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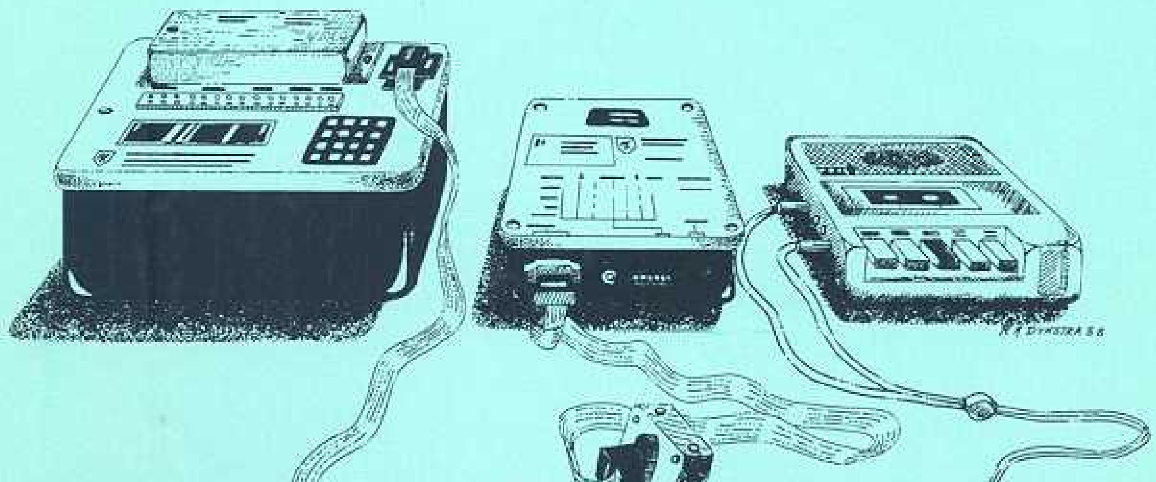
Using datalogger systems for environmental monitoring in forest research: an overview and case study

D.G. Brand, M.D. Flannigan, and P.S. Janas

Information Report PI-X-81
Petawawa National Forestry Institute



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Cover: Illustration details a datalogger (CR21X, Campbell Scientific) attached to both solid state and cassette storage devices. This configuration maximizes data recovery when there are occasional temperature extremes in the operating environment.

USING DATALOGGER SYSTEMS FOR ENVIRONMENTAL MONITORING IN FOREST RESEARCH: AN OVERVIEW AND CASE STUDY

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ABSTRACT

This is an introduction for forest researchers to the monitoring of environmental conditions with automatic data loggers. The report discusses various aspects of the experimental design (definition of what, where, how, and when to measure), the technological design, and the management of environmental monitoring research programs. A case study of a large field installation with continuous monitoring of 92 sensors is used to demonstrate the design, operation, and management of data from a research project. Automatic data collection with environmental sensors increases the ability of forest researchers to quantify conditions and explain secondary influences on results. Care must be taken, however, in proper selection of variables to measure; choice of hardware, sensors, and peripherals; correct installation and system protection; and effective data management.

RÉSUMÉ

Il s'agit d'un guide d'initiation au processus de surveillance des conditions environnementales à l'aide d'enregistreurs de données automatiques qui s'adresse aux chercheurs forestiers. Le rapport aborde différents aspects de la conception à titre expérimental (quoi, où, comment et quand mesurer), l'étude technique et l'administration de programmes de recherche en évaluation environnementale. L'étude individuelle d'une grande installation comportant la surveillance constante de 92 détecteurs est utilisée pour démontrer les méthodes de conception, d'exploitation et de gestion des données dans le cadre d'un projet de recherche. La collecte automatique de données à l'aide de détecteurs environnementaux accroît la capacité des chercheurs forestiers de quantifier les conditions et d'expliquer les facteurs secondaires qui influent sur les résultats. Il faut prendre soin cependant de bien choisir les variables à mesurer : choix du matériel, des détecteurs et des périphériques; installation et système de protection appropriés; et bonne gestion des données.

USING DATALOGGER SYSTEMS FOR ENVIRONMENTAL MONITORING IN FOREST RESEARCH: AN OVERVIEW AND CASE STUDY

I. Introduction

Advances in microchip electronics and computer circuitry in the past decade have led to the popularization of portable, low cost, data recording instruments. Two distinct types of these instruments have emerged, both with an ability to store and transfer large quantities of data to personal computers without additional keypunching or proofing. The first type, consisting of the so-called "electronic notebooks", are primarily designed to replace pencils and field tally or data entry sheets. Examples include the Husky Hunter, Omnidata Polycorder, Dap Microflex, and Digitech Memo. The other class comprises those instruments known as "dataloggers"[1], such as the Campbell Scientific Micrologger, Handar multiple access data acquisition system, Omnidata Easy Logger, and Wescor Delta Logger. Unlike the "electronic notebooks", these record data from external sensors and normally have no provision for direct entry by the user. Dataloggers are versatile and are used in a number of different fields, such as industry, security systems, and automotive diagnosis, as well as environmental or meteorological data monitoring. This report will pertain to environmental monitoring using dataloggers.

The use of automatic dataloggers to monitor environmental conditions in forest research has become increasingly common throughout the world. Dataloggers have the ability to continuously monitor a variety of microclimatic sensors in remote locations and, properly configured, generally require minimal upkeep and maintenance. Unfortunately, prospective users are frequently unfamiliar with the requirements and capabilities of such systems and, with an increasing number of data loggers available, may find it difficult to decide on an appropriate model. Even with a manufacturer in mind, the user must devote some time to ensuring that a system (including the required sensors) is adequate for the specified use, while at the same time retaining cost-effectiveness.

The present report is written for forest researchers who are just beginning or are considering the use of dataloggers in their research. We discuss the biological considerations in the design of an environmental monitoring program, the hardware and software features of dataloggers, and popular types of meteorological sensors. Rather than presenting an exhaustive description of sensors and of environmental monitoring, which has been the subject of several texts, we will concentrate on forestry applications and present a case study of an experiment that uses several types of sensors. Our hope is that, despite an ever-increasing variety of dataloggers and sensors, this report will enable a researcher to design a monitoring program with technology that suits experimental objectives.

II. Designing an environmental monitoring program

While there is technology available to provide the researcher with an ability to monitor environmental conditions and automatically store data, the data collected must be of a kind, accuracy, precision, and measurement frequency to satisfy objectives of the study. These concerns are of particular importance to the forest researcher, who, although not an expert in micrometeorology, requires environmental information to complement growth or physiological studies. Moreover, in these studies a range of environmental variables is often desired, leading to questions of what should be measured, where, and when. In the following section we will attempt to identify some considerations involved in answering these questions.

Klebs (1913) first proposed a relationship between genetics, environment, plant physiology, and growth. In effect his concept states that the genetic makeup of a plant, influenced by en-

[1] In this paper the term datalogger will also include equipment commonly referred to as Data Collection Platforms (DCP). A DCP is a type of datalogger that communicates via satellite.

vironment, controls physiological processes that, in turn, determine growth. The concept of environmental influence was further discussed by Mason and Langenheim (1957) and elaborated by Spomer (1973). They considered that plants contact the environment through the transfer of energy and materials (water, nutrients, photosynthetically active radiation, etc.). These transfers are controlled by environmental conditions (soil moisture tension, soil temperature, photon flux density, etc.). In the study of plant environment, we are interested in the conditions that influence transfer of these resources, because they determine environmental stress (sensu Levitt 1972).

Researchers who wish to quantify the differences between sites, or the results of some silvicultural treatment, must consider what environmental conditions are of importance. In most cases environmental conditions are not independent and, therefore, a single treatment can affect many variables. For example, scarification can effect soil temperature, soil moisture tension and, through reduction in competition, light intensity. Environmental monitoring records environmental conditions, aiding interpretation of why a certain treatment is more or less effective on a given site type or why a treatment that improves one condition fails to improve growth. The concepts of environmental stress and tree growth response are interlinked. The environment influences the tree, but it is the tree response that defines the stressfulness of environmental conditions.

The selection of which environmental conditions to monitor is determined partly by previous knowledge of the system, partly by the nature of the hypotheses being tested, and partly by cost. In general, the environmental resources of importance are energy, moisture, and nutrients. Other resources such as CO_2 are generally not sufficiently important to forest growth to warrant monitoring. The availability of energy to plants is a function of photosynthetic photon flux density and soil and air temperature. Water stress is a function both of the availability of water to the plant (e.g. soil moisture tension) and atmospheric demand (e.g. relative humidity or vapor pressure deficit). Nutrition, less easily measured directly, can be thought of as a flux density of nutrients to the plant root (Ingestad et al. 1981).

Environmental conditions directly affecting the plant are often determined by site features. For example, soil moisture tension will be a function of slope position, aspect, parent material, and rainfall. Soil temperature will be a function of heat capacity, heat conductivity, and incident radiation. Nutrient availability will be determined by available pool sizes, pH, and biological activity. Some of these variables can be quantified by assays, others by sensors.

After deciding on a group of environmental conditions to measure, the researcher must determine how to measure the variables, where to measure them, and at what frequency. Many variables need to be measured only once if they are static quantities such as texture, parent material, or aspect. Most environmental conditions, however, are dynamic and a variety of sensor types have been developed to monitor change. In general, as plants exploit a space that often has variable environmental conditions, it is important to decide where a measurement should be taken. In designed experiments or systematic monitoring of different sites, the researcher must determine both the variation within a site or treatment, and the variations among treatments and sites.

In irregular terrain spring soil temperature can be strongly related to microsite. Light interception by competing vegetation can also vary dramatically over short distances. To cope with environmental variability within sites, sensors can be replicated or regression analyses performed against more easily measured variables. For example, light intensity around sample trees can be estimated on the basis of a light probe-calibrated competition index (Brand and Janas 1988). It is important that all treatments or sites be monitored to the same degree, or else comparisons may prove invalid.

