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**Radiation Densitometry in
Tree-Ring Analysis:
A Review and Procedure
Manual**

1985

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**RADIATION DENSITOMETRY IN TREE-RING ANALYSIS:
A REVIEW AND PROCEDURE MANUAL**

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ABSTRACT

An X-ray densitometry of wood facility is being established by the Environmental Sciences Division, Oak Ridge National Laboratory (ORNL). The objective is to apply tree-ring data to determine whether or not there is a fertilizer effect on tree growth from increased atmospheric carbon dioxide since the beginning of the industrial era. Intra-ring width and density data, including ring-mass will be determined from tree-ring samples collected from sites located throughout the United States and Canada.

This report is designed as a guide to assist ORNL scientists in building the X-ray densitometry system. The history and development of X-ray densitometry in tree-ring research is examined and X-ray densitometry is compared with other techniques. Relative wood and tree characteristics are described as are environmental and genetic factors affecting tree growth responses.

Methods in X-ray densitometry are examined in detail and the techniques used at four operating laboratories are described. Some ways that dendrochronology has been applied in dating, in wood quality, and environmental studies are presented, and a number of tree-ring studies in Canada are described. An annotated bibliography of radiation densitometry in tree-ring analysis and related subjects is included.

It is noted that to determine whether or not there is a fertilizer effect from increased CO_2 , the other factors affecting tree growth must be considered. The approach should be to obtain detail and

accurate tree-ring width and density data from many diverse and widely distributed sites, and then apply advanced statistical techniques to separate the hypothesized CO₂ effect from the many other factors that affect tree growth.

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PREFACE

Traditional tree-ring analyses (ring-width and ring density) have been utilized in time-series studies to establish historical knowledge of past influences (climate, air pollution, etc.) on tree growth. The hypothesis that increasing atmospheric carbon dioxide constitutes a fertilizer effect to forest or tree growth poses an interesting concept. If net wood production increases from elevated CO_2 it must be from increased photosynthates, which, in part, is ultimately transformed into new xylem (wood) tissue.

It has been suggested that traditional dendrochronology parameters (ring-width and ring density) are suitable to detect a CO_2 tree-growth signal. A more precise estimator of wood production is the mass of wood in the ring. Procedures for determining the mass of wood require simultaneous measurement of ring width and wood density. Several laboratories have developed tree-ring densitometry facilities. For the purpose of our study (determination of wood mass), there are three options available to ORNL to measure ring density:

1. Subcontract to an existing densitometry laboratory for services.
2. Support a technician at an existing laboratory, dedicated solely to ORNL work.
3. Operate a densitometry facility at ORNL.

At ORNL there are scientists expert in radiography, densitometry, electronics, and computer sciences with many years experience. The major components, with some alterations, of a state-of-the-art tree ring laboratory are currently available in the non-destructive testing

laboratory of the Metals and Ceramics Division. Considering the expertise at ORNL, it was decided that the work could be conducted cost effectively in-house. In addition, a tree-ring densitometry laboratory would be a valuable tool available to additional ecological considerations.

In this report, examples of the applications of tree-ring analyses in ecological studies and descriptions of selected laboratories are discussed. The review is intended primarily to provide sufficient background to enable the researchers to design a laboratory.

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1. INTRODUCTION

There is speculation that the increase in atmospheric carbon dioxide since the start of the industrial era has had a measurable worldwide effect on growth of crops and forests, but there has been no definitive test of this hypothesis. Firm evidence, positive or negative, would have significant implications for national and global CO₂ policy. If it can be shown that CO₂ fertilization has stimulated plant growth in the field, the virtual certainty of future CO₂ increase suggests important impacts on agriculture and forestry and on policy decisions about fossil fuel combustion. Confirmation or denial of the growth enhancement hypothesis would help in resolving the controversy over the role of the biosphere in the global carbon budget.

There appears to be no feasible way to determine whether there has been global stimulation of crop growth by CO₂. On the other hand, tree rings offer sets of long-term biological data from which a global trend of enhanced photosynthesis is most likely to be detectable.

If CO₂ fertilization increases net wood production, it must be through augmented production of photosynthate which is translocated from leaves and converted to new xylem tissue. The additional xylem increases the mass of the tree, especially the bole. Production of wood has commonly been estimated from measurements of ring width. A more precise estimator of wood production, whether or not growth has been stimulated by CO₂ increase, is the mass of wood in the ring. Procedures for determining the mass of wood in a ring segment utilize simultaneous measurement of ring width and wood density, using X-ray densitometry (Lenz et al. 1976, Parker et al. 1980).

Recent developments in biological and geophysical research, in field data collection and processing, and in signal detection and time-series analysis suggest that a test of the fertilization hypothesis is now feasible using available data sets and additional data from selected sites.

This report presents a review of the development and application of X-ray densitometry, and other methods that have been used to measure intra-ring density. Methods used at other institutions are examined, environmental and genetic characteristics of trees and wood are discussed, applications of X-ray densitometry of wood are described and some alternative systems proposed. This compilation should assist in upgrading a system at Oak Ridge National Laboratory that is capable of making state-of-the-art ring width and density measurements.

2. HISTORY AND DEVELOPMENT OF X-RAY DENSITOMETRY IN TREE-RING RESEARCH

Traditional methods in dendrochronology have been based on measurement of whole annual rings. During the past twenty years, techniques in dendrochronology have been greatly improved through the use of methods that measure the intra-ring density pattern of the rings. X-ray densitometry is generally considered the superior method.

In 1973, when the status of radiation densitometry of wood was reviewed by Parker and Kennedy (1973), there were about ten institutions active in this field. Smith (1977) reports that there were 24 laboratories throughout the world using the technique of X-ray densitometry of wood in 1976. Evertsen (1980) lists 30 laboratories in 18 countries engaged in radiation densitometry of wood by 1980.

The amount and quality of data that can be obtained from the annual ring is greatly enhanced through the use of X-ray densitometry when compared with the use of measurements of whole annual ring. X-ray densitometry permits segregation of the annual ring into components of earlywood, latewood, width and density. These can be expressed as a number of parameters including ring mass.

Many of the methods developed earlier in this century (Douglass 1919, 1929, 1935, 1937, 1946 and Schulman 1956, 1958) are still very valid and useful. A brief account of the history of the development of dendrochronology is presented as background to the development of X-ray densitometry of wood.

2.1 Development of Dendrochronology

The recorded observation of the relationship between time and the diameter growth of trees dates back at least two millenia to Theophrastus, the student and successor of Aristotle. A number of botanists, foresters, and astronomers in Europe and America in the 18th and 19th centuries understood that rings in trees are annual in nature and some even understood the principle of crossdating between tree-ring series (Studhalter 1956). However, it was not until the work of A. E. Douglass in the 20th century that dendrochronology developed as a recognized and continuing field of scientific investigation. In 1901, the idea occurred to Douglass that the growth of the pines and junipers in northern Arizona should depend on the annual available moisture and thus reflected in the width of the annual rings (Giddings 1962).

In 1904 Douglass tested this idea by watching the pattern of wide and narrow annual rings formed in the cross sections of stems of different trees growing in the same area. In the years that followed, Douglass developed techniques to facilitate crossdating and chronology building (the summarizing and temporal extension of annual ring-width records from different trees into a single "tree-ring chronology").

The potential for tree-ring dating was recognized early by the southwestern archaeologists. In 1916, Douglass first received samples of prehistoric wood. Crossdating of wood and charcoal samples from a number of different southwestern Indian ruins proceeded until by the 1920's a number of "floating chronologies" existed. These floating chronologies provided crossdating between samples of the same site and between sites but were not tied down to calendar years.

This 585 year-long floating chronology, that Douglass called the "Relative Dating Series," was compiled from beams from Aztec, Puelo Bonito, Cliff Palace, Betatakin and other Indian ruins from the southwest. Haury (1962) has recorded the dramatic moment, when in 1929, a charcoal beam from a ruin in Show Low, Arizona, provided the ring sequence required to crossdate the Relative Dating Series with the tree-ring chronology that Douglass had compiled from living trees from the area. This event was the climax of years of technique development, crossdating and chronology building by Douglass and his associates. At this one moment in time, the calendar-year dating of many major ruins in the southwest was accomplished.

This story has been repeated many times, using the crossdating technique, building living-tree chronologies and chronologies of updated samples, and finally, matching the two series to provide calendar dates of previously updated samples. A good example of this is a floating chronology constructed by Giddings (1952) from tree-ring samples from prehistoric sites on the Kobuk River in Alaska, which were dated by matching the floating chronology with a living-tree chronology.

The work begun by Douglass has continued and has been greatly expanded upon by the Laboratory of Tree-Ring Research in Tucson, Arizona (Stokes and Smiley 1968, Fritts 1976; see also issues of the Tree-Ring Bulletin). Tree-ring laboratories have been established in many parts of the world using the techniques and principles developed in Arizona.

2.2 Mechanical-Optical Methods of Measuring Total Ring Widths

Instruments that measure total ring width have been in use for many years (Douglass 1943, Eklund 1949). The usual technique is to observe ring boundaries on the transverse surface of a tree-ring series under a low-power microscope. Some of these instruments have been computerized and automated, so that digital ring-width data are recorded directly on magnetic tape or disc; or ring-width plots are produced as a sample is being measured. Total ring-width values can be produced accurately by these instruments if the operator is skillful. However, the instruments are not very accurate for measuring earlywood or latewood components separately. The transition between earlywood and latewood is very gradual on some wood samples and these instruments

rely on the subjective judgement of an operator to make decisions on boundary location.

