rate can be obtained by using the lowest flow rate that gives the same zero and span values as at higher rates. This latter procedure results in the same sample cell pressure as during a regular measurement run and helps conserve calibration gas. Automatic calibration once a day (Table 2) allows the researcher to notice any changes in instrument performance that might indicate the onset of a serious problem. If calibrations are done manually, they should be done at least once per month. **Calibration records should be saved in all cases.**

For water vapour, only zeroing is possible when doing tower calibrations. This is done when the CO<sub>2</sub> zero and span are done (both gases are dry). See procedure above. To do daily checks on the span or sensitivity of the IRGA water vapour detector, the IRGA water vapour measurement should be compared (using a 1:1 plot) with a Vaisala HMP humidity sensor (calibrated every 6-12 months, see the meteorological measurements protocol) mounted at the same level as the EC sensors. A week of half-hourly mean values should be adequate for the analysis.

Table 2. IRGA calibration frequency

		Open		Closed	
		CO <sub>2</sub>	H <sub>2</sub> O	CO <sub>2</sub>	H <sub>2</sub> O
Zero	<b>On tower</b>	Monthly	Monthly	Daily	Daily
	<b>Off tower</b>	6-12 months	6-12 months	Annually	Annually
Span	<b>On tower</b>	Monthly	-	Daily	-
	<b>Off tower</b>	6-12 months	6-12 months	Annually	Annually

### *Off tower calibration of closed path IRGAs*

This should be done every 6-12 months assuming that tower calibrations are done at least at the intervals suggested above. These are done following procedures described in the instrument manuals. Flow rates must be kept low (0.5-1.0 L min<sup>-1</sup>) as specified in the manual. During the dew-point calibration, the length of the tubing between the dew point generator and the IRGA must be kept short (< 20 cm) so the calibration of the closed-path IRGAs must be done without the sampling tube. This means that in this calibration the effect of the sample tube is not accounted for.

#### *On tower calibrations of open path IRGAs*

These must be done manually using the LI-COR calibration chamber. Since this requires a long Dekaron tube from the hut, it is only possible to use gas cylinders and not the dew point generator. As indicated in Table 1, the H<sub>2</sub>O span can not be done this way.

#### *Off tower calibrations of open path IRGAs*

This must be done manually once a month if the on tower calibrations described above have not been done. If they have been done then every 2-4 months should be adequate if no problems (i.e., unexpected zero drifts, CO<sub>2</sub> span changes or presence of extra noise) have been observed during the on tower calibration procedure. It requires the use of the chamber provided by LI-COR.

#### *IRGA CO<sub>2</sub> detector calibration (zero and span) and water vapour detector zero*

For all sites and all IRGAs (i.e., LI-6262, LI-7500, LI-7000), whether it is automatic or manual calibration, the procedure is:

- 1) Keep the data acquisition system running in the normal operating mode.
- 2) Run the zero gas and record the voltages from CO<sub>2</sub> and H<sub>2</sub>O concentration, pressure and temperature channels.
- 3) Run the calibration gas and record the voltages from CO<sub>2</sub> and H<sub>2</sub>O concentration, and pressure and temperature channels.
- 4) Do not adjust any potentiometers on the IRGAs or change any values in the data acquisition software.
- 5) If using the LI-6262, use the above voltages to calculate the gains and offsets, and record these values.

If you are manually calibrating the LI-7500 or LI-7000, the procedure continues as follows:

- 1) Run the zero gas again and then use the software to “zero” the instrument.
- 2) Run the calibration gas again and use the software to “span” the instrument.
- 3) Run the zero and calibration gases through the now calibrated instrument, and record the measured values. If the values disagree with the true values, repeat the calibration.

#### *IRGA water vapour detector span*

The IRGAs should also be manually calibrated using a dew point generator (LI-610): monthly for the LI-7500 and once a year for the LI-6262 and LI-7000. As indicated above, the length of the tubing between the LI-610 and the IRGA must be kept short (< 20 cm) so the calibration of the closed-path IRGAs must be done without the sampling tube. These manual calibrations can be done in the instrument hut on site or in the laboratory.

#### *Sonic anemometer-thermometer calibration*

Each flux station should attempt to carry out short-term (3-10 day) comparisons of their operating field sonic anemometers with their spare unit. The spare unit should be mounted at the same level as the field unit.

An important goal of the cross-site EC calibration program is to assess the performance of the sonic anemometer operating at the main site of each flux station.

An important daily check is the comparison of half-hour values of "cup wind speed" calculated from horizontal wind vector components ( $u$  and  $v$ ) measured by the sonic anemometer ( $\sqrt{u^2 + v^2}$ ) with wind speed measured by the R.M. Young propeller-vane anemometer. The agreement should be within 5%.

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**FLUXNET-CANADA  
MEASUREMENT PROTOCOLS FOR METEOROLOGICAL  
VARIABLES**

**The EC/Met Expert SubGroup  
of the Measurement Standardization Working Group**

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## INTRODUCTION

The purpose of this document is to standardize measurement protocols for meteorological instruments installed at the Fluxnet Canada sites. Discussion of each instrument is broken into five sub-sections which describe 1) Instrument Description and Theory, 2) Instrument Function, 3) Instrument Mounting, 4) Calibration and Servicing, and 5) Special Instructions. Sub-section 1) provides information on the specific instrument as well as some theory as to how the instrument measures the variable in question. Sub-section 2) briefly describes the function of the instrument with some direction as to how the instrument should be operated. Sub-section 3) provides some guidelines as to instrument location and setup. Sub-section 4) discusses calibration procedures and schedules as well as routine servicing requirements. Sub-section 5) indicates any special instructions that may be necessary for the installation or operation of the equipment. Much of the information in this document is derived either from instrument manuals or from user experience. The user of this document should refer to the specific instrument manuals or the instrument manufacturer for more detailed information.

Table 1.1 lists the mandatory meteorological measurements at Fluxnet-Canada sites. Where standard instruments have been adopted, they are listed in Table 1.2. First, the measurement of net radiation is standardized at all mature sites using the Kipp and Zonen CNR1 net radiometer. This is now generally accepted to be the best instrument for measuring net radiation and is superior to the measurement from a net pyrrographimeter alone. The CNR1 measures all four components (incoming and outgoing shortwave and longwave radiation) separately, and net radiation is the algebraic sum of the four. It also has the added advantage of providing the data to calculate the shortwave reflection coefficient of the surface. Secondly, the measurements of up- and down-welling PAR are standardized at all sites using the Li-COR LI190. In addition, diffuse PAR is measured at mature forest sites using the Delta-T BF3. Thirdly, the Vaisala HMP45 is used at all sites to measure air temperature and humidity. Where possible, the instrument is housed in an aspirated shield. For disturbed sites with power restrictions, an unaspirated shield is acceptable. In addition, air temperature is measured above the canopy at all mature sites using the MetOne aspirated shield and the Omega RTD-810. Fourthly, the Geonor T200 accumulating gauge is used at all mature sites to measure total precipitation, and the Hydrological Services precipitation gauge (model CS700, Campbell Scientific) and the Campbell Scientific SR50 sonic snow depth sensor are used at all sites to measure rainfall and snow depth respectively. Lastly, the measurement of soil moisture is standardized across the network by using soil moisture reflectometers available from Campbell Scientific (model CS615/CS616). This sensor requires *in situ* calibration, especially for sites where the soil has a high clay and/or organic content.

**Table 1.1: Mandatory Meteorological Measurements**

	<b>Mature forest and peatland sites</b>	<b>Disturbed sites</b>
Radiation	<ul style="list-style-type: none"> <li>Net above canopy (using a network standard 4-way net radiometer<sup>1</sup>)</li> <li>Down- and up-welling photosynthetically active radiation (PAR) above canopy</li> <li>Net and PAR below canopy where a significant canopy exists</li> <li>Diffuse PAR above canopy (forest only)</li> </ul>	<ul style="list-style-type: none"> <li>Net above canopy</li> <li>Down- and up-welling PAR, above canopy</li> <li>PAR below canopy where a significant canopy exists</li> </ul>
<b>METEOROLOGY, ABOVE CANOPY</b>	<ul style="list-style-type: none"> <li>Air temperature and relative humidity (aspirated and shielded)</li> <li>Wind speed and direction</li> </ul>	<ul style="list-style-type: none"> <li>Air temperature and relative humidity (shielded)</li> <li>Wind speed and direction</li> </ul>
Meteorology within canopy	<ul style="list-style-type: none"> <li>Air temperature and relative humidity (shielded)</li> </ul>	<ul style="list-style-type: none"> <li>Air temperature and relative humidity (shielded), where a canopy exists</li> </ul>
Meteorology, other	<ul style="list-style-type: none"> <li>Barometric pressure</li> <li>Precipitation (all-weather accumulating gauge)</li> <li>Rainfall</li> <li>Snow depth</li> </ul>	<ul style="list-style-type: none"> <li>Barometric pressure, not needed if &lt;5 km of mature stand</li> <li>Rainfall</li> <li>Snow depth</li> </ul>
Soil	<ul style="list-style-type: none"> <li>Soil temperature profile (2, 5, 10, 20, 50, 100 cm, 2 replicate profiles)</li> <li>Soil moisture profile (by depth to at least 50 cm, or, where the roots go deeper, to the rooting depth, 3-6 depths, 2 replicate profiles)</li> <li>Water table depth (peatlands)</li> </ul>	<ul style="list-style-type: none"> <li>Same as mature forests and peatlands.</li> </ul>

1. This instrument provides downwelling and upwelling shortwave radiation, and downwelling and upwelling longwave radiation as outputs.

**Table 1.2: Fluxnet-Canada Standard Meteorological Instruments**

Variable	Instrument	Mature Forest	Mature Peatland	Satellite
<b>NET RADIATION (FOUR-COMPONENT)</b>	Kipp and Zonen CNR-1	•	•	
Net radiation	No mandatory standard			•
PAR (down- and upwelling)	Li-Cor LI190	•	•	•
Diffuse PAR	Delta-T BF2	•		
Above-canopy air temperature	Omega RTD-810 in a MetOne 076B-1 aspirated shield	•	•	
Above-canopy air temperature and relative humidity	Campbell Scientific/Vaisala HMP45C	•	•	•
Precipitation (accumulated)	Geonor T200x	•	•	
Wind speed at T200 height	No mandatory standard	•	•	
Rainfall rate	Hydrological Services CS700	•	•	•
Snow depth	Campbell Scientific SR-50	•	•	•
Wind speed and direction	RM Young 05103	•	•	•
Pressure	CS105 (Vaisala)	•	•	
Soil moisture	Campbell Scientific CS616	•		•
Soil heat flux	No mandatory standard	•	•	•

## RADIATION

*Shortwave (Solar), Longwave (Far Infrared), and Net Radiation*

### Instrument Description and Theory

These radiation streams will be measured with a Kipp and Zonen CNR1 net radiometer. This instrument is made up of two CM3 (305 – 2,800 nm spectral range, shortwave) pyranometers and two CG3 (5,000 – 50,000 nm spectral range, longwave) pyrgeometers. Each of the pyranometers and pyrgeometers consists of a thermopile sensor with a black absorbent coating. The manufacturer indicates the instrument has an operating temperature range of -40°C to 70°C, and an expected accuracy of  $\pm 10\%$  per daily totals. One of the pyranometers faces up to measure total (direct + diffuse) downwelling solar radiation (or global solar radiation) ( $S_{td}$ ,  $\text{W m}^{-2}$ ) and one faces down to measure upwelling (reflected) solar radiation ( $S_{tu}$ ,  $\text{W m}^{-2}$ ).

One of the pyrgeometers faces up to measure downwelling longwave radiation ( $L_d$ ,  $\text{W m}^{-2}$ ), which originates largely from emission from the air layer within 200 m of the Earth's surface. The other faces down to measure upwelling long wave radiation ( $L_u$ ,  $\text{W m}^{-2}$ ), which is the radiation reflected by land surface and as a result of its surface temperature and emissivity,  $\varepsilon =$

0.90-0.97 (i.e.,  $\varepsilon\sigma T_s^4$ ), where  $\sigma$  is the Stefan-Boltzmann constant,  $5.67 \times 10^{-8}$  W m<sup>-2</sup> K<sup>-4</sup>), and the reflected downwelling longwave radiation,  $(1 - \varepsilon)L_d$ , that is small in magnitude compared to the upward emitted component, i.e.,

$$L_u = \varepsilon\sigma T_s^4 + (1 - \varepsilon)L_d \quad (1)$$

From the four measurements, the following can be calculated:

Net downward (downwelling) shortwave radiation:

$$S_n = S_{td} - S_{tu} \quad (2)$$

Net downward (downwelling) longwave radiation:

$$L_n = L_d - L_u \quad (3)$$

Net radiation (sometimes referred to as net all-wave radiation)

$$R_n = S_{td} - S_{tu} + L_d - L_u \quad (4)$$

Albedo ( $\alpha$ ), the fraction of downwelling solar radiation reflected by the land surface, can be calculated using:

$$\alpha = S_{tu}/S_{td} \quad (5)$$

Substituting Eqs. (1) and (5) in Eq. (4),  $R_n$  can be written as:

$$R_n = (1 - \alpha)S_{td} + \varepsilon(L_d - \sigma T_s^4) \quad (6)$$

Land surface temperature ( $T_s$ ) can be derived from  $L_u$  and  $L_d$  using Eq. (1) with an estimate of surface emissivity.

## Instrument Function

It is recommended to measure each of the four sensor outputs using a double-ended input to the data logger (e.g., CSI CR10, 21X, 23X or CR5000) with the shield connected to an earth ground. Solar irradiance (i.e.,  $S_{td}$  and  $S_{tu}$ ) is calculated from the pyranometer voltage output ( $V$ ) from  $V/C$ , where  $C$  is the pyranometer sensitivity. The radiometer temperature ( $T_r$ ) required in the calculation of longwave irradiance (i.e.,  $L_d$  and  $L_u$ ) is measured using a Pt-100 RTD temperature sensor, which should be measured using a 4-wire bridge requiring 2 double-ended CSI data logger channels.  $L_d$  and  $L_u$  are calculated from the pyrgeometer voltage output using  $V/C + \sigma T_r^4$ , where  $T_r$  is in Kelvins.  $R_n$  should be calculated using Eq. (4). Although the four sensors can be connected in series to give a net radiation signal directly (because all four sensors are calibrated to equal sensitivity ( $\approx 10-35 \mu\text{V}/(\text{W m}^{-2})$ ) at the factory, it is not recommended because of

possible measurement errors due to grounding complications. Measurement should be made at 1-s intervals with recording of half-hour mean, minimum and maximum values. It may be necessary to program 1-s scans into a separate “high-speed” table to ensure enough time for the completion of all instructions measuring core climate variables.

### Instrument Mounting

The instrument should be mounted to ensure minimum effects of mounting structure (solar panels, lower radiometer, boom, guy wires, etc.) on the measurement, and, in the case of down facing sensors, to obtain a view of the surface that is representative of the ecosystem. The latter should correspond with the eddy covariance flux footprint at the study site. The temperature of tower framework can affect the downwelling and upwelling longwave radiation measured by CNR1. Furthermore, the shortwave reflectivity of the framework can affect the upwelling and downwelling solar radiation. Because of this, the CNR1 should be mounted as far as practical away from the tower. It should be mounted on the south side to prevent the portion of the tower above the CNR1 from casting a shadow on the instrument. It also eliminates the shadow of the tower and the CNR1 boom on the vegetation directly beneath the instrument, which would reduce upward reflected shortwave and emitted longwave radiation. The further above the surface downward-looking sensors are mounted, the more of the land surface is “seen” (a good thing), but more of the view is occupied by the tower (a bad thing).

As a rule of thumb, 95% of the radiation measured by a downward-looking sensor (which is largely diffuse) mounted a distance  $h$  above the surface originates from a circular area with a radius of  $3h$  directly below the radiometer. So if the instrument is 6 m above the surface (top of the vegetation canopy), most of upwelling radiation comes from an area with a radius of 18 m. The radiometer should be mounted as far from the tower as possible to avoid the effects of the tower framework on the measurement. The view factor calculation required to determine the effect of the framework is quite complicated. In fact, the distance from the tower is determined by the practicality of mounting, i.e., maintaining a level instrument with minimum effect of wind and snow loading on the boom. From experience at the BERMS sites, it is feasible to mount the instrument 3 m from the tower. At BERMS the instrument is mounted at the end of a 2" x 2" (outer dimensions) square aluminum pipe that slides inside a 2 ¼" x 2 ¼" (outer dimensions) square aluminum pipe, which is mounted on the tower. Use of nylon pegs mounted on the inside of the outer pipe makes sliding the inner pipe relatively easy. The smaller pipe is kept level and steady with the supporting galvanized or stainless steel cable (1/8" diameter) extending from the end of the inner pipe (near the attachment of the CNR1) to the tower above and below the CNR1. After the initial leveling, the pipe can be pulled in for radiometer maintenance and, pushed out until the cables are tight and inserting a locking pin through both pipes. Level can be achieved by using a permanently-mounted level bubble and a small polished stainless steel mirror oriented at 45° attached on the CNR1 side of the level for easy visibility of the level bubble from the tower. The pitch of the instrument can be adjusted by loosening or tightening a turnbuckle attached to the vertical support cable. The roll can be adjusted via the CNR1 mount which should consist of a tubular receptacle equipped with a set screw. The CNR1 can then be rotated to level and locked into place with the set screw.

## **Calibration and Service**

It is important that the sensitivity of the CNR1 sensors be checked annually using a Fluxnet-Canada "standard" unit. Kipp and Zonen provide a recalibration service that provides an accuracy of <3% and suggests it be done every two years. \*\*\* All radiometers used to measure net radiation will be calibrated on a regular basis, at least every second year, at the National Atmospheric Radiation Centre (MSC, Downsview).

Routine servicing of the CNR1 is minimal. At every service trip, the domes should be visually inspected for debris or scratching. Domes should be cleaned with a soft cloth. Instrument level should be routinely checked at least every 2 months and adjusted accordingly. Detailed field notes should reflect any servicing or adjustments.

## **Special Instructions**

The CNR1 has a 24-Ohm heater. Using it will introduce small measurement errors (e.g., small ( $10 \text{ W m}^{-2}$ ) offsets in the CM3). Minimal heating is advised (e.g., 2-6 W). Heating will improve overall accuracy especially in winter months by eliminating dew and frost deposition. By applying 12 VDC, it provides 6 W (watts) of heating of the instrument for dew prevention. Up to 50 W of heating is possible but the manufacturer will not specify accuracy in this situation. It is important to keep a record of when and how much heating was used, and be prepared to reject data collected when power was high.

### *Photosynthetically Active Radiation (PAR)*

## **Instrument Description and Theory**

These radiation streams (often referred to as photosynthetic photon flux density (PPFD) in  $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$ ) should be measured using the LI-COR Inc. LI-190SA quantum sensor. This instrument has a spectral response very close to "ideal quantum response" (equal response to all photons) in the 400-700 nm waveband and has sharp cut offs at both ends of the waveband. The instrument is cosine corrected up to 80° angle of incidence, is extremely linear and has an accuracy of ±5%. It should be used with a model 2290 millivolt adapter (a 604-Ω resistor) that converts the current from the silicon photodiode to millivolts.

## **Instrument Function**

The output can be measured either using single or double ended inputs on a CSI data logger. It should be measured at 1-s intervals (its time constant is 10  $\mu\text{s}$ ), and half-hourly mean, minimum, and maximum values recorded. It is recommended that 1-5 minute mean values be recorded for downwelling total (direct plus diffuse) PAR in order to obtain a record (in addition to the 30-min values) of short-term changes in PAR and solar irradiance.

## **Instrument Mounting**

The quantum sensor for measuring downwelling total PAR can be mounted on the upper most position on the tower for convenience of servicing and insuring no effect of the tower on the measurement. The sensor for measuring upwelling PAR should be mounted facing downward near the CNR1 on its boom.

## **Calibration and Service**

The calibration of these instruments should be checked annually using a laboratory standard LI-190SA quantum sensor calibrated by LI-COR Inc.

Routine service trips should include a visual inspection of the sensor to ensure that it is free from debris and that the mount has remained level.

## **Special Instructions**

N/A

### *Downwelling Diffuse PAR*

## **Instrument Description and Theory**

This radiation stream will be measured using a Delta-T Devices Ltd. BF2 (now upgraded to the BF3) sunshine sensor, which uses an array of photodiodes and a shading pattern to measure the direct and diffuse components of PAR ( $\mu\text{mol m}^{-2} \text{ s}^{-1}$ ). The pattern of clear and opaque areas on the acrylic dome is matched to the pattern of photodiodes so that at least one photodiode always sees an unobstructed solar disc and at least one is always in full shadow. The onboard microprocessor uses these readings to calculate the direct, diffuse and total PAR values.

## **Instrument Function**

The sensor, which is cosine corrected, provides 2 analogue outputs (1 mV per  $\mu\text{mol m}^{-2} \text{ s}^{-1}$ ) corresponding to diffuse and total PAR. Measurements should be made at 1-s intervals (its time constant is <200 ms), and half-hourly mean, minimum, and maximum values recorded.

## **Instrument Mounting**

The BF2 or BF3 should be mounted near the LI-COR Inc. LI-190SA quantum sensor that measures downwelling total PAR.

## **Calibration and Service**

The calibration of the BF2 (total PAR) should be checked annually using a laboratory standard LI-190SA quantum sensor calibrated by LI-COR Inc.

## **Special Instructions**

Use of the heater option is recommended for dew and frost prevention. The manufacturer indicates the accuracy is  $\pm 15\%$ . The ratio of downwelling total PAR measured by the BF2 to that measured by the LI-190SA should be used to assess the quality of the BF2 data.

## **CORE CLIMATE**

### *Atmospheric Pressure (CS105 Barometric Pressure Sensor)*

#### **Instrument Description and Theory**

The CS105 analog barometer has been constructed to output a linear voltage signal of 0 to 2.5 VDC that corresponds to a pressure range of 60 to 106.0 kPa. The unit comes with 76.2-centimetre lead and is designed to be installed inside the ENC12/14 and ENC16/18 (CSI) enclosures.