Some environmental variables can be monitored according to existing standards and practices. If standard information such as air temperature, dewpoint temperature or relative humidity, and wind speed and direction is required, the measurement protocol for these variables is outlined by the World Meteorological

Organization (1983). If the measurements are meant to calibrate a model, the sensor locations may be specified (e.g. soil temperature at specific depths) but, more commonly, the need is to characterize an average condition or define a range of conditions.

Some general rules of thumb can be used when no appropriate standards and practices exist. Radiation measurements are best made concurrently above and below plant canopies to define light interception. Soil temperature and soil moisture tension measurements should be made at representative locations (avoiding depressions or humps) at either a single mineral soil depth, such as the middle of the root zone, or at a range of depths representing the entire root zone. Soil moisture tension, in particular, will give different pictures at different depths, as drying tends to follow a 'front' down through the soil profile. Thus, a sensor at a 5 cm depth could read –3.0 MPa, while one at 30 cm reads –0.05 MPa.

The frequency of monitoring a given condition should be a function of its temporal variability. For example, soil temperature at depth and soil moisture tension change very slowly over a period of days, whereas light intensity, relative humidity, and soil surface conditions follow strong diurnal trends, and wind speed and direction changes constantly. Low frequency monitoring can be misleading because most sensors do not respond instantaneously to environmental change. Rather, the sensors show a time constant (response speed) (Fritschen and Gay 1979). This time constant for any sensor can generally be found in the specifications. Tanner (1963) suggests a measurement frequency of twice per time constant but, for many sensors with very short time constants (i.e. quantum sensors), this can exceed the datalogger capability. In general, with automatic dataloggers it is easy to collect frequent measurements and then average, rather than measure infrequently and lose information.

Finally, there is the question of how accurate (close to true value) and precise (variability around mean) measurements should be. In this regard consideration should be given to the impact of error on the interpretation of data. For example, measurement of soil moisture tension for forest research tends to be more critical at higher levels of water availability, where a 0.05 MPa error can have significant impact. However, at higher tensions accuracy is less important; the interpretation of a value of –2.0 MPa is not much different from –2.1 MPa (the soil is dry and root growth cannot occur). More important and controllable is the error introduced by inadequate or sloppy monitoring methods (e.g. temperature fluctuation at thermocouple junction points, disturbing the soil around sensors, or inadequate shielding for air temperature or humidity sensors). Most sensors themselves come with reasonably detailed description of their limitations, and the usual tradeoff is between accuracy and price.

III. Selecting a Datalogger

A. General

Prior to selecting a datalogger, be thoroughly familiar with the requirements of their data monitoring systems. Major categories of items and restrictions to consider include:

1) quantity and type of data required and the desired precision and accuracy;

2) number and types of sensors needed to collect above data and their approximate relative locations within the research site;

3) field location for data collection;

4) required frequency of data collection;

5) available computing facilities;

6) cost constraints.

When reviewing data requirements, the user should first focus attention on the expected range of particular data values over the time period of operation. In some cases, more than one type of sensor will be required to accurately record readings over a given range. For example, very wet soils are best measured with tensiometers for soil water potential, whereas soil psychrometers or resistance blocks are preferred for dry soils.

Information on the number and type of sensors to be used is required to determine the number of input (analogue) and output (excitation) channels required on a datalogger. Some dataloggers have channel expansion boards or multiplexers which effectively expand the number of channels available for data input. Expansion boards also reduce the cost and lead length of cabling to sensors. In some cases, they also reduce the individual sensor costs if they include electrical components that can replace those found in individual sensors (e.g. certain soil gypsum blocks). However, even with a sufficient number of channels, the system may only accommodate a limited number of sensors. The relative locations of sensors should be known to determine how many expansion boards are required and whether the datalogger program can handle such a sequence of measurements.

Most datalogger manufacturers supply a variety of sensors for use with their recorders. It may be advisable to consult with the manufacturer to determine compatibility of non-approved sensors.

If only a single type of sensor is needed, specialty dataloggers may be available to handle the measurements. Usually, such dataloggers are manufactured by the same company producing the sensors. An example is the Delta Logger (Wescor Inc.) which records, stores, and downloads physiological measurements from a compatible tensiometer. The advantages of using these dataloggers are that they are designed to work with specialized sensors and should have the necessary software and hardware to yield reliable and accurate data. Specialty dataloggers tend to have simpler installation and programming requirements, and lower cost than multipurpose dataloggers.

Datalogger packages are available from many manufacturers. These packages can have any number of sensors and have been assembled to meet the needs of a large group of users or of users with a requirement for a large number of dataloggers. Most of these packages have been designed for operational monitoring programs but can be used for research.

The possible sampling frequency varies with each datalogger and is limited by the number of sensors being monitored. If a large number of instruments are included in the system, the time required for scanning all sensors may not achieve the desired sampling frequency, resulting in missed measurements. The user should decide on an appropriate sampling frequency based on factors such as the anticipated variability of sensor readings, the number of instrument replicates for a given experimental treatment, and the precision desired for experimental values.

The diurnal range in expected data values should assist the user in determining how frequently data should be scanned by each sensor (i.e. the sampling frequency) and whether this data should be averaged over a given time period. For instance, a relatively stable condition such as soil temperature at a depth of several decimetres may require only one reading per day, without additional averaging. A variable such as wind speed, however, changes constantly and the user may select a sampling frequency of once every 10 sec, with the resulting data averaged over 15 min. Note that frequent sampling can cause rapid battery drain.

The sampling frequency and averaging intervals are needed to determine how many data values will be stored in the datalogger's initial memory and final memory, respectively. This, in turn, will determine the memory requirements for the datalogger. The amount of memory available depends on the number of bytes allocated to each data point, in addition to the number of data values. The number of bytes per data point may depend on the logger used, and also on data resolution (number of digits recorded). High resolution data may be needed if the experiment calls for a high degree of precision, such as when only a small change in measurement has a significant effect on the variable of interest or the variable being measured changes very slightly over time. The manufacturer should provide the number of bytes per data point so that a user is able to calculate how much data can be stored in the memory.

B. Selected hardware characteristics

The following hardware features of dataloggers should be considered when making a selection. Most manufacturers provide datalogger specifications on hardware characteristics similar to those discussed below.

B.1 Analogue input channels

The number of channels available for sensor hookup is an important consideration for experiments involving a large number of sensors. If an insufficient number of channels are available, the user should determine whether channel expansion is possible (see Section III A). It is also possible to use several dataloggers for a given experiment, but this increases the work of programming, data retrieval, and troubleshooting, and also the probability of one unit failing.

The channels available should permit both single-ended (readings are referenced to ground or a standard voltage) and differential (readings are based on the difference in voltage between two inputs) measurements. Single-ended measurements enable the use of up to twice the number of sensors as differential measurements. The sensor supplier can usually advise which of the two measurement types is most appropriate for a given application.

If rapid data scanning is required for many sensors, it is advisable to consult datalogger specifications on the number of channels that can be scanned per unit time. Unless it is absolutely essential, very frequent scanning intervals (e.g. less than 1 min) are not recommended, because these necessitate more frequent battery servicing (unless a higher amperage source in installed) and, in the case of switching relays etc., more stress on certain electromechanical components.

B.2 Digital count inputs

These channels can perform several functions that are required for environmental measurements. In one mode, they enable counting of inputs for a specified number of pulses, such as for tipping bucket rain gauges. In another mode, they may also measure frequencies, such as those generated by anemometers.

B.3 Digital or analogue voltage outputs

These usually act as excitation channels by providing a sensor with a given voltage prior to taking a reading. Voltages should be user-adjustable and should include both DC and AC excitation. (AC is required for resistance measurements in certain soil moisture potential sensors such as gypsum blocks, some relative humidity or dewpoint probes, and leaf wetness sensing grids). Voltage outputs can be used to control external devices or activate switching relays, like those found on channel expansion boards. Finally, they can also serve as alarms to signal sensor malfunctions.

B.4 Time recording

For most research applications it is essential to have a datalogger with accurate internal time based on the 24 h clock, day, month (optional), and year. Some events require recording time in terms of seconds or even fractions of a second. This information should be recorded at the start of each data sequence. A clock or other timing mechanism is also required to operate time-dependent external switching or relay devices. On some equipment, resetting the time may also require that the sensor programming be re-entered, which can be very time consuming. The accuracy of the clock cited in the manufacturer's specifications should be compared with what is required for the investigation.

B.5 Protection

It is recommended that the datalogger selected have all input and output connections protected by spark gaps or zeners. These help lessen the possibility of damage to datalogger internal components from voltage surges generated by nearby lightning strikes. The grounding plate connected to spark gaps should have provision for connection to heavy gauge copper wire that will be routed to a grounding rod, preferably in wet soil. Some manufacturers also recommend and supply compatible spark gap-protected junction boxes for dataloggers. These are claimed to provide additional protection from lightning. They also simplify the task of removing the datalogger from the site, as common wires leading from sensors (e.g. ground connections) can be connected to terminal strips on the junction box, thereby reducing the number of wires directly connected to the datalogger.

If the datalogger is to be stored in an exposed location, knowledge of the environmental durability, especially moisture resistance, of the unit is essential. Peripherals such as data storage units, tape recorders, and channel expansion boards need similar care. All exposed switches or keypads should have weatherproof coverings. In the case of the microprocessor in dataloggers, there should be provision for keeping this component free from condensation by including a suitable desiccant such as silica gel. Additional protection in the form of waterproof containment units, preferably made of plastic, is also recommended for outside locations. The user may consider additional protection, such as sealing off openings for wire leads with waterproof caulking or constructing water resistant external shells around the equipment.

Although most manufacturers do not make their dataloggers and accessories resistant to damage from vandals or animals, the user should look for any features on sensors and equipment housings that may reduce damage from these causes. The list may include locking mechanisms or provision for reinforced holes for padlocks, flat, dark paint finishes such as green or light brown that can camouflage, noise-reduced/free relay mechanisms, distasteful materials. The researcher may also want to locate the datalogger and sensors in an area with a low threat from vandals. All wires leading to sensors should be buried if possible. Take care, however, to note the locations of these trenches, as future activities in the area, such as planting or removing sample vegetation, may cause damage to wiring that can be difficult and expensive to locate.