One advantage of using a system of X-ray densitometry to obtain ring-width and ring-density component (earlywood and latewood) measurements is that an operator is not required to make a judgement on earlywood-latewood or latewood-earlywood boundary locations of each ring. Density levels can be chosen for these boundaries and the system can be programmed to "trigger" automatically at these points. The decision as to what density levels are to be used may be a subjective one made by an operator, but the boundaries located during sample scans will be consistent and objectively located by the instrument. The electro-mechanical scanning densitometer is faster than traditional operator-controlled ring-width measuring instruments, because the scanning densitometer can make a rapid and continuous traverse of a sample without stopping at every ring boundary.

2.3 Development of X-Ray Densitometry

Various radiation, light and mechanical techniques have been developed to study the within-ring density variations in wood samples (Cameron et al. 1959, Marian and Stumbo 1960, Green 1964, 1965, Green and Worrall 1964, Harris 1969, Kawaguchi 1969); but perhaps the most successful method, X-ray densitometry, was pioneered by Polge (1963, 1965a, 1965b, 1965c, and 1966) during the 1960's.

The basic technique of X-ray densitometry is to produce a radiograph (negative image) of a transverse (or radial) cross section of a wood sample by transmitting X-radiation through the wood onto a

sheet of X-ray sensitive film. The film is then developed and scanned on a densitometer that converts the film density of the wood image to an analog signal. This signal represents the intra-ring density variations and the width components of the annual rings.

Particular aspects of the techniques employed vary from laboratory to laboratory. For example, some laboratories radiograph cylindrical increment cores, while others cut the wood samples to a uniform thickness before they are radiographed. Some laboratories use a stationary technique, with the X-ray generator positioned several meters from the film and wood sample. Other laboratories use an in-motion technique for making the exposure.

Techniques in radiography of wood samples have been extensively developed during the past 20 years. β -ray and X-ray absorption have been used to obtain detailed measurements of intra-ring density. These methods have certain advantages over previously devised techniques for measuring intra-ring density.

Very high-resolution radiographs of wood samples can be produced by X-ray techniques, particularly if the samples are of uniform thickness and in-motion radiography is used. Large quantities of accurate and detailed intra-ring density data can be obtained from radiographs of wood samples with a scanning densitometer, particularly if it is interfaced directly with an on-line computer. These intra-ring density data provide new and useful information for fields that deal with the forest environment or the structure and properties of wood.

Many laboratories began using radiography during the last twenty years incorporating new electro-mechanical instruments (microdensitometers) with digital computers. X-ray densitometry is undergoing a stage of experimentation and development in tree-ring analysis and many innovations and improvements may be added in the future. The next stage in the development of this field should be one of extensive use of intra-ring density data in practical application.

2.4 Comparison of X-ray Densitometry with Other Techniques

2.4.1 Beta radiation method

Beta radiation was used in England during the late 1950's to produce intra-ring density data by the radiographic technique (Cameron et al. 1959, Phillips 1960, Phillips et al. 1962), but most workers engaged in this type of research since then have used X-ray densitometry.

The β -ray and X-ray methods have been compared (Harris and Polge 1967) and it may be concluded from the evidence presented that the X-ray technique is superior, in that it produces more accurate and detailed data in a shorter time period because of the higher intensity. In defending the β -ray technique, Phillips (1968) presented some detailed intra-ring density chart recordings, but admitted that the disadvantages of this technique are slow scanning time, and the need for very thin sections. The X-ray technique can use thicker samples and because of higher radiation intensity the data is obtained much faster. However, the β -ray technique should not be completely discounted for having useful applications.

2.4.2 Gamma radiation

Another attempt at direct scanning was proposed by Woods and Lawhon (1974) whereby soft gamma radiation was used for the radiation source. Differences in gamma absorption by latewood and earlywood were translated into measures of relative wood density, radial growth, and percentage earlywood and latewood. This modification was progressive in that the intermediate steps of film exposure and processing were omitted. A limitation of the technique is that relative ring width and density were determined instead of absolute width and density.

2.4.3 Photometric methods

Very detailed intra-ring density plots have been produced by scanning photometric instruments, pioneered in Canada by Green and Worrall (1964), and Green (1964, 1965). Elliott and Brook (1967) used an improved technique to record cell wall/lumen ratios. These methods involve measurements of light transmitted through transverse microtome sections. A scanning microphotometer is used to measure transmitted light, while intra-ring density data are plotted on a chart recorder and also may be converted to digital form and recorded on tape for computer analysis. The limitations of these techniques are that the preparation of microtome sections is very time-consuming and, also, it may be difficult to obtain the same degree of opacity in the staining of each sample, leading to errors in intra-ring density determination.

2.4.4 Gravimetric methods

Gravimetric methods for measuring density on relatively large whole samples are generally rapid and accurate, but these methods are impractical for large-scale intra-ring density determinations because they are extremely time-consuming. However, limited data have been obtained from serial tangential microtome sections from which micro-specific gravity was subsequently determined (Ifju et al. 1965, Kennedy 1966). Gravimetric methods are best suited for measuring large samples and provide a good means of calibrating systems using X-ray densitometry, but the X-ray technique is superior for measuring intra-ring density.

3. WOOD CHARACTERISTICS

3.1 Anatomical and Morphological

Among vascular plants, development and growth throughout the life of the organism is a continual process of cell divisions from embryonic tissues called meristems. Meristems not only produce new cells, but also perpetuate themselves as undifferentiated generative tissues. Meristems are located at the apices of all shoots and roots and in plants characterized by secondary increases in thickness processes (woody plants). The latter are known as lateral meristems. The combined activity of apical and lateral meristems results in the complex plant body. Apical meristems expand the plant body, increases its surface, and produces the reproductive organs. The lateral meristem is primarily concerned in expanding the body by increasing the volume of the conducting system. Both apical and lateral meristems

(e.g., cambium) show seasonal fluctuations in their activity with a slowing down or complete stoppage of cell divisions during winter months in the temperate zones.

The cambium is in the shape of a cylinder with cell divisions differentiating inwardly into secondary vascular tissues (xylem cells). It is the periodic (seasonal) activity of the cambium that results in a distinct growth layer. In cross section the layers are termed growth rings. If the growth is truly a seasonal phenomenon and occurs only once, the layer is termed an annual ring. Because of external influences (disease, precipitation, temperature, air pollution, etc.) the activity of the cambium may be inhibited temporarily, resulting in an apparent second growth layer during the same growing season. This layer is termed a false annual ring and requires crossdating with additional specimens to establish the proper chronology. Because of the seasonality in cambial activity the number of growth layers is indicative of the age of the plant.

The clarity of transition from one annual ring to another depends on the species and the growing conditions at the time of cell development. The distinction between the successive rings is related to a structural difference between xylem cells differentiated in the early and late periods of the growing season. Wood produced early in the growth period (earlywood) typically has larger cells with less cell wall volume to cell lumen (void) volume ratio than wood produced late in the growth period (latewood). The transition from earlywood to latewood is gradual and not easily discernible except by densitometric analysis, whereas the distinction between latewood of one season and

earlywood of the next season is obvious (Figure 1). It is this characteristic of growth among trees (especially conifers) that has permitted scientists to apply traditional dendrochronological techniques and time-series analysis to assess climate (Fritts 1976) and air pollution (Parker et al. 1974b) effects on forest trees. The same technology (tree ring studies) has the potential to discern whether increased atmospheric CO_2 constitutes a fertilizer effect to trees since the advent of the industrial era.

4. METHODS IN X-RAY DENSITOMETRY

There is no standard set of procedures followed by all laboratories engaged in X-ray densitometry of wood. There are a number of workable options that can be taken. One reason for this diversity is that X-ray densitometry of wood is a relatively new field and techniques are still being developed. Also, requirements, facilities and opinions vary from laboratory to laboratory.

Some of the alternative methods that can be used are illustrated in Figure 2. These methods will be explained in this section and the relative merits of each will be discussed. Four X-ray densitometry systems will be described in the following section.

4.1 Field Collecting and Sample Storage [Fig. 2(2-1 to 2-4)]

Most tree-ring samples used in X-ray densitometry are 5 mm increment cores taken from living trees. Small subsamples (approximately the size of the 5 mm cores) also are used. These are cut from larger diameter cores, from cross-sectional discs, blocks cut

Figure 1. Intra-ring density profile of an annual ring. The arrows indicate boundaries for earlywood-latewood (ELDY) and latewood-earlywood (LEDY).

from stumps or cut from other types of larger wood blocks. Some samples used in X-ray densitometry, such as archaeological samples, are in the form of charcoal (Stokes and Smiley 1968).

If the wood samples are allowed to dry without being constrained in some manner, they usually will warp. Examples of containers used are paper or plastic drinking straws, glass tubes (open on the ends), rolls of paper, plant presses, or special grooved plastic containers. If the containers are air-tight, mold may form on the samples. Once the samples have reached the air-dry state they are not subject to mold or warping.