#### **Instrument Function**

The unit can be operated in either a continuous or power-up mode. Mode selection is controlled by a single jumper found on the front of the unit. In continuous mode (with the jumper installed), the barometer provides a constant drain on the power supply. In power-up mode (with the jumper removed), the datalogger activates the barometer one second prior to taking a measurement. After the measurement is taken, the datalogger powers down the barometer until the next reading, conserving battery power. This mode requires more time than the continuous mode so caution must be used when incorporating this instrument in a “fast-scan” table. Because atmospheric pressure is slow to change, sampling at high frequencies is not necessary. In most applications, measuring atmospheric pressure once every 20 to 60 minutes is adequate. For consistency, pressure should be sampled at the same frequency as other core climate variables (i.e. every 30 minutes).

A 0.197 mV/metre drop results along CS105 leads. In long leads, the voltage drop will cause the barometric reading to be offset by approximately 0.11 kPa per 30 metre of lead length. As a result, extremely long leads should be avoided. The CS105 barometer has no user-serviceable parts. Manufacturer of the units recommends that the units undergo recalibration every year.

#### **Instrument Mounting**

Instrument can be attached to the wall (inside a logger hut) beside the logger to minimize cable lengths. It can also be installed, as recommended by CSI, inside a ENC12/14 or ENC16/18 (CSI) enclosure. A breather tube is provided to vent the instrument to the outside atmosphere if installed in an air-tight enclosure. When installed, the height of the instrument from ground level should be noted.

## **Calibration and Service**

A calibration check on the sensor should be performed on a yearly basis using a floating standard. If installed in an outdoors enclosure, the vent tube should be checked for obstructions or moisture on a routine basis.

## **Special Instructions**

None

### *Air Temperature and Relative Humidity*

#### **Instrument Description and Theory**

Air temperature and relative humidity (RH) are measured simultaneously with the HMP45C probe. In addition, air temperature will be measured above the canopy at all mature sites using the MetOne aspirated shield and the Omega RTD-810.

#### **Instrument Function**

The HMP45C air temperature measurement range offered by the probe is from -39.2 to 60°C, coinciding with an output signal range of 0.008 to 1.0 VDC. The RH range is from 0.8 to 100% (non-condensing), also with an output signal range of 0.008 to 1.0 VDC. The response time of the RH sensor is 15 seconds at 20 °C with the Teflon membrane filter installed. The voltage drop along the leads will cause an error of about 0.56 °C and 0.56% in the temperature and RH measurements with every 30 metres of additional cable length.

The Omega RTD-810 contains a high-precision 100-Ohm platinum resistance thermometer, that should be measured using a 3- or 4-wire half bridge with stable, high precision bridge resistors (available from Campbell Scientific).

#### **Instrument Mounting**

At each main tower site, the air temperature and relative humidity will be measured at four levels: base of canopy, at approximately 1.5 m height, in mid canopy, and above the canopy. The above-canopy air temperature measurement will be done using the aspirated Met One shield and the Omega RTD (AmeriFlux standard). We recommend that a temperature/relative humidity sensor (HMP45C) be inserted into the same shield to measure relative humidity. The second measurement of air temperature from the HMP45C is acceptable redundancy in the measurement procedure. The in-canopy levels need not be aspirated, and we recommend the use of a HMP45C sensor in a 12-plate naturally ventilated shield. It is important to mount the unaspirated shields as far from the tower structure as possible to minimize any error imposed by the structure, e.g., through interference with wind flow in the generally less turbulent flows typical of the canopy space. A minimum distance of 3 m from the tower is reasonable. Above the canopy in the free flow of the atmosphere, it is not so critical to mount the Met One shield as far from the tower as the unaspirated shields. We recommend this shield be positioned at least 1 m from the tower structure and pointed into the prevailing wind.

At each satellite (disturbed) site, where a canopy exists, the above- and below-canopy HMP45C sensors need not be aspirated but should be in 12-plate shields. If the site has a well-developed canopy, >5 m in height, it is desirable to place a third sensor at mid-canopy level. The same mounting procedure is recommended for these shields as for those on the main tower. If the satellite site is either bare or has low-growing vegetation, then only one level of measurement is needed, and we recommend that it be at 1.5 m above the surface, the standard height of measurement at a weather station.

Where possible, we recommend the use of fine-wire thermocouples to add further redundancy to the air-temperature measurements.

### **Calibration and Service**

The HMP45C sensor in general needs very little upkeep. A regular examination of the radiation shield should be made to ensure it is free of debris and that the internal ventilation of the shield is unimpeded. The screen at the end of the probe should also be checked. Should the Teflon filter and RH chip require cleaning, light cleaning in distilled water is recommended. Be careful not to scratch the RH chip. Manufacturer of the probe recommends that the probe be recalibrated annually. One way to perform a simple calibration check is to employ a roving HMP45 and radiation shield mounted in close proximity to the instrument in question.

### **Special Instructions**

The HMP45 is a modular instrument meaning that the sensor can be decoupled from the rest of the instrument infrastructure. This allows for easier instrument changes but has caused problems due to disconnection. Stress on the instrument may pull the connections apart leading to loss of data. This physical connection should be checked on a regular basis.

*Temperature (ASPTC + Fine Wire Thermocouple)*

### **Instrument Description and Theory**

The ASPTC is an aspirated shield equipped with a fine-wire (0.0076 cm diameter) chromel-constantan thermocouple (TC) to measure air temperature.

### **Instrument Function**

Forced ventilation of the unit draws approximately 140 mA at 12 VDC from the power supply. For continued operation of the ASPTC, it is essential that sufficient power is available on site. A 12V 18AH battery can be used to back-up the AC power supply to operate the ventilators during brief power outages. In absence of backup power, it is recommended that an AC power monitor be installed on the circuit operating the ventilators and logged so that the status of the ventilators can be determined.

## **Instrument Mounting**

The ASPTC can be mounted on the tower with the same kind of cross arm and mounting bracket assembly employed with the HMP45C probe

## **Calibration and Service**

For proper operation, the intake opening and the TC of the ASPTC should be free of debris. Use care to remove the debris, especially around the TC. Be sure not to break the TC junction. The unit requires very little upkeep. Life expectancy of the fan system is about seven years under normal working conditions however the fan should be checked routinely for debris (insects) and cleaned if necessary. Fans that have experienced extensive debris should be changed more frequently. Calibration is not required.

## **Special Instructions**

Fans that become inoperable become a source of heat and will bias temperature observations.

### *Wind Speed and Direction (05103)*

## **Instrument Description and Theory**

The wind monitor senses both horizontal wind speed and direction. Wind speed is directly proportional to the propeller rotation (the serial number on the propeller should be directed into the wind). Maximum maintained wind speed that can be measured with the system is  $60 \text{ m s}^{-1}$ .

## **Instrument Function**

Wind direction is discerned by a potentiometer, which requires that a constant excitation voltage (<15 VDC) be applied for its operation. The output signal is an analog voltage that is directly associated to the angle of the horizontal wind.

Grounding of the unit is equally crucial. Static charges accumulated during certain weather conditions can discharge through the transducers, causing them to produce incorrect signals or even fail. To guide the discharge away from the transducers, the mounting post must be hooked up to a good ground. Avoid applying paint (or other insulating substances) on the mounting pipe at the point where the wind monitor makes contact with its mount. Towers embedded in concrete should have several grounding points.

## **Instrument Mounting**

Proper placement of the wind monitor is crucial. Wake turbulence from trees and other tall structures upwind can greatly influence measurements. To get meaningful measurements, situate the wind monitor well above (including the tower on which it is installed) or upwind of major obstacles. The wind monitor mounts on a regular 2.54 cm metal pipe, with an outside diameter of 3.4 cm.

Two people are needed to install the wind monitor – one person to mount and adjust the unit and the other to read the generated output (e.g., from a datalogger display or voltmeter) and direct the adjustment of the unit’s orientation with respect to a reference location in the horizon. An orientation ring is supplied so that the unit may be quickly removed and re-installed to its original position without losing unit orientation.

### **Calibration and Service**

In general, the wind monitor should not require calibration before it is placed in the field. Recalibration of the unit may be needed in some circumstances, especially after maintenance and when the unit’s performance degrades. Re-calibration of the unit can be done by a qualified technician or in-house with the appropriate apparatus such as the Vane Angle Bench Stand (Model 18112; RMY) for calibrating wind direction and the Anemometer Drive (Model 18801/18810; RMY) for wind speed.

### **Special Instructions**

Campbell Scientific data loggers provide three options for data output (instruction 69). We recommend the use of option 0 (mean horizontal wind speed, unit vector mean wind direction, and standard deviation of wind direction). In some cases option 2 (mean horizontal wind speed, resultant mean wind speed, resultant mean wind direction, and standard deviation of wind direction), which resolves mean u and v, may also be used.

## **PRECIPITATION**

### *Accumulating Gauge*

#### **Instrument Description and Theory**

Total precipitation should be measured using an accumulating gauge such as the Geonor T200 at all mature sites and at satellite sites that are more than 10 or 20 km from the mature site. Accumulated precipitation is measured with the T200 via a vibrating wire sensor. Increased weight (precipitation) in the collection bucket produces greater strain on the vibrating wire that increases the frequency of the output. The frequency is determined via a P27 instruction and converted to precipitation amount. A more comprehensive description of gauge setup and operation appears in Appendix A.

#### **Instrument Function**

The sensor requires a 12volt excitation that can either be applied continuously or switched on and off to conserve power (see Appendix A). Input and output from the sensor is via two wires that terminate into a CSI interface. The interface is then wired to the data logger. The frequency is measured via an analog channel on the logger. It is recommended that accumulated precipitation be measured every 15 to 30 minutes (higher frequency data allows for better quality control).

## **Instrument Mounting**

The T200 manufacturer provides a 1-m pedestal for mounting the gauge and the Alter wind shield. The pedestal needs to be solidly anchored into the ground to prevent movement of the gauge and to minimize wind vibrations. The pedestal should be mounted plumb to facilitate easy leveling of the gauge. When the gauge is mounted on the pedestal, caution should be taken to ensure that the vibrating wire sensor is mounted on the north side of the gauge to minimize diurnal heating of the sensor (sensor heating produces a small frequency change not related to precipitation). The orifice of the gauge should be at a height above any surrounding obstructions (such as a fenced enclosure) to reduce turbulence at gauge height. A wind speed instrument (a cup wheel anemometer is recommended) should be installed at gauge height. If the gauge is installed in a low-wind environment (within a thick canopy with wind speeds generally less than 2 m/s), a wind speed instrument may not be required. Corrections for gauge undercatch due to wind (most significant for snow) are being developed for the Geonor T200.

The accumulating gauge should be located within a natural clearing in the canopy. If the height of the nearest obstruction is  $h$ , then the gauge should be located at a distance of at least  $2h$  from this obstruction. If this is not possible, the gauge should be located in the center of the obstructions.

## **Calibration and Service**

The T200 has a 600 mm capacity and should be emptied at the user's discretion when the total precipitation in the gauge approaches this value. Gauge servicing is described in Appendix A. The sensor requires no service.

A calibration check of the vibrating sensor should be performed every two years by placing known weights in a clean bucket and observing the change in frequency. The response to weight should remain linear otherwise the instrument should be replaced.

## **Special Instructions**

See Appendix A for more details on gauge mounting and operation. Note that this instrument can be vulnerable to bear damage especially because of the contents of the collection bucket (oil and anti-freeze). The gauge can be made nearly "bear-proof" by surrounding the gauge with electric fencing or installing the gauge inside a 100 sq ft (at least) chain link enclosure (see photos in Appendix A)

## *Tipping Bucket Rain Gauge*

### **Instrument Description and Theory**

The Hydrological Services tipping bucket rain gauge (CS700) should be used to determine warm season precipitation rate. This gauge will not measure solid precipitation and should not be solely used to determine accumulated precipitation, even in summer. However, the gauge can be used as a proxy source of accumulated precipitation if an accumulating gauge malfunctions.

The CS700 operates through the use of two small tipping buckets that collect the equivalent of 0.2 mm of rain before spilling their contents and resetting the bucket. Each tip closes a magnetic switch that is read by pulse channel on a datalogger.

### **Instrument Function**

The switch mechanism is read via a pulse channel on a datalogger. Each pulse represents a tip that represents 0.2 mm of precipitation. A multiplier of 0.2 is required. Total precipitation should be accumulated over a 30-minute period but shorter time periods may be used if required.

Data from the tipping bucket should be eliminated or ignored during the cold season as the gauge is not designed to measure solid precipitation.

### **Instrument Mounting**

The instrument is designed for mounting on a horizontal surface. It may be desirable to mount the instrument several centimeters above the surface to facilitate rapid drainage out the bottom of the instrument. The gauge should be installed as close to the ground as possible to limit wind induced errors and it should be installed away from surrounding obstructions (same as in 4.1.3). It may be necessary to concrete a base into the ground to support the gauge. The instrument needs to be level that can be accomplished by using a base with adjustable bolts.

### **Calibration and Service**

The CS700 should be calibrated yearly via a calibration kit that can be used in the field. The gauge can be adjusted via set screws to change the number of tips associated with a known volume of water.

During the operation period, the gauge should be checked regularly for level and for debris. A debris screen prevents obstruction from getting into the mechanism but this screen needs to be cleaned regularly, especially during leaf fall. After each servicing, the switch mechanism should be tested by applying 10 tips and observing these tips on the datalogger. During servicing, detailed field notes should be taken to record the state of level, amount of debris in the gauge, and any servicing or testing performed on the gauge.

### **Special Instructions**

Use of this gauge in the field has shown a vulnerability to rodent damage. The cable coming out of the mechanism through the bottom of the gauge should be armored to prevent chewing. This armoring should be carried through from the gauge to the datalogger. Since this gauge needs to be installed away from obstacles, it becomes vulnerable to other animal damage. To prevent damage from large animals, it is recommended that an electrified fence be installed around the instrument.

## *Snow Depth Sensor*

### **Instrument Description and Theory**

The SR50 Sonic Ranging Sensor should be used to measure point snow accumulation and ablation. The gauge can be used as a proxy source of winter accumulated precipitation if an accumulating gauge malfunctions, given assumptions of new snow density.

The SR50 measures the distance between the sensor and a target surface by sending out ultrasonic pulses at 50 kHz and listening for returning echoes bounced back from the target. The time from transmission to return is proportional to the distance based on the speed of sound, which varies with air temperature. A simple calculation is applied to initial measurements to correct for the influence of temperature. The SR50 makes use of a unique multiple echo processing algorithm to improve measurement reliability, basing every measurement on several readings. A maximum of 3 seconds is required for measurement.

A measure of air temperature is not performed by the SR50, requiring an extra sensor to be mounted near the SR50. A Campbell Scientific 107F probe is recommended, housed in a Gill radiation shield.

### **Instrument Function**

The SDI-12 Serial Digital Interface standard can be used to communicate with Campbell Scientific CR23X or CR10X data loggers (SDI-12 is optional for the CR10), allowing measurement of up to ten sensors connected to a single digital I/O channel. A group of four jumpers inside the SR50 allow an address of 0-9 to be set, but it is easiest to use a different control port for each SR50 than to reset the addresses within the sensor. SR50 sensors are shipped from the factory with their addresses set to 0. Instruction 105 is used (see Special Instructions).

The temperature correction is completed in multiple steps in the datalogger program, following the equation

$$Distance = Reading (T_K / 273.15)^{0.5} \quad (7)$$

#### **WHERE THE AIR TEMPERATURE IS IN KELVINS.**

The corrected output value is the distance from the sensor to the snow surface, and needs to be expressed as a snow depth. As snow accumulates, the distance between the sensor and the surface will decrease. Correction is best completed in late spring. This snow-free distance measurement is used as the sensor height, and snow depth can be back-calculated

$$depth = h_{sensor} - distance \quad (8)$$

Late-spring correction has many advantages to measuring instrument height or snow depth under the SR50. The SR50's large field of view makes it difficult to accurately measure the sensor

height, and so it is best to use the snow-free distance measured by the SR50. The pre-winter distance is not recommended because the plants that have grown over the summer are still upright and may effectively be the SR50 target surface. This vegetation will often be flattened over the winter, so that the spring distance measurement more closely represents sensor height. In addition, measures of snow depth over the winter should not be used to correct the SR50 distance measures. Manual measurements often do not accurately measure the depth of snow at a point but rather the depth to some resisting surface, which is often below the actual snow pack when moss, lichen or low herbs are present. In such cases the SR50 and the manual measurements represent different depths (this problem is avoided where plywood is used under the SR50, see following section). Sensor height or snow depth measurements can be used to estimate real-time snow accumulation during the winter, but should not be used to calculate the final snow depth record.

### Instrument Mounting

The sensor has a field of view of approximately 22°. The closest object to the sensor within this field of view will be used as the target surface, so it is important to consider preparing the area on the ground within this field of view. The clearance radius can be calculated from instrument height as follows

$$r_C = 0.194h_{\text{sensor}} \quad (9)$$

The SR50 should be mounted at a minimum of 0.5m and maximum of 10m from the snow surface, with improved accuracy when the sensor is close to the surface. A sensor height of 1.75m above the ground surface (clearance radius = 0.34m) is a reasonable level for most applications, but an estimate of maximum accumulated snow depth is required where snow accumulation can exceed 1.25m. Distance measurements are referenced to the wire mesh on the face of the transducer. The temperature sensor should be mounted at the same height as the SR50, but not in the field of view.

Measurement quality will be affected if the sensor is not perpendicular to the surface. The SR50 should be mounted in a level area where snow will accumulate evenly (i.e. not at the edge of a snowdrift).

Measurement quality will also be affected if the surface is rough or uneven. This is best avoided by locating the sensor over very low vegetation (either natural or manually trimmed). Best results in terms of having a level, even surface are obtained when a section of plywood is placed under the sensor.

An arm extension should be used to displace the SR50 from the mounting platform, to avoid having the platform in the field of view; the instrument height and the calculated clearance radius will determine the length of the extension. The SR50's threaded mounting stem (1" thread) facilitates mounting the sensor to an arm. The most convenient hardware for this purpose is a steel pipe elbow that can be installed onto the end of a threaded 1" pipe.

## **Calibration and Service**

Desiccant is used in both the transducer housing and the main body, and should be inspected and replaced regularly. Annual inspections are generally sufficient, except in humid environments where more frequent replacement may be necessary.

### **Special Instructions**

Early snowfall data is of poor quality when the first snow falls on top of vegetation. As snow accumulates the vegetation will be weighed down, affecting the measured snow depth. The result is a confusing depth signal with high variability. It is recommended that this data not be used for analysis aside from date of first snow fall.

If the target is in motion (moving more than 4 cm per second relative to the sensor), the SR50 will be unable to acquire a reliable reading and a value of 0 will be output. This would occur during blowing snow conditions, or when wind is causing the sensor to vibrate. Adequate securing of the sensor platform is essential, in both the vertical and horizontal planes.

Low density fresh snow is a poor reflector of the sound waves, and so signals immediately after a snowfall event may be missing. Because snow particles begin to metamorphose immediately upon reaching the surface, this effect is not normally persistent.

Poor surface reflectance will result in a bad reading from the SR50, which will affect the output data if an averaging instruction is used. This can be avoided by measuring the SR50 only once during the output interval, but more frequent measures will provide greater information on snow conditions during that period.

## **SOIL VARIABLES**

### *Soil Temperature*

#### **Instrument Description and Theory**

Temperature should be measured at each flux station in mature and disturbed sites via thermocouples or thermistors. Copper-constantan thermocouples are most commonly used for this purpose.

#### **Instrument Function**

Thermocouples can be referenced directly to a data logger reference temperature device (RTD). Thermistors are a resistance type measurement and require only a single ended connection and an excitation connection to a datalogger. It is advisable that groups using thermocouples to check the absolute calibration of the RTD if the logger is old and has not been calibrated recently.

## **Instrument Mounting**

Soil temperature measurement sites should be a 1 m<sup>2</sup> (minimum) undisturbed area of ground, preferably located on flat ground with a level homogeneous terrain within a 10 m radius of the site.

It is common to install such instruments on a wooden dowel with depth intervals marked as required. The dowel is then pushed or pounded down into the soil to the appropriate depth. Profile measurement depths should be 2, 5, 10, 20, 50, and 100 cm where possible (note depths 5 through 100 cm correspond to World Meteorological Organization recommended standards). Two replicate profiles are suggested for each mature and disturbed site. When installing doweling, it is important that the soil remain tightly packed around the doweling.

## **Calibration and Service**

Thermistors, which can be purchased from a number of suppliers, should be calibrated before installation. There are usually no serviceable parts to either thermocouples or thermistors. RTD devices should be calibrated every few years.

## **Special Instructions**

When installing soil thermistors or thermocouples, it is a good idea to bury 50cm of cable at the same depth as the sensor to avoid vertical conduction of heat to the sensor.

## *Soil Moisture*

## **Instrument Description and Theory**

Soil moisture will be measured with Campbell Scientific Inc. CS615 or CS616 water content reflectometer probes. The probes measure water content by relating signal time delay with liquid water content of the soil. These probes can be monitored conveniently on Campbell Scientific data loggers.

## **Instrument Function**

CS615s can be wired in a variety of ways to either a CSI datalogger or to a multiplexer. Soil moisture is usually measured at longer time scales such as every 4 hours.

## **Instrument Mounting**

Site considerations for the soil moisture profiles are the same as for soil temperature measurement. Soil moisture is a very difficult variable to measure well because of the high degree of spatial variability as a result of minor changes in the soil profile's characteristics and variation in surface vegetation and microtopography. Hence, there must be significant replication, both vertically and horizontally, in these measurements at all stations.

The main consideration for profile depth measurements is to capture water dynamics in the rooting zone. Typically this is to a depth of 50 cm with moisture measurements at 5, 10, 20, and 50 cm. Deeper sensors should be installed where necessary. In peatland soils, the main consideration is the unsaturated zone above the water table. Recognizing that the water table fluctuates seasonally, some knowledge of the maximum water table depth is required.

Two replicates of soil moisture profiles are mandatory at mature and disturbed site because of the spatial heterogeneity in this variable. Where possible, three or more replicate profiles are recommended.