B.6 Operating characteristics and conditions

Users should review the manufacturer's specifications for accuracy at a given level of sensitivity and temporal stability under the anticipated operating conditions. The manufacturer should also specify the temperature and relative humidity operating range for the component concerned. It is worthwhile, when dealing with new or less common sensors, to determine what type of environmental durability testing program has been conducted by the factory. Although most factories test for operation under temperature extremes, several do not carry out tests under varying levels of relative humidity.

B.7 Power supply

One should consider the power requirements of the system. In field locations where AC current is available, an AC/DC transformer may be available to operate a datalogger. Also, a backup set of batteries should be available to run the system in the event of a power failure. In remote field locations with no AC power supply, the datalogger system should have a low power circuitry, enabling operation on dry or wet cell batteries. The approximate amount of power drain, based on the number and type of sensors and the execution interval, can usually be estimated from the datalogger manufacturer's specifications. This will allow the user to determine the battery storage capacity requirement in amp hours. The user should monitor battery voltage as registered by the datalogger, if it has this function, and be aware that voltage drops rapidly near the end of battery life. Battery storage capacity (amperage) can be increased by wiring an external set of batteries in parallel, each with the correct voltage to power the datalogger. These batteries must not be connected in series as this may increase battery voltage to a level damaging to a datalogger. Another potential power source for some dataloggers is the use of rechargable batteries in combination with solar collectors.

B.8 Communication/Data Storage

A large memory capacity will be especially important for dataloggers in remote locations, where regular visits, telephone line modem hookup, or transmission of data through UHF/VHF radio or satellite transmissions are not feasible. Backup may be provided by using an external solid state data storage unit with erasable programmable read only memory (EPROM), or a cassette recorder, if operation of a recorder is feasible (air temperature above $-10^{\circ}C$). These devices are recommended for all datalogger applications, as they permit expanded data storage capabilities while on site, and a means of backup in the event of memory failure as a result of low batteries, lightning strikes, etc.

Data captured by dataloggers are usually transferred to a computer for additional manipulation and the production of graphic or tabular summaries. On some systems, the data can be transferred directly from the datalogger to a printer, and this data is summarized in the required format, with appropriate headings, etc. In most cases, however, data will be sent from the datalogger, data storage module, or cassette tape, to a micro, mini, or mainframe computer. The required software and hardware for such applications must be available, and should be compatible with the computer system. Most dataloggers have provision for data transfer to IBM-PC and compatible microcomputers. For these and other applications, such as printers and telephone modems, the datalogger should also have RS232C communications ability with a variety of baud[1] rate selections possible (e.g. 300 to 9600). The user should ensure that the selected datalogger is capable of retrieving stored data without interrupting data collection.

C. Data display and programming features

An easily accessible and clearly visible liquid crystal display (LCD) is essential for data. The datalogger should be able to show details such as current and stored data values arranged by day and time, battery condition (voltage) and, if possible, values over a selected period which contain erroneous or out-of-range data. This allows you to verify that the data is correct and is being stored appropriately. It is important that display of any of the above verifiers be possible simultaneous with data collection.

The datalogger usually has two programming modes for input and output processing. The input mode defines how each input channel is read and converted to standard engineering units. In cases where sensors are supplied by the datalogger manufacturers, equations to convert sensor outputs to these units will be provided. Before purchasing non-standard equipment the user should investigate whether such conversions are available. It is desirable to know confidence intervals for such equations; these should be supplied in the instruction manual for a given sensor. Sensors may also have been individually calibrated. Again, the user should be able to enter the calibration for each sensor into the program.

The datalogger's output program should have the ability to compress or summarize data collected over an user-defined interval. Many dataloggers are able to provide averages, maxima, or minima for each sensor over a user-programmable, time-dependant interval, and these data are stored in the "final" memory. Such dataloggers have a separate memory allocated for the data scanned initially and the "final" memory in which averaged (or otherwise manipulated) data is stored. In such cases, an useful feature is the ability to change the amount of memory allocated between these two functions. This enables an increase in final memory if only a small number of sensors are sampled, or an increase in the initial memory to accommodate a large number of sensors.

Although not essential, it is desirable for the datalogger to have the ability to flag or mark sensor readings beyond a user-defined range of acceptable values. This feature can be used to determine, for instance, if sensor equipment is malfunctioning, or if environmental extremes which have major consequences on the experimental results have occurred (i.e. frost, heavy rainfall, or high wind speed).

IV. Popular types of meteorological instrumentation available for dataloggers

A. Solar Radiation Sensors

A.1 Pyranometer and Net Radiometer

The pyranometer (Fig. 1) measures total shortwave radiation from the sun (direct) and sky (diffuse). The receiver, which is exposed continuously to the vagaries of weather, is enclosed in a glass or quartz case that must be kept clean and dry. The glass or quartz casing not only protects the receiver from the elements, but also transmits selected wavelengths (between 0.35 and 2.8 μm for glass and between 0.25 and 4.0 μm for quartz). The receiver surface has two or more elements. One half of each element is black to absorb incident radiation, while the

[1]The baud rate is the rate at which information is transmitted and received by electronic equipment. Units are in bytes per second.

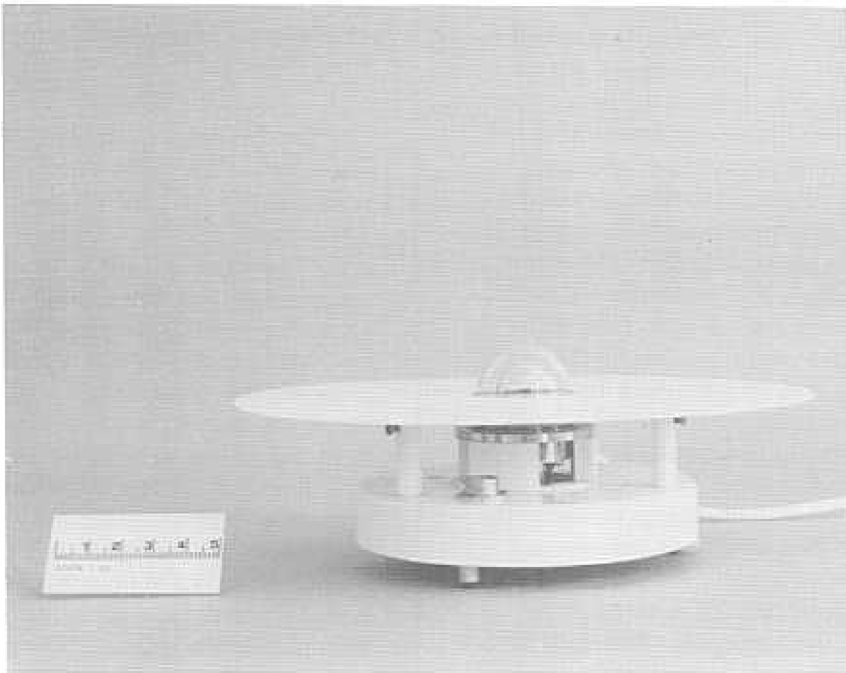

Figure 1. Pyranometer.

remainder is white with a high reflectivity in the shortwave spectrum. The temperature difference between the black and white elements is dependent on the incident solar radiation. The pyranometer can also be employed to measure direct or diffuse components of solar radiation and surface albedo (reflectivity).

The net radiometer has been designed to measure net all-wave (short and long) radiation (incoming – outgoing). The net radiometer is positioned a short distance above ground and has two identical blackened sensing elements; one facing downward and the other upward. The net radiation is proportional to the temperature difference between the two elements. The sensor is usually enclosed in a sphere of polyethylene to protect it from the environment. Polyethylene or a similar plastic is used because of its transparency to both long and short wavelengths.

The standard unit of radiation measurement is the megajoule per square metre (MJ m^{-2}) or watts per square metre (W m^{-2}). The sampling interval for the pyranometer and net radiometer should be kept relatively short (e.g. 5 min) but this is dependant on the nature of the investigation.

Additional information on pyranometers and net radiometers can be found in Lee (1978), Monteith (1972), Sellers (1965), and Unwin (1980).

A.2 Quantum Sensors

Quantum sensors (Fig. 2) are commonly used in photosynthesis studies which require measurement of solar radiation in the 400 to 700 nm waveband (Federer and Tanner 1966). The standard measurement unit is referred to as the quantum flux density and is expressed as $\mu Em^{-2} sec^{-1}$ with $1\mu E = 6.02 \times 10^{17}$ photons. A reading of about 2000 $\mu Em^{-2} sec^{-1}$ may be recorded in full sunlight (Anon. 1985).

These sensors require initial and periodic calibrations (every two years is recommended by a major quantum sensor maker) using a standard light source to convert the sensor output voltage to the quantum flux density. For ac-

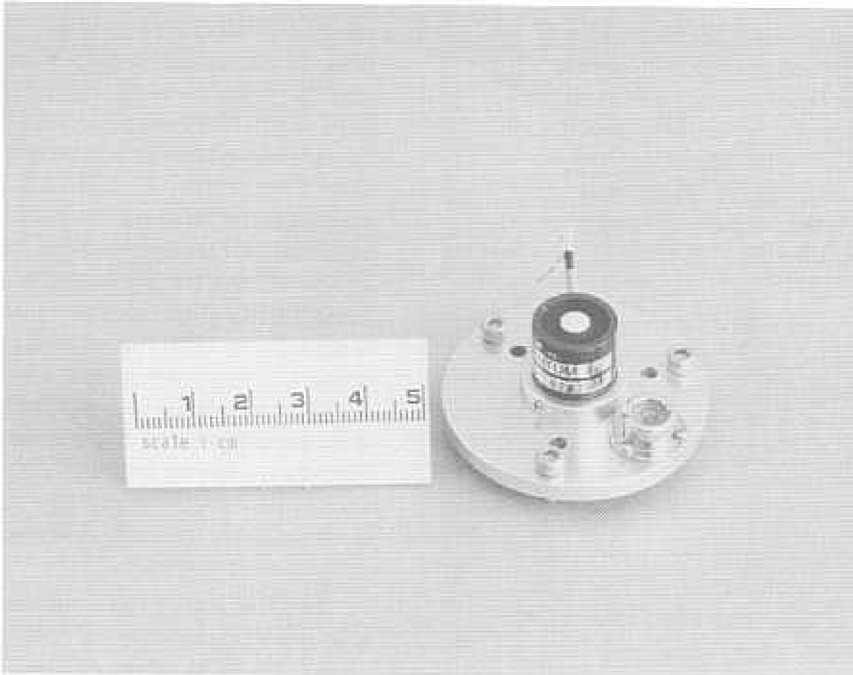

Figure 2. Quantum sensor.

curate readings, it is important that the detector housing be kept free of dirt and that the mounting fixture be correctly levelled.