An alternative method to storing the samples in constraining containers as soon as they are collected, is to store them in an alcohol solution. This prevents the resin from drying in the cores and affecting subsequent sample preparation procedures.

4.2 Removal of Extractives [Fig. 2(2-5, 2-6)]

Wood extractives are those substances that can be readily removed by dissolution in water, alcohol or other solvents. Some laboratories routinely remove extractives from all samples, some never remove extractives and some laboratories will remove or not remove the extractives depending on the condition of the samples or the requirements of the study being conducted. There may be heavy concentrations of extractive materials in annual rings that were formed at times other than when the rings were formed. The usual objective of dendrochronological studies is to determine how much wood material was formed during a particular time period. The presence of extractives may distort the results obtained in density determinations.

Resin and other substances are removed by various methods. Samples can be boiled in water to remove the water-soluble compounds; and alcohol, benzene, acetone or other chemicals can be used for various lengths of time to remove other extractable substances. Some researchers contend that the method of extraction used should be varied according to species and condition of the samples. Further research needs to be conducted on this subject in order to determine standard and acceptable practices. However, it may be concluded that removal of extractives improves the quality of the intra-ring density data obtained; but it is more of a problem for samples of some particular species than it is for others.

4.3 Cutting the Wood Samples to a Uniform Thickness [Fig. 2(2-7, 2-8)]

It is generally accepted that radiographic images, to be used for intra-ring density determination, are of better quality if the wood samples that are radiographed have been cut to a uniform thickness. If the X-ray exposures are made using round increment cores, only a very limited width of the image of the sample ($\leq 25\%$) on the film is useful for densitometer scanning. If the densitometer scan deviates from this region, the system will be measuring wood of reduced thickness. In the densitometer scanning procedure, it is useful if the operator can change the line of scan in order to avoid aberrations such as flaws in the wood.

A number of tools have been designed and built especially for the purpose of cutting wood samples to a uniform thickness for X-ray densitometric analysis (Kusec 1972, Olson et al. 1978, Cown and

Clement 1983). These tools use twin hollow-ground circular saw blades or a device with a router is used. Saw blades or router bits produce a surface that is superior to a sanded surface because (1) sanding fills the lumen with sanding dust, (2) grit from the sandpaper may be embedded in the wood, and (3) it is difficult to obtain uniform thickness with the sanding technique.

In order to produce study samples of good quality, it is important that these surfacing devices be of good design and construction and are properly maintained. If the wood cells are crushed or torn and if uniform thickness is not obtained, the density data values will be inaccurate.

The 5 mm increment cores or other small samples are somewhat fragile and it is necessary to mount these samples on small wooden sticks prior to cutting (Parker 1970). This provides added stability for cutting to the desired thickness, usually 1 mm or 2 mm.

4.4 Conditioning of Wood Samples to a Standard Moisture Content [Fig. 2(2-9, 2-10)]

Low energy X-rays are markedly absorbed by water, therefore the amount of X-rays that are transmitted through a wood sample is greatly influenced by its moisture content. This moisture causes the wood to expand and the thickness must be considered in measurement of density. Ideally, it would be better to radiograph the wood samples in an oven-dry condition, but the technical requirements for doing this make this method impractical.

If the wood sample from a living tree is radiographed before it reaches the air-dry state, a considerable difference in X-ray transmission can be observed between heartwood and sapwood (Polge 1965a, Parker 1970).

The humidity of an X-ray densitometry laboratory may vary from day to day or season to season. To assure accurate density data, the room in which the wood samples are processed should be of a known and consistent humidity level or the samples should be put in a conditioning chamber before processing. This is especially important if the density calibration blocks or wedges are made of some material other than wood or paper. If the calibration samples are made of wood or paper they will expand, contract and absorb moisture similar to the way the tree-ring sample will respond to moisture changes. However, the calibration samples that are made of wood or paper are significantly more heterogenous than a plastic material.

4.5 Exposing the Tree-Ring Sample to a Radiation Source [Fig. 2(2-11 to 2-18)]

Intra-ring density measurements have been determined by radiation methods using either an isotopic radiation source or an X-ray tube. Most laboratories have selected the method using the X-ray tube as being more useful. With the X-ray generator, the researcher can more easily control the amount and frequency of radiation; and the stability of radiation output can be maintained over a longer period of time.

The next consideration is whether to measure intra-ring density indirectly through the use of film or by measuring the radiation

transmitted through the sample with a non-film detector. Each method has distinct advantages. For example, the film method permits a permanent image of the tree-ring sample to be made, and allows the researcher the opportunity to view the entire surface (usually transverse) of the specimen. Annotations, such as calendar-year dates can be made directly on the film, while aberrations of the wood sample, such as cracks, can be seen and avoided during densitometer scanning. Scan lines can be marked on the film so that duplicate or alternate scans can be made. In addition, photographic prints can be made for examination and publication.

One advantage of the direct-scanning method is that the film step is omitted, thus saving time of processing. However, the major advantage is obtaining a higher sensitivity to a given variation in sample density.

An X-ray densitometry facility that uses both methods (film and direct scanning) would be optimum. This system would take advantage of the best features of both methods. The method chosen for processing samples would depend on the nature of the samples and the requirements of the particular study.

The direct scanning technique is by design an in-motion system, whereby either the tree-ring sample or the radiation source is in motion during the irradiation of the wood.

If film is used, the system can be either "in-motion" (Echols 1970, Parker 1970, Parker and Jozsa 1973b, Jacoby and Perry 1981) or "stationary" (Polge 1963, Parker and Meleskie 1970, Parker and Jozsa 1973b, Lenz et al. 1976). For the in-motion film system, the wood

sample and film are traversed through a collimated beam of radiation with the radiation source held stationary; or the wood sample and film are held stationary and the radiation source is moved. The advantage of moving the radiation source is that this method requires a traversing carriage only one half as long as that required by the other method. The disadvantage of moving the radiation source is the increased weight of shielding over the weight of the sample and film. This makes constant-speed traversing more difficult to attain.

For the in-motion systems, the radiation source is placed near (~ 30 cm) to the wood sample and film, while for the stationary systems, the distance is about 2.5 m.

The in-motion system has many advantages over the stationary system for absolute density determination, except in the case of very small samples. The advantages of the in-motion system include:

1. The X-ray beam passes through a much shorter column of air or other medium;
2. Parallax is greatly reduced and the collimated beam of X-radiation passes through the sample parallel to the wood grain regardless of the length of the tree-ring sample; and
3. The amount of radiation reaching the wood sample over its entire length is more constant than radiation from a stationary source exposing film under a sample of comparable length (except for very short samples).

The problem of parallax, which results when the X-rays penetrate the wood at an angle other than parallel to the longitudinal tracheids, causes blurring of the film image and results in inaccurate intra-ring density measurements.

The stationary technique has some advantages for special applications (other than absolute intra-ring density determination). It is useful for producing picture images of large wood samples, such as tree stem discs; or for producing images of many samples at one time on a single sheet of film, as long as absolute density determination is not required.

An X-ray facility that uses both methods, in-motion and stationary, would be optimum.

4.6 Calibrating to Obtain Absolute Density Values [Fig. 2(2-19, 2-20)]

If accurate density values are to be obtained, it is necessary to calibrate the system using samples of known density and thickness. This is true regardless of the methods used (direct X-ray scanning or use of film; or in-motion technique or stationary technique).

Wood density is defined in a number of ways, but in this report we are referring to "basic density" as defined by Elliott (1970) which is calculated from oven-dry weight and green volume and is used synonymously with "bulk density" and "nominal specific gravity." It is usually expressed as gm/cm^3 or kg/m^3 .

The usual procedure used in calibrating an X-ray densitometry system for wood analysis is:

1. Measure, by gravimetric methods, a number of wood samples that have considerable range in density;
2. Prepare the "calibration blocks" for X-ray densitometry by cutting them to the same thickness as the tree-ring samples to be processed;

3. Radiograph the calibration blocks at the same time as "stepped density calibration wedges." Calibration wedges can be made of wood, a wood product (such as paper), or some other material (plastic). The combination of thickness and density of the selected material must have similar attenuation of X-rays as the wood sample to be analyzed.
4. Compare the film density (or X-ray transmission in the case of direct X-ray scanning) of the calibration block images with the stepped wedge images and assign "density equivalent" values to each of the steps on the stepped wedges.
5. Radiograph the calibrated stepped wedges with each tree-ring sample that is processed and assign density values to the intra-ring density profiles as determined from the stepped wedges.

If an on-line computer is used, it is easy to correct for non-linearity that may have been introduced during the irradiation of the samples, making of the radiographs, or at other steps in the procedure.

If only qualitative, relative density values are needed, or just a graphic illustration is required, it is not necessary to use calibration wedges. For most studies, including the determination of annual-ring mass, density calibration is required and is one of the most important steps in the process of X-ray densitometry of wood.

4.7 Scanning the Film on a Densitometer [Fig. 2(2-21 to 2-30)]

The X-ray densitometry of wood laboratories in existence have used custom-built densitometers (Parker et al. 1973b, Jacoby and Perry 1981)

or have modified commercially-available models (Polge 1965a, Lenz et al. 1976). A scanning densitometer that is adequate for accurate measurement of intra-ring density of wood, is a fairly complex and expensive instrument.