### **Calibration and Service**

Although the time domain reflectometry (TDR) method is now widely recognized as a standard method for soil moisture measurement, calibration of individual probes is critical. CS615/616 probes are supplied with generalized calibration curves for mineral soils. However, it is recommended that a field calibration of all probes be conducted (typically against gravimetric samples) before permanent installation. There are particular problems in achieving good calibrations for organic (peat) soils for both the CS615/616 and gravimetric techniques. Recommended reading on this topic can be found in Pepin *et al.* (Can. J. For. Res., 1992, v22, pp.534-540) and Kellner and Lundin (Nordic Hydrol., 2001, v32, pp.315-332).

### **Special Instructions**

CS615 probes should be installed to avoid simultaneous activation of probes within close proximity of each other. This results in radio interference and effects the observations.

## **MINOR ENERGY BALANCE TERMS**

The surface energy balance equation can be stated as

$$\mathbf{R}_n = \mathbf{H} + \lambda E + \mathbf{Q}_g + \mathbf{Q}_a + \mathbf{Q}_w + \mathbf{Q}_b + \mathbf{Q}_c + (\mathbf{Q}_m + \mathbf{Q}_s), \quad (10)$$

where  $\mathbf{R}_n$  is the net radiation flux density,  $\mathbf{H}$  is the sensible heat flux density,  $\lambda E$  is the latent heat flux density,  $\mathbf{Q}_g$  is the soil heat flux density,  $\mathbf{Q}_a$  and  $\mathbf{Q}_w$  are the sensible and latent heat storage, respectively, in the air layer below the level of measurement of  $\mathbf{H}$  and  $\lambda E$ ,  $\mathbf{Q}_b$  is the heat storage in the aboveground biomass,  $\mathbf{Q}_c$  is the energy flux density associated with the CO<sub>2</sub> flux (i.e., through photosynthesis and respiration),  $\mathbf{Q}_m$  is the energy used to melt snow, and  $\mathbf{Q}_s$  is the change in heat storage of the snow pack. All terms in equation (1) have units of W m<sup>-2</sup>.

This section will treat the measurement recommendations for  $\mathbf{Q}_g$ ,  $\mathbf{Q}_a$ ,  $\mathbf{Q}_w$ , and  $\mathbf{Q}_b$ .

#### *Soil heat flux*

\*\*\* needs to be written

### *Biomass heat storage*

In a homogeneous canopy, we recommend sampling at least two trees. In a mixed canopy, the number of trees sampled will depend on the size range (i.e., the range of diameters at breast height). It is impossible to state a single number of samples that will be required for all sites. The key is to sample across all size components and to use an appropriate weighting scheme for the temperatures to give an integrated estimate of the canopy heat storage.

In a homogeneous forest composed of a single species of the same age, it might be appropriate to assume that the thermal behaviour of a single tree represents the whole canopy. However, if the forest is composed of a mixture of species or has a range of trees of different age or size, this methodology will fail unless there is an effective sampling of a spatial average that is representative of the canopy. Therefore, it is recommended that the first priority is to sample the canopy and identify the species present, the age structure of the canopy, and the range of diameter at breast height (dbh). It is preferable if this survey is extensive across the flux source region, often termed the flux footprint. Based on these data, a sampling strategy should be developed to capture the expected range in thermal behaviour of the Q<sub>b</sub> term

The biomass heat storage is distributed across five components: understory, leaves, branches, bole sapwood, and bole heartwood. The majority of the standing aboveground biomass will be in the bole, and it is reasonable therefore to concentrate on this component as the primary target for temperature measurement. As well, the temperature of the heartwood and sapwood must be measured separately because there can be significant differences in their temperatures and moisture contents, and moisture content is the primary control of the heat capacity of the bole, which, along with temperature change rate, controls the changes in biomass heat storage. If there is a significant understory it should be sampled separately.

It is recommended that in each tree bole that is selected for measurement, temperature sensors be inserted through the bole from north to south in at least three radial locations (sapwood north, heartwood, and sapwood south). These measurements should be taken at a minimum of two heights. The two recommended heights should be the same as those for the sampling of air temperature and relative humidity at the mid- and lower-canopy levels. If it is logistically feasible, a third measurement height near the top of the canopy would be useful and recommended

### *Sensible and latent heat storage*

These are derived from the profile measurements of air temperature and relative humidity, which are described in Section 3.2.

### *Photosynthetic energy flux*

The  $Q_c$  term is found from the eddy covariance measurement of CO<sub>2</sub> flux ( $F_c$ ) above the canopy and the profile measurement of CO<sub>2</sub> storage in the air layer from that level to the ground ( $F_s$ ):

$$Q_c = k(F_c + F_s), \quad (2)$$

where k is the heat of assimilation of carbon,  $0.5 \text{ J } \mu\text{mol}^{-1}$ .

## DATA LOGGER CONSIDERATIONS

Needs to be written. Should include:

- Sampling and output frequency
- Grounding considerations
- DE vs SE measurements
- Wire characteristics, lead lengths, settling time
- Use of multiplexers

## CALIBRATION

Instrument specific calibration instructions are included in the discussion above. Here we summarize the planned deployment of the Roving Meteorological Standard Package.

### *Roving Meteorological Standard Package*

\*\*\* Incomplete.

Discuss use of NARC facilities to calibrate roving standard CNRI, and plans for calibration of other instruments in the roving package.

## **APPENDIX A Geonor T-200 Accumulating Precipitation Gauge Installation and Operation Procedures**

This appendix is intended as a supplement to the T-200 user's manual. The information is based on experience of the Climate Research Branch in installing and operating the T-200 gauge. Please refer to the manual for general installation and operating procedures.

### **1. Data Logger Programming**

To use the Geonor T-200 gauge with Campbell Scientific data loggers, a signal adaptor circuit (part number 455055) is required. This adaptor circuit can be purchased directly from Geonor. On the instrument side of the circuit are the red (A) and black (or blue; B) wires from the T-200. On the logger side of the circuit are 12 VDC input (C), analog ground (F), and a signal output (E). The signal output is connected to a single ended channel on the datalogger. The instrument is read using a P27 instruction as outlined below. Note that the input and final storage locations as well as the input channels should be customized by the user.

```
1: Period Average (SE) (P27)
1: 1 Reps
2: 14 200 kHz Max Freq @ 2 V Peak to Peak, Freq Output
3: 3 SE Channel
4: 1500 No. of Cycles
5: 150 Timeout (units = 0.01 seconds)
6: 3 Loc [ Pre_Hz ]
7: 1000 Mult
8: 0.0 Offset
```

The P27 instruction reads the frequency output from the T-200 using a 200kHz maximum frequency at a range of 2 volts peak to peak. After some trial and error, it was found that the observations were stable if the frequency was averaged over 1500 cycles using a timeout period of 150 msec. A multiplier of 1000 converts the observation from KHz to Hz.

Some mathematical manipulation is required to convert the frequency observation into precipitation. This is accomplished using the formulas provided in the user manual, the coefficients for the sensor (see calibration sheet) and the following instructions:

```
; (coefficient B)

2: Z=F (P30)
1: 9.17484 F
2: -6 Exponent of 10
3: 42 Z Loc [ Pre_B ]
;(coefficient A)

3: Z=F (P30)
1: 1.72472 F
2: -2 Exponent of 10
3: 43 Z Loc [ Pre_A ]
```

```

;(zero frequency)

4: Z=F (P30)
1: 1064.9 F
2: 00 Exponent of 10
3: 44 Z Loc [ Pre_F0 ]

;(subtracts zero frequency from observation, F-Fo)

5: Z=X-Y (P35)
1: 3 X Loc [ Pre_Hz ]
2: 44 Y Loc [ Pre_F0 ]
3: 45 Z Loc [ Pre_F_F0 ]

;(squares F-Fo)

6: Z=F (P30)
1: 2 F
2: 00 Exponent of 10
3: 46 Z Loc [ Pre_Sq ]

7: Z=X^Y (P47)
1: 45 X Loc [ Pre_F_F0 ]
2: 46 Y Loc [ Pre_Sq ]
3: 47 Z Loc [ F_F0sqrd ]

;(multiplies coefficient A by F-Fo)

8: Z=X*Y (P36)
1: 43 X Loc [ Pre_A ]
2: 45 Y Loc [ Pre_F_F0 ]
3: 48 Z Loc [ PartA ]

;(multiplies coefficient B by F-Fo squared)

9: Z=X*Y (P36)
1: 42 X Loc [ Pre_B ]
2: 47 Y Loc [ F_F0sqrd ]
3: 49 Z Loc [ PartB ]

;(adds two parts of the equation

10: Z=X+Y (P33)
1: 48 X Loc [ PartA ]
2: 49 Y Loc [ PartB ]
3: 4 Z Loc [ Precip_mm ]

```

The above instructions will produce a raw estimate of accumulated precipitation. It is advisable to do a calibration check on each sensor/gauge set prior to installation. This procedure is described in Section 2. The addition of the following instruction is required to adjust for re-calibration:

```
11: Z=X*F (P37)
1: 4 X Loc [ Precip_mm ]
2: 9.8496 F
3: 4 Z Loc [ Precip_mm ]
```

where F is the multiplier. A multiplier less than 1 suggests that the gauge is overestimating the weight in the bucket.

Usually the T-200 vibrating wire sensor is turned on as soon as 12 volt power is supplied to the instrument and then remains on. This represents a significant power draw and may not be desired when power is limited (i.e. remote sites using a battery for power). This draw can be minimized using the switched 12 volt supply available on a CR10X or CR23X. The following instructions are used:

; Inserted before the P27 instruction,

```
1: If time is (P92)
1: 25 Minutes (Seconds --) into a
2: 30 Interval (same units as above)
3: 48 Set Port 8 High

2: If time is (P92)
1: 29 Minutes (Seconds --) into a
2: 30 Interval (same units as above)
3: 30 Then Do
```

Instruction 1 turns on the power for the T-200 5 minutes before a 30-minute observation. This allows the instrument to warm up and stabilize. Instruction 2 waits until 1 minute before the 30-minute interval before executing the P27 instruction. After instruction 11, a P86 is used to set port 8 low to turn off the power for the T-200. The final instruction is a P95 to end the loop that was started with instruction 2.

Logging data more frequently (i.e. at least every 30 minutes) improves the user's ability to assess and control the quality of the data. This is discussed further in Section 6

## 2. Calibration

**Caution: During calibration, extreme caution is required not to drop the weights into the bucket. This will damage the vibrating wire sensor.**

The above program, with some modifications, can be used to calibrate the instrument. The program should omit all instructions used for power conservation and the multiplier in instruction 11 should be set to 1. The instrument is calibrated by adding known weights to the bucket until the maximum capacity is reached (equivalent to 600mm of precipitation). The weight is converted to equivalent precipitation using the area of the inlet = 200 cm<sup>2</sup>. The accumulated weight in grams can be converted to precipitation by multiplying by 0.05. When the instrument readings are compared to calculated amounts, the slope of the regression line becomes the multiplier.

Although the factory calibrations are usually accurate, it was found that they can be improved through recalibration. It is important that recalibration be performed on gauge/sensor groupings that will stay consistent over the service period of the instrument.

### **3. Installation**

It is highly recommended that the pedestal supplied by Geonor be used for mounting the T-200. The pedestal is very sturdy and allows for the quick and easy installation of an Alter type windshield. The base of the pedestal is engineered to be bolted to a base that is concreted into the ground. In some situations, the pedestal may be concreted directly into the ground. There are several advantages to concreting a base into the ground. The base can be concreted deeply into the ground (concrete tubes may be used) allowing for greater stability. The bolts on the base can be used as an additional leveling mechanism to adjust for such things as minor frost heaves. The platform can also be used to raise the gauge off of the ground to clear obstacles such as a fenced compound (See Figures below). Regardless of mounting method, the pedestal and gauge require high stability to minimize movement of the gauge. Movement of the gauge will produce significant errors during observations. This is especially true in high wind environments.

When installing the T-200, the vibrating wire sensor should be installed on the north side of the instrument. This prevents heating of the sensor over the course of the day. Daytime heating will influence the frequency of the sensor due to thermal expansion of the vibrating wire mechanism. This will ultimately effect the observations. This phenomenon is discussed further in Section 5.

A protected compound is recommended to prevent vandalism and animal damage. The enclosure should minimize disruptions to air flow around the instrumentation to prevent turbulent eddies that may effect the catch efficiency. The top of the gauge (and preferably the entire Alter shield) should be above the top of the compound. An anemometer should be installed at gauge height to facilitate the correction for wind-induced under-catch. Wind correction curves for the T-200 are in development.



**Left:** Pedestal mount concreted into ground with a height extension bolted between base and pedestal. **Right:** Pedestal mount with integrated height extension. **Below:** Typical T200 installation.



## 4. Servicing

The T-200 should be serviced at least twice per year but this schedule is highly dependent on precipitation. Although the gauge has a 600 mm capacity, up to 80 to 100 mm is consumed with the gauge "charge" which is a mixture of anti-freeze and oil. Anti-freeze is used to melt solid precipitation as it enters the bucket. Oil is used to prevent evaporation from the bucket. Although anti-freeze is only required when the temperature drops below freezing (and snow instead of rain is expected), oil should be used all year. The gauge should be serviced in the fall prior to snowfall by adding 1.5 to 2 L of anti-freeze and 0.5 to 0.75 L of oil. In the spring, less anti-freeze and more oil (i.e. 1 L) are required.

During servicing, try not to disturb the gauge on the 30-minute interval. Damage could occur to the vibrating wire sensor if it is jarred during operation. The sensor will make an audible whine while operating. After unclipping and removing the outer skirt from the instrument, find the black set-screw on the side of the vibrating wire sensor. Tighten this screw clockwise until finger tight. This screw will prevent damage to the sensor due to jarring during servicing. **BE SURE TO LOOSEN THE SCREW AT LEAST 4 ROTATIONS AFTER COMPLETING THE SERVICING!** After screw is tightened, the bucket can be removed from the assembly and drained into a waste bucket. Geonor provides a siphon with each gauge and this usually works well to empty the bucket. When replacing the bucket, align the black dot on the rim of the bucket with the sensor. Once the bucket is in place, the set-screw can be loosened to resume operation. The operation and weight of the gauge can be checked by changing the following instructions (changes in bold):

```
1: If time is (P92)
1: 3 Minutes (Seconds --) into a
2: 5 Interval (same units as above)
3: 48 Set Port 8 High

2: If time is (P92)
1: 4 Minutes (Seconds --) into a
2: 5 Interval (same units as above)
3: 30 Then Do
```

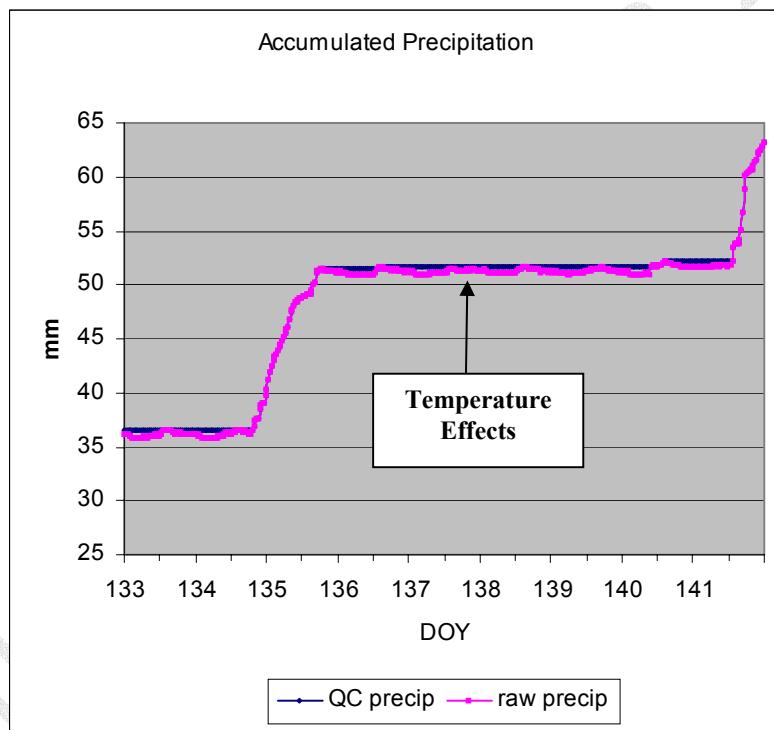
## 5. Data Quality Assurance and Control

There are several specific problems that can occur to the T-200 data that need attention after data collection. These problems are largely due to the properties of the vibrating wire sensor.

Although the problem of wind pumping is minimal (unlike the Belfort gauges), a diurnal signature is sometime present in the raw data. This is due to diurnal temperature changes of the sensor. Daytime heating causes thermal expansion of the vibrating wire and this changes the frequency of the output even if no change occurs in the bucket's contents. The change in accumulation is usually under 0.75 mm and is obvious when the data is graphed. These effects can then be removed.

One of the simplest ways to filter out most of the false values is to determine a maximum accumulated precipitation value and then disallow this value to decrease. As shown in the above figure, the raw value (pink line) increases and decreases over the period of the day while the QCd values (blue line) are constrained to a previous maximum value. This works well with the exception of certain situations that produce a small under- or over-estimate in accumulated precipitation. This involves some qualitative judgment but these observations can usually be identified and repaired.

Another occurrence that causes data problems is evaporation. Although using oil in the collection bucket can eliminate most evaporation, long hot and dry periods can occasionally produce evaporation. This requires a manual correction at the occurrence of the next precipitation event. The filtering mechanism above does not allow the QCd values to decrease which means that during the next precipitation event, the weight in the bucket would need to increase to this previously established level before precipitation accumulated. This produces an underestimation of precipitation and requires a manual correction.



**Example of the diurnal temperature effects of the vibrating wire sensor (pink line) and the result of quality control (blue line)**

**SOIL AND CANOPY PROCESSES**

## AUTOMATED SOIL RESPIRATION

### 1. Variable(s) to be measured

Continuous measurement of soil CO<sub>2</sub> efflux or soil respiration with automated chambers.

### 2. Final temporal and spatial scale that the measurements should be rolled up to

Half-hourly, daily and annual effluxes at plot and stand level.

### 3. Spatial characteristics

#### 3.1 How many samples are needed?

Six or more permanent soil chambers should be used to account for spatial variability at each site.

#### 3.2 How should they be chosen?

The location of the soil chambers should be chosen to represent the different physical (microtopography, forest floor thickness, etc) and biological (moss, lichen cover) characteristics of the ground surface at each site.

#### 3.3 How will the scaling up to the stand be performed (if pertinent)?

Soil CO<sub>2</sub> efflux will be calculated on a ground area basis (m<sup>2</sup>). Scaling up to the stand level will require (1) correcting for the area occupied by the trees (tree basal area) and (2) weighting of individual chamber effluxes according to the type of ground surface they represent.

### 4. Temporal characteristics

#### 4.1 Within day: When and how many times?

Soil CO<sub>2</sub> efflux should be measured each half-hour of the day to account for diurnal variability in CO<sub>2</sub> efflux.

#### 4.2 Within year: When and how many times?

Soil CO<sub>2</sub> efflux should be measured daily throughout the year, even in winter, to account for the seasonal variability in CO<sub>2</sub> efflux.

#### 4.3 How will the scaling to the year be performed (if pertinent)?

It will be done by keeping the system running as continuously as possible throughout the year. Small data gaps should be filled by interpolation, while longer gaps should be filled using relationships between measured soil CO<sub>2</sub> efflux and environmental variables such as soil temperature and moisture.

### 5. Measurements

#### 5.1 Instruments and set up required/suggested

Continuous measurements of soil CO<sub>2</sub> efflux will be made using a non-steady state flow-through type automated chamber system (Drewitt et al. 2002). The system is equipped with 6 Plexiglas chambers (~65 L, 50 cm inner diameter) inserted 2-5 cm into the soil. The chambers consist of two separate 15 cm tall cylinders (collar and lid) joined together with a hinged aluminum frame. The lid is closed at the top with a 2-mm thick Plexiglas sheet. Each chamber has a gear motor for opening and closing the lid. A CSI CR10 datalogger controls chamber selection and records

environmental data (soil temperature, light, etc.) useful in analyzing CO<sub>2</sub> effluxes. Air is circulated between each chamber and a LI-COR LI-6262 infrared gas analyzer (IRGA) using 15-m long Dekaron tubing with an AC linear pump at approximately 7 L min<sup>-1</sup>. The IRGA, which measures chamber CO<sub>2</sub> and water vapour concentration, is calibrated daily. The system consists of a temperature-controlled IRGA box, a pump box (containing pump, solenoid valves and mass flow controller), a control box (containing the data logger and associated electronics for chamber selection) and the chambers (each with a small relay board for motor control).

Chamber air is sampled for a period of 5 minutes every half-hour. Soil CO<sub>2</sub> efflux ( $F_s$ , □mol C m<sup>-2</sup> s<sup>-1</sup>) is calculated using the following equation:

$$F_s = \frac{PV_e S_m}{RTA} \quad (1)$$

where  $P$  is the atmospheric pressure (Pa),  $S_m$  is the rate of change of CO<sub>2</sub> concentration (mixing ratio) in the chamber headspace during the measurement period (□mol C mol<sup>-1</sup> dry air s<sup>-1</sup>),  $R$  is the universal gas constant (8.314 J mol<sup>-1</sup> K<sup>-1</sup>),  $T$  is the chamber air temperature (K) and  $A$  is the surface area of ground covered by the chamber (m<sup>2</sup>).  $V_e$  is the “effective volume” of the chamber head space (m<sup>3</sup>) and takes into account adsorption of CO<sub>2</sub> on the chamber walls and leaks through the collar and lid. For example, if  $P = 95$  kPa (95,000 Pa),  $V_e = 80$  L (0.080 m<sup>3</sup>),  $S_m = 20$  ppmv min<sup>-1</sup> (0.333 □mol C mol<sup>-1</sup> dry air s<sup>-1</sup>),  $T = 15^\circ$  C (288.15 K),  $A = \pi(0.25\text{ m})^2 = 0.196\text{ m}^2$ , then  $F_s = 5.4$  □mol C m<sup>-2</sup> s<sup>-1</sup>.