The amount of light received during a particular period can vary significantly because of cloud cover or amount of canopy shade (movement from wind, etc.). Thus, the sampling interval should be kept relatively short (e.g. 1 to 5 min) compared to other less variable conditions, such as soil temperature and moisture.

B. Temperature Sensors

There are three common types of sensors used to measure air or soil temperature that can be attached to dataloggers. Two sensors, the resistance thermometer and the thermocouple, depend on electrical properties of metals to measure temperature, while the third sensor, the thermistor, depends on the electrical properties metallic oxides.

The resistance thermometer is based on the principle that a metal's resistance to the flow of electricity increases with temperature. If the resistance characteristics of a metal are known, a temperature can be obtained by measuring the resistance to a small but known electrical current. Platinum is the element of choice for resistance thermometers because of its stability.

Thermocouples are constructed by joining two dissimilar metal wires at two junctions. A voltage is generated which is proportional to the temperature difference between the junctions. At one junction (reference) the temperature (voltage) is known; thus, the temperature at the other junction can be found from a measurement of voltage and an understanding of the electrical properties of the two metals. One common thermocouple is made of copper and constantan (Cu-Cn) which develops about 0.04 millivolts/°C. Several thermocouples may be connected together in series. Such an arrangement is called a thermopile and is used as a means of increasing sensitivity.

Thermistors use the principle that resistance to the flow of electricity is temperature dependant. For true metals, resistance increases with increase in temperature but, depending on composition, the opposite can be true for thermistors. Thermistors, which are usually composed of metallic oxides, also exhibit a remarkable sensitivity to temperature change. The change of resistance with temperature is non-linear for a pure metallic oxide. By combining two or more oxides the output may be linearized over a given temperature range. For this reason the thermistor is the most frequently used temperature sensor in dataloggers.

During measurement of air temperature the sensor has to be shielded from the elements, with particular attention given to radiation. Depending on the type of sensor and the investigation, the temperature sensor may have to be ventilated.

Calibration of temperature sensors should be performed preferably before and after each experiment and at least annually. Calibration should be performed over the expected range of temperatures by comparing the sensor with one or more reference temperature sensors. If a temperature sensor is not recording the temperature accurately it should be discarded.

Additional information on temperature sensors can be found in ASTM (1981), Doebelin (1966), Schooley (1986), Wang and Felton (1983), and Fritschen and Gay (1979).

C. Relative humidity Sensors

Different moisture variables that can be measured or calculated include relative humidity, specific humidity, dew point temperature, mixing ratio, and vapour pressure. In this report we will only discuss the measurement of relative humidity with sensors commonly used with dataloggers. Two sensors meet the above requirements: the electrolyte impedance sensor and the capacitive polymer sensor.

The electrolyte impedance sensor operates on the principle that the impedance of the liquid electrolyte or processed plastic wafer changes with ambient relative humidity. The capacitive polymer sensor operates under the principle that the capacitance of the solid polymer changes with relative humidity.

Relative humidity sensors should be calibrated at least once a year. Calibration is performed using chemical salts or humidity chambers, or via comparison to reference instruments. Field checks should be performed by using a portable relative humidity sensor. A handheld psychrometer is ideal for field verification of the relative humidity. The psychrometer measures the wet and dry bulb[1] temperatures. The relative humidity is then calculated from the psychrometric equation. This field verification allows a check on the relative humidity and temperature. Both the impedance and capacitance sensors have a temperature monitor, as relative humidity is a strong function of temperature. The elements for both the impedance sensor and the capacitance sensor should be replaced according to the manufacturers manual (usually every year or two).

Readings from the electrolyte impedance sensor and capacitive polymer sensor are in the range of 0-100% relative humidity. The sampling frequency is a function of the experiment and can range from once a minute to once a day. The relative humidity sensors also need to be shielded from radiation and the weather. Muller and Beekman (1987) discuss the problem of hysteresis with some of the capacitive polymer sensors. Obtaining accurate relative humidities after one day of saturation can take up to a week for some sensors.

Additional information on humidity sensors can be found in the proceedings of the International Symposium on Moisture and Humidity (1985).

D. Soil moisture potential Sensors

Continuous monitoring of soil moisture conditions using dataloggers is only possible with sensors belonging to the soil water potential group. This section will briefly review the following instrumentation belonging to this category: electrical resistance sensors, tensiometers, and thermocouple psychrometers.

[1] The dry bulb temperature is the ambient temperature. The wet bulb temperature is the lowest temperature to which the air is cooled by evaporating water at a constant atmospheric pressure. The wet bulb temperature is obtained by covering the temperature sensor with a moist jacket of clean muslin and then ventilating it by means of a fan or sling.

Standard measurement units for water potential measurements are in Pascals (Pa) although bars are still commonly used (1 atmosphere of pressure ≈ 0.05 MPa = 1 bar). As soil moisture potential usually has only a small diurnal variation, there is normally no need to use a frequent sampling interval. For example, if results are to be analyzed on a daily or weekly basis (as opposed to hourly), a sampling interval of 30 min to an hour is more than sufficient. In some circumstances it may be advisable to conduct measurements even less frequently (as little as twice daily) in situations where soil temperatures fluctuate greatly, or when sensors are sensitive to temperature gradients.

D.1 Electrical Resistance Units

These soil moisture potential sensors operate on the basis of measuring the electrical resistance of wires embedded in a porous reference material, in the soil, subjected to an alternating current. Resistance of the blocks, then, is related to the water content in the sensor matrix, which is in equilibrium with the soil moisture potential. Popular materials for the reference matrix include fiberglass, nylon, and gypsum. In the case of fiberglass and nylon blocks, the ions conducting electricity are furnished by the soil solution and, hence, their operation is restricted to non-saline soils (Campbell 1987). Gypsum blocks, however, supply ions into solution and create a relatively stable conducting medium in a wide variety of soils.

All three types of sensors are individually calibrated by relating resistance to meter readings and resistance to soil moisture potential. Some gypsum block manufacturers supply formulae that apply to all blocks, eliminating individual calibration requirements. This may be satisfactory for many applications, but researchers requiring high degrees of accuracy may need to consult the manufacturer on a recommended procedure for individual block calibration.

Gypsum blocks are most accurate in moist soils of less than 1 bar tension. In dry, coarse-textured soils, these units can break away from the soil and produce extremely high and inaccurate readings. To reduce this problem and encourage better soil contact, it is recommended that a small amount of fine soil slurry such as wet clay be deposited around the block after it has been inserted in the soil. It has been claimed that in their usual measurement range (0.1 to 15 bars), gypsum blocks have an absolute measurement uncertainty of ± 10% (Carlson and Salem 1987). The advantages of these blocks, compared to non-resistance type sensors, include the ease with which a large number can be installed and monitored with remote dataloggers, low cost, and relative ease of calibration (this may not even be necessary for certain brands). Gypsum blocks are also better equipped to operate in saline soils as they have some buffering capacity. On the negative side, this ion transfer results in block degradation and blocks may have to be replaced as often as every year, especially in moist, fine-textured soils. Also, their range of operation is narrower than psychrometers, and their potential accuracy is poorer than both tensiometers and psychrometers.

Fiberglass blocks have a wide variety of pore sizes and thin moisture elements, so these units can respond to a range of soil moistures in a short period of time. Their main disadvantages are poor sensitivity in the drier moisture ranges and a lack of buffering capacity in saline soils, due to a lack of ionization material to buffer against soluble salts. Therefore, their use is usually restricted to very moist to moderately moist, non-saline soils. Also, because the material in these blocks may be less uniform than that in gypsum blocks, calibration of individual sensors is required.

In all types of electrical conductivity units, readings are subject to temperature errors because electrical resistance varies inversely with temperature. As a result, it is recommended that the sensors should not be placed at a depth shallower than 10 cm, to minimize the effect of soil temperature fluctuation and moisture gradients. Positioning at shallower depths may necessitate taking moisture readings when soil temperatures are relatively isothermal (i.e. late evening or early morning).

D.2 Tensiometers

Tensiometers operate on the principle of measuring the suction force needed to equilibrate liquid water across a porous membrane with the soil solution (Campbell 1987). This suction force is the soil matrix water potential. Tensiometers are most useful up to 0.85 bars tension. Thus, they are particularly well suited to experiments involving irrigation, or where soils remain relatively moist. In such conditions tensiometers perform quite accurately and, unlike some other types of sensors, are durable and fairly inexpensive. Also, the vacuum gauges of tensiometers retain their initial calibration for a long period. However, as the tensiometer is a water-filled device, it does require periodic servicing to replace water loss and it may be subject to freezing.

D.3 Thermocouple psychrometers

The thermocouple psychrometer is a widely used water potential sensor, particularly in the laboratory analysis of soils. It is accurate over a wide range of soil moisture tensions, up to 80 bars (Brown and Chambers 1987). Its operation is based on measurement of the water potential (humidity) of the vapour phase of a small sample of air, contained in a porous ceramic bulb placed in the soil. This humidity measurement is related to the soil water potential. To measure the humidity present, a current is run through a thermocouple against its normal potential, cooling the thermojunction below the dew point and causing the water in the air to condense. The current is then interrupted to allow the water to evaporate and warm the junction. The extent to which the junction warms is related to the humidity and to the soil water potential. Using current technology, a thermocouple psychrometer is capable of achieving a water potential measurement accuracy of 0.05 bars (Briscoe 1984). However, unlike tensiometers or resistance blocks, they are not reliable at low soil water potential values (very moist soils).