Some laboratories have used a double-beam recording microdensitometer manufactured by the Joyce-Loebl Company in England. However, modifications to this unit are needed for efficient use in tree-ring analysis. The desired modifications include:

1. A viewing screen that allows the operator to observe an enlarged image of the annual rings being scanned;
2. The signals from the densitometer (radial distance scanned and intra-ring density) must be in digital form (need an analog to digital converter).
3. The densitometer must be designed so the operator can easily change scan speed during operation.

If the densitometer is custom-built for tree-ring studies, these features can be built into the original instrument (Jacoby and Perry 1981, Jacoby, personal communication 1984, Parker et al. 1973b, 1980). The Joyce-Loebl instrument has been modified to provide a digital distance signal and to allow the operator good speed control through the use of a stepping motor. It also has been modified (Ernst Schär, personal communication 1984) to provide a good image of the rings being scanned through the use of a video camera and display unit.

Twenty years ago, when X-ray densitometry of wood was first being developed, digital computers adequate for operating a tree-ring densitometry system were quite expensive. Today they are not. The

practical way to operate this type of system today is with an on-line computer. This allows the inclusion of a number of useful features (Parker et al. 1980) such as:

1. Immediate conversion of voltage values to density values;
2. Immediate conversion of radial steps to ring-width factors;
3. Efficient calibration of density;
4. Automatic "triggering" of ring boundaries;
5. Storage of large quantities of data;
6. Rapid and controllable scanning speed and data recording;
7. Easy interfacing with peripheral devices such as keyboards, video screens, plotters, printers, storage device, etc.; and
8. Reduction in errors of data transcription by eliminating such steps as recording data manually from strip-chart recordings.

4.8 Other Considerations in Methodology

A number of decisions need to be made regarding form and rendering of data. One of these is the width of the step to be incremented across the annual rings. Common units (steps) used are 0.1 mm, 0.01 mm and 0.001 mm. The unit of 0.01 mm is most commonly used.

Another decision that needs to be made is whether to store "raw" density readings taken at the 0.01 mm units or refine these data during the on-line densitometer scan and record calculated width and density parameters as well as a standardized density profile (Parker et al. 1980).

The earlywood-latewood boundary needs to be defined and data recorded according to this definition. However, by recording the data

as described above (Parker et al. 1980), it is possible to redefine the boundary and recalculate the width and density parameters from the stored data, without having to rescan the sample on the densitometer.

4.9 Conclusion

Some alternative methods that have been used or can be used are illustrated in Figure 2. The options to be taken by the Oak Ridge National Laboratory in methodology will be determined by examining the merits of methods that have been used by other laboratories and by incorporating recent advances in technology.

5. EXAMPLES OF FOUR X-RAY DENSITOMETRY SYSTEMS

The techniques used at four currently operating wood laboratories are explained in this section. There has been an exchange of ideas concerning methodology between these laboratories and some of the techniques used are similar. These various techniques are examined and the more desirable features of each are highlighted.

5.1 Techniques in X-Ray Densitometry Used at the Western Forest Products Laboratory (now Forintek Canada Corporation), Vancouver, British Columbia, Canada

An X-ray scanning machine and a tree-ring scanning densitometer with a computerized data-acquisition system (Parker and Jozsa 1973b, Parker et al. 1973b, 1980) are used to produce intra-ring density

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Figure 2. Alternatives in methodology for X-ray densitometry of wood samples.

measurements of wood samples at the Western Forest Products Laboratory. The X-ray machine can be used to make conventional radiographs of wood samples from a distance of up to 7 feet (2.13 m), but the density values are obtained by using an in-motion radiographic technique. Air-dry, 2 mm thick transverse wood samples, usually extending from pith to bark, are used. These samples are prepared from 5 or 16 mm diameter cores or from wood blocks that are glued between two mounting sticks (Parker 1970) and machined to a smooth and uniform thickness by a twin-blade saw (Kusec 1972). Paper calibration wedges made from Douglas-fir mechanical pulp are placed on the bare (without paper envelope) X-ray film. A collimated beam of X-radiation (20 kVp and 2 mA) is emitted through a 0.33-inch-wide (8.38 mm) slit onto a tree-ring sample and film that are located 12.5 inches (31.75 cm) below the 0.3 mm focal spot of the X-ray generator. The specimen and film are supported by a 4-foot-long (1.22-m) carriage that travels at a uniform speed beneath the X-ray unit. A hydraulic system is used to provide constant-speed and vibration-free carriage traversing during a scan. The usual scanning speed is 2 inches (5 cm) per minute. The X-ray beam penetrates a tree-ring sample at the desired perpendicular angle, even for samples from large-diameter trees, when this narrow-slit scanning technique is used. The X-ray generator can be positioned at the desired angle if the cells in the tree-ring sample are not properly aligned.

A fine-grained, high-resolution film (Kodak Type-R single-coated industrial X-ray film) is used. An X-ray exposure is made in total darkness, but a safelight (Kodak Series 68 brown filter with a 25-watt

bulb) is used for film loading and developing. Film is processed with Kodak liquid X-ray chemicals and developed in a tank with automatic temperature controls and nitrogen-burst agitation.

The radiographs are scanned on a computerized densitometer. Intra-ring density and ring-width data are produced by the data-acquisition system. Density values for each 0.01 mm radial increment on tree-ring samples are produced in analog form on a chart recorder; or in digital form by a computer system that includes a mini-computer, a disc drive, a printer, a magnetic tape unit, and an X-Y digital plotter. The system can be programmed in a number of ways to produce intra-ring density plots, or integrate the data to derive values for such factors as earlywood width, latewood width, total ring width, minimum, maximum or total ring density, total sample density, mean latewood density, ring mass, etc.

A scanning densitometer was designed and fabricated specifically to scan radiographs of tree-ring samples and has the following useful features: (1) a xenon-arc lamp and regulating unit for very bright and stable illumination of the film image on the density-measuring photodiode and viewing screen; (2) an optical and light-intensity measuring system that permits the measuring of very small areas of tree-ring image on film (routinely 0.01 x 0.0625 mm or 0.05 x 0.0625 mm); (3) a viewing screen that allows an operator to monitor a 10 X image of a tree-ring sample during the scanning operation; (4) a stepping motor and film-transport system that moves film in exact 0.01 mm increments, in both forward and reverse directions, at speeds of 4 to 300 steps per second or at one step at a time.

An on-line computer makes the system very versatile. An operator can choose programs or select options to produce data in a variety of forms. Also, a computer can be used as a calculating instrument for comparison of tree-ring data and other data, such as weather records, hydrological data, silvicultural treatments, etc.

5.2 Techniques in X-Ray Densitometry at the Swiss Federal Institute of Forestry Research (SFIFR), Birmensdorf, Switzerland

X-ray densitometry methodology at the SFIFR was originally described by Lenz et al. (1976), and later with examples of the application of tree-ring analysis to time and climatic studies (Schweingruber 1983). The system is a stationary X-ray source utilizing film and calibration wedges to determine intra-ring density.

Cores from 4 to 12 mm thickness are affixed to a wooden mounting block, which is placed in a graduated sample holder from the cutting instrument to determine the grain orientation (angle of the cutting edge of the saw to the long axis of the fibers). For precision, high-speed cutting saw (double-blade) is used to prepare a core-strip of uniform thickness (1.2 ± 0.01 mm). Each core-strip is measured for thickness tolerance, catalogued for identification, and indexed for overlapping sections. The quality of the core-strip is such that no additional preparation (polishing, etc.) is necessary.

Prior to radiographing, each core-strip is placed in a Soxhlet apparatus to remove extractables. After clearing, the samples are climatized in the radiography laboratory to 10% moisture content. A density calibration wedge is placed in the film cassette with the

samples to be radiographed. A continuous-tone black and white photograph is taken of the samples before radiography as an important visual reference source during densitometric scanning to locate breaks, overlaps, and anomalies. A 10 minute exposure (12 kV and 20 mA) is made from 2.5 meters from a totally stationary system. Exposed films are developed at a local hospital.

The processed film is scanned with a modified Joyce-Loebl densitometer interfaced with a microcomputer. Scanning speed is controlled by a foot operated activator switch which permits the operator freedom to hand control orientation of the slit aperture. Each film is standardized on the basis of the exposure of the calibration wedge and the mean thickness of the sample set represented. Core samples are measured at 0.01 mm step increments. A remote TV camera and monitor assists the operator in varying the aperture (slit) orientation for the most accurate alignment and in avoiding anomalies. Data are transferred from the densitometer to a strip-chart recorder for visual record and across a microprocessor interface onto a floppy disc for digital record. Intra and inter-ring boundaries are identified where density variations exceed threshold limits. At the end of each ring the microprocessor automatically calculates data summaries, including maximum ring density, minimum ring density, earlywood width, latewood width, annual ring width, percent latewood, average earlywood density, average latewood density, average ring density, earlywood production, latewood production, and annual ring production.

5.3 Techniques in X-Ray Densitometry Used at the Forest Research Institute, New Zealand Forest Service, Private Bag, Rotorua, New Zealand

A beta-ray system, used to study wood density, was in operation from 1968 to 1979 at the New Zealand Forest Research Institute (Harris 1969). This has been replaced by a system that uses direct scanning with X-rays (Cown and Clement 1983). The newer system is similar to that described by Woods and Lawhon (1974) using an isotopic source of X-rays (^{55}Fe) but the New Zealand system includes complete computer control of the scanning operation.