$V_e$  should be calculated twice a day using the procedure of Drewitt et al. (2002), which was originally proposed by Goulden and Crill (1997). During these effective volume calibrations, each of the regular 5-minute chamber measurements is immediately followed by a 5-minute measurement during which a gas of known concentration is injected. The following equation is then used to calculate the effective volume in m<sup>3</sup>:

$$V_e = \frac{F_I C_I}{S_{mI} - S_m} \quad (2)$$

where  $F_I$  is the flow rate of the injected gas (m<sup>3</sup> s<sup>-1</sup>),  $C_I$  is the concentration (mixing ratio) of the injected gas (□mol mol<sup>-1</sup>),  $S_{mI}$  is the rate of change of CO<sub>2</sub> concentration during gas injection (□mol mol<sup>-1</sup> s<sup>-1</sup>),  $S_m$  is the rate of change of CO<sub>2</sub> concentration without gas injection (□mol mol<sup>-1</sup> s<sup>-1</sup>). For example, if  $F_I = 10$  cm<sup>3</sup> min (0.166 x 10<sup>-6</sup> m<sup>3</sup> s<sup>-1</sup>),  $C_I = 10\%$  CO<sub>2</sub> (by volume) (0.1 mol mol<sup>-1</sup>),  $S_m$  is the same as above,  $S_{mI} = 32.4$  ppmv min<sup>-1</sup> (0.54 □mol C mol<sup>-1</sup> dry air s<sup>-1</sup>), then  $V_e = 0.080\text{ m}^3$  or 80 L. In this case, the ratio of  $V_e$  to the geometric volume of the chamber head space is about 1.2.

To check that the system has no leaks, a “calibration chamber” should be used daily. This chamber should have a volume similar to that of the soil chambers and should be sealed except for the IRGA input and output plumbing connections. When it is used in the above  $V_e$  measurement procedure, it should give a value of  $V_e$  equal to its geometric volume.

## **5.2 Specific methodologies to perform the measurement**

### **5.3 Potential problems/pitfalls to avoid**

1. Leaks that go unnoticed. The calibration chamber is important in this regard and checks system performance.
2. Water table rising at wet sites that can result in water being drawn into the IRGA.
3. Leaving a chamber lid closed for too long that can cause damage to the flora and fauna on the soil surface.

## **6. Post measurement processing**

### **6.1 Sample processing in the lab**

None required.

### **6.2 Data processing**

Half-hourly soil CO<sub>2</sub> efflux for each chamber is calculated directly at the site using a PC with a MATLAB program. The calculations can also be done directly using the datalogger.

### **6.3 What should the final data set contain?**

The final dataset should contain for each half-hour:

- Time at the end of the half hour;
- Soil CO<sub>2</sub> effluxes for all soil chambers
- CO<sub>2</sub> concentrations of air near the ground surface (these are obtained from the concentration measurements made just as each lid is closing)
- Effective volumes for all soil chambers plus the calibration chamber;
- Air temperature for all soil chambers;
- Soil temperature at 2 cm for all soil chambers;
- PAR (depending on amount and type of vegetation in the chambers)
- Characterization of the forest floor at each chamber, e.g., thickness of forest floor, coarse wood debris, etc.

## **7. What other supporting measurements are required?**

The calculations require half-hourly measurements of atmospheric pressure (*P*). Analysis of soil CO<sub>2</sub> efflux data benefit from the availability of half-hourly soil moisture content and temperature profiles (0-1 m depth).

## **8. Contact for further information**

Andy Black ([ablock@interchange.ubc.ca](mailto:ablock@interchange.ubc.ca)) and David Gaumont-Guay ([dguay@interchange.ubc.ca](mailto:dguay@interchange.ubc.ca)).

## **9. References**

Drewitt, G.B., T.A. Black, Z. Nesic, E.R. Humphreys, E.M. Jork, R. Swanson, G.J. Ethier, T. Griffis and K. Morgenstern. 2002. Measuring forest floor CO<sub>2</sub> fluxes in a Douglas-fir forest. Agric. For. Meteorol. 110:299-317.

Goulden, M.L. and P.M. Crill. 1997. Automated measurements of CO<sub>2</sub> exchange at the moss surface of a black spruce forest. Tree Physiol. 17:537-542.

## HETEROTROPHIC SOIL RESPIRATION

### 1. Variable(s) to be measured

Heterotrophic soil respiration in the field. We will measure soil respiration in small trenched plots ( $1 - 2 \text{ m}^2$ ) and in the main plot (undisturbed) as done by many others (see review by Hanson et al. 2000). The purpose of trenching is to kill all roots inside the trenched plot, so that only heterotrophic respiration occurs. The ratio of respiration in trenched plots to the main plot gives a rough estimate of the ratio of heterotrophic respiration to total soil respiration. However, heterotrophic respiration in trenched plots is most likely greater than in the main plot because of the increase decomposition of the killed roots. Therefore, we will also measure decomposition rates of buried bag samples of root materials following Epron et al. (1999) to adjust downwards the estimates of heterotrophic respiration made directly from trenched plots.

Where present, we will measure periodically the carbon efflux from standing dead trees, and coarse woody debris on or near the ground.

### 2. Final temporal and spatial scale that the measurements should be rolled up to

Daily and/or annual flux at the stand level.

### 3. Spatial characteristics

#### 3.1 How many samples are needed?

Five trenched plots with two soil respiration collars should be a sufficient number of samples.

#### 3.2 How should they be chosen?

Ten pairs of soil collars should be placed in the stand and measured biweekly for 2-3 months. Collars in a pair should be approximately 0.5 m apart.

#### 3.3 How will the scaling up to the stand be performed (if pertinent)?

### 4. Temporal characteristics

#### 4.1 Within day: When and how many times?

Usually soil respiration will be measured once per day at each soil collar.

#### 4.2 Within year: When and how many times?

Bi weekly during the entire period that the site is accessible.

#### 4.3 How will the scaling to the year be performed (if pertinent)?

We will compute the ratio of respiration in trenched plots ( $R_t$ ) to respiration in the main plot ( $R_s$ ) for each measurement date and linearly interpolate daily values of  $R_t/R_s$  between measurement days. We will use the  $Q_{10}$  determined by automated, continuous soil respiration systems to estimate soil respiration rate at  $10^\circ\text{C}$  ( $R_{s10}$ ) for each measurement day and linearly interpolate between daily values of  $R_{s10}$  between measurement days. Daily ecosystem soil respiration will be calculated with the following equation:

$$R_s = \sum R_{s10} \times Q_{10}^{(T_s-10)/10} \times 1800 \times (12/100000)$$

Where  $T_s$  is half hourly mean soil temperature, 1800 scales from flux per second to flux per half hour, (12/1000000) converts from  $\mu\text{moles}$  to g C, and the calculations are summed for each day using a set value for  $R_{s10}$ .

Daily estimates of  $R_t$  will be obtained from the daily  $R_s$  computed above as follows:

$$DailyR_t = DailyR_s \times R_t/R_s$$

Estimates of annual  $R_h$  will be made by adjusting annual  $R_t$  for decomposition of killed roots by using site averaged estimates of root biomass and measured rate of weight loss of buried bags of root samples. We will also add respiration of CWD to our estimate of annual  $R_h$ .

## 5. Measurements

### 5.1 Instruments and set up required/suggested

Soil respiration will be measured with LI-6400 and LI-6200 equipped with soil respiration chambers. Collars will be left in place for most of the season. Collars should be relocated shortly after leaf shedding in autumn, particularly in deciduous stands.

Trenches need to be dug to the depth of the C horizon to sever all roots. Methods for digging trenches will vary with rooting depth, and stoniness, but should minimize impact. Line trenches with landscaping fabric should be used to prevent or delay regrowth of root systems into the plot. Refill trenches to re-establish hydraulic continuity between the trenched plot and surrounding area.

Chambers used to measure stem and branch respiration will be used to measure CO<sub>2</sub> efflux from coarse woody debris that is in early stages of decomposition. CWD in later stages of decomposition will be placed in sealed chambers for measurement of CO<sub>2</sub> efflux, and moisture content will be determined in the laboratory.

### 5.2 Specific methodologies to perform the measurement

Use standard Li-cor methods.

### 5.3 Potential problems/pitfalls to avoid

## 6. Post measurement processing

### 6.1 Sample processing in the lab

### 6.2 Data processing

### 6.3 What should the final dataset contain?

## 7. What other supporting measurements are required?

Soil temperature and soil moisture at locations of soil respiration measurement. Continuous monitoring of soil temperature and moisture at the site.

## 8. Contact for further information

Mike Lavigne ([mlavigne@nrcan.gc.ca](mailto:mlavigne@nrcan.gc.ca))

## **9. References**

Epron D, Farque L, Lucot E, Badot P-M (1999) Soil CO<sub>2</sub> efflux in a beech forest: the contribution of root respiration. *Ann. For. Sci.*, **56**, 289-295.

Hanson PJ, Edwards NT, Garten CT, Andrews JA (2000) Separating root and soil microbial contributions to soil respiration: A review of methods and observations. *Biogeochemistry*, **48**, 115-146.

Fluxnet-Canada 2003

## FINE ROOT DYNAMICS

### Fine Root Dynamics - Minirhizotrons

#### 1. Variable(s) to be measured

Root production and mortality, root longevity, root carbon turnover

#### 2. Final temporal and spatial scale that the measurements should be rolled up to

Daily or monthly root production or mortality

#### 3. Spatial characteristics

##### 3.1 How many samples are needed?

Minimum of 10 tubes per site

##### 3.2 How should they be chosen?

Randomly located transects or plots within footprint of tower

##### 3.3 How will the scaling up to the stand be performed (if pertinent)?

Root carbon production and turnover estimates from the volume data (RLDv or RBDv; see below) can be converted to a per ha basis knowing the depth of the soil profile sampled.

#### 4. Temporal characteristics

##### 4.1 Within day: When and how many times?

None

##### 4.2 Within year: When and how many times?

Measurements made once a month from May to September or October

##### 4.3 How will the scaling to the year be performed (if pertinent)?

Root growth during growing season

#### 5. Measurements

##### 5.1 Instruments and set up required/suggested

###### Installing Tubes

A coring device is needed to create a hole for the Plexiglas tubes. We have used a metal tube with a coring bit that is pounded into the ground with a hydraulic-driven jack hammer. More details on our apparatus can be obtained by contacting me and others can be found in Smit et al. (2000). Once the tubes are in the ground they need to be secured to prevent the tubes from turning. A 4-5' piece of rebar can be hammered in next to the tube and the tube secured to the rebar with nylon ties. If snowpacks are deep, two rebars should be placed underneath the tube to create a notch for the tube to rest on in order to prevent the tubes from breaking due to the weight of the snowpack. The interior portion of the tube above the ground should be sprayed with black paint to reduce light into the tube and then with white spray paint on the outside to reduce heating from the sun. A no. 9 stopper is used to seal the top of the tube and we also use pop cans (one end removed and clean so as not to attract bears) to place over the stopper and a plastic bag over the can with some

tape. In areas of heavy snowfall the exposed tube should be braced with triangular supports to prevent the collapse of the tube. In addition, the exposed portion of the tube should be insulated to prevent any cold channel effect.

## 5.2 Specific methodologies to perform the measurement

### Root measurements

Root images are collected with the BTC-2 minirhizotron camera system (Bartz Technology, Santa Barbara, CA) using an index handle to determine the position of the camera head in the tube. Root images should be collected from the top face of the tube to facilitate comparisons between locations. Root images will be collected from the same location once a month throughout the growing season.

## 5.3 Potential problems/pitfalls to avoid

1. The biggest pitfall to minirhizotron installation is not getting good contact between the tube and the soil which results in air gaps between the tube and soil and will affect root growth.
2. Turning plexiglas tubes after installed in ground – scratches tubes and could reduce visibility
3. Not securing the tubes in ground – if they twist you will not be able to follow roots through time

## 6. Post measurement processing

### 6.1 Sample processing in the lab

We are using the RooTracker software from Duke University to analysis the captured root images in the lab. Root images are traced each month to follow root production and mortality. Root codes should include species (if possible grass vs tree), color (white, brown, black) and mycorrhizal infection (yes, no)

### 6.2 Data processing

A good discussion of analysis of root images is given by Hooker et al. (2000)

### 6.3 What should the final data set contain?

Normally, minirhizotron root data is presented as length of root per  $\text{cm}^2$  of tube area and can be calculated for known depth increments. However, this approach does not lend itself for comparing root data with aboveground measurements of biomass. Thus root length per tube area needs to be converted to a root length density basis by the following equation (Johnson et al., 2001):

$$\text{RLDv} = L / (A * \text{DOF})$$

Where RLDv is the volumetric root length density ( $\text{m m}^{-3}$ ), L is root length, A is the viewing area and DOF is the depth of field. The DOF has varied from 2 to 3 mm. Johnson et al. (2001) suggests that root coring be used to determine the DOF constant. The RLDv can then be converted to a root biomass density ( $\text{g m}^{-3}$ ) (RBDv) knowing the specific root length ( $\text{m g}^{-1}$ ) for the various diameter classes (Johnson et al., 2001) as well as biomass on a carbon basis knowing the amount of carbon in the root tissue. Estimates of root standing crop, production and turnover (mortality) for both root length densities and biomass (using the specific root length conversion) can then be determined based on the amount of new root lengths or the amount of root that has disappeared.

## **7. What other supporting measurements are required?**

Soil temperature and soil moisture measurements, rainfall

Aboveground NPP, stand characteristics

Fine root biomass from root cores taken near the minirhizotron tubes will be valuable for comparing minirhizotron estimates of RLDv and RBDv.

## **8. Contact for further information**

Ken Van Rees ([vanrees@sask.usask.ca](mailto:vanrees@sask.usask.ca))

## **9. References**

Hooker, J.E., R. Hendrick and D. Atkinson. 2000. The measurement and analysis of fine root longevity. P 273-304 In A.L. Smit, A.G. Benough, C. Engels, M. van Noordwijk, S. Pellerin and S.C. van de Geijn (eds.) Root methods: A handbook. Springer, Berlin.

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Smit, A.L., E. George and J. Groenwold. 2000. Root observations and measurements at (transparent) interfaces with soil. P 235-271 In A.L. Smit, A.G. Benough, C. Engels, M. van Noordwijk, S. Pellerin and S.C. van de Geijn (eds.) Root methods: A handbook. Springer, Berlin.

## FOLIAR NUTRIENT CONCENTRATION

### 1. Variable(s) to be measured

*Foliar nutrient concentrations:* Concentrations of total N, P, K, Ca and Mg in needles or/and leaves of dominant tree species in each main plot.

### 2. Final temporal and spatial scale that the measurements should be rolled up to

NA

### 3. Spatial characteristics

#### 3.1 How many samples are needed?

Ten (10) trees will be sampled for each main tree species (maximum of 3 species) and for each main plot.

The number of plots depends on the heterogeneity of the site. For uniform sites, we suggest 3 or 4 plots. For non-uniform sites, we suggest at least 1 or 2 plots for each identifiable vegetation community (Source: Brian Amiro).

#### 3.2 How should they be chosen?

Each sample will be prepared from current year needles or leaves (with petiole) exposed to light (first third of the canopy) taken from three (3) branches of each sampled dominant or co-dominant trees. Only green and entire needles or leaves will be sampled.

#### 3.3 How will the scaling up to the stand be performed (if pertinent)?

NA

### 4. Temporal characteristics

#### 4.1 Within day: When and how many times?

NA

#### 4.2 Within year: When and how many times?

The sampling needs to be carried out only once between the end of July and the middle of August for the deciduous trees and in September for evergreen trees.

#### 4.3 How will the scaling to the year be performed (if pertinent)?

NA

### 5. Measurements

#### 5.1 Instruments and set up required/suggested

NA

#### 5.2 Specific methodologies to perform the measurement

NA

### **5.3 Potential problems/pitfalls to avoid**

NA

## **6. Post measurement processing**

### **6.1 Sample processing in the lab**

Foliage from the branch samples will be combined per tree and oven dried (70°C) during 48 hours. A composite sample per plot and species will be prepared by combining an equivalent weight (10.0g) of samples of all individual trees per species and plot. Original samples per tree will be kept dry at room temperature for individual chemical analysis if needed in the future. The composite sample will then be ground to 100 mesh. Dry combustion (LECO) for total C, N and S (if available) determination is recommended. The following procedures are recommended for P, K, Ca and Mg:

- Wet peroxyde-sulfuric acid digestion with Selenium (Keeney and Nelson 1982 pp. 643-698 in: Ed. Page/Miller/Keeney 1982. Methods of Soil Analysis part 2-Chemical and Microbiological Properties Second Edition. Also described in details in Alef and Nannipieri 1995: Methods in Applied Soil Microbiology and Biochemistry p.79 Academic Press).
- P determination following the Molybdenum blue method. Ref: Watanabe and Olsen 1965 in: Ed. Page/Miller/Keeney 1982. Methods of Soil Analysis part 2-Chemical and Microbiological Properties Second Edition. Procedure 24-3.4 p.413.
- K, Ca and Mg analysed by atomic absorption

Analytical determination will be done in three (3) replicates. Certified standards of plant material must be used.

### **6.2 Data processing**

### **6.3 What should the final data set contain?**

Final data set should contain:

- 1) identification of site, plot, tree species, tree number (mixed 1-10 or 1,2,3...10), analytical replicate number (1, 2, 3) and date of sampling;
- 2) the measured concentration of N in % and P, K, Ca and Mg in ppm;

## **7. What other supporting measurements are required?**

None

## **8. Contact for further information**

Robert Boutin or David Paré  
1055, du P.E.P.S.  
Sainte-Foy (Quebec)  
G1V 4C7  
(418)-648-5445  
[rboutin@rncan.gc.ca](mailto:rboutin@rncan.gc.ca)

## **9. References**

Camiré,C. et M. Brazeau. 2002. Sols forestiers – Notes de cours. Fac. For. Géom., Univ. Laval, Québec

## **10. Cost.**

The main cost is technician time. Field work: each plot = 10 samples x 1-3 species = 10-30 samples. One to three hours depending on tree species number and tree height. Laboratory work, composite samples: preparation: one to two hours per composite sample depending if deciduous or coniferous. Analysis: one hour per composite sample.

Fluxnet-Canada 2003

## LITTERFALL AND BRANCHFALL

### 1. Variable(s) to be measured: *Litterfall and branchfall*

### 2. Final temporal and spatial scale that the measurements should be rolled up to

Seasonal measurements of litterfall and seasonal or annual measurements of branchfall at the stand/tower site level.

### 3. Spatial characteristics

#### 3.1 How many samples are needed?

This depends upon the range of site associations within a tower site. At a minimum, one plot should be installed within each of the major site associations (stand types) found within a tower site. Within each plot, multiple litterfall and branchfall traps should be placed. Different placement and number of traps can be used, and the exact number may depend on the spatial variability in stand structure. In eastern forests, we have found that 8 traps placed systematically (regular spacing along parallel transects) within 400 m<sup>2</sup> plots were usually (but not always) sufficient to capture the spatial variability (an additional trap would reduce the coefficient of variation of total debris mass by less than 5%). In western forests, we currently use 9-10 litterfall traps spaced on a systematic grid within a 40m x 40m area (Trofymow et al. 1991). Branchfall traps are larger in size within a minimum of 4 within the permanent plot area.

#### 3.2 How should they be chosen?

Within the plot, traps can be place systematically or randomly. A systematic layout of traps allows for the placement of brushed trails, minimizing trampling within the plot, which might interfere and affect other measurements/studies being conducted within the plot.

#### 3.3 How will the scaling up to the stand be performed (if pertinent)?

By determining total trap area and applying an appropriate multiplier.

### 4. Temporal characteristics

#### 4.1 Within day: When and how many times?

NA

#### 4.2 Within year: When and how many times?

Litterfall traps are emptied ideally seasonally, but at least every six months. One possibility is to sample about mid-season i.e., February, May, August and October. Early spring and late fall sampling also works well in the boreal forest. Late fall sampling captures the recent leaf fall of deciduous litter, while early spring captures the debris from snow and ice damage to coniferous crowns.

Branchfall traps could be measured seasonally, but given the more episodic nature of the fall, an annual or twice yearly sample would suffice.

### **4.3 How will the scaling to the year be performed (if pertinent)?**

Litterfall and branchfall traps measure cumulatively. Mass fall per period can be calculated from the mass data and the numbers of weeks the traps were out and the mass/season and mass/year calculated.

## **5. Measurements**

### **5.1 Instruments and set up required/suggested**

Litterfall traps should be constructed so that the collected litter remains above the ground, otherwise if in contact with the ground the litter can begin to decay. Two possible designs are presented below. The first is a circular aluminum frame collection trap  $0.186 \text{ m}^2$  ( $2 \text{ ft}^2$ ) in area. Each trap has an open bottom (10 cm –15 cm diameter opening) conical mesh collection bag made of shade cloth material (0.5 mm mesh Pooltex fabric) clamped at the bottom with a large spring clip. This allows rainwater to pass through and traps to dry rapidly but still trap finer canopy litter. Traps were elevated 75 cm off the ground to ease sample recovery and prevent overgrowth by herbaceous vegetation. A second, design is made out of 8-foot-long treated 2"x6" lumber (please forgive the english units!). The board is used to make a ca. 2'x2' square frame, yielding an internal dimension of  $0.286 \text{ m}^2$ . The bottom is covered by a nylon screen mesh (the type used for window screens), and a  $\frac{1}{4}$  inch carpenter cloth (metal mesh). The carpenter cloth adds a rigid support to the nylon mesh. The trap is laid horizontally on wooden supports (we use local woody debris) so that the mesh is not in contact with the ground. The large lumber pieces and the metal mesh make the trap snow-resistant. The treated wood resists decay and porcupine attacks.

Branchfall traps consist of 2 m x 2 m squares of landscape cloth pinned to a previously cleared area of ground.