The requirement for a cooling current limits the number of dataloggers that can operate this instrument. In general, only the most expensive loggers have the capability to accurately generate very low voltages. The sensors themselves are also much more expensive than the electrical resistance units mentioned above. Another drawback is the comparative difficulty of calibrating these sensors by measuring samples of known water potential, especially for *in situ* measurements (Boyer 1987, Briscoe 1984).

Another factor limiting the psychrometer's use in the field for continuous data monitoring applications is its extreme sensitivity to temperature gradients, such as those found in the soil rooting zone (Campbell 1987, Briscoe 1984). Differences between the temperature of the soil and thermocouple junction greatly affect the accuracy of the measured soil water potential. Therefore, Brown and Chambers (1987) recommend that these psychrometers be installed no shallower than at a 15 to 30 cm depth (depending on soil texture; deeper installations are required in fine-textured soils) and in a horizontal rather than vertical position. They also suggest that 5 to 10 cm of lead wire be placed near the psychrometer sensing head to reduce the effects of heat conduction. It may also be wise to conduct sampling at times during the day when soil temperature gradients are minimized.

E. Rainfall sensors (Raingauge)

Rainfall is most commonly measured by using a tipping bucket mechanism to produce an electric pulse every time a predetermined amount of rainfall has been received (.25 mm or .01"). The raingauge (Fig. 3) is a cylinder with a funnel to direct rainfall into a divided bucket pivoted at the centre. Rain collects on one side of the bucket until, when this is full, the mechanism tilts, discharging the collected rain, and allowing the other side of the bucket to start filling. When the mechanism tilts, a magnet momentarily closes a reed switch and a pulse is emitted. A raingauge that weighs the incoming rainfall can also be used. The weight can be converted to rainfall amount through a simple equation.

Calibration of tipping bucket raingauges can be achieved by slowly pouring a volume of water equivalent to a specified number of tips of the bucket. A similar procedure can be used for the weighing raingauge. Typically, the factory calibration is good for a number of years unless there is an accumulation of material in the tipping bucket.

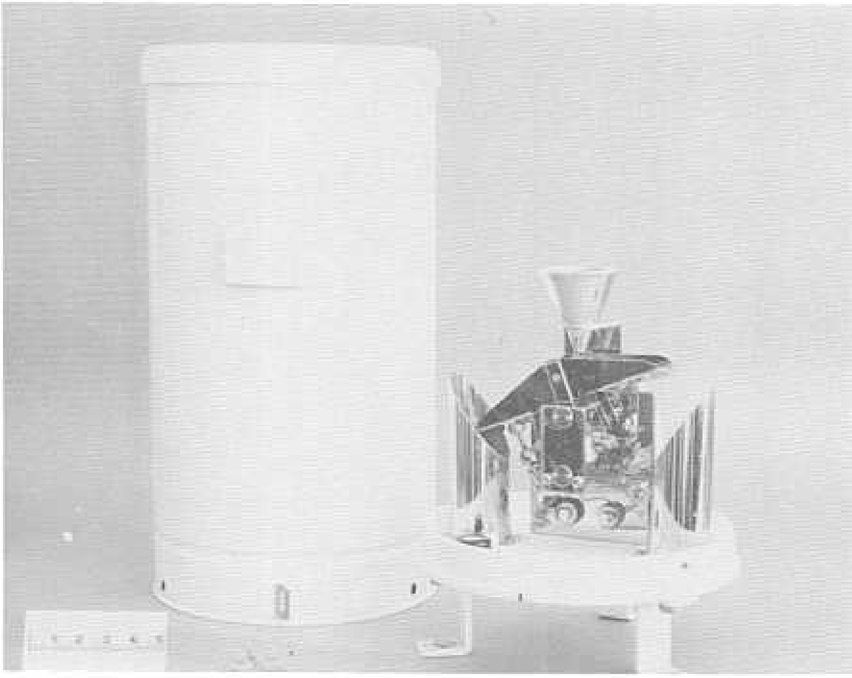

Figure 3. Tipping bucket raingauge.

F. Wind speed and direction sensors

Wind speed is measured by an anemometer and wind direction is measured by a vane. Usually only the horizontal wind speed is measured but anemometers are available to measure vertical velocity. The most common type of anemometer is the cup anemometer (Fig. 4). The cups, usually three, are free to rotate around a vertical axis. The rotation of the cups generates a voltage which can be used to obtain the wind speed. The anemometers are calibrated in the factory and each unit comes with a simple equation to convert voltage to wind speed. Another type of cup anemometer uses a chopper disc on the anemometer shaft which cuts a light beam a number of times per revolution. A pulse is generated every time the light beam is interrupted. The pulse frequency is proportional to the wind speed. The light chopper anemometer requires a significant power supply and is most suitable for areas with access to AC power. Where AC power is not available the rotation of the cups, and thus the wind speed, can be determined by using a magnetic reed switch instead of a light beam. Another type of anemometer uses propellers instead of cups. This anemometer can either point into the wind or two units can be used to obtain wind components, thereby eliminating the need for a wind vane. Other types of anemometers include hotwire anemometers and sonic anemometers.

Wind vanes (Fig. 4) often use a potentiometer with a narrow dead band. The voltage from the potentiometer can be converted into a direction. Wind vanes can also use optoelectronic techniques and magnetic reed switches to determine wind direction.

The researcher must decide at what height to measure wind speed and direction. This decision will be dependant on the nature of the investigation. The standard height for climate stations is 10 m, in a clearing where the distance between the anemometer and any obstruction is at least ten times the height of the obstruction (WMO 1983). At whatever height the researcher places the anemometer, the exposure will have to be considered.

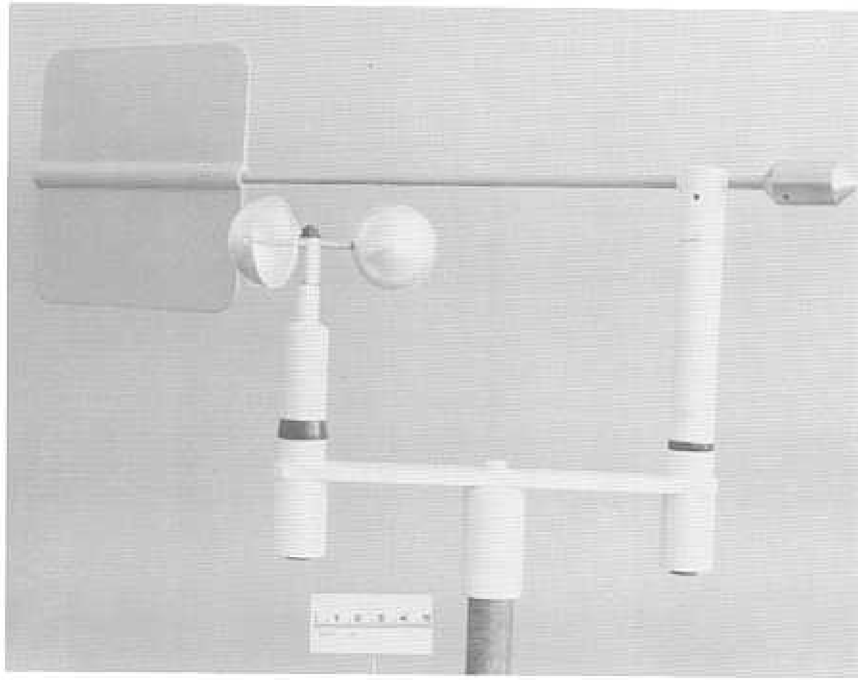

Figure 4. Three-cup anemometer and windvane.

V. Datalogger installation at the Petawawa National Forestry Institute (Cartier Lake): A Case Study

A. Introduction

The 21X data logger from Campbell Scientific Corp. was chosen to monitor selected environmental conditions (air and soil temperature, soil moisture potential, relative humidity, and photosynthetically active radiation) at a research plantation located in the northwest corner of the PNFI Research Forest on the north shore of Cartier Lake. The experiment investigates the effect that factors such as soil temperature, mineral nutrition, and brush competition have on plantation establishment and early growth (Brand and Janas 1988, Brand 1988).

B. Experimental design

This research plantation consists of a series of 20 x 40 m plots, each containing 200 trees (100 trees each of white spruce and white pine), that have been treated to create different conditions of soil temperature (three levels: cool, moderate, and warm soils), mineral nutrition (two levels: fertilized and unfertilized), and brush competition (two levels: brush-controlled and uncontrolled). These 12 treatments (3x2x2) create a range of conditions for seedling growth. The experiment is replicated in four blocks and the design is a complete block, split-plot factorial (Fig. 5).

The objective of the experiment is to quantify the extent to which specific environmental conditions affect survival and growth of the planted conifers. To accomplish this, a sample of trees (three per plot per species) from each of the 48 plots is selected annually for assessment of a number of growth measures and various developmental and nutritional characteristics. This data will be analyzed to determine whether significant treatment effects are present. The environmental monitoring facilitates defining the treatment effects in terms of light, moisture, and temperature conditions.