In this direct-scanning technique, the 2 mm thick wood samples are irradiated from a collimated ^{55}Fe radiation source. An X-ray scintillation detector and pulse counter measure and record the radiation transmitted through the wood sample. The sample carriage, driven by a stepping motor, increments the wood sample a specified distance when a certain number of pulses are recorded. Operational scanning speeds range between 10 and 20 mm/minute. Normal increments are 0.1 mm but this can be changed if desired. The effective slit size on the wood sample (the area that is being interrogated at any time) is 2.0 x 0.1 mm.

The wood samples used in this system are 5 mm diameter increment cores or radial blocks machined to 5 mm x 5 mm. They are resin-extracted by refluxing with methanol in a Soxhlet apparatus for 24 hours, then conditioned to 10% moisture content by storing in a controlled atmosphere (25°C and 50% relative humidity). Drying racks are used to prevent warping of the samples. Before scanning on the densitometer, they are cut to a uniform 2 mm thickness.

An on-line computer is used in calibrating the system and in the direct scanning to determine intra-ring density. It is noted that the degree of attenuation of the collimated beam when passing through wood depends on: (1) sample thickness, (2) sample moisture content, (3) sample density, and (4) the attenuation coefficient for wood. If thickness, moisture content and attenuation are known, density can be calculated.

The attenuation factor is determined for each group of wood samples by using a number of short (20 mm) lengths of wood from each batch to be scanned. The basic density of these calibration samples is determined by the standard maximum moisture content method (Smith 1954).

Data acquisition and data processing are handled by computer programs under the control of the densitometer/computer system operator. Intra-ring density data are displayed in digital and graphic form on a video screen and by a printer/plotter.

Cown and Clement (1983) suggest that there may be some advantages of replacing the ^{55}Fe radiation source with a small X-ray generator as described by Jacoby and Perry (1981). This would eliminate the problems introduced by the short half-life of ^{55}Fe of reducing scanning speed over time and requiring its replacement at two-year intervals. In 1964, Foster et al. (1964), developed a sophisticated direct scanning technique for reactor fuel plants at ORNL.

5.4 Techniques in X-Ray Densitometry Used at the Lamont-Doherty Geological Observatory, Palisades, New York

The X-ray densitometry system being used at the Tree-Ring Laboratory at Lamont-Doherty Geological Observatory is described by

Jacoby and Perry (1981). X-ray negatives are made of wood samples and calibration wedges on an in-motion X-ray scanning device that was designed and built for tree-ring density analysis. The radiographs are scanned on a custom-built, computerized densitometer to extract the intra-ring density data.

The tree-ring specimens analyzed vary from 1 mm to 2 mm in thickness and are cut to a uniform thickness by a router-planner device built for this purpose. The wood samples are resin-extracted and X-rayed in the air-dry condition. The calibration wedges are constructed of developed but unexposed X-ray film and range from one to five sheets in thickness. Density is expressed in relative rather than absolute terms.

Radiographs of the wood samples are produced by the in-motion techniques, even for tree-ring specimens up to 40 cm in length. A stepping-motor, lead-screw mechanism is used to advance the wood samples and film through a collimated beam of X-rays. A double-slit system is used to collimate the beam such that the area exposed to radiation at one time is 1 mm by 10 mm in size. The distance from the X-ray source to the specimen is approximately 15 cm. "Soft" X-rays are used that are generated at settings ranging from 20 to 30 kVp and 10 to 24 mA. The step increments are 0.005 mm and the scanning speed is variable from 0.5 to 4.0 mm/sec. The speed commonly used is 2 mm/sec.

This in-motion X-ray system has several advantages over the hydraulic in-motion system described by Parker and Jozsa (1973b) and Parker et al. (1980). The Lamont-Doherty system is less bulky and

scanning speed is more easily controlled. One disadvantage is that it is not designed to produce radiographs of large wood samples for picture-image analysis.

The lead-screw and stepping-motor principal also is used for the custom-built microdensitometer. The densitometer has a moderately large (approx. 15 cm) viewing screen that permits the operator to see enough of the image of the wood and calibration wedges to select a proper scan line and avoid aberrations (G. Jacoby, personal communication, 1984). The densitometer is operated on-line with a computer which permits good operational control and extensive data storage.

6. APPLICATIONS OF X-RAY DENSITOMETRY IN DENDROCHRONOLOGY

Tree-ring analysis may be considered to have been applied in three major ways: (1) the dating of events; (2) the study of climate and other aspects of the environment; and (3) in wood-quality studies. X-ray densitometry of wood may be considered as a technique used in the field of dendrochronology. From the time dendrochronology was established as a field of scientific investigation early in the 20th century, it has been applied in many ways, but until the past two decades, the techniques used were almost exclusively tree-ring width analysis.

The applications of ring width analysis and intra-ring density analysis are not mutually exclusive. Ring density analysis can be applied generally in all of the ways that ring width analysis has been applied. In addition, density analysis (X-ray densitometry in this

case) can be used in some studies where ring width analysis is of limited value.

The works of Douglass (1919, 1924, 1935, 1937) and Schulman (1956, 1958) discuss the applications of dendrochronology to climate, cycles and dating during the first half of the 20th century. Reughton (1962) has reviewed the applications of tree-ring analysis to 1962. Applications of dendrochronology in Canada have been outlined by Hoeller (1982). Applications of tree-ring dating have been reported by McGinnies (1963) and Bannister (1963) for the southwestern United States and by Parker et al. (1984a) for Canada and the northwestern United States. Application of tree-ring studies to climate is reported by Fritts (1972, 1976).

6.1 Dendrochronology as Applied to Dating, Wood Quality, and Environmental Studies

Tree-ring analysis has been used for many years in the United States and Europe to date the construction of prehistoric dwellings. Other archaeological items, such as animal traps, bark-stripped trees, and logs and trees from which planks and canoe-construction logs were removed, have been dated by the tree-ring method. Dendrochronology has been used to date historic structures in Canada and Europe. Wooden art objects also have been dated by this method.

Driftwood has been dated to record the events of lake levels created by a surging glacier, raised beaches and the change in the course of a river. Tree rings have been used to date glacial moraines, glacial trim lines, rates of alluviation, flooding, ice jamming, forest

fires, volcanic eruptions, timberline migration, stream erosion and landslides. Annual ring analysis also has been used in forensic investigation to identify wooden objects associated with theft and murder cases and to date a bonfire that was used to consume the body of a murder victim (Parker and Jozsa 1980).

The quality of wood depends on tree species and the environment in which the trees grew. Dendrochronology has been used to study the relationship between wood quality and environment. For example, the effect of silvicultural treatments, such as fertilization and thinning have been assessed through tree-ring analysis.

One of the most important applications of dendrochronology is to provide proxy climatic data, e.g., reconstructed temperature and precipitation records. Some of the items mentioned above as "dated events" also can be considered aspects of the environment. Dendrochronology has been used to provide detailed information about river runoff, lake levels, landslides, flooding, ice jamming, landforms in permafrost regions, radioisotopic composition of the atmosphere, insect infestations of forests, forest biomass, water supply, snowmelt, and glacial movement. A preliminary investigation has been conducted to determine if there is a relationship between volcanic eruptions and tree growth.

6.2 Tree-Ring Studies in Canada

X-ray densitometry has been used in most of the tree-ring studies conducted in Canada but some have involved only ring counts or ring width analysis. An X-ray densitometry of wood facility was in use at

the Geological Survey of Canada in Ottawa, Ontario from 1968 to 1970 (Jones and Parker 1970, Parker 1970, Parker and Meleskie 1970). This system was used, in a joint study by the Geological Survey of Canada and Inland Waters, to demonstrate the strong relationship between tree-ring maximum density of Engelmann spruce (Picea engelmannii) growing at high elevations in the Rocky Mountains of Alberta, and August mean maximum temperature. Maximum density was also correlated highly with August river runoff (Parker and Henoch 1971). It was shown that, although there was little ring-to-ring variation in width, there was marked and consistent variation in the maximum density parameter.

In other studies on white spruce (Picea glauca) or black spruce (Picea mariana) conducted in the Northwest Territories (Parker 1976), in Quebec (Parker et al. 1981e) and in Manitoba (Parker et al. 1983), it was determined that this strong relationship between tree-ring maximum density and summer temperature (particularly August) exists for the high-latitude spruce trees as well as for the high-elevation spruce.

In these studies, using an X-ray densitometry facility that was established in Vancouver in 1971, it was determined that there is a positive but poor correlation between ring width and summer temperature ($r = 0.25$) and a strong correlation between maximum density and summer temperature ($r = 0.7$ or higher). X-ray densitometry was required to obtain the density data.

In a study involving only ring counts (Heginbottom and Parker 1970), dates were obtained for moraines of several glaciers in British Columbia.

In 1971, 1972 and 1973, a tree-ring study was conducted along the possible pipeline route of the Mackenzie, Liard and South Nahanni Rivers, Northwest Territories (Parker 1971, 1972, Parker and Jozsa 1973a, Parker et al. 1973a). A combination of ring counts, ring-width analysis and ring-density analysis was used in a number of applications. Landslides, ice jamming and flooding were dated. Tree-ring chronologies were built and related to climatic factors (Parker et al. 1973a, Parker 1976). Tree-ring analysis was used to determine rates of alluviation at three locations (Parker et al. 1973a) and tree-ring characteristics were related to permafrost conditions and ice-induced landforms (Hench et al. 1975).