### **5.2 Specific methodologies to perform the measurement**

The size material sampled by the litterfall traps includes leaves, needles, cones, twigs and other material. A 1 cm diameter is used as a size cutoff for the twigs. If a large branch falls on the trap with attached fine twigs and needles, trim off the small material (diameter < 1 cm) and consider the trimmed material as part of the collection for the trap. Bag materials into a paper bag and label.

Woody material greater than 1 cm diameter in size is sampled on the branchfall traps. Trim branches on trap to the edge of trap area, cutting off and discarding twigs (and attached needles) less than 1 cm diameter. Tree boles or branches attached to fallen trees are excluded and should be measured as part of the tree mortality through remeasurement of tagged trees or re-measurement of downed woody debris transects (previous logs marked). Bag material and label.

### **5.3 Potential problems/pitfalls to avoid**

Litterfall traps will be tipped or flattened by animals or falling trees. Place traps close to, but not on, established access or game trails. Take repair materials and some extra traps if possible to fix or replace damaged traps. Record if the trap was tipped greater than  $30^\circ$ , perforated or otherwise damaged. If greater than this angle, then consider this trap a missing value and calculate plot values based on the number of remaining traps. You may still want to collect litter in the trap to

add to the bulk sample for chemical analysis. For the square wooden traps, brush to the outside any material fallen onto the edge of the frame.

## **6. Post measurement processing**

### **6.1 Sample processing in the lab**

Litterfall samples should be air-dried immediately to stabilize the samples. Prior to processing, the samples should be dried in a forced-air oven at 70°C for 24 hours and the total mass weighed. Samples should then be sorted into component categories ie. (1) Needles (total or green/brown if desired), (2) leaves, (3) twigs (1 cm in diameter and less), (4) fructifications, (5) bark chips and other material. Each component should be weighed separately.

Sorting of conifer litter is greatly simplified by using a 2 mm mesh (no. 10). Vigorous shaking will let most spruce and fir needles pass through the mesh, usually along with a small amount of very fine debris that just gets included with the needles. Hand sorting of the remainder of debris is then completed relatively quickly by removing the remaining needles, then the broadleaves, then the twigs, and then the fructifications. The rest, bark chips and other material, can be lumped together or, depending on local interest, divided up further as desired. We have found that a single person can process up to 24 traps per day in this manner. A single plot of 8 traps, with 2 retrievals per year, should therefore generate less than a day's work for the sorting.

For chemical analyses (N, P, K, Mg, Ca), each component from all traps can be bulked into a single sample, mixed and a subsample taken for subsequent grinding (using a Wiley or coffee mill) and analysis. C concentrations of each component should be measured once on each plot to ensure the %C values is close to the 50% C normally assumed for plant material.

Branchfall samples should be air-dried to stabilize the sample. The entire sample can then be oven-dried and weighed or the air-dry mass determined and a subsample oven-dried (70°C for 48 hours) to convert air-dry to oven-dry mass.

### **6.2 Data processing**

Calculate the mean periodic mass fall of the total and component litterfall as:

$$(\text{Sum(trapmass g})/1000) \text{ kg} / (\text{number of traps}) \times (10,000/\text{single trap area m}^2) \text{ ha}$$

Annual C and elemental nutrients (depending on which elements used) returns can be calculated from the component concentrations applied to the component mass to determine periodic returns, which are then summed to calculate annual nutrient returns.

### **6.3 What should the final dataset contain?**

Masses: SiteID, plotID, trapID, date, interval (days), totalmass (g), needlemass (g), leaf mass (g), twig mass (g), fructification mass (g), and bark and, other mass (g) notes

Nutrients: (N in g/kg, all others in mg/kg): SiteID, plotID, date,  
needleN, leafN, twigN, fructificationN, bark and other N,  
needleP, leafP, twigP, fructificationP, bark and other P,  
needleK, leafK, twigK, fructificationK, bark and other K,

needleCa, leafCa, twigCa, fructificationCa, bark and other Ca,  
needleMg, leafMg, twigMg, fructificationMg, bark and other Mg  
needleS, leafS, twigS, fructificationS, bark and otherS (optional)

### **7. What other supporting measurements are required?**

Ideally litterfall and branch fall traps are placed in plots within which total ecosystem C stocks have also been measured. This would allow for calculation of net primary productivity, specific needlefall rates, estimation of rates of forest floor turnover, and relationship to other stand level variables. Data will also complement any studies in which forest floor respiration measurements are made.

### **8. Contact for further information**

J.A. (Tony) Trofymow ([trofymow@pfc.forestry.ca](mailto:trofymow@pfc.forestry.ca))

### **9. References**

Trofymow, J.A.; Barclay, H.J.; McCullough, K. 1991. Annual rates and elemental concentrations of litterfall in thinned and fertilized Douglas-fir. Can J. For. Res. 21:1601-1615.

Vogt, K.A. and Grier, C.C. and Vogt, D.J. 1986. Production, turnover and nutrient dynamics of above- and belowground detritus of world forests. Adv. Ecol. Res. 15:303-377.

**Co-Locating Fluxnet-Canada  
Decomposition, Resin Probe, and *In vitro* Soil Incubation Studies  
June 2003**

In 2003 three studies will be installed at various Fluxnet-Canada sites to measure decomposition rates over 4 years using standard litter materials (Trofymow), nutrient availability by resin probes (Prescott), and mineralizable C and nutrients through *in vitro* incubations of surface forest floor and underlying mineral soil (Paré).

At the 2003 Fluxnet-Canada Annual meeting and subsequent discussions it was decided that there would be an advantage in having the decomposition study, resin probe study, and *in vitro* soil incubation study co-located on the same 16 sites and mini-plots being set up for the decomposition study. This results in some synergy, in that measurements of available nutrients from the resin probes can be compared to the mineralizable nutrients measured in the *in vitro* incubations potentially leading to calibration of the resin probe technique for its use in determining available nutrients in subsequent years and sites. Having these sites and mini-plots in place could also lead to a study in later years to do *in situ* estimates of mineralizable nutrients with buried bags, though that method has its problems (Prescott). Measures of available nutrients can be tested as a covariate in the decomposition study. The plan is to have installation of these studies occur simultaneously within a site, and completed within the same two-month time period, July –August 2003 across all 16 sites.

*Decomposition study and miniplots*

The Fluxnet-Canada protocol for the cross-station decomposition study describes the 16 sites (Trofymow). At each site six 2x2m miniplots are established, three (numbered 1,2,3) clustered around the soil sensor instrumentation and the other three (numbered 4,5,6) distributed across the site. Further information on installation of the miniplots, chopstick strings (annual decay rates) and litterbag strings (cumulative decay rates) can be found in the decomposition study protocol or available from J. Trofymow or R. Ferris.

*Resin probes*

Resin probes will be distributed to site collaborators from the supply company (WesternAg). Ten pairs (anion/cation) of resin probes will be sent for each of the 16 sites. One pair of probes should be installed in each of the 6 miniplots within the area of the soil collected for the *in vitro* incubation. The other 4 pairs of probes can be installed elsewhere in the site but it is suggested that duplicates be installed in the 3 miniplots in the instrumented cluster (ie. 2 pairs of probes one in each of clustered miniplots 1,2,3 (6 pair total); 3 pair one in each of miniplots 4,5,6; 1 pair elsewhere in the site). Record the date of installation and miniplot number. Resin probes are to be retrieved after 60 days and returned to WesternAg for analysis. Detailed information on installation and collection of the resin probes will be sent within the probes or will be available from C. Prescott.

*Soil collection for *in vitro* incubations*

Soils for the *in vitro* incubations are to be collected from the 16 sites and ONLY from miniplots 1,2,3 in each site. Each sample is composed of five subsamples collected from within the miniplot boundary. A ca. 10x10cm sample of the FH layer of the forest floor (L layer and green material removed)\* is collected with a wood template and a knife and placed into one plastic bag.

A 5-6cm diameter core of the underlying mineral soil to 15cm is then collected into a second bag. Bulk the five surface FH subsamples in one bag and the five underlying mineral soil subsamples in the second bag. Label each bag with site, miniplot number and depth. Keep soils cool (2- 4°C) until they can be shipped by courier to David Paré. Samples should be sent as soon as possible and packed tightly inside the cooler with newspaper in order to minimize vibration. Further information on the soil collection is in the *in vitro* incubation protocol or available from D. Paré.

\*in case of very thick organic layer samples (such as is found in peatlands and some black spruce sites): remove the green moss layer and sample the first 20 cm starting from the point where roots are visible and going downward. Do not send waterlogged mineral soil samples.

*Study design contact information:*

*Resin probe study*

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*In vitro incubation study*

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*Decomposition study*

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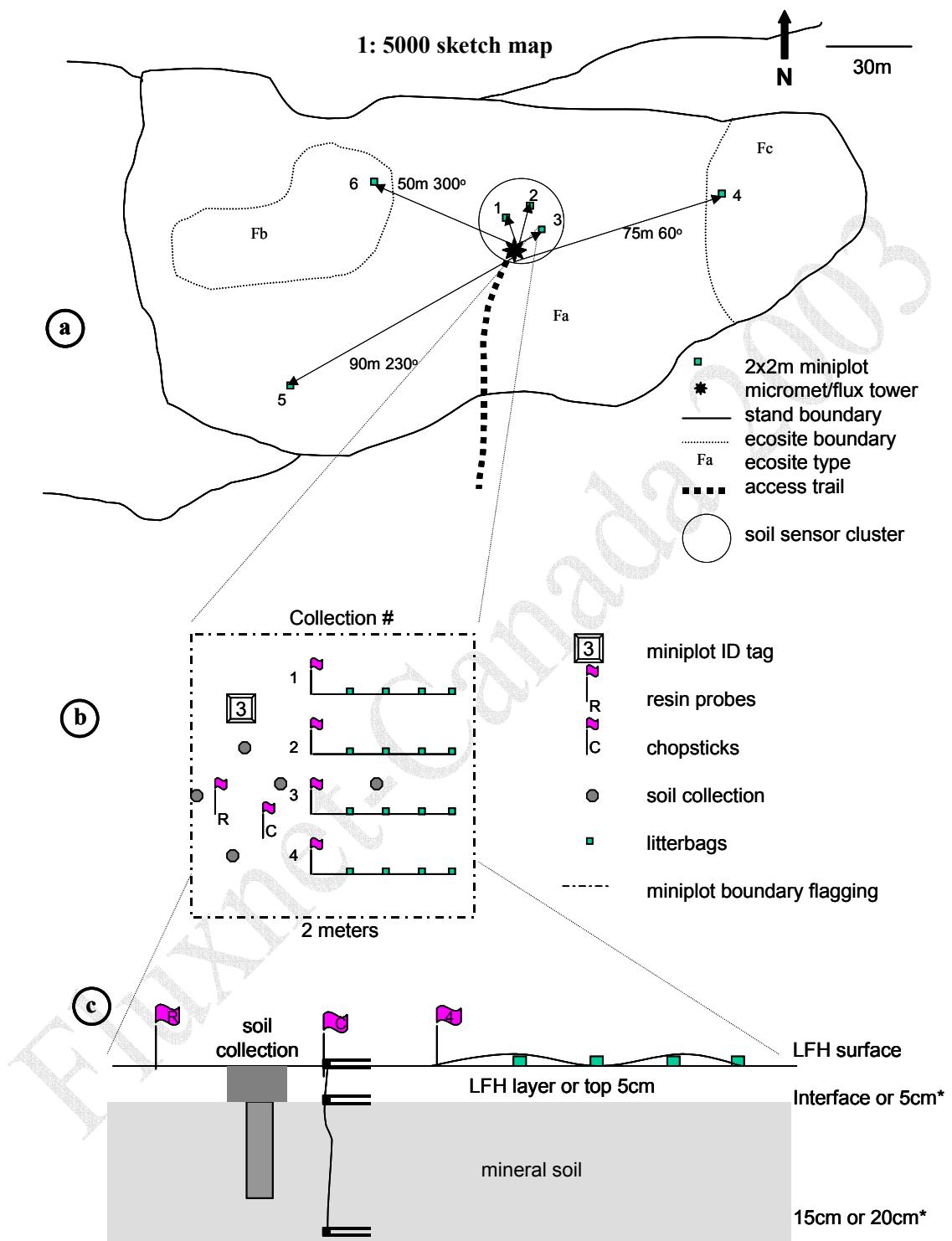


Figure 1: Examples of (a) miniplot location map, (b) miniplot layout, and (c ) arrangement of litterbag string, chopstick string, and resin probes. \*Installation depths in wetland sites.

## LITTER DECOMPOSITION

### 1. Variable(s) to be measured

*Litter decomposition – A cross-station decomposition study.*

Objectives:

1. Determine site-specific decomposition rates for standardized litter materials over a 4-year period,
2. Relate decomposition rates to *in situ* microclimate and local weather,
3. Relate decomposition rates to measurements of total site respiration from CO<sub>2</sub> flux towers and soil respiration from chambers,
4. Use relationships to assist in development of total ecosystem C cycling model, to be tested at each site.

### 2. Final temporal and spatial scale that the measurements should be rolled up to

Annual rates of and cumulative litter decay over a 4-year period.

### 3. Spatial characteristics

#### 3.1 How many samples are needed?

Four miniplots within a site is considered minimum to estimate a site mean, more miniplots if site is more variable. The site area instrumented for air and soil microclimate should contain replicate miniplots.

*Cross-station decomposition study* - Decomposition miniplots are to be installed at 16 sites. A total of 6 miniplots are to be installed per site, 3 clustered within the soil sensor instrumentation close to the tower, the other 3 miniplots distributed across the site. The miniplots will also be used for other studies of nutrient availability using resin probes (Prescott) and *in vitro* incubations of soil collections (Pare) as described in the Fluxnet-Canada protocols.

- 14 – At 5 upland forest stations each with a recent clearcut and closed canopy stand, plus 4 extra sites
  - 3 - BC coastal - 1949 Douglas-fir, 1999 clearcut, 1989 pole sapling
  - 5 - SK BERMS – old jackpine, clearcut jackpine, old aspen, old black spruce, burn jackpine
  - 2 – ON Groundhog – mixed wood forest, clearcut
  - 2 – QC CPRS – black spruce, clearcut
  - 2 – NB Nashwaak– balsam fir, clearcut
- 2 – wetland stations, 1 site each
  - 1 – AB LaBiche – treed fen peatland
  - 1 – ON Mer Bleue – raised bog peatland

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16 sites total

Total annual samples (chopsticks):

16 sites x 4 collection x 3 depth x 1 material x (3 miniplots. instrumented area + 3 uninstr. miniplots) = 1152

Total cumulative samples (litterbags):

16 sites x 4 collection x 1 depth x 4 material x (3 miniplots instrumented area + 3 uninstr. miniplots) = 1536

Installation and collections:

Miniplots and materials to be installed at all sites in the period July – August 2003 and collected at about the same date as the installation in 2004, 2005, 2006, 2007.

### **3.2 How should they be chosen?**

The miniplots within a site should cover the range of stand conditions or ecotypes at that site.

*Cross-station decomposition study* – Within the instrumented area the 3 replicate miniplots should be placed each adjacent to replicate sensors (if any), otherwise in a systematic manner, each replicate at least 10m apart all within a 15m radius. The other 3 replicate miniplots should be distributed to cover the range of major ecosite type within the site or stand.

### **3.3 How will the scaling up to the stand be performed (if pertinent)?**

*Annual* – Relate decay rates to *in situ* microclimate measurements summarized each year for 4 years. Prepare microclimate surface or denote fraction of stand with different microclimates and use decay/microclimate relationship to calculate stand total.

*Cumulative* – Mean of miniplots within stand. If sufficient numbers of miniplots measured consider weighting by the proportion of each ecotype within the stand/site.

## **4. Temporal characteristics**

### **4.1 Within day: When and how many times?**

NA

### **4.2 Within year: When and how many times?**

*Annual* – Collection and replacement once a year is sufficient.

*Cumulative* – Collection once a year is sufficient.

*Cross-station decomposition study* - Site collaborators to install experiment July – August 2003 and conduct annual placement/sampling in and initial lab processing in 2004, 2005, 2006, 2007. PFC to complete lab analysis and prepare annual data reports for collaborators.

### **4.3 How will the scaling to the year be performed (if pertinent)?**

NA

## **5. Measurements**

### **5.1 Instruments and set up required/suggested**

*Cross-station decomposition study*

*Miniplots* - A 2x2m miniplot is set up at 6 locations in each site. Within the instrumented area 3 miniplots (numbered 1,2,3) are setup adjacent to soil temperature and moisture sensors. Miniplots should be separated by at least 10m and within a 15m-radius area encompassing the soil sensor arrays. Elsewhere in the site setup 3 other additional uninstrumented miniplots (number 4,5,6). The perimeter of each miniplot should be flagged and a tree in the miniplot flagged and tagged. The tag should have "Fluxnet decomposition study," miniplot number, contact person, and phone number. On clearcuts or sites without trees a 2m - 2"x2" stake should be installed to mark the miniplot location. On each miniplot 4 strings of litterbags for the cumulative decay measurements and 1 string of chopsticks for the annual decay measurements are to be placed. Upon installation a sketch map of the site should be prepared indicating the bearing and distance to each miniplot from some fixed point such as the flux/micromet tower and a photo of each miniplot taken and returned to PFC. PFC will supply the flags and tags for each site.

*Annual* – Birch chopsticks will be a common material type that will installed and replaced annually. These have been used previously for an annual decay study (Trofymow 1998), tend to be more robust than tongue depressors (Titus pers comm.), another common substrate used for annual decay studies.

*Cumulative* – Litterbags (20 x 20cm) filled with ca 5.0g of a common material types (aspen leaves, black spruce needles, 15N tagged Douglas-fir needles, birch wood) will be installed once and a set of bags retrieved annually over 4 years. Litterbags will be constructed and filled following methods described for the CIDET (Trofymow and CIDET Working Group 1998). Extra empty bags will be made available to collaborators wishing to measure cumulative decay of other site-specific litter types.

## **5.2 Specific methodologies to perform the measurement**

### *Cross-station decomposition study*

*Annual* – Oven dry, pre-weighed and labeled sets/strings of chopsticks will be sent from PFC to each site collaborator. A set consists of 3 chopsticks strung together with 20cm string and an attached string label. Collaborator to place 3 sets, one in each of the miniplots in the instrumented plot and the other 3 sets one each in 3 other plots within the stand/site. The chopsticks in each set are placed at 3 depths, on the surface, at forest floor organic/mineral interface (5cm in organic soil), and at 15cm below the LFH/mineral interface in mineral soils, 20cm in organic soils. Chopsticks are inserted horizontally. A shovel is used to pry aside soil/forest floor to 25cm, a probe (eg. metal spike) is used to make a horizontal hole to insert the chopstick on the undisturbed side of the hole, and soil replaced. The string tag is left at the surface and pinned with a wire flag. Each year the sets of chopsticks are retrieved put in a plastic bag, miniplot number, depth and collection date recorded, and a new set of chopsticks installed. Upon installation the string number assigned to each miniplot and depth of each chopstick number are checked and the date of installation recorded. PFC will supply the list of string numbers sent to each site.

*Cumulative* – Oven-dry, pre-weighed and labeled sets/strings of litterbags will be sent from PFC to each site collaborator. A set consists of 4 strings of litterbags. Each string consists of with 240cm of string, 4 litterbags, and an attached string label. Collaborator to place 3 sets in the instrumented plot and the other 3 sets in 3 other miniplots within the stand/site. The litterbags are

distributed along the length of string ca. 0, 40, 80, 120, 160 cm and bags placed tag side down on the surface of the forest floor. Live moss or lichen under each bag is removed so that it is in contact with decaying forest floor material and cover or bury string between bags to avoid pulling bags out. The string tag is pinned to the ground with a flag. Each year a set/string of litterbags is retrieved, miniplot number and collection date recorded. Upon installation the string numbers assigned to each miniplot are checked and the date of installation recorded. PFC will supply the list of string numbers sent to each site.

### **5.3 Potential problems/pitfalls to avoid**

*Annual* – Avoid breaking chopstick when installing by using tool to prepare horizontal hole. Sticks especially the buried ones will need to be carefully extracted and gently pulled out and collect any sections that have broken off.

*Cumulative* – String aids retrieval and minimized losing bags but need to bury or cover the string so bags not pulled. Make sure bag is placed in good contact with forest floor, tag down (shiny tag attracts animals).

## **6. Post measurement processing**

### **6.1 Sample processing in the lab**

*Annual* – Record date of collection. Clean/ wash off adhering soil, dry at 48 hr at 70oC before weighing. Weigh without tag and record tag number and chopstick weight. Return chopstick with tag and datasheet to PFC.

*Cumulative* – Record date of collection. Clean off adhering soil, dry at 48 hr at 70oC before weighing. Weigh to 0.01 g, record weight and return bags and data sheet to PFC for chemical analyses.

### **6.2 Data processing**

Calculate and express results as % mass remaining or % mass loss. If done over multiple times (cumulative) the values can be Ln transform and plotted to see if mass change follows exponential decay (Ln %mass should fit linear regression). Use microplot values as replicates for the site to calculate the mean and standard error in %mass loss for the site. Means and SE can then be used to compare sites and stations. PFC will do the annual data summary for the cross-station decomposition study.

### **6.3 What should the final dataset contain?**

*Annual* - Station, site, collection number, depth, material, miniplot number, instrumented or uninstrumented flag (I or U), install date, collect date, string number, stick number, initial oven dry mass, final oven dry mass, % mass remaining.

*Cumulative* - Station, site, collection number, material, miniplot number, instrumented or uninstrumented flag (I or U), install date, collect date, string number, bag number, empty bag tare, total initial oven dry mass, net initial oven dry mass, total final oven dry mass, net final oven dry mass, % mass remaining, initial elements (C g/kg, N g/kg, S g/kg, P mg/kg), final elements (C g/kg, N g/kg, S g/kg, P mg/kg), CO<sub>3</sub>-C mg/kg (optional - any sites with soil carbonates).

## **7. What other supporting measurements are required?**

### *Site micromet data*

For the site, daily measurements of mean temperature, noon relative humidity, noon snow depth (or date of snow disappearance) precipitation, wind speed and light. If onsite micromet data is limited and the main site is closeby (within 5km), the first three should be measured on site and the latter three could be taken from the above canopy sensors from the main site.