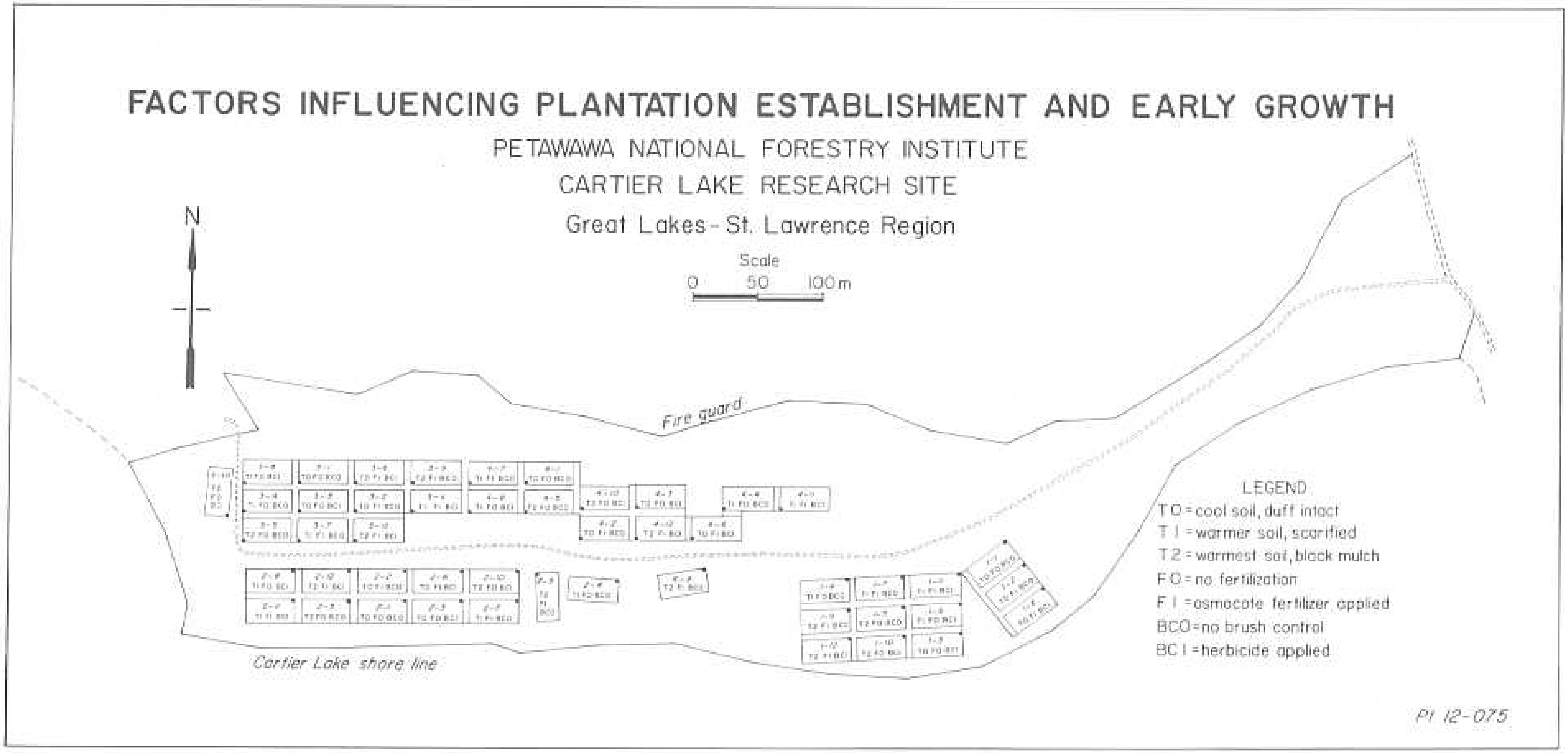

Figure 5. Block and plot layout at the Cartier Lake research site.

C. Sensor types and layout

Selected environmental conditions are monitored in representative locations throughout two of the plantation's blocks (i.e. covering 24 plots) through the May to September growing season. There are 88 sensors and their layout is illustrated in Fig. 6.

thermocouples are used to measure air temperature in four brushed and four unbrushed plots. The air temperature thermocouples have been placed at an aboveground height of 30 cm in screen shelters. Soil moisture potential in each plot is measured using a Delmhorst gypsum block (Campbell Scientific model 223) placed at a 10 cm mineral soil depth. Relative humidity (RH) is monitored using a Campbell Scientific model 207 relative humidity probe in one

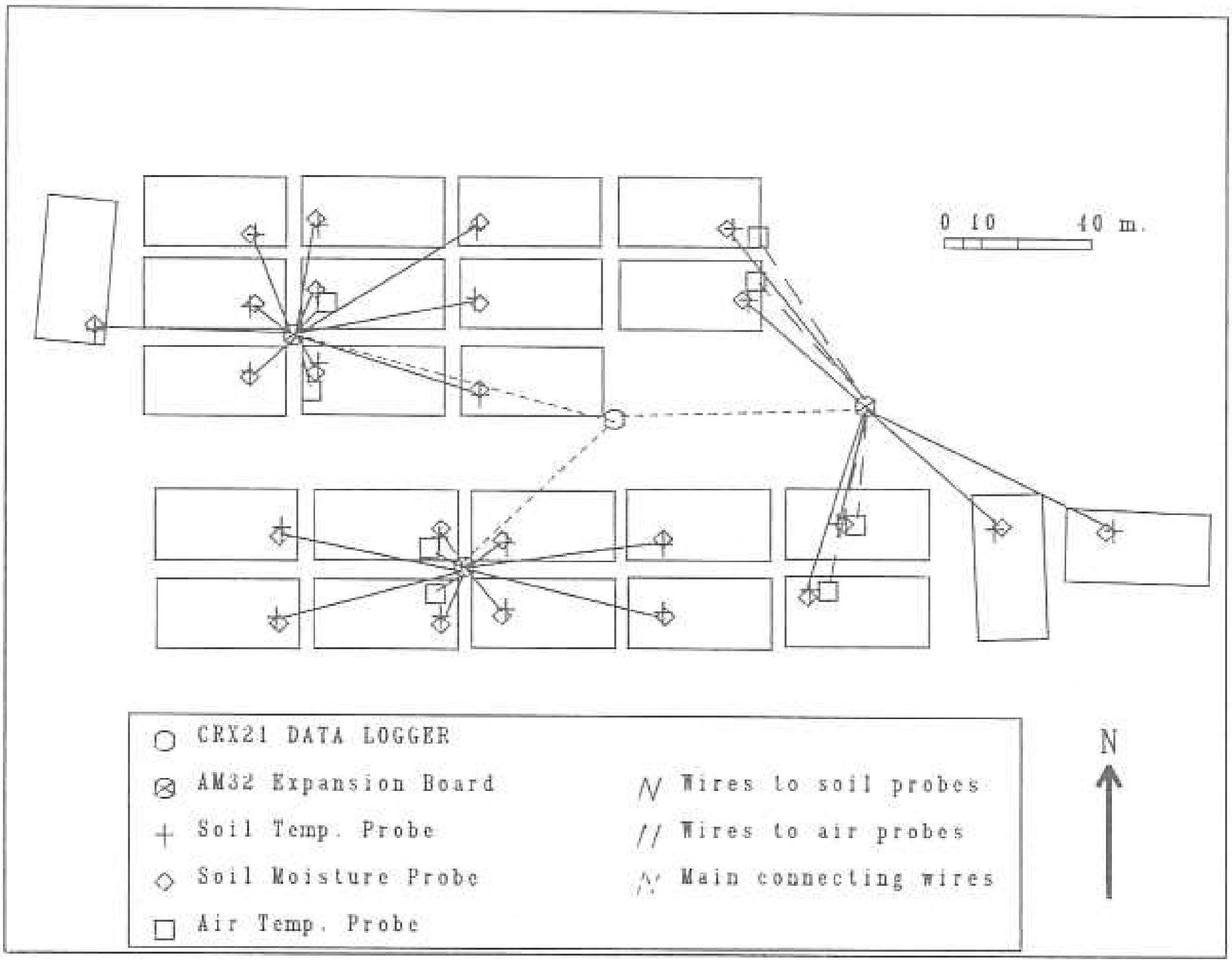

Figure 6. Locations of the monitoring equipment and sensors at the Cartier Lake research site.

Soil temperature at 2 and 10 cm depths below the mineral soil surface in each plot is measured using Campbell Scientific model 105T copper-constantan thermocouples. The same

brushed and one unbrushed plot; these sensors are also equipped to measure air temperature. Relative humidity sensors are placed 30 cm above ground in shelters of the same design as the air temperature sensors. Six quantum sensors from Li-Cor (model LI190SB) were selected to monitor the effect of varying levels of competing vegetation on incident photosynthetically active radiation (PAR). Five of these were placed at 30 cm heights in plots having varying levels of brush competition, and the sixth sensor (the control) was placed at a 180 cm height in a brush controlled plot. These sensors indirectly measure the amount of light received by each of the trees being sampled annually. This is accomplished by first obtaining a quantified index of plant competition around each light sensor and then comparing the indices to the actual light intercepted (cf. Brand 1986). Regression equations are then developed to relate incident PAR to the index of competition measured around the light sensors. Later, by obtaining indices of plant competition around each sample tree, we can use the same equations to estimate the amount of PAR received by each tree throughout the growing season.

The RH sensors and quantum sensors are hooked up directly to the datalogger, whereas the other sensors are wired into three channel expansion boards (Campbell Scientific AM32 multiplexers). Direct connection of the RH and PAR sensors to the datalogger was necessary because it is not possible to operate more than two or three different types of sensors through a given expansion board (B. Day, Campbell Scientific, Chatham, Ont. pers. comm.).

Appendix 2 provides a summary of the datalogger system components for the Cartier Lake research site.

D. Data management

The Campbell Scientific 21X datalogger is positioned in a central location relative to plantation blocks 2 and 3 which contain the sensors. It is sheltered in a small cabin and obtains power from two 12 volt, marine or recreational vehicle type rechargeable batteries.

Sensor measurements are taken at 5 min intervals (the sampling interval) and these data are averaged by the datalogger every 2 h, on the hour. At the start of the first season (1986), a 10 sec sampling interval was used for all sensors. This resulted in rapid drainage of the battery reserves to the point of system failure and resultant loss of several days' data. It may have also caused unnecessary wear on the relay mechanisms found in each of the expansion boards. Later, 5 min sampling intervals were used. Upon inspection of the data, it was decided that a 5 min interval produced results more than adequate for the planned analysis.