X-ray densitometry has been used to investigate the interaction of environmental and genetic factors that influence tree growth (annual ring formation). Annual ring profiles of hardwood and softwood have been compared (Cown and Parker 1978). Intra-ring features of Douglas-fir from five different provenances in Oregon, Washington and British Columbia were compared and it was shown that the tree-ring characteristics are more strongly influenced by environmental factors than by differences in genetic factors (Cown and Parker 1979). Annual ring width and density patterns in red alder (Parker et al. 1979) were examined by radiography and it was illustrated that both false rings and absent rings may be features of the same tree-ring series, leading to inaccurate age determination.

The effect of climate on forest production (biomass) has been the subject of several studies (Parker et al. 1981c, Jozsa et al. 1982).

The good quality of the radiographic image has been used to detect crystalline lignans in western hemlock (Parker et al. 1974a), examine annual layers in fish bones (Jozsa and Parker 1981) and measure density profiles in waferboard (Steiner et al. 1978).

In one study (Heger et al. 1974), it was determined that for Douglas-fir at one site in British Columbia, annual ring density is determined to a larger extent by cell-wall thickness than it is by cell diameter.

The effects of the silvicultural practices of thinning and fertilization on intra-ring characteristics and pulp yield have been studied in detail by X-ray densitometry (Parker et al. 1976, Johnson and Parker 1978a, 1978b).

X-ray densitometry has been used to study the effect of air pollution on trees in British Columbia (Parker et al. 1974b), Montana (Jozsa et al. 1981) and Alberta (Parker et al. 1981a). Air pollution usually has the effect of reducing ring width and maximum density, but increasing minimum density.

The possible relationship between volcanic eruptions in the 19th century and tree growth has been investigated (Parker 1983). Some relationship was suggested by the reduced growth in 1816, the "year without a summer" and the Tambora eruption in 1815 but this topic has not been studied extensively enough to draw any conclusions. No strong and consistent relationship was discovered between tree growth over an extensive area and volcanic activity.

Wood samples, containing more than 1000 annual rings, have been submitted, along with intra-ring density data, to several radioisotope laboratories for calibration purposes and other studies (Parker and Jozsa 1974, Parker 1977, Parker et al. 1978, Bramhall and Parker 1978).

Intra-ring density data were provided to the Canadian Atmospheric Environment Service for a drought study (Parker 1980b).

Dendrochronology has been used to date driftwood in the Yukon (Parker 1980a, Clague et al. 1982), in the Northwest Territories (Parker 1982) and in Manitoba (Hudson Bay) (Parker et al. 1983). This dating, of these high latitude spruce and larch samples, was done by using X-ray densitometry and computer crossdating (Parker 1967, 1970); and it may not have been possible by using ring width alone. These studies provided information about a lake formed behind a surging glacier, the date of the change in the course of a river, and dates of raised beaches.

Some archaeological sites have been dated by the tree-ring method in the Yukon (Parker et al. 1984b), and in British Columbia (Stryd 1979, Jozsa et al. 1980a, Jozsa et al. 1980b, Parker and Johnson 1975, 1977, Parker 1984b). Usually, X-ray density was used and the best parameter for dating purposes has been found to be maximum ring density. For the very dry sites, however, ring width is a better parameter to use for dating.

Recently, ring widths have been used to date a number of historic log structures in British Columbia (Parker 1984a, Parker et al. 1984b, 1984c). These buildings are located in dry areas where the trees are apparently responding more to moisture supply than to variations in temperature.

A general conclusion, drawn from observations on a number of studies, is that trees growing in high-elevation and high-latitude environments, respond in their annual ring series most to variations in temperature reflected in maximum ring density; and trees grown in semi-arid conditions respond most to ground moisture as it influences ring width. X-ray densitometry can be used to measure both ring width and ring density parameters, a prerequisite for any intensive and extensive study using tree rings to study environmental conditions.

The diversity of the many applications of dendrochronology illustrates the complexity of using tree rings to answer questions about the environment. However, since trees are widely distributed, long-lived and sensitive recorders of environmental conditions, they can provide the answers regarding the question of whether or not there is a response of tree growth to the fertilizer effect of elevated CO₂.

7. ENVIRONMENTAL AND GENETIC FACTORS AFFECTING TREE GROWTH RESPONSES

7.1 Tree Response

Tree growth is a product of the tree's environment and its genetic composition. This growth varies with geographic location, species and other factors. The response of a tree to its environment can be used to study wood quality, quantity and the nature of the environment.

There are a number of forms of growth response that can be measured. These are such things as: tree height, tree diameter, crown form, annual ring width and density components, age growth trend, reaction wood, scars, traumatic resin canals, false annual rings, etc. Trees respond to environmental conditions in so many ways, and because

this response varies with geographical location and different species, it is necessary to understand all of the factors involved even though a particular project is concerned with only one factor.

We are concerned with whether there is a discernible effect of elevated levels of CO_2 on tree growth. However, the other factors affecting growth need to be understood and their influence considered in calculating the CO_2 effect. The tree growth characteristics to be studied in this project are basically those related to annual ring parameters, particularly ring mass. In order to draw valid conclusions about CO_2 effect from the data, the influence of those factors that are not directly related to CO_2 concentration, such as fire damage, tree competition, temperature, precipitation, etc., need to be eliminated from the data series.

This section outlines some of the environmental and genetic factors that affect tree growth and consideration is given regarding what can be done to produce data series that will provide information on the hypothesized effect of elevated CO_2 on tree growth.

7.2 Direct Climatic Factors

Climate can be considered as it varies from one geographic location to another or it can be considered as it varies through time as year-to-year variation, short-term fluctuations or long-term trends. All of these are reflected in annual ring variation or other aspects of tree growth. The relationships between climate and tree growth can be determined by comparing weather data series of factors, such as temperature, precipitation, and solar radiation, with tree-ring series.

Methods that provide intra-ring width and density data, such as X-ray densitometry, are the most useful for this purpose. As noted previously, ring width may provide the best information about precipitation and ring density may furnish the best information about temperature. The relationship between solar radiation and tree-ring parameters has not been extensively investigated because the solar data records are not long. However, it might be expected that solar radiation should correlate highly with tree-ring data.

It has been demonstrated (Parker 1976) that each of the various intra-ring variables, i.e., earlywood width, latewood width, total ring width, minimum ring density, maximum ring density and mean ring density, correlate differently with monthly temperature and precipitation records. Because of this varied response to climate, the intra-ring variables provide detailed proxy climatic data for intra-annual fluctuations, year-to-year fluctuations, short-term fluctuations and long-term trends.

7.3 Natural Disturbance

In addition to the direct climatic factors mentioned above, tree growth may be affected by "natural" environmental factors. A list of some of these would include: competition with other plants, frost damage, wind damage, scarring (floods, slides, animals), landslides, fire, earthquakes, lightning, insect and fungal damage, soil type, plant succession and volcanic activity. Each one of these factors could be dealt with extensively, but it is sufficient here to note that each one of them can affect tree growth either by reducing growth by

damaging the tree or accelerating growth by creating more favorable growth conditions. It may be a complicated situation in that, for example, a fire may cause damage and reduced growth to some trees but result in a release effect for other trees. Some of these factors, such as forest fires, frost damage, floods, landslides, and lightning may be related to climate, but they do not provide the consistent periodic climatic records as provided by temperature and precipitation data.

7.4 Human Disturbance

It has been only in very recent times that the human species has had the power to drastically alter the environment on earth. The effect of "human" disturbance now may exceed that of "natural" disturbance on the forest environment. The impact of man on the environment has accelerated dramatically in the 19th and 20th centuries as a result of industrialization and population increase.

One result of human activities has been an elevated level of CO_2 in the atmosphere. In order to use tree growth to measure this, it is necessary to consider other factors related to human activities that also affect tree growth. Some of these are: logging, road construction, burning, agriculture, grazing of domestic animals, air pollution, urban development, water diversion, silvicultural practices, introduction of exotic species to an area and dam construction. Again, it should be noted that each one of these factors could be dealt with extensively but it is sufficient to state here that each factor should be considered within the context of the tree-ring site being sampled.

and its influence on tree growth accounted for when analyzing tree-ring data to determine the possible effect of elevated levels of CO₂.

7.5 Contrasting Factors or Conditions

One approach for sorting out the respective influence of various environmental and genetic factors on tree growth, is to examine trees growing under contrasting conditions. For example, if it is suspected that trees may respond differently to some factor at different elevations, the trees growing at one elevation can be compared with trees growing at a different elevation.

7.5.1 Environmental Contrasts

In collecting tree-ring samples at many sites, it may be observed that there are marked micro-site differences. For example, trees growing on north-facing slopes may be quite different from those growing on south-facing slopes, or trees growing near a stream may be different from those growing away from the stream.

The contrasts between local, regional and global effects should be considered. The grouping of data sets from many, widely-separated sites may help in segregating the global effect of CO₂ changes from local and regional effects of climate or other factors.

The growth of northern tree line trees should be compared with trees growing on the southern border of the Boreal Forest in order to determine the effect of latitude on growth. The effect of elevation and the respective effect of temperature and precipitation should be determined by comparing tree-ring series of trees from different elevations.