### *Soil sensor data*

Within the instrumented plots daily measurements of temperature and % moisture at 2, 5, 10, 20 and 50cm should be taken as per the Fluxnet-Canada protocols. At minimum the surface, forest floor organic/mineral interface (5cm in organic soil), and 20cm is required to allow for regression estimates with annual decay rates.

In at least one uninstrumented miniplot (4, 5 or 6), measurements of surface temperature using stand-alone mini-data loggers (eg. Onset) would be helpful optional measurements to determine the variation in microclimate within a stand/site. PFC will supply one mini-logger per site to be placed at installation and returned the next year. Record the date of installation, miniplot number, and date of retrieval.

### *Site characterisitics*

Ideally the decomposition microplots can be located within permanent sample plots established at a site and measured using the NFI ground plot protocol as described in the FLUXNET-Canada C-stock protocol. If not, identify which of the permanent plots has conditions most similar to the decomposition microplot. See Trofymow and CIDET Working Group (1998) for list of information needed for each plot.

## **8. Contact for further information**

J.A Trofymow ([ttrofymow@pfc.forestry.ca](mailto:ttrofymow@pfc.forestry.ca)) or B. Titus ([btitus@pfc.forestry.ca](mailto:btitus@pfc.forestry.ca))

*Cross-station decomposition study* - PFC will prepare the sticks and litterbags, do the chemical analyses, and manage the data for all those participating in the cross-station decomposition study. Collaborators will prepare miniplots, install and collect sticks and litterbags, provide or locate plot/site description data, provide or locate site climate and plot microclimate data. All collaborators would participate in analysis of data and preparation of reports and papers from results.

## **9. References**

Trofymow, J.A. 1998. Detrital carbon fluxes and microbial activity in successional Douglas-fir forests. p.51-53. in J.A. Trofymow and A. MacKinnon (ed.). Structure, Processes, and Diversity in Successional Forests of Coastal British Columbia: Proceedings of a Workshop. Feb. 17 - 19, 1998. Victoria, B.C. Northwest Science. Vol. 72 Special Issue No. 2

Trofymow, J.A. and CIDET Working Group. 1998 CIDET - The Canadian Intersite Decomposition Experiment: Project and site establishment report. Inf. Rep. BC-X-378. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria. 126p

## Cross-station decomposition study sites and collaborators

### Collaborator Site

Trofymow	BC coastal - 1948 mature Douglas-fir forest
Trofymow	BC coastal - 1999 clearcut Douglas-fir forest
Trofymow	BC coastal - 1989 pole-sapling Douglas-fir forest
Amiro	SK BERMS – old jackpine forest
Amiro	SK BERMS – 2002 clearcut jackpine forest
Amiro	SK BERMS – old aspen forest
Amiro	SK BERMS – old black spruce forest
Amiro	SK BERMS – 1998 burn jackpine forest
Morrison	ON Groundhog – mixed wood forest
Payne et al.	ON Groundhog – 2002? clearcut forest
Pare'	QC CPRS – mature black spruce forest
Pare'	QC CPRS – clearcut black spruce forest
Lavigne	NB Nashwaak– mature balsam fir forest
Lavigne	NB Nashwaak– 2001? clearcut balsam-fir forest
Flanagan	AB LaBiche – treed fen peatland
Moore	ON Mer Bleue – raised bog peatland

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## IN-VITRO INCUBATION OF SOILS

### **1. Variable(s) to be measured**

*In vitro* long term soil respiration at different temperatures: This procedure generates curves of C release from soil heterotrophic respiration both from the forest floor and the mineral soil. The parameters describing these curves are used for modelling fluxes of heterotrophic soil respiration; they also provide an analytical assessment of the soil organic matter labile pool. Periodically soil CO<sub>2</sub> evolution is measured. Also soils are leached periodically and total nitrogen, ammonium and nitrate are being measured. Total organic C is measured in leachates.

### **2. Final temporal and spatial scale that the measurements should be rolled up to**

### **3. Spatial characteristics**

#### **3.1 How many samples are needed?**

At each site six 2x2m miniplots are established, three (numbered 1,2,3) clustered around the soil sensor instrumentation and the other three (numbered 4,5,6) distributed across the site. Apart from the *in vitro* incubation, these miniplots are used for decomposition study (Trofymow) and Resin sticks (Prescott). Soils for the *in vitro* incubations are to be collected ONLY from miniplots 1,2,3 in each site

#### **3.2 How should they be chosen?**

Each sample is composed of five subsamples collected from within the miniplot boundary. A ca. 10x10cm sample of the FH layer of the forest floor (L layer and green material removed)\* is collected with a wood template and a knife and placed into one plastic bag. A 5-6cm diameter core of the underlying mineral soil to 15cm is then collected into a second bag. Bulk the five surface FH subsamples in one bag and the five underlying mineral soil subsamples in the second bag. Label each bag with site, miniplot number and depth. Keep soils cool (2- 4°C) until they can be shipped by courier to David Paré. Samples should be sent as soon as possible and packed tightly inside the cooler with newspaper in order to minimize vibration. Further information on the soil collection is in the *in vitro* incubation protocol or available from D. Paré.

\*in case of very thick organic layer samples (such as is found in peatlands and some black spruce sites): remove the green moss layer and sample the first 20 cm starting from the point where roots are visible and going downward. Do not send waterlogged mineral soil samples.

#### **3.3 How will the scaling up to the stand be performed (if pertinent)?**

Average respiration for a given soil layer in a main plot at fixed incubation temperatures (3, 10 and 22°C), will be computed from the values of the four (4) sub-plots. Average respiration for the stand will be computed from the average of each main plot.

### **4. Temporal characteristics**

#### **4.1 Within day: When and how many times?**

#### **4.2 Within year: When and how many times? :**

Periodic measurement of respiration will be carried out at:

- 1) Each week during the first 2 months;
- 2) Each 2 weeks during the next 4 months;
- 3) Each month during the next 6 months.

#### **4.3 How will the scaling to the year be performed (if pertinent)?**

One periodic measurement will give, for a given soil layer and incubation temperature, the total heterotrophic C-CO<sub>2</sub> evolved per gram of oven-dried soil for a 24-hours period. Cumulative respiration (carbon mineralization) will be computed assuming a daily rate equal to the average daily rate between 2 consecutive measurements.

### **5. Measurements**

#### **5.1 Instruments and set up required/suggested**

In the lab, sub-samples will be mixed together and passed to a 4-6 mm screen; roots and coarser debris will be discarded. Water content, total C and total N will be measured. Soil will be incubated at field capacity in a (Mason type) jar (500 ml) with a rubber septum installed on the metal cover. A wet weight of 25 g for the organic layer and 100 g for the mineral layer is sufficient. The soil will be deposited in a plastic cup with a screen in the bottom. This will allow periodic leaching (6 to 8 weeks) with 100 ml of a dilute solution (K<sub>2</sub>SO<sub>4</sub> 0,005 M) to avoid accumulation of toxic decomposition products and will keep the soil at field capacity. Ammonium and nitrate concentrations will be measured in the leachates with a spectrophotometer (Lachat). On selected leachates, total N and total C will be measured. Measurement of CO<sub>2</sub> will be carried on with a LI-COR 6200 modified for syringe injection (application note 131 from LI-COR). This technique is quite simple and a reading of a CO<sub>2</sub> measurement is obtained near 30 seconds after the injection.

#### **5.2 Specific methodologies to perform the measurement**

Modification of the LI-COR 6200 will bring the air flux around 125-150 µmol s<sup>-1</sup>. A known volume (2 to 10 cc depending on the sample concentration) will be injected with a syringe through a rubber tube in the scrubbed air stream (~ 0 ppm CO<sub>2</sub>). Standard gases (CO<sub>2</sub> =600 or 1200 ppm ( $\pm$  2%)) will be utilised for calibration. Peak of CO<sub>2</sub> is given by the range value (1R) computed by the LI-COR 6200. There is a linear relation with intercept =0 between CO<sub>2</sub> concentration and peak concentration. Initial CO<sub>2</sub> concentration (time =0) will be subtracted from the final value CO<sub>2</sub> (time ~24 hours) to obtain the CO<sub>2</sub> respired.

#### **5.3 Potential problems/pitfalls to avoid**

When a measured peak concentration goes over around 1200 ppm, the IRGA detector of the LI-COR 6200 becomes saturated. It is recommended to inject a smaller volume (5 or 2 cc) of another air sample from the jar when the first injection gives value over 1000 ppm.

### **6. Post measurement processing**

#### **6.1 Sample processing in the lab**

When soil preparation is done and when the supporting measurements are available (see section 7), only the periodic leaching is required (section 5.1).

## **6.2 Data processing**

Total CO<sub>2</sub> evolved in µmoles during an incubation period of ~24 hours is equal to:

$$\{[\text{finalCO}_2] - [\text{initialCO}_2]\} * (\text{number of } \mu\text{moles in the jar})$$

Final and initial CO<sub>2</sub> are in ppm and the number of µmoles in the jar is:

$$(10^6/22.4) * \{(273+T^\circ)/273\} * (V_j - V_{s+c})$$

where T° is the incubation temperature in °K, V<sub>j</sub>, the total volume inside the jar in litre and V<sub>s+c</sub>, the volume of the soil and the plastic container in litre.

## **6.3 What should the final data set contain?**

Final data set should contain:

- 3) identification of site, horizon, incubation temperature, replicate and period of measurement;
- 4) the calculated respiration rate in µg C g<sup>-1</sup> C h<sup>-1</sup>
- 5) the cumulated days of incubation
- 6) Total initial C content in %

## **7. What other supporting measurements are required?**

Initial water content and total C content of each incubated layer to express the results by unit of C. Total volume of incubated material (soil and plastic container) is also needed.

## **8. Contact for further information**

Robert Boutin or David Paré  
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## **9. References**

Application note #131 edited by LI-COR

- The method described as been adapted from:
  - Côté, L., Brown, S, Paré, D. Fyles, J., Bauhus, J. 2000. Dynamics of carbon and nitrogen mineralization in relation to stand type, stand age and soil texture in the boreal mixedwood. Soil Biol. Biochem. 32: 1079-1090.
  - Nadelhoffer, K.J. 1990. Microlysimeter for measuring nitrogen mineralization and microbial respiration in aerobic soil incubations. Soil Sci. Soc. Am. J54: 411-415.

## **10. Cost**

The main cost is technician time: each main plot= 4 forest floor+ 4 mineral soil samples; 3 temperatures=24 microcosms; 22 measurement dates; a trained technician can handle 250 samples per week (pre and post measurements, data processing). 10 main plots= approximately 6 months technician time.

# DISSOLVED ORGANIC CARBON

## 1. Variable(s) to be measured

Dissolved organic carbon (DOC) fluxes, DOC lability, DOC sorption and mineralization and DOC:DON relationships.

## 2. Final temporal and spatial scale that the measurements should be rolled up to

Weekly to annual measurements of DOC flux from atmospheric deposition to export from the soil profile.

## 3. Spatial characteristics

### 3.1 How many samples are needed?

The number needed depends on the spatial variability of the vegetation and soil at each site. In general, atmospheric deposition will be measured at one site, near the main meteorological tower. Throughfall will be measured in replicate (probably 10 per site) funnels located within the forest canopy, to capture variations in canopy type and density. At the present time, it is not proposed to measure stemflow – although DOC concentrations are high, the volumes of water are small and thus it makes a small, and spatially concentrated component of the overall DOC budget. At sites where the tree architecture warrants, stemflow collection could be made.

Soil water will be sampled by replicate lysimeters, to capture the main variability spatially and with depth: probably 4 per depth at each site.

If possible, water sampling should be performed at a stream draining the catchment with site characteristics.

To assess DOC lability, samples of soil water from throughfall, litter, organic horizons and B horizon will be collected twice per year (spring and late summer) from the collectors noted above.

To assess DOC sorption and mineralization, samples from the major subsoil horizons will be collected from triplicate pits at the site; the samples will be bulked.

### 3.2 How should they be chosen?

To represent the major variability at the site.

### 3.3 How will the scaling up to the stand be performed (if pertinent)?

Scaling up will use the observed DOC concentrations and the flux of water, either measured (e.g. precipitation, throughfall, stemflow) or calculated from site measurements (particularly subsoil water fluxes and out of the profile).

## 4. Temporal characteristics

### 4.1 Within day: When and how many times?

N/A

### 4.2 Within year: When and how many times?

At one to two week intervals, depending on precipitation frequency and person-power resources available at each site.

#### **4.3 How will the scaling to the year be performed (if pertinent)?**

As noted above, with this frequency.

### **5. Measurements**

#### **5.1 Instruments and set up required/suggested**

Funnels for precipitation and throughfall, stem collars for stemflow, zero tension (organic layers) and tension (subsoil layers) lysimeters to collect soil water (Qualls et al. 2000). Filtering through 0.45 µm glass-fibre filters on-site.

#### **5.2 Specific methodologies to perform the measurement**

At McGill, all samples will be analyzed for DOC (on Shimadzu TOC 5050) and absorbance at a wavelength of 280 nm (as an index of aromaticity and humification – Kalbitz et al. 2000). A selection of samples (ca. 10%) will be analyzed for carbohydrates (Dubois et al. 1956) and dissolved organic nitrogen, NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N, to establish the broad pattern at each site. More detailed characterizations will be made once the patterns have been established.

DOC lability will be measured by incubating solutions in the laboratory and measuring DOC loss in the solution and CO<sub>2</sub> emission. The details of this have yet to be worked out, as there is no standard method but DOC researchers are attempting some standardization so that results will be comparable. Similarly, the DOC chemistry will be determined. It is hoped that the measurements of DOC flux within the soil profile and these measures of lability can be combined to assess the contribution of DOC to soil “respiration”, particularly with the automatic chambers being installed at each site.

DOC sorption will be made on the organic leachates at each site with the main subsoil samples, with some cross-sorption being made with a limited range of subsoil samples (Moore et al. 1992). Solutions of varying DOC concentration (commonly 0 – 80 mg L<sup>-1</sup>) will be treated with subsoil samples overnight and supernatent DOC concentration determined. Sorption isotherms provide information on strength of sorption, null-point etc. Soil samples will be analyzed for org. C, clay content and oxalate- and pyrophosphate-extractable Fe and Al, which have been found to be the main controls on DOC sorption. Differences in DOC chemistry (particularly hydrophobicity) will be measured to explain variations in sorption among DOC solutions (Moore and Matos 1999).

Remineralization of DOC will be assessed by long-term incubation of selected mineral soils, and determining CO<sub>2</sub> emission to identify org. C pools (Collins et al. 2000; McCracken et al. 2002).

#### **5.3 Potential problems/pitfalls to avoid**

Collaboration with site people is required to collect, process (filter) and transport the DOC solutions efficiently to minimize contamination and DOC breakdown prior to analysis. Storage should be at 4°C prior to transport. Considerable support of the site is also required in the provision of water flux data, especially in the soils, to calculate DOC fluxes.

### **6. Post measurement processing**

#### **6.1 Sample processing in the lab**

See above

## **6.2 Data processing**

Calculation of fluxes of DOC from concentrations and water fluxes, relationship between DOC properties at each site and lability, sorption and subsoil mineralization. Relationship between DOC and DON/ $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N.

## **6.3 What should the final dataset contain?**

Weekly to monthly fluxes of DOC at each site (pristine and disturbed).

## **7. What other supporting measurements are required?**

Water fluxes in the soil. Runoff in stream, if available.

## **8. Contact for further information**

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## **9. References**

Collins, HP, ET Elliott, K Paustian, LG Bundy, WA Dick, DR Huggins, AJM Smucker & EA Paul (2000). Soil carbon pools and fluxes in long-term corn belt agroecosystems. *Soil Biol. & Biochem.* 32: 157-168.

Dubois, M, KA Gilles, JK Hamilton, PA Rebers & F Smith (1956). Colorimetric methods for determination of sugars and related substances. *Anal. Chem.* 28: 350-356.

Kalbitz, K, S Geyer & W Geyer (2000). A comparative characterization of dissolved organic matter by means of original aqueous samples and isolated humic substances. *Chemosphere* 40: 1305-1312.

McCracken, KL, WH McDowell, RD Harter & CV Evans (2002). Dissolved organic carbon retention in soils: Comparison of solution and soil measurements. *Soil Sci. Soc. Am. J.* 66: 563-568.

Moore TR, W Desouza & J-F Koprivnjak (1992). Controls on the sorption of dissolved organic carbon in soils. *Soil Sci.* 154: 120-129.

Moore TR & L Matos (1999). The influence of source on the sorption of dissolved organic carbon by soils. *Can. J. Soil Sci.* 79: 321-324.

Qualls, RG, BL Haines, WT Swank & SW Tyler (2000). Soluble organic and inorganic nutrient fluxes in clearcut and mature deciduous forests. *Soil Sci. Soc. Amer. J.* 64: 1068-1077.

## WOODY TISSUE RESPIRATION

### 1. Variable(s) to be measured

Woody tissue respiration.

### 2. Final temporal and spatial scale that the measurements should be rolled up to

Half hourly, daily and annual fluxes at plot and stand level.

### 3. Spatial characteristics

#### 3.1 How many samples are needed?

Twenty stem samples and ten branch samples.

#### 3.2 How should they be chosen?

Choose ten trees by dividing the range of diameters into 5 classes and selecting two trees from each class. One collar should be installed near breast height and a second collar installed near the mid crown of each tree. Additionally, one collar should be installed on a mid crown branch.

#### 3.3 How will the scaling up to the stand be performed (if pertinent)?

Stem and branch surface areas can be used to scale up to the stand. There are alternative approaches to scaling based on dividing total surface area into strata based on segment diameter and tree dbh that can improve precision.

### 4. Temporal characteristics

#### 4.1 Within day: When and how many times?

Usually woody tissue respiration will be measured once per day at each collar, with measurements made bi-weekly. On three occasions per year (early growing season, late growing season, and post growing season) repeated measurements should be made at as wide a range of temperatures as possible using either an automated system (possibly using the automated soil respiration system) or manually over a one to four day period.

#### 4.2 Within year: When and how many times?

Bi-weekly during the entire period that the site is accessible.

#### 4.3 How will the scaling to the year be performed (if pertinent)?

Measurements from intensive sample periods will be used to establish the value of a temperature response coefficient (possibly  $Q_{10}$ ), and measurements made bi-weekly will be adjusted to a reference temperature (i.e.  $R_{10}$ ). Estimates of respiration rate at a reference temperature will be interpolated from measured values for intervening days. Therefore, half hourly woody tissue respiration rate is calculated as follows:

$$R = R_{10} \times Q_{10}^{(T-10)/10}$$

where  $R$  is woody-tissue respiration rate, and  $T$  is average woody tissue temperature measured on site for the half hour. Estimates of daily and annual woody tissue respiration are made by summing half hourly estimates.

## **5. Measurements**

### **5.1 Instruments and set up required/suggested**

Woody tissue respiration can be measured with almost any portable gas analyzer, custom-made collars that are attached to the tree at the beginning of the field season and left in place until the end of the field season, and a custom-made chamber that remains attached to the portable gas analyzer all year while moving among collars.

At the end of the growing season increment cores are collected from the middle of the stem surface encompassed by the collar.

### **5.2 Specific methodologies to perform the measurement**

Follow standard procedures of the portable gas analyzer.

### **5.3 Potential problems/pitfalls to avoid**

## **6. Post measurement processing**

### **6.1 Sample processing in the lab**

Sapwood width, ring width and bark thickness are measured on increment cores.

### **6.2 Data processing**

Measurements made after the growing season can be used to estimate maintenance respiration during the whole year, by assuming that the  $R_{10}$  and  $Q_{10}$  measured in autumn can be used in the equation above for the entire year. This is the so-called ‘mature tissue’ approach to subdividing total respiration into growth and maintenance components. Growth respiration on half hour to annual time scales is estimated as the difference between observed total respiration and calculated maintenance respiration.

### **6.3 What should the final dataset contain?**

## **7. What other supporting measurements are required?**

Continuous monitoring of woody tissue temperature at the site.

## **8. Contact for further information**

Mike Lavigne ([mlavigne@nrcan.gc.ca](mailto:mlavigne@nrcan.gc.ca))

## **9. References**

## STAND TRANSPiration

### 1. Variable(s) to be measured

Stem transpiration using sap flow velocity

### 2. Final temporal and spatial scale that the measurements should be rolled up to

Daily measurements of transpiration at the stand level

### 3. Spatial characteristics

#### 3.1 How many samples are needed?

Oren et al (1998) suggest using between 10-20 trees in order to obtain a coefficient of variation of 15% or less. However, if a basal-area weighted sampling is used, the sample size can be reduced to 5 to 10 trees.

#### 3.2 How should they be chosen?

We recommend using a basal-area-weighted random draw procedure to select the sample trees. In this manner, the sampling is biased towards the tree diameter classes that contribute the most to the transpiration flux (Martin et al. 1997). Trees with large apparent defects such as rot or cankers at breast height cannot be used in the selection process and must therefore be rejected.

#### 3.3 How will the scaling up to the stand be performed (if pertinent)?

An estimate of daily stand-level transpiration ( $E_s$ , in mm of water day $^{-1}$ ) is computed from the transpiration of each sampled tree ( $E_t$ , in litres of water day $^{-1}$ ) as:

$$E_s = \frac{E_t}{100 g_t} G_s$$

where  $g_t$  is the basal area of the tree (dm $^2$ ), and  $G_s$  is that of the stand (m $^2$  ha $^{-1}$ ). These stand-level estimates obtained from individual trees are averaged per stand to obtain a value of mean daily stand transpiration.

### 4. Temporal characteristics

#### 4.1 Within day: When and how many times?

Continuous measurements should be made every 20 to 30 minutes

#### 4.2 Within year: When and how many times?

Measurements should be carried out if possible from soil thaw to leaf fall.