Up to 16 days low resolution (4 character) data from this site can be stored in the 40K memory of the datalogger before requiring transfer to tape. However, as a result of the remote location of the 21X (approx. 15 km from the Institute), prolonged data storage capabilities were needed. A cassette tape recorder (Tandy model CCR-82) equipped with a 60 min cassette tape met the requirement for less frequent downloading, as up to 90 000 data points (80 days' data) could be stored. The system is configured to transfer data from the 21X to the cassette recorder after 512 data points are entered in the datalogger's final storage. Data transmission to tape takes place approximately every 11.25 hours.

For additional protection at sub-freezing temperatures (when the tape recorder is unreliable) and to serve as a backup in the event of tape recorder failure, a Camp'ell Scientific model SM64 solid state data storage module, capable of storing up to 32,768 data points (29 days' data) was also wired to the datalogger.

Downloading of data is carried out every two weeks, if feasible, at which time data from the storage module is transferred to the reverse side of the cassette. In this way, when examining the tapes acquired at season's end, data recorded by both the tape recorder and storage module for a particular period can be examined via the same cassette. In the first season, data from the tape was transferred to our VAX minicomputer files by installing a Campbell Scientific PC 201 tape read card in an IBM PC-AT and using the microcomputer software package SMART-TERM. Later, the Campbell Scientific C20 cassette interface was used to transfer data into a microcomputer and, from there, to the VAX minicomputer.

Although two weeks is the maximum recommended interval for downloading, it is our policy to check the datalogger operation whenever we visit the research plantation for other purposes. It is also advisable to make more frequent visits during periods of inclement weather, which may adversely affect the system (e.g. lightning storms). A log book is used to record all particulars during visits. Information that should be recorded includes: dates and times when the system is down (no screen display), programming changes made throughout the season, suspect sensor readings, current battery voltage, program signatures (these values change only when the program has been modified or tampered with), the cassette tape counter value (needed to determine if the tape has advanced since the last visit), and the date and time of data downloading.

E. System protection

The datalogger was placed in a sheltered cabin to protect the unit from vandalism and weather damage, and to allow users of the system to make regular inspections and programming changes in reasonable comfort. This area is well ventilated to reduce the possibility of equipment damage from high temperatures. The datalogger is protected from lightning strikes by a heavy gauge wire connection to an outside grounding rod. Although the datalogger is equipped with spark gaps, additional protection is afforded by use of a Campbell Scientific 038 junction box.

To reduce temperature fluctuations in the channel expansion board containers (supplied by the manufacturer), these were placed in styrofoam-insulated wooden boxes placed about 15 cm above ground. Silicone caulking was placed around the wiring in the two openings leading from the original equipment enclosures to protect against moisture infiltration. It was also necessary to place large, ventilated wooden enclosures around each box to protect wires leading from these boxes from animal damage. The expansion board boxes came equipped with screw-down clamps, so additional protection in the form of a padlock around the outer box was not necessary.

All wires leading to the sensors were buried to a depth of 5 to 10 cm to protect against animal gnawing or inadvertent damage during, for example, walking tours or brush control operations in these plots. Of the three types of exposed sensors, it was decided that the relatively expensive RH probes and quantum sensors would be removed at the end of the season to protect against winter damage and vandalism and, in the case of the quantum sensors, to also enable biennial recalibration. It was impractical to remove all of the (buried) wiring connected to each sensor, so the wire adjacent to a sensor was cut. This wiring is spliced using reusable wire connectors at the start of each season. Thermocouples are estimated to have a 10-year life in the field and are not disturbed after installation.

F. Data recovery results and problems

Based on experience from two growing seasons, this datalogger system has performed to our expectations. The tabular and graphic summaries produced using SAS and SAS/GRAPH software on this data are in accord with most biophysical principles. Figures 7a to d provide examples of the actual graphs produced from the Cartier Lake data logging system for soil moisture, soil temperature, RH, and PAR.

The estimated data recovery in terms of number of lines of data recorded compared to the potential total for 1986 was 87.6% and for 1987 was 84.4%. The reasons for lost data were attributed to external factors, not faulty datalogger components. Lightning strikes close to the research site were responsible for much of the system downtime. Based on a comparison of this datalogger system with similar, scaled-down systems at two other sites at Foleyet, Ont. and Prince George, B.C., it seems that increasing the area of coverage with datalogger-based sensors results in an exponential increase in the amount of system downtime resulting from lightning strikes. The other two sites, compared to Cartier Lake, each have approximately half the area of sensor coverage (1 vs. 2 ha) and 48 compared to 88 sensors. In 1987 no system downtime was attributed to lightning strikes at the other two sites. At Cartier Lake, however, the datalogger was not operating on five separate occasions, all immediately following lightning storms.

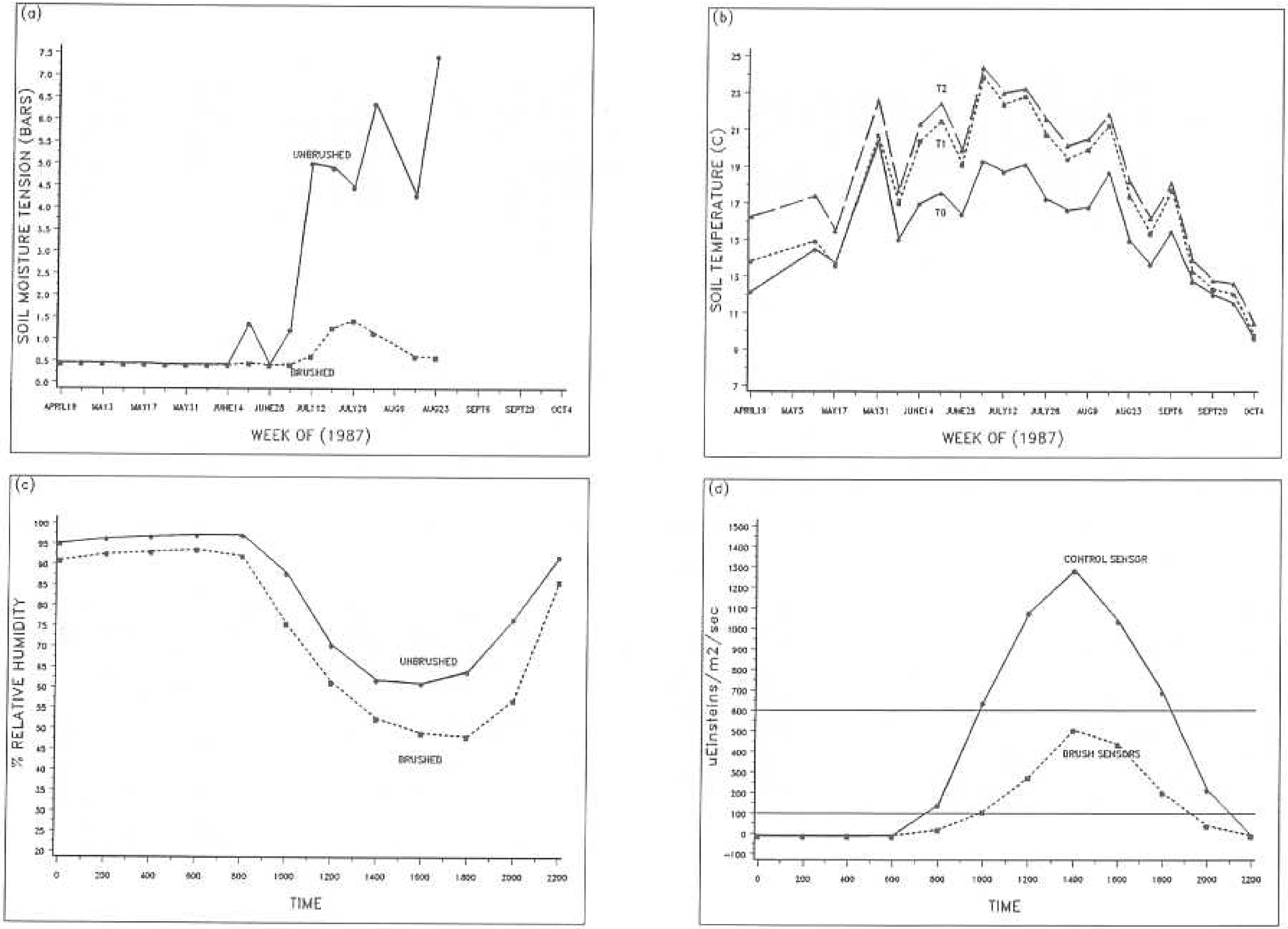

Figure 7a-d. (a) Weekly soil moisture tension for two levels of brush control at Cartier Lake, PNFI; (b) Weekly mean soil temperatures at a depth of 10 cm for three levels of site preparation at Cartier Lake, PNFI; (c) Average hourly RH for August 1987 at Cartier Lake, PNFI; (d) Average hourly PAR for August 1987 at Cartier Lake, PNFI.

Fortunately, no part of the datalogger system suffered damage from these storms over two years because of adequate spark gap protection and grounding. Obviously, there may have been certain factors, such as local terrain and weather conditions, which made the area vulnerable to lightning strikes, but this damage threat may also be related to the large coverage area and number of sensors. It is recommended that those researchers contemplating similar magnitudes of sensor coverage concentrate on minimizing sensor lead length by judicious placement of expansion boards or by using more than one datalogger. Remember that long cables are very costly, and the costs of extra dataloggers or expansion boards can be offset by savings in cable costs. In addition, all units must be properly grounded, and spark-gapped junction boxes should be installed between sensors and dataloggers.

The only other factor which caused complete system failure was inadequate battery voltage. However, this only occurred once and was remedied by increasing the sampling interval from 10 sec to 5 min and by installing two heavy duty recreational vehicle batteries in parallel. The latter measure enabled us to remove a battery for recharging without having to shut down the datalogger. Only one recharge was necessary in the 1987 season.