Other comparisons that need to be made are coastal and interior sites, dry and wet sites, tropical and temperate sites, and sites near or displaced from large bodies of water such as the Great Lakes.

7.5.2 Genetic Contrasts

One method that can be used to separate the influence of genetic factors from environmental factors is to compare data from trees at one location that are grown from seeds from other locations. This was done in analysis of tree-ring samples from five Douglas-fir provenances from the Pacific Northwest (Cown and Parker 1979). In this case, it was determined that intra-ring density and width data were affected to a larger extent by geographic location (environment) than by seed source (genetics).

In determining what influence different genetic factors may have on intra-ring data, species and sub-species differences should be considered as well as differences for the same species within sites and between sites.

7.6 Conclusion

In order to isolate and measure the effect of CO_2 increases on tree growth, the other factors that affect tree growth must be understood, measured and eliminated. Damaged trees should be avoided whenever possible. It may be possible to locate trees that are relatively unaffected by climatic factors but markedly affected by CO_2 concentrations.

One approach to determine if there is a global effect of elevated levels of CO_2 on tree growth, is to examine the tree-ring series derived from many sites at widely-dispersed locations.

8. PROCEDURE USED AT ORNL

8.1 Introduction

The approach followed at ORNL is to use a number of intra-ring width and density parameters in an effort to detect the hypothesized effect of elevated levels of CO_2 on tree growth, but primary attention will be given to ring mass. Ring mass represents the actual amount of wood substance produced on the stem of the tree and both ring-width and ring-density are necessary to derive the product.

The ultimate objective is to determine in quantitative terms, the amount of carbon that may be removed from the atmosphere and incorporated in forest trees. Ring mass is a better expression of this than either ring-width or ring-density alone. Several studies illustrate the use of both ring-width and ring-density (and their product, ring-mass) to measure the effects of environmental factors on tree growth. One study (Parker et al. 1976) was concerned with the effect of the silvicultural practices of fertilization and thinning on tree growth and pulp yield, and the other study (Parker et al. 1974) was concerned with the effects of air pollution on tree growth. Both of these studies required the use of both ring-width and ring-density in evaluation of the effect of these environmental factors on tree growth. Also, ring-mass (labeled "ring weight") is evaluated by Parker et al 1976, as it reflected the various treatments of fertilizer

application and thinning. The same type of quantitative data is required in assessing the hypothesized effect of increased atmospheric CO₂ on tree growth.

8.2 Sites, Samples and Archive Data Available for Early Analysis

The tree-ring chronology sets will represent a number of parameters: total ring width, maximum ring density, total ring density, ring mass, etc. An effort will be made to produce the best qualitative data for the objectives of this project. To do this, attention will be given to field collection, data acquisition, data processing and analytical methods.

The sites and individual trees selected for study are those that are least affected by factors such as forest fires, industrial pollution and other perturbations that are not the primary concern of this investigation. Coastal Douglas-fir and perhaps other conifer stands in the northwestern U.S. and in British Columbia are among the most plausible sites for an early test of the hypothesized CO₂ effect. Considerable ecological and stand data on these forests already exist, and there is a suitable archive of core data which can be analyzed. Other high latitude sites (Northwest Territories) where the length of the growing season is governed more by temperature than water stress, may provide suitable data. Cores or data from several locations also are available for early analyses. Available data will be analyzed concurrent with processing of new samples.

Archive data (magnetic tapes) from 49 tree-ring sites have been obtained from Public Archives, Ottawa, Canada. These data sets represent research of M. L. Parker and associates while at the Western Forest Products Laboratory in Vancouver, British Columbia. All of the tapes contain data from the Tree Ring Input Program, TRIP (Parker et al. 1980) and consist of the following parameters: distance from pith (RSX), ring width (RW), earlywood width (EW), latewood width (LW), ring density (RD), earlywood density (ED), latewood density (LD), minimum density (MND), and maximum density (MXD). In addition there is an intra-ring density profile for each ring consisting of 100 measurements. The TRIP chronologies are essential to calculate wood production (ring mass) and ring volume. One-third of the site tapes include summary chronologies (indices) of short-term fluctuations greater than 10 years in length and year-to-year fluctuations; both derived from a weighted running mean or the expected growth trend. A complete listing by site location, tape number, and species are identified in Table 1.

Among the initial samples to be processed at Oak Ridge are sections from two woody species, loblolly pine (Pinus taeda) and sweetgum (Liquidambar styraciflua), which were grown in the Duke University Phytotron at different atmospheres of carbon dioxide (350, 500 and 650 ppm), but constant temperature, soil moisture, relative humidity and light intensity. Each species is represented by 15 seedlings cultured over several growing seasons. The samples are of sufficient length to permit replicate samples from individual trees. The samples will be analyzed by X-ray densitometric techniques and the results compared for evidence of a growth response to the different CO₂ regimes.

Table 1. Listing of archival tapes (number), species, and site locations for 49 sites in Canada and the northwestern United States. The tapes were received from Archives Branch, Public Archives, 395 Wellington Street, Ottawa, Canada.

Site location	Tape number	Species
1. Kwinkwaga Lake, Ont.	PA9996	White spruce
2. Simons Harbour, Ont.		Red pine
3. Iron Lake, Ont.		Red pine
4. White Lake, Ont.		Red pine
5. Swan Hills, Alta.	PA9995	White spruce
6. Kananaskis, Alta.		Douglas-fir
7. Gang Ranch, B.C.		Douglas-fir
8. Kitimat, B.C.	PA9994	Western hemlock
9. Kitimat, B.C.		Western red cedar
10. Haney, B.C.		Douglas-fir
11. Haines Junction, Y.T.	PA9993	White spruce
12. Canyon Mountain, Y.T.		White spruce
13. Wolverine Plateau, Y.T.		White spruce
14. Decoeli Mountain, Y.T.		White spruce
15. Montana Mountain, Y.T.		White spruce
16. Annie Lake, Y.T.		White spruce
17. Dolomite Lake II, N.W.T.	PA9989	White spruce
18. Aklavik, N.W.T.		White spruce
19. Fort McPherson, N.W.T.		White spruce
20. Cariboo Hills, N.W.T.		White spruce
21. Arctic Red River, N.W.T.		White spruce
22. Parson, B.C.	PA9988	Douglas-fir
23. Vermont/Burns, B.C.		Douglas-fir
24. Crystalline Creek, B.C.		Douglas-fir
25. Bugaboo, B.C.		Engelmann spruce
26. Fort Resolution, N.W.T.	PA9985	White spruce
27. Prelude Lake, N.W.T.		White spruce
28. Fort Vermilion, Alta.		White spruce
29. Olympic Peninsula, Wa.		Western red cedar
30. Silver City, Yukon	PA9983	White spruce
31. Silver City, Yukon		White spruce
32. Hesquiat, B.C.		Western red cedar
33. Pemberton, B.C.		Lodgepole pine

Table 1. (continued)

Site location	Tape number	Species
34. Olympic Peninsula, Wa.	PA9981	Douglas-fir
35. Alsek Driftwood, Y.T.		White spruce
36. Kitwanga, B.C.		Western hemlock
37. Shawnigan, B.C.		Douglas fir
38. Stave Lake, B.C.		Yellow cedar
39. Suwannee River, Man.	PA9977	White spruce
40. Suwannee River, Man.		Black spruce
41. Beautiful Lake, Man.		Black spruce
42. Root Lake, Man.		Black spruce
43. Riding Mountain, Man.		Black spruce
44. Churchill River, Man.		Black spruce
45. Dawson, Y.T.	PA9976	White spruce
46. Nago, Y.T.		White spruce
47. Whitehorse, Y.T.		White spruce
48. Lake Louise, Alta.		Engelmann spruce
49. Columbia Icefield, Alta.		Engelmann spruce

In addition, comparisons between ring-width, ring-density, and ring-mass will be made to determine which parameter provides the least variable chronology, and whether there is evidence for the postulated CO_2 effect. Comparisons will be made within a species (loblolly pine) from several stands of a single site (Tall Timbers Research Station, Leon County, Florida) and between species (loblolly, long leaf, and short leaf pine) at the same site. The Tall Timbers site was selected because it is remote from industrial pollution, has adequate meteorological data, and contains stands of old trees (up to 350 years old). For the between species comparison, samples consist of duplicate cores from 15 trees of each species. The within species comparison consists of cores from 15 trees from each of three stands on the Tall Timbers properties. Primary attention will be directed to assessing wood production (ring mass) for evidence of a CO_2 effect.

8.3 Sample Collection, Preparation, and Processing at ORNL

At Oak Ridge a computerized scanning densitometer system is currently operational in the Non-Destructive Testing Laboratory of the Metals and Ceramics Division. Scientists in that division, expert in radiography and densitometry, are working in conjunction with the Environmental Sciences Division in utilizing tree rings to ascertain if evidence of a growth response to increasing atmospheric CO_2 is contained in the tree-ring time series. As noted in Figure 2, several alternatives were available for analyzing tree rings. Because the system at the Oak Ridge National Laboratory utilizes existing equipment, certain modifications in techniques and instrumentation were necessary.