#### 4.3 How will the scaling to the year be performed (if pertinent)?

Summation of the daily sap flow rates

## **5. Measurements**

### **5.1 Instruments and set up required/suggested**

We have used both Granier probes and Heat Pulse Velocity (GreenSpan) sensors. In either case, one has to know the likely depth of the active sapwood as a function of DBH, and the sap velocity profile as a function of depth. The Granier probes are interesting because they integrate along their length and thus provide depth-averaged measurements. They can also be built readily and driven by regular dataloggers. The empirical nature of their post-processing also eliminates night drift. On the down side, they require continuous heating, which makes them challenging to operate from batteries/solar panel in remote locations. They are also very sensitive to heat contamination so thermal insulation is a major concern.

The GreenSpan HPV probes are interesting because they provide low-maintenance, continuous measurements (when resin blockage is not a problem). The pulsed nature of the measurements means that batteries will last one month or longer. On the down side, they run only on proprietary GreenSpan loggers and the packages of one logger and 4 probes are expensive (about \$5,000 US). Also, they are point measurements and therefore require a better a-priori knowledge of sapwood depth and radial sap velocity profile. Finally, night time measurements will show non-zero values because of the inability of the company software to resolve low rates of thermal diffusion from sap-driven convection. These values must be eliminated in the post-processing.

### **5.2 Specific methodologies to perform the measurement**

As mentioned above, ideally, one has to know the likely depth of the active sapwood as a function of DBH, and, if the sapwood is deep (in the order of many centimeters), the sap velocity profile as a function of depth. Granier sensors integrate along their whole length, and placement is therefore as deep as possible within the sapwood area. For single-sensor HPV probes, ideal placement is at a depth corresponding to the approximate center of the flux profile (this will be closer to the bark than the average sapwood depth as the outer layers correspond to a larger diameter, hence to a larger sap wood area). With double-sensor HPV probes, the probe depth should permit both sensors to be within the sapwood, while providing for a good flow gradient between the sensors. When sapwood is quite deep and the flow velocity decreases linearly with depth, I would recommend using two HPV single-sensor probes placed at widely different depths in order to better capture the velocity gradient.

Exact probe location on the tree should be random. We use 1.3 m as our standard probe height, and use a random draw of horizontal angle to determine the location of the probe along the stem circumference.

### **5.3 Potential problems/pitfalls to avoid**

We have had serious problems with using HPV sensors in balsam fir likely due to resin blockage. We now move one half of the probes every second week with a new location on the stem chosen at random as for the other times.

## **6. Post measurement processing**

### **6.1 Sample processing in the lab**

None for the Granier probes. Periodic measurements of xylem water contents required for the HPV sensors.

## 6.2 Data processing

Granier probes: Transformation of the raw data into sap flux densities is done according to Granier 1987. Sap flux density ( $u$ ,  $\text{m s}^{-1}$ ) is computed as:

$$u = 119 \times 10^{-6} \times K^{1.231}$$

and

$$K = \frac{(dT_m - dT)}{dT}$$

where  $dT_m$  and  $dT$  are the difference between the thermocouple measurements at time of no flux (lowest nightly value) and when flow is positive. If the probe depth covers all sapwood depth, since the probe integrates along its whole length, total sap flow ( $\text{m}^3 \text{s}^{-1}$ ) is obtained as:

$$F = u \times S_a$$

where  $S_a$  is the total sapwood area ( $\text{m}^2$ ). For deep sapwoods, with linearly decreasing sap flow velocity with depth, sapflow ( $\text{m}^3 \text{s}^{-1}$ ) can be computed for each tree for each time period as:

$$F = \pi \times u \times \left[ R^2 - \frac{(a^2 + aR + R^2)}{3} \right] \times \frac{(R-a)}{(p-a)}$$

where  $R$  is the inside bark radius of the tree,  $a$  is the radius to the heartwood-sapwood interface, and  $p$  is the average measurement depth. The value of  $a$  has to be obtained for each tree from a locally-derived function. The total stand transpiration is computed as in 3.3. A similar approach can be taken with HPV measurements, except that, since these are point-in-space measurements, not integrated radially as in the Granier sensor, a better checking of the flow profile (or use of two probes) will be required.

## 6.3 What should the final dataset contain?

Final dataset should contain, for each time period (20 or 30 minutes), the sap flow volume of each sample tree, the sapwood area of each tree, that of the stand, and the total stand transpiration. Additional information should include species of each tree sampled.

## 7. What other supporting measurements are required?

Inventory of dbh distribution per species in a standard plot in which sap flow measurements are performed.

## 8. Contact for further information

Pierre Bernier ([pbernier@RNCan.gc.ca](mailto:pbernier@RNCan.gc.ca))

## **9. References**

Granier, A., 1987. Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. *Tree Physiol.* 3: 309-320.

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## **XYLEM PRESSURE POTENTIAL**

### **1. Variable(s) to be measured**

Pre-dawn and mid-day xylem water potential

### **2. Final temporal and spatial scale that the measurements should be rolled up to**

Instantaneous

### **3. Spatial characteristics**

#### **3.1 How many samples are needed?**

Usually, a sample of 10-15 measurements is sufficient to obtain a stable average.

#### **3.2 How should they be chosen?**

In the case of mature trees, for both pre-dawn and mid-day measurements, there needs to be samples taken at different levels of the crown. I would recommend one third of samples to be taken in the lower, mid and upper canopy positions respectively. Avoid current-year shoots until bud set (early to mid August). For regeneration in stands that do not have canopy closure, canopy position is not important (less discrimination between shade and sun foliage). A smaller number of samples may be sufficient in such a case.

#### **3.3 How will the scaling up to the stand be performed (if pertinent)?**

Arithmetic average of measurements

### **4. Temporal characteristics**

#### **4.1 Within day: When and how many times?**

Pre-dawn should be taken between 2 and 4 AM (before dawn). Mid-day should be taken between 12h00 and 2h00 (period of maximum stomatal depression), local standard times.

#### **4.2 Within year: When and how many times?**

This is a simple but specialized and time consuming measurement that must be carried out within an experimental context, as it will vary with environmental conditions. Measurements during dry spells when the NEE drops noticeably will certainly help explain the observation. In many models, the link between soil water depletion and reduction in transpiration and productivity is made via soil and xylem water potential, and such measurements will thus help parameterize the appropriate functions.

#### **4.3 How will the scaling to the year be performed (if pertinent)?**

Not pertinent

### **5. Measurements**

#### **5.1 Instruments and set up required/suggested**

Standard pressure chamber capable of measurements up to 40 bars

#### **5.2 Specific methodologies to perform the measurement**

Standard pressure chamber measurement as per Ritchie and Hinckley (1975). For conifers in general, and pines in particular, it is often difficult to distinguish water from resin. Place a small

piece of brown absorbing paper on the cut end. Water exuding from the cut will immediately darken the paper, while resin will not.

### **5.3 Potential problems/pitfalls to avoid**

Recommendation is for measurements within at most one hour from sampling. Tests must be made if longer storage periods are planned. At all times after excision, samples must be kept in humidified vials in a dark cooler. Humidify the vial or bag in which the sample is stored, but avoid having so much humidity that the cut end may come in contact with liquid water.

## **6. Post measurement processing**

### **6.1 Sample processing in the lab**

No particular sample processing

### **6.2 Data processing**

No particular data processing

### **6.3 What should the final dataset contain?**

Final dataset should contain date and time of sampling, as well as the individual measurements annotated w/r to sample characteristics (e.g. species, upper, mid or lower crown, etc...)

## **7. What other supporting measurements are required?**

Soil water content, meteorological data.

## **8. Contact for further information**

Pierre Bernier ([pbernier@rncan.gc.ca](mailto:pbernier@rncan.gc.ca))

## **9. References**

Ritchie, G.A. and T.M. Hinckley, 1995. The pressure chamber as an instrument for ecological research. Advances in Ecological Research, 9:1165-1254

# PHOTOSYNTHESIS

## 1. Variable(s) to be measured

A:Ci curves, light response curves and maximum stomatal conductance,  $A_{max}$

## 2. Final temporal and spatial scale that the measurements should be rolled up to

Point measurements at the leaf /shoot level

## 3. Spatial characteristics

### 3.1 How many samples are needed?

Measurements need to be made to cover the within-crown spatial variability, provide enough samples to perform the empirical fit of the Farquhar equations, as well as cover possible rejections of curves due to mishaps. Since this sampling may have to be repeated a few times during the summer, about 5 leaves/shoots from different canopy positions would suffice for the A:Ci and the light response curves for deciduous species. For conifers, multi-year needle retention generates an additional element of variability, and can be addressed by additional measurements, or by sample selection (see below).

### 3.2 How should they be chosen?

For full canopy characterization: For deciduous species, choice of sample is to be made to cover the range of light environments, but with a sampling bias towards the more strongly lit portions of the crown that are more photosynthetically important. For example, if 6 samples are taken, take 3 in the sunlit portion, 2 in the mid-crown, and 1 in the lower portion. For conifers with short needle retention (e.g. jack pine), choose randomly between current-year and one-year-old shoots. For conifers with multi-year retention (e.g. black spruce), we have found (Bernier et al, 2001) that the use of current year or one-year-old foliage produced a significant bias in the estimate of canopy photosynthesis, whereas unbiased estimates were obtained using needles with median properties (3-year old cohorts in the case of the Bernier et al 2001 study). Although this may have to be checked with the Modelling Group to optimise the match between field measurements and model requirements, our recommendation would be to perform measurements on two-year-old needles for trees that have needle retention up to 5-6 years, and three-year-old needles for trees with longer needle retention (up to 12 years in balsam fir).

### 3.3 How will the scaling up to the stand be performed (if pertinent)?

Not pertinent

## 4. Temporal characteristics

### 4.1 Within day: When and how many times?

No particularly bad time during the day, except if measurements are made *in situ*, under droughty conditions, in which case it is preferable to perform measurements early in the morning to avoid moisture stress. Under more humid conditions, avoid periods with moisture such as dew present on foliage or twigs as this would result in an overly large value of stomatal conductance. Early morning branch excision is also recommended for measurements made *ex situ* during droughty conditions.

#### **4.2 Within year: When and how many times?**

If required, measurements should be made in early summer (mid-June), mid-summer (mid-July) and late summer (late August-early September) to capture possible drift in leaf properties.

#### **4.3 How will the scaling to the year be performed (if pertinent)?**

Not pertinent

### **5. Measurements**

#### **5.1 Instruments and set up required/suggested**

A good, hand-held photosynthesis with micro-climate control is required, either a LI-6400, or an ADC-LCA4 or any machine of this type, with either an actinic or halogen light source that provide incident radiation ( $Q$ ) up to 1500 umol m<sup>-2</sup> s<sup>-1</sup>, and with a CO<sub>2</sub> control that can scrub down to about 50 ppm and enhance up to 900 ppm.

#### **5.2 Specific methodologies to perform the measurement**

in-situ versus ex-situ: Both methodologies have pros and cons. Our preference goes for in-situ because of the minimal disturbance to the shoots/foliage, and because they can be done (and are usually done) under VPD and temperature conditions that vary from one measurement to the other, a situation that enables the extraction of VPD and temperature effects. Ex-situ, on the other hand, requires no canopy access, permits far more controlled measurements to be taken, but is also artificial in that liquid xylem films are ruptured and the shoot is subjected to transport stress. Our experience with conifer species is that excision of 2-3 ft. branch portions doesn't affect the photosynthetic properties of shoots even after 12 hours (or storage overnight). The excised branches should be re-cut under water as soon as possible after excision and stored as such in a cool, dark place until measured. Allow at least 30 min. acclimation at high light before performing measurements in order to achieve full photosynthetic induction. In the field, our experience has been that no more than 5 to 6 A:Ci or light response curves can be achieved in a day.

A:Ci – Under light saturated conditions ( $Q>1500-2000$  umol m<sup>-2</sup> s<sup>-1</sup>) and ambient or controlled temperature and VPD, we recommend the following procedure: acclimate leaf/shoot at 360 ppm to measure A<sub>max</sub>, then move to 50 ppm and ramp back up to 900 ppm, adding a measurement at 600 ppm. Equilibrium with the new CO<sub>2</sub> concentrations should be based upon reaching a stable Ci – no need to wait further for acclimating before recording data as it might feedback on photosynthesis, especially at low Ci. This variable is computed internally by the measurement system, integrates nearly all available information, and is quite sensitive to fluctuations in stomatal conductance (gs) and photosynthesis.

Light response: Under ambient CO<sub>2</sub> and standard or ambient temperature and VPD levels, perform five measurements of A under a range of light conditions. This range goes from saturation (above 1200 umol m<sup>-2</sup> s<sup>-1</sup>) to total darkness (obtained in the field by wrapping the cuvette in aluminum foil). Target light levels for the three intermediate points should be at or near points of physiological interest according to the recommendations of Hanson et al (1987). Aim for light at the compensation point (around 30 umol m<sup>-2</sup> s<sup>-1</sup>), a point in the steepest portion of the light response curve and one point nearer to the zone of curvature. These last two will be species-dependent. We have used about 200 umol m<sup>-2</sup> s<sup>-1</sup> and 600 umol m<sup>-2</sup> s<sup>-2</sup> for black

spruce. Working from the highest to the lowest light levels, equilibration times may be up to 5-10 minutes. Again Ci stability is a good criterion.

Values of maximum stomatal conductance should be obtained from the other measurements taken, unless specific stress (extensive soil drought for example) prevents the full range of gs to be expressed.

### **5.3 Potential problems/pitfalls to avoid**

Some special precautions need to be taken for both in-situ and ex-situ procedures. For in-situ, when doing light response curves with an artificial light source during the day using a conifer cuvette, shield the bottom portion of the cuvette with opaque black material to avoid contamination of response from ambient light. Also, as mentioned above, avoid mid-day or droughty periods when an additional signal may dominate the response. For ex-situ, check the integrity of the sampling and transport procedures by comparing field and lab maximum photosynthesis.

## **6. Post measurement processing**

### **6.1 Sample processing in the lab**

Key lab processing is the determination of foliar area for conifer shoots. Different investigators have their own preferences. Ours goes to a method that combines information on needle cross-sectional area and total needle length in the needle sample. Cross sectional area is obtained by slicing a single thin section in the middle portion of 5 needles within the shoot (on fresh material only) which can be scanned in very high resolution. We put the five sections on transparent "scotch-tape" mounted across an empty slide frame, along with a bit of 0.5mm pencil lead to be used as a scale. The frames are scanned with a slide scanner with a resolution of 2000 DPI or greater, and the perimeter is obtained with the NIH-image software. Total needle length of the sample is obtained through a regular scanner and image processing software such as Win-Seedle (or Mac-Seedle) from Régent Instruments. Average needle cross-section times needle length gives total area. A small correction needs to be made for needle tapering that can be measured for single needles as the ratio of the average perimeter of thin sections taken from one tip of the needle to the other (say 15 sections) to that of the central section.

### **6.2 Data processing**

#### **6.2.1. Correcting for leaf area in conifers**

In measurements of conifer shoots, we recommend using a fictitious leaf area of 1000 mm<sup>2</sup> at measurement time. Post-processing of data for actual leaf area can be done as follows:

Since all measurements are taken by assuming a total leaf area of 1000 mm<sup>2</sup>, values of photosynthesis (A), transpiration (E) and stomatal resistance ( $Rs=1/gs$ ) are adjusted a posteriori using half of the all sided leaf areas (HASLA), and using the following equations:

$$A(\text{corrected}) = A(\text{uncorrected}) * 1000 / \text{HASLA}$$

$$E(\text{corrected}) = E(\text{uncorrected}) * 1000 / \text{HASLA}$$

$$Rs(\text{corrected}) = (((Rs(\text{uncorrected}) + Ra) * HASLA) / 1000) - Ra$$

where Ra is the aerodynamic resistance to water vapour, and is set at 0.4 m<sup>2</sup> s mol<sup>-1</sup> for the LCA-4 cylindrical cuvette (check manual for other cuvettes). The intercellular CO<sub>2</sub> concentration is recomputed using the equation of von Caemmerer and Farquhar (1981):

$$Ci = (((gc - (E(\text{corrected})/2)) * Can) - A(\text{corrected})) / (gc + (E(\text{corrected})/2))$$

where Can is the CO<sub>2</sub> concentration in the air stream coming out of the cuvette, E is in units of mol m<sup>-2</sup> s<sup>-1</sup>, and where gc is the total conductance for CO<sub>2</sub> and is given by:

$$gc = 1 / ((1.6 * Rs(\text{corrected})) + (1.37 * Ra))$$

### 6.2.2. Fitting the A:Ci curve

Following the standard equations of von Caemmerer and Farquhar (1981), the A:Ci curve is modeled as:

$$An = \min \{Ac, Aj\} - Rd;$$

$$Ac = Vcmax (Ci - \Gamma^*) / (Ci + Kc (1 + O/Ko));$$

$$Aj = J (Ci - \Gamma^*) / (4Ci + 8\Gamma^*);$$

$$J = (\phi I + J_{\text{max}} - ((\phi I + J_{\text{max}})^2 - 4\theta \phi I J_{\text{max}})^{0.5}) / 20$$

where An is net CO<sub>2</sub> assimilation rate, Ac and Aj are the Rubisco-limited and light-limited gross photosynthesis rates, respectively, Vcmax is the maximum rate of carboxylation,  $\Gamma^*$  is the CO<sub>2</sub> compensation point in absence of dark respiration (Rd), O is the oxygen concentration, and Kc and Ko are the Michealis-Menten constants for CO<sub>2</sub> and O<sub>2</sub>, respectively, J is the rate of electron transport, J<sub>max</sub> is the CO<sub>2</sub>- and light-saturated electron transport rate, I is the incident irradiance,  $\phi$  and  $\theta$  are the quantum yield and convexity of the photosynthesis light response curve described below.

The initial portion (i.e Ci < 200 ppm) of the A:Ci curve should be fitted to the Rubisco-limited function, Ac, using standard non-linear regression techniques. Fitting the model requires  $\Gamma^*$ , Kc, and Ko to be known and Vcmax and Rd to be estimated. Recently, Bernacchi *et al.* (2001) have provided improved *in vivo* estimates of  $\Gamma^*$ , Kc, and Ko as well as temperature response functions for all the parameters included in the model. We recommend using these parameters as they perform better than previous *in vitro* estimates. Having fitted the Ac function, it is then possible to fit the entire A:Ci curve as the minimum of the Ac and Aj functions, using the parameters of the light response curve described below to substitute for J and simultaneously estimate J<sub>max</sub>.

### 6.2.3 Fitting the light response curve

The non-rectangular hyperbola remains the most commonly used function describing the response of photosynthesis to light. Following Leverenz (1987):

$$An + Rd = (\phi I + Pm - ((\phi I + Pm)^2 - 40 \phi I Pm)^{0.5}) / 2\theta.$$

This is the same equation used to describe the electron transport rate (J), above, but here Jmax is substituted for Pm, the light-saturated gross photosynthesis rate.

### **6.3 What should the final dataset contain?**

Final dataset should contain the values of gs, Ci and photosynthesis along with the corresponding environmental variables (Q, VPD, Ca, Temperature). A separate file should contain the equation parameters by shoot/leaf, the leaf/shoot hemisurface area, the leaf/shoot dry mass and a field describing canopy position.

## **7. What other supporting measurements are required?**

### **8. Contact for further information**

Nigel Livingston ([njl@uvic.ca](mailto:njl@uvic.ca))

Pierre Bernier ([pbernier@RNCan.gc.ca](mailto:pbernier@RNCan.gc.ca))

## **9. References**

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## **PHENOLOGY**

### **1. Variable(s) to be measured**

Leaf phenology: date of budbreak, date of full leaf development, date of leaf fall, curing of ground vegetation

### **2. Final temporal and spatial scale that the measurements should be rolled up to**

Stand and site average at specific dates through the year.

### **3. Spatial characteristics**

#### **3.1 How many samples are needed?**

One per site if uniform, more if non-uniform.

#### **3.2 How should they be chosen?**

Within flux footprint.

#### **3.3 How will the scaling up to the stand be performed (if pertinent)?**

Spatial averaging based on variability in the vegetation.

### **4. Temporal characteristics**

#### **4.1 Within day: When and how many times?**

Not applicable.

#### **4.2 Within year: When and how many times?**

Periodic when the vegetation is changing. Need to sample on dates in spring and fall when there are key phenology developments.

#### **4.3 How will the scaling to the year be performed (if pertinent)?**

Not applicable.

### **5. Measurements**

#### **5.1 Instruments and set up required/suggested**

Camera to record phenology. Alternative is to measure reflected PAR to get change in site characteristics caused by green vegetation development.

#### **5.2 Specific methodologies to perform the measurement**

Take photographs daily or every few days when changes are occurring.

#### **5.3 Potential problems/pitfalls to avoid**

Aspen canopies can green up as individual clones, which can vary by many days. May need to compare phenology near the tower with areas further upwind within the flux footprint to be assured of uniformity.

### **6. Post measurement processing**

#### **6.1 Sample processing in the lab**

Not applicable.

## **6.2 Data processing**

Not applicable.

## **6.3 What should the final dataset contain?**

For each year, key dates for budbreak, full leaf out, leaf senescence, and curing (browning) of ground vegetation if appropriate.

## **7. What other supporting measurements are required?**

Incoming and outgoing PAR would help determine development of “greenness”.

## **8. Contact for further information**

Brian Amiro ([bamiro@nrcan.gc.ca](mailto:bamiro@nrcan.gc.ca))

## **9. References**

## **CARBON STOCKS AND SITE CHARACTERISATION**

## CANOPY STRUCTURE MEASUREMENT USING OPTICAL INSTRUMENTS

### 1. Variable(s) to be measured

Gap fraction, gap size distribution, plant area index (PAI), clumping index, leaf area index (LAI), and crown closure.