The most common causes of invalid sensor readings were errors in the original program, which had been re-entered (such as after lightning strikes) or modified. We learned that once a satisfactory program had been developed, its correct entry or re-entry into the datalogger could be verified by checking the program signature in the data logger's initial storage location; this value is unique to a given set of program instructions.

Other relatively infrequent causes of out-of-range sensor readings included: broken sensor wires caused by damage to wiring which was improperly buried and subject to low-cutting brush saws; loose wire connections on the expansion boards, junction box, or datalogger; burned out resistors for the soil gypsum blocks, associated with current surges during lightning strikes; and vandalism. Based on these and other experiences, we developed a troubleshooting guide (available from the senior author) for this datalogger system that can be used by anyone checking the system.

Conclusions

Much forest research relates to differences in environmental conditions between sites or on sites with different treatments applied. Until recently, systematic environmental monitoring of more than the most basic variables was difficult and time consuming. Automatic dataloggers have greatly facilitated this type of monitoring and should lead to increased understanding of the environmental control of forest productivity. The case study presented includes continuous monitoring of 88 sensors as an integral part of the experimental design. This design provides data on the growth response to quantified changes in environmental conditions. Experiments of this kind provide information of more general use than those testing environmentally unquantified treatments and will lead to the development of more rational criteria for designing reforestation regimes.

Acknowledgments

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References

American Society for Testing and Materials (ASTM). 1981. Manual on the use of thermocouples in temperature measurement. ASTM Special Technical Publication 470B. Philadelphia, Pa.

Anon. 1985. LI-190SZ quantum sensor instruction manual. Publ. No. 8511-52. Li-Cor Inc., Lincoln, Neb.

Boyer, J.S. 1987. Thermocouple psychrometry in plant research. Pages 25-35 *in* International Conf. on Measurement of Soil and Plant

Water Status, Vol. 3, Utah State Univ., July 6-10, 1987.

Brand, D.G. 1986. A competition index for predicting the vigour of planted Douglas-fir in southwestern British Columbia. Can. J. For. Res. 16: 23-29.

Brand, D.G. 1988. Growth analysis of the response of white spruce and white pine to soil temperature, nutrition, and brush control. For. Ecol. Manage. (In press)

Brand, D.G.; Janas, P.S. 1988. Growth and acclimation of planted white pine and white spruce ssedlings in response to environmental conditions. Can. J. For. Res. 18: 320-329.

Briscoe, R.D. 1984. Thermocouple psychrometers for water potential measurements. *In* Proc. Advanced Agricultural Instrumentation Seminar, NATO Advanced Study Institute, Ciocco, Italy, May 27-June 9, 1984.

Brown, R.W.; Chambers, J.C. 1987. Measurements of *in situ* water potential with thermocouple psychrometers: a critical evaluation. Pages 125-36 *in* International Conf. Measurement of Soil and Plant Water Status, Vol. 1. Utah State Univ., July 6-10, 1987.

Campbell, G.S. 1987. Overview: soil water potential measurement. Pages 115-18 *in* International Conf. Measurement of Soil and Plant Water Status, Vol. 1. Utah State Univ., July 6-10, 1987.

Carlson, T.N.; Salem, J.E. 1987. Measurement of soil moisture using gypsum blocks. Pages 193-99 *in* International Conf. Measurement of Soil and Plant Water Status, Vol. 1. Utah State Univ., July 6-10, 1987.

Doebelin, E.O. 1966. Measurement systems: application and design. McGraw-Hill Book Company, New York, NY.

Federer, C.A.; Tanner, C.B. 1966. Sensors for measuring light available for photosynthesis. Ecology 47: 654-57.

Fritschen, L.J.; Gay, L.W. 1979. Environmental instrumentation. Springer-Verlag, New York, NY.

Ingestad, T.; Aronsson, A.; Ågren, G.I. 1981. Nutrient flux density model of mineral nutrition in conifer ecosystems. Studia For. Suecica 160: 61-71.

International Symposium on Moisture and Humidity. 1985. Moisture and humidity measurement and control in science and industry, Washington, D.C. Instrument Soc. Amer., Research Triangle Park, N.C.

Klebs, G. 1913. Über das Verhaltniss der dussenwelt zur Entwicklung der Pflanzen. Sitzunsber. Heidelb. Akad. Wiss., Abt. B 5, 1-47.

Lee, R. 1978. Forest microclimatology. Columbia Univesity Press. New York.

Levitt, J. 1972. Responses of plants to environmental stresses. Academic Press, N.Y.

Mason, H.L.; Langenheim, J.A. 1957. Language analysis and the concept environment. Ecology 38: 325-340.

Monteith, J.L. 1972. Survey of instruments for micrometeorology. IBP Handbook No. 22. Blackwell Scientific Publications. London.

Muller, S.H.; Beekman, P.J. 1987. A test of commercial humidity sensors for use at automatic weather stations. J. Atmos. Oceanic Tech. 4: 731-735.

Schooley, J.F. 1986. Thermometry. CRC Press Inc., Boca Raton, Fla.

Sellers, W.D. 1965. Physical climatology. Univ. Chicago Press, Chicago, Ill.

Spomer, G.G. 1973. The concept of "interaction" and "operational environment" in environmental analyses. Ecology 54: 200-204.

Tanner, C.B. 1963. Basic instrumentation and measurements for plant environment and micrometeorology. Dept. Soils Bull. 6, Univ. Wisconsin, Madison, Wis.

Unwin, D.M. 1980. Microclimate measurement for ecologists. Academic Press, London.

Wang, J.Y.; Felton, C.M.M. 1983. Instruments for physical environmental measurements. Vol. 1. (2nd ed.) Kendall/Hant Publishing Company, Dubuque, Iowa.

World Meteorological Organization. 1983. Guide to meteorological instruments and methods of observation. WMO No. 8., Geneva, Switz.

Appendix 1: A listing of selected datalogger manufacturers in North America

Company	Address	Data logger products
Aanderaa DC Instruments	560 Alpha St. Victoria, B.C. V8Z 1B2 Tel: 604-386-7783	
A.I.R. Inc.	1880 S. Flatiron Court Boulder, Co. 80381 Tel: 303-443-7187	Airsonde Tethersonde
Allen-Bradley	135 Dundas St. Cambridge, Ont. N1R 5X1	DataMyte Electronic Notebook
Campbell Scientific, Inc.	(Head Office): P.O. Box 551 Logan, Utah 84321 Tel: 801-753-2342 Telex: 453058 (Canada):	CR7X measurement and control system CR10 measurement and control system 21XMicrologger™
Campbell Scientific Inc.	9525-41 Ave. Edmonton, Alberta T6E 5X7 Tel: 403-434-9421 Telex: 037-2966 EDM or 192 Ste. Claire St. Chatham, Ont. N7L 3J6	
Climatronics Corp.	140 Wilbur Place Airport International Plaza Bohemia, NY 11716 Tel: 516-567-7300	
Data Metric - Dresser Industries Inc.	340 Fordham Road Walmington, Mass. 01887 U.S.A.	Portable: 100VT-Direct reading Air, water velocity, and temperature meter
Electronic Controls Design	13626 South Freeman Road Marlino, Ore. 97042-9639 U.S.A.	Data Loggers 10-40 channels AC-DC
Forest Technology Systems Ltd.	841 Goldstream Ave. Victoria, B.C. V9B 2X8	Thermaloggers FTS 6100 Fire Weather Station

Company	Address	Data logger products
Geneq Inc.	223 Signet Drive Weston, Ont. M9L 1V1	Portable Dataloggers Easy-Logger Field Unit - 12 channels Omnidata Polycorder - 10 channels DataMac - data collector (Electronic Notebook)
Handar	1380 Borregas Ave., Sunnyoak, Ca. 94089-1094 Tel: 408-734-9640	570A Hydromet data acquisition system Data Collection Platform Versatile-Satellite or remote controlled
Honeywell Ltd.	740 Ellesmere Road Scarborough, Ont. M1P 2V9 416-293-8111	Datalogger "Omnilight" 8M36 AC 4 channel 12VDC will be available second quarter 1988
Li-Cor, Inc.	Box 4425 Lincoln, Neb. 68504 Tel: 402-467-3576 Telex: 910-621-8116	.LT-1200S datalogger (Minimum data set recorder)
Metrodata Systems Inc.	Box 1307 Norman, Okla. 73069 Tel: 405-329-7007	
Metrosonics Inc.	P.O. Box 23075 Rochester, NY 14692 U.S.A.	DataLogger dP-721 - 8 channel AC-DC portable
Multitest Electronics Inc.	148 Colonnade Rd., Ste. 208 Nepean, Ont. K2E 7J5	Portable DataLogger DDL 4000 & 4020 AC & Battery 12V 16 ANALOG 4 SW contact channels
Omnidata International Inc.	P.O. Box 3489 Logan, Utah 84321 Tel: 801-753-7760 (Canada): Geneq Inc., 223 Signet Drive, Weston, Ont. M9L 1V1 Tel: 416-747-9889	Easy Logger™ system Datapod™

Company	Address	Data logger products
Wescor Inc.	459 South Main St., Logan, Utah 84321 Tel: 801-752-6011 Telex: 4930393 WESC UI (Canada): Geneq Inc., 223 Signet Drive Weston, Ont. M9L 1V1 416-747-9889	Delta Logger™

Appendix 2: Datalogger system components for the Cartier Lake research plantation

Supplier	Item	Quantity	Cost (1986 $)
Campbell Scientific Canada Corp., Edmonton, Alta.	21X Micrologger™	1	3700
	SM64 storage module	1	1230
	PC201 tape read card & IBM software	1	1040
	AM32 multiplexers (expansion boards)	3	4000
	soil gypsum blocks (model 223)	24	340
	thermocouples (105T)	56	2190
	Li-Cor quantum sensors (LI190SB)	6	3900
	mounting & levelling fixtures for quantum sensors	6	576
	cassette recorders (Tandy CCR-82)	2	300
	relative humidity probes (207)	2	790*
	junction box (038)	1	570*
	cassette write only interface (SC92)	1	125
	multiplexer wiring	3	180

*purchased in 1987