The LAI is defined as one half the total green leaf area per unit ground surface area (Chen and Black, 1992). On sloping surfaces, the LAI should be projected to the normal to the slope. The basic equation for obtaining the true LAI from optical measurements is (Chen, 1996):

$$L = (1 - \alpha)L_e\gamma_E / \Omega_E \quad (1)$$

where  $L$  denotes LAI,  $\alpha$  is the woody-to-total plant area ratio;  $L_e$  is the effective LAI;  $\gamma_E$  is the needle-to-shoot area ratio; and  $\Omega_E$  is the foliage element clumping index. A foliage element refers to a conifer shoot or a broad leaf. If no correction is made using this woody-to-plant area ratio, i.e., alpha=0, the plant area index (PAI), including both green leaves and non-green materials, is obtained from Eq. (1). The effective LAI is the starting point for optical measurements of LAI, as optical instruments normally acquire the canopy gap fraction data through measuring radiation transmission. From the gap fraction, the effective LAI can be calculated under the assumption of a random spatial distribution of leaves. As the distribution is often not random, the effective LAI generally differs considerably from the true LAI. It is therefore necessary to make corrections with respect to the leaf spatial distribution pattern. In conifer stands, needles are grouped first in shoots, which are often dense and allow little penetration by light. Shoots of conifer needles are therefore treated as foliage elements and a correction for this leaf grouping effect is made using the needle-to-shoot area ratio. For broad leaf stands, individual leaves are considered as the element, and no such correction is necessary, i.e.,  $\gamma_E=1$ . Foliage elements are usually further grouped into canopy structures at large scales such as branches and tree crowns. This clumping at scales larger than the shoot is quantified using the element-clumping index, which can be derived from optical measurements of canopy gap size distribution. The clumping index was found to vary with zenith angle (Chen, 1996; Kucharik et al., 1997). The recommended range of solar zenith angle for making TRAC measurements is 35° to 60°, which is representative of the mean clumping conditions. Fisheye photographs can be used to study the angular variability of clumping index. In optical gap size or gap fraction measurements, all objects above ground including leaves and woody materials affect LAI measurements. Since we are interested in green leaves only, these effects need to be removed by incorporating a woody-to-total plant area ratio. LAI-2000 and fisheye photography can also produce gap fraction near the vertical direction, i.e., in the first annulus from 0° to 15° zenith for LAI-2000 or similarly derived from photographs. This gap fraction can be approximately taken as the crown closure.

### Measurement Protocols

LAI measurement protocols are developed to obtain the necessary variables given at the right hand side of Equation (1). The following strategies should be followed in LAI measurements at all locations:

- (1) Measure  $L_e$ , using fisheye photography or LAI-2000 at all sites if possible, otherwise  $L_e$  is measured at a few solar zenith angles using TRAC. A  $\sin \theta$  weighting scheme should be used to obtain the stand average when TRAC data were acquired at more than one zenith angle.

- (2) Measure the element clumping index  $\Omega_E$  using TRAC at all forest sites.
- (3) Measure the needle-to-shoot area ratio where possible. Since it is highly labour intensive to acquire this number, the suggested values below can be used as the default values. When this variable is measured, it is recommended that you use the volume displacement method for measuring needle area outlined in the Appendix of Chen et al. (1997) and the multi-angle projecting method for measuring shoot area described in Chen (1996).
- (4) Measure the element width where possible, otherwise the suggested values below can be used. The width is taken as the square root of half the largest projected leaf area for broad leaves. For conifer shoots close to cylindrical or spherical shapes, it can be approximated as the square root of the product of shoot length and diameter. Detailed theories and methods for handling the projection of foliage elements on the ground surface at various solar zenith angles and azimuth angles relative to the transect direction are given in Chen and Cihlar (1995a) and the TRAC manual (Leblanc et al., 2002b). The width can also be approximately found from measured gap size distributions by TRAC or photographs using the P-approach described in Chen and Cihlar (1995b).
- (5) Estimate the woody-to-total area ratio where possible, otherwise the suggested values below are used for the major boreal forest types.

### **1.1 Variable(s) to be estimated**

Needle-to-shoot area ratio and woody to plant area ratio suggested values from literature (Chen, 1996; Gower et al., 1999):

Needle-to-shoot area ratio:

- Black spruce (*Picea mariana*): 1.30-1.40;
- Jack pine (*Pinus Banksiana*): 1.20-1.40;
- Red pine (*Pinus resinosa*): 2.08;
- Scots pine (*Pinus sylvestris*): 1.75;
- Douglas Fir (*Pseudotsuga menziesii*): 1.77

Woody to total area ratio.

- Black spruce (*Picea mariana*): 0.12-0.17;
- Jack pine (young) (*Pinus Banksiana*): 0.03-0.05;
- Jack pine (old) (*Pinus Banksiana*): 0.11-0.34;
- Red pine (*Pinus resinosa*): 0.07;
- Douglas Fir (*Pseudotsuga menziesii*): 0.08
- Aspen (*Populus tremuloides*): 0.21-0.22
- Oak-hickory: 0.11
- Sitka spruce: 0.23

Element width (mm):

- Black spruce (*Picea mariana*): 30 ;
- Jack pine (*Pinus Banksiana*): 50;

- Red pine (*Pinus resinosa*): 130,
- Scots pine (*Pinus sylvestris*): 70 ;
- Douglas Fir (*Pseudotsuga menziesii*): 50
- Aspen (*Populus tremuloides*) : 50

## **2. Final temporal and spatial scale that the measurements should be rolled up to**

Seasonal or annual measurements at the stand/tower site level

## **3. Spatial characteristics**

### **3.1 How many samples are needed?**

At each forest flux tower site, the strategy is to obtain the mean LAI of the footprint area of the tower. A transect to the west of the tower is the best. With more resources, two additional transects to the NW and SW of the tower can also be used. A transect should be at least 300 m long to characterize the footprint variability.

### **3.2 How should they be chosen?**

Along the transect(s), a permanent marker is placed every 10 m on the forest floor. These markers along the transect(s) are the locations for distance marker for TRAC and for LAI-2000 or fisheye photographs.

### **3.3 How will the scaling up to the stand be performed (if pertinent)?**

For TRAC, LAI can be calculated every 10 m or for the whole transect length. Software has been developed to use all photographs in single analysis or for individual photographs. For LAI-2000, a stand average is obtained as the arithmetic mean of the effective LAI at various locations.

## **4. Temporal characteristics**

### **4.1 Within day: When and how many times?**

Measurements of TRAC should be taken on clear days or in the time window without the effect of clouds on direct solar radiation.

For fisheye photography and LAI-2000, measurements should be taken under diffuse sky conditions, either near-dawn, near dusk, or under overcast conditions.

### **4.2 Within year: When and how many times?**

For coniferous sites, one measurement per year in the growing season.

For deciduous stands, one visit before leaf out and one at maximum LAI (July-August) as a minimum. If possible, frequent measurements every 2 weeks during the growing season would add useful information on the seasonal variation.

### **4.3 How will the scaling to the year be performed (if pertinent)?**

The spatial variability down to cm and up to 100m can be obtained from TRAC measurements. These would be very useful for studying spatial scaling. Mean and standard deviation of LAI for 10 m segments should be provided to modelers.

## 5. Measurements

### 5.1 Instruments and set up required/suggested

Optical methods are used in this study to acquire a large number of data points for remote sensing algorithm development. All of them are commercially available.

(1) TRAC (Tracing Radiation and Architecture of Canopies), which was developed at the Canada Centre for Remote Sensing (Chen and Cihlar, 1995a) and commercialised by the Third-Wave Engineering ([mikek@3wce.com](mailto:mikek@3wce.com)), Ottawa, Canada. The TRAC measures the transmitted direct photosynthetically active radiation (PAR) along transects beneath a plant canopy using a walking and high-frequency (32 Hz) sampling technique. From the high-spatial density (100 points/m) PAR data along a transect, both the canopy gap fraction and gap size distribution are obtained. A theory was developed to derive the element-clumping index from the gap size distribution and to calculate the effective LAI and the true LAI (Chen and Cihlar, 1995a).

(2) Digital Hemispherical Photography. Nikon cameras, with a fish-eye adapter, are used, i.e., model CoolPix 990 or better. The hemispherical photographs cover a range of view zenith angle from 0° to 93°, but the processing is done from 0° to 75°. The measured gap fraction and gap size distribution from image segmentation into canopy, sky and mixed canopy-sky pixels is used to invert for effective LAI and clumping index (Leblanc et al., 2002a and 2002b). Digital cameras represent an advancement in the measurement techniques. However, there are still remaining issues, such as chromatic aberration causing blue light focusing shift and gap distortion (Fraser et al., 2001), overexposure and underexposure balance at various zenith angles (Chen et al., 1991), and loss of small gaps. It is recommended (Tony Trofymow and Sylvain Leblanc) that Nikon Coolpix 4500 should be used instead of Coolpix 990 to reduce the problem of chromatic aberration.

(3) LAI-2000 Plant Canopy Analyzer (Welles and Norman, 1991) commercially available from Li-Cor Inc., Lincoln, NE, USA. The LAI-2000 measures the gap fraction in five annuli covering the zenith angle range from 0° to 75° based on diffuse radiation transmission through the canopy. The measured gap fraction data are inverted to obtain the effective LAI under the assumption of a random spatial distribution of leaves. The effective LAI can be converted into LAI when the total clumping (i.e., at scales smaller and larger than the shoot) is known.

Fisheye cameras and LAI-2000 have the advantage of hemispherical exposure, providing better angular coverage than TRAC, and therefore the  $L_e$  from them is more reliable than that from TRAC in extensive stands. As fisheye cameras and LAI-2000 derive the gap fraction from diffuse radiation transmission, it is less restricted by the sky conditions than TRAC, which requires cloud-free conditions near the sun's direction during measurements. Gap size distributions can also be obtained from fisheye photographs and clumping indices can also be estimated (Leblanc et al., 2002a). However, the new methodology has not been widely applied and validated, therefore it is recommended to use the combination of TRAC and fisheye cameras or LAI-2000 (Chen, et al., 1997).

In the field experiment, the following devices are to be prepared in addition to the optical instruments:

Tripod.

Flags.

Tape or laser ranger with compass for flagging.

GPS

## **5.2 Specific methodologies to perform the measurement**

Flagging should be put every 5 or 10 m to indicate where the photographs or LAI-2000 are to be taken for repeatability. The camera should be leveled, and hold at about 1.5 m.

TRAC should be used within 3 hours of solar noon, or in the zenith angle range from 35° to 60°.

## **5.3 Potential problems/pitfalls to avoid**

**Edge effects:** Photographs should be taken no closer to the edge of a desired canopy sampling area than 2.75 (or 1.56 for measurement at 57.3° only) times the height of the canopy, e.g. when the area surrounding a plot has different conditions than the canopy that you desire to measure.

For example:

Canopy height of 5 m: photographs not closer than 13.75 m from edge

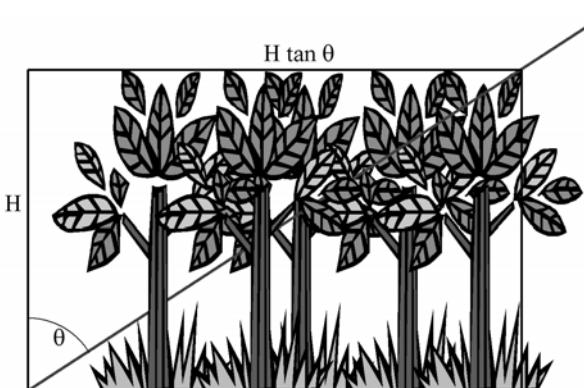
10 m: 27.5 m,

20 m: 55 m

30 m: 82.5 m

50 m: 137.5 m

Plots should be large enough to take 6 photographs.



### **Topography:**

The angular retrieval of clumping index is problematic on sloping terrain as the path through the canopy changes for all hemispherical photograph pixels. Plant area index (PAI) and LAI can be retrieved, as they are not angular parameters. It is recommended that 2 photographs be taken at each point for canopy on slopes. One photograph leveled, and one tilted to be taken parallel to the slope normal (see diagram above).

### **Photograph contrast:**

If photographs appear too dark or bright on the digital camera view, a second photograph can be taken with different camera setting.

### **Understory:**

LAI-2000 is recommended for measuring the LAI of understory in forest stands. Digital images, even taken above and below the understory, are not able to differentiate easily the gaps in overstory and understory. Precautions should be taken when placing the sensor: it should be away from the nearest leaves at a distance at least 10 times the leaf width. Putting cameras beneath short grass is difficult. TRAC has the same problems.

### **Wetland:**

LAI-2000 is recommended. Clipping of leaf samples are encouraged.

## **6. Post measurement processing**

### **6.1 Sample processing in the lab**

None

### **6.2 Data processing**

Software for TRAC includes TRACOM.com, TRACwin.exe. A software such as Photoshop is needed to extract the blue channel of the digital photographs. Two programs have been written for the analysis of digital hemispherical photographs: DHP.exe (Leblanc et al., 2002a and 2002c) and TRACWin.exe version 2.5 and up (Leblanc et al., 2002b). Additionally, the Gap Light Analyzer (GLA), version 2, (Fraser et al., 2000) is also available for caculating the effective LAI. DHP.exe is recommended as the standard, while GLA can be used as a comparison.

### **6.3 What should the final dataset contain?**

Final dataset should contain date and time of sampling, table with the following fields:

Effective Plant Area Index ( $57.3^\circ$ )

Clumping Index ( $57.3^\circ$  or Kucharik et al., (1999) parameters b,p,k and  $R^2$  of the fit)

Needle-to-shoot used

Woody to total area ratio used

Softwares avaialble to assist the analysis: DHP.exe, TRACWin.exe and GLA

## **7. What other supporting measurements are required?**

Stem density, DBH, stand age.

## **8. Contact for further information**

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# CARBON STOCKS, SITE VEGETATION AND SOIL CHARACTERISTIC PROTOCOLS

## 1. Variable(s) to be measured

The NSERC/CFCAS research network proposal for Fluxnet-Canada (Version 2.0) outlines the need for mandatory measurements of site characteristics (Table 2.4b in proposal). Here we outline the protocols to be used within the network to characterize the sites. We have followed the general elements that were originally outlined in the proposal.

Carbon stocks: Aboveground biomass, surface detrital carbon, mineral soil carbon

Vegetation: Site history, species composition, canopy height, rooting depth

Soil: Classification, texture, bulk density, coarse fragment fraction, water retention characteristics, pH, Cation Exchange Capacity, nitrogen, phosphorus, potassium, percent base saturation, mineralizable nitrogen

Note: Root biomass is included here as a basic rough baseline, but detailed protocols are given in a separate document as part of the fine root protocols linked to the minirhizotron measurement program

The basic methodology follows the National Forest Inventory (NFI) protocols (see companion document). Minor modifications to these protocols are expected and will be updated when appropriate.

## 2. Final temporal and spatial scale that the measurements should be rolled up to

Temporal scale: annual mean

Spatial scale: Representative of the footprint sampled by the flux towers.

## 3. Spatial characteristics

### 3.1 How many samples are needed?

Sufficient numbers of measurement plots need to be installed to cover the range in ecosystem types (site association) within the stand (or tower site) being measured. The distribution and area of ecotypes within each stand needs to be known and used to stratify the stand to locate measurement plots. Ecotypes (site associations) have been defined for each province and territory (Ponomarenko and Alvo 2001) and represent the lowest order in the ecosystem classification used in the province.

At least 3 measurement plots should be installed per ecotype found within the stand.

### 3.2 How should they be chosen?

Plots should be representative of the flux footprint. The distance from the flux tower depends on the tower height. For most Fluxnet-Canada sites, plots should be at distances upwind (based on wind direction information) of between 100 and 1000 m from the tower. They need to be distributed by ecotype.

### **3.3 How will the scaling up to the stand be performed (if pertinent)?**

For uniform sites, the plot information can be averaged to get the overall site characteristics. For non-uniform sites, a flux footprint climatology needs to be overlain on a spatial map of stand characteristics to determine the percentage contribution for each vegetation community. If high-resolution air photo or multispectral images are available (10-100cm/pixel) the measurement of individual tree crowns of overstory trees in the stand can be used to determine actual stand densities within each ecotype rather than the estimates from the measurement plots (Gougeon 2000).

## **4. Temporal characteristics**

### **4.1 Within day: When and how many times?**

Not applicable.

### **4.2 Within year: When and how many times?**

Sampling needs to be done once, typically done in the late summer or early fall at the end of the growing season when tree height and diameter growth has ended.

### **4.3 How will the scaling to the year be performed (if pertinent)?**

Sampling will reflect maximum carbon stocks for the year.

## **5. Measurements**

### **5.1 Instruments and set up required/suggested**

See the ground plot methods in National Forest Inventory Ground Sampling Guidelines.

Standard instruments and tools used for forest cruise and soil survey. Each measurement plot consists of one NFI ground plot. If larger permanent plots are installed (eg. 60m x 60m or 1ha) within a site for measurements of other attributes and component fluxes (eg. microclimate, soil moisture, soil respiration, litterfall,) consider installing 3-4 replicate NFI measurement plots to adequately sample variation within the larger permanent sample plot (e.g., USDA Forest and Inventory Analysis Program 2002)

### **5.2 Specific methodologies to perform the measurement**

See the ground plot methods in National Forest Inventory Ground Sampling Guidelines.

Fixed area circular plots are used to measure and tag large overstory (11 m radius) and small understory trees (4 m radius). Line transects (2 – 30 m long) are used to measure woody debris, surface substrate cover and thickness, and understory cover. Clip plots (4 – 1 m<sup>2</sup>) are used to measure understory biomass, fine woody debris (5mm-10mm), forest floor mass (bulk density and take samples for %C). A soil pit is used to measure mineral soil bulk density by horizon, take samples for %C and nutrients and determine coarse fragment content.

Root biomass methods are not given in the NFI protocol. Fine root methodologies are described in a separate document that links to soil minirhizotron protocols. Given the ephemeral nature of fine roots, a single sampling of roots only provides approximate information. However, it can provide some key data to be used to compare sites. Within each tree plot, we suggest taking four samples to determine root profiles down to a depth of 50 cm if possible. These can be collected using a corer (typically diameter of about 5 cm), or by excavating in the side of a soil pit. The volume of sample needs to be determined as well as the soil weight to give mass of roots per volume and weight of soil. The samples should be taken at 5 cm vertical increments, washed, and

roots separated and weighed. Fine roots (< 2mm diameter) and coarser roots (>2 cm diameter) should be determined.

### **5.3 Potential problems/pitfalls to avoid**

The NFI protocols describe the basic methodology and were developed as an inventory standard. There is some flexibility in altering methods. For example, rectangular plots can be used instead of circular ones, coarse woody debris can be measured using a triangular set of lines, and plot sizes can be adjusted to reflect the density of vegetation.

The ability to detect changes over periods of one to five years will depend on the quantity to be measured and the site. It is unlikely that most site characterization parameters can be measured to a sufficient degree of precision to confidently pick up changes over periods of less than five years. Even periods longer than five years may not be sufficient to verify changes. There will be many exceptions, especially for rapid differential changes in components such as above-ground biomass at young sites, or if the forest changes because of some catastrophic event (e.g., windthrow). The initial baseline level of site characterization may need to have more detail if change detection is a goal. We highly recommend that this be considered on a site basis and base the decision on the variability of a parameter in space and time compared to the magnitude of change expected.

The small plots where destructive samples (ground vegetation clip plots) were taken should be permanently marked to ensure that subsequent destructive samples are not taken at the same location.

We highly recommend tagging all trees with numbers within a plot. This allows incremental changes to be compared on the same tree if they are re-sampled in the future.

The standard NFI ground plot only calls for one soil pit. If the plot has quite variable soils (vary in depth, rock outcrops, pit/mounds etc.) consider doing more than one pit.

Fine roots are not separated in the NFI procedure but included with the forest floor or mineral soil sample. Coarse roots are only estimated by regression from the overstory mensuration data.

## **6. Post measurement processing**

### **6.1 Sample processing in the lab**

See the ground plot methods in National Forest Inventory Ground Sampling Guidelines. Understory, detritus, and soil samples need to be returned to the lab for determination of oven dry mass and %C. Forest floor detritus will need to be sieved of small (>5mm) roots. Soil will need to be sieved of small roots and >2mm coarse fragments. Subsamples are then dried to determine moisture content, %C and other nutrients if required. The dry biomass clip plots are typically based on dry weight measured after oven drying samples at 80°C for 24 hours.

### **6.2 Data processing**

See the ground plot methods in National Forest Inventory Ground Sampling Guidelines.

To determine the biomass and C/ha in the overstory trees requires biomass regression curves. Biomass regression curves have been derived for most tree species for most of Canada's forest

regions (Penner et al. 1997) and will allow for the calculation of bole, branch, leaf and for some species coarse root biomass. Methods for developing site-specific biomass regression curves are available (Aldred and Alemdag 1988, Gower et al. 1997). The NFI project at CFS, Pacific Forestry Centre, can aid in the selection of the appropriate conversion routines.

To determine the understory biomass and C/ha requires data on oven dry biomass/m<sup>2</sup> from clip plots and % understory cover within the measurement plot.

To determine forest floor detrital C/ha requires data on forest floor bulk density (by depth if greater than 10 cm), mean thickness, and % forest floor cover within the measurement plot. Fine roots (<5mm) were not sieved out and are included in the total.

To determine mineral soil C/ha (to at least 60cm) requires data on bulk density of <2mm soil by horizon (sampled by depth or pedogenic layer), horizon thickness, and soil depth if less than 60 cm. Fine roots (<5mm) were not sieved out and are included in the total.

To determine woody debris C/ha requires volume of woody debris/ha by size, species, and decay class; wood density for the different classes of material; %C of the different decay classes (%C rises with decay class).

Determination of fine (<5mm) and small (5mm – 25mm) roots requires a separate sampling and measurement protocol. Biomass regression equations are available for some overstory species to estimate coarse root biomass. Otherwise a separate protocol is required to actually measure or determine coarse root biomass.

### **6.3 What should the final dataset contain?**

See the NFI protocol “ground plot attribute” data table. The Fluxnet plots are not intended to be an official part of the NFI system. However, there is an opportunity to have the data housed there, in addition to being housed within the network. A mechanism to allow housing of the data at both locations is being developed, and the appropriate database method is being investigated.

### **7. What other supporting measurements are required?**

Air photography, forest cover, silviculture history, site association, soil survey, and terrain maps and GIS files. All will be useful in helping determine the distribution of ecotypes (site associations) within the stand (tower site). If unavailable or limited then transects will need to be run through the stand to map the areal extent of the ecotypes within the stand.

### **8. Contact for further information**

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