The basic technique of X-ray densitometry is to produce a negative image of a traverse cross section of a wood core sample by collimating a beam of X-radiation through the wood onto a sheet of X-ray film. The film is developed and scanned on a densitometer that converts the film density of the wood image to digital form, representing the intra-ring density variations and the width components of the annual rings. The methodology used at ORNL is depicted in Figure 3. The following text provides details of each step.

Increment borers with from 4 mm to 12 mm diameter bits are available for sample collection. For our purpose we have found that a 5 mm diameter core is best for machining to a uniform thickness for radiography. Duplicate cores from opposite sides of the tree bole are extracted at ~ 1.4 m above ground level. Care must be exercised in sample collection to insure that the borer is held perpendicular to the long axis of the xylem (wood) cells. If the borer is held at a slight angle from perpendicular, errors in both ring-width and ring-density measurements will be introduced in the data. To facilitate proper orientation, an adjustable bore guide, and holder is used to stabilize the borer and to decrease core warping and twisting.

The extracted core is placed in a drinking straw for safe keeping, and coded for identification. Tree diameter is measured. This information is important to determine distance to pith and to facilitate computation of ring-volume and ring-mass (wood production). Any obvious site characteristic or individual tree feature (canopy position, competition, evidence of fire, etc.) is recorded. Immediately upon arrival at the laboratory, each individual core is

[illegible]

Figure 3. Flow diagram of procedures used in X-ray densitometry of tree cores. Highlighted steps indicate the alternatives used at ORNL.

placed between two, grooved drying blocks (wood construction) to prevent bending and distortion during the drying period. The blocks are secured with tape and allowed to dry (~ 14 days) at room temperature.

Most coniferous woods possess some resins or extractives which may interfere with sample cutting and influence density measurements. Some extractives include waxes, fats, resins, phytosterols and nonvolatile hydrocarbons, and are extractable with dichloromethane. Additional extractives, such as low molecular weight carbohydrates, salts and other water soluble substances can be removed by an ethanol-benzene mixture. The ethanol-benzene mixture contains 2 parts benzene to 1 part ethanol (95%). The extraction process can be carried out on the core or on the strip after the core has been cut. Our experience suggests that extraction should be completed prior to machining the sample, since some of the extractives are crystalized from the heat of friction and stick to the saw blades. The extractor is a Soxhlet apparatus consisting of an extraction flask, extraction tube, and condenser. The boiling rate of the solvent is adjusted to 6 cycles per hour for a total of 24 to 30 cycles (4-5 hours). After drying, the cores are ready for machining to a uniform thickness.

The cores are glued onto wooden mounts with the tracheids lying perpendicular to the length of the mounting board. The mount is placed in a sample holder from the cutting machine, which can be adjusted to correct for deviation of tracheid orientation relative to the cutting plane. Inspection of the cores under a microscope reveals the deviation in orientation. In the event of core twisting during

collection, the sample can be subdivided to minimize the twist. The deviation of desired tracheid orientation is noted and scribed on the mounting stick.

Mounted cores are secured in the saw sample holder at the corrected angle and cut to a uniform thickness. The cutting machine is a variable, high-speed precision saw, consisting of twin-blades (carbide tip) separated by a divider of appropriate thickness. For our purpose, strips 1.2 mm thick are desirable. Cutting precision of the saw is ± 0.01 mm. Best results are obtained at a cutting speed of ~ 2000 rpm. After cutting the strips are measured throughout their lengths for quality control. An advantage of the large diameter (12 mm) cores is that one can cut more than one strip, thus reducing the possibility of eliminating a specific core due to improper thickness.

Core strips are marked for identification with an ink that will not impart error during radiography. In the case where a core had to be subdivided because of excessive twist, it is necessary to identify and mark by notch coding on the strip, those areas of overlapping for continuous scanning with the densitometer. The strips are placed in a exposure cassette and a black and white, continuous tone photograph taken. The black and white photo is an important reference during densitometer scanning, especially where there are overlapping sections of a core. The exposure cassette contains an internal step wedge and a continuous wedge of cellulose acetate for calibration. Prior to radiography the strips are acclimatized to the environment of the X-ray unit (20°C and 50% relative humidity to assure constant hygroscopic

conditions). The samples are placed on Kodak RP/M film and radiographed in a helium atmosphere from 10 to 25 kv depending on sample thickness.

Inter- and intra-ring properties are determined from the processed X-ray films using a Joyce-Loebl microdensitometer interfaced with a microcomputer. The densitometer measures density by passing a beam of light from a narrow slit through the X-ray film, and recording the brightness. Each film is individually standardized on the basis of the exposure of a step wedge and a continuous wedge of cellulose acetate with each set of core strips. Calibration of the densitometer for the difference between optical densities as measured and wood densities is achieved with the radiographed wedges. Core samples are measured for intra-ring properties every 0.01 mm, beginning with the current season's ring. Data are transferred from the densitometer to a strip-chart plotter for a visual record and across a microcomputer interface onto a floppy disc for a digital record. At the end of each ring the microcomputer calculates data summaries for several parameters: maximum ring density, minimum ring density, earlywood width, latewood width, annual ring width, percent latewood, average earlywood density, average latewood density, average ring density, earlywood production, latewood production, and annual ring production.

8.4 Method Used for Standardizing and Summarizing Tree-Ring Data

A major problem that dendrochronologists face in dealing with most tree-ring data is the removal of non-climatic trends, such as the growth trend, and averaging these data in some standard form without inadvertently removing features that should be retained.

The "raw data" produced by the X-ray densitometry system described here consists of: (1) ring-width values in 0.01 mm units, and (2) maximum ring-density values in g/cm^3 measured at 0.01 mm increments along the scanned portion of a tree-ring sample. These raw data are "standardized" by converting them into indices (ratio of observed value to fitted trend, yielding values with a mean of 1.00) by removing the growth trend (and sometimes other trends or fluctuations). The standardized data (indices) for all samples are then "summarized", or averaged, to produce a summary or "master" chronology for the site.

This procedure is illustrated in Figure 4. The "A", "B" and "C" components are described: "A" is the growth trend; "B", the short-term fluctuations greater than 10 years in length; and "C", the year-to-year variations. Various data processing programs are used to produce an "A", a "B", a "C" and a "B & C" chronology from the raw data of each tree-ring sample. These data are then averaged with data from other tree-ring sample series to produce the summary chronologies.

If tree-ring data are averaged without removing the growth trend, non-climatic fluctuations related to the age of the tree will be included in the chronology. Therefore, it is essential that the growth trend be removed. However, variation due to climate may be removed inadvertently, if proper techniques are not used in this procedure.

One method for removing the growth trend (the "A" component) from tree-ring series, utilizes a digital-filter with a length of 60 years (Parker 1970). This method is designed to remove the growth trend and the non-climatic surges in growth, such as tree growth release after a

Figure 4. The "A", "B", and "C" components of a tree-ring series. Data used in this example are ring width values of a white spruce tree from Cri Lake, Quebec (from Parker et al. 1984a).

forest fire. Tree-ring indices (in the form of our "B & C" chronology) are produced by calculating deviations from a growth-trend line through the raw data values.

The "B and C" chronologies are obtained from the tree-ring indices (the "B & C" chronology). This is done by using a digital-filter technique with a length of 13 years (Parker 1970). The "B" chronology is the estimated curve which is a weighted running mean. Deviations from this line are the year-to-year fluctuations, or the "C" chronology. The "C" chronology type has proven to be the form most useful for dating purposes.

8.5 Procedure for Determining Ring (Mass) Production

Procedures for determining the mass of wood in a ring segment by simultaneous measurement of ring width and wood density will be employed in attempts to identify differences of growth patterns over the past several centuries. Ring mass takes into account both the volume and the density of the wood produced in any one growth year. To calculate ring mass or weight requires a measure of ring width and radius along with an average ring density. Ring width and density are primary parameters derived from core measurement already discussed. Ring radius can be determined either from tree diameter taken at the position and time of core extraction or from the estimated distance from pith to the innermost ring recorded. Total ring area, A_t , at age or year t , is given by:

$$A_t = \pi [(r_t + w_t)^2 - r_t^2] \quad (1)$$

where r_t is the radial distance from pith to the inside ring boundary and w_t represents width of ring at age or year, t . Volume is estimated from ring area based on a 1 cm thick cross-section. The same procedure can be used to formulate volumetric growth of earlywood and latewood production. The mass or weight (g) of ring wood produced or of its earlywood and latewood components can be calculated as the product of average wood density (g/cm^3) and volume (cm^3). Figure 5 shows a time series of calculated ring mass for a single tree of Douglas-fir from interior Canada. It demonstrates the yearly and long-term variability of ring mass data that must be dealt with in data analysis. From this sample illustration, a gradual increase in ring mass following 1870 may reflect the CO_2 enhancement effect. However, data from a single tree is certainly insufficient for drawing any such conclusions; and many other factors of historical and/or environmental origin may also contribute to such trends.

8.6 Removal of the Influence of Non- CO_2 Enhancement Factors

The statistical problem is to detect an hypothesized gradually increasing trend in tree growth since about 1860 (or perhaps 1890). Tree-ring widths almost universally show a decreasing trend with age. Data on ring mass will mostly be used, but determination of mass depends on measurement of ring width. Continuous trends generally present a more difficult detection problem than step function responses.

The normal declining trend of ring width (raw data in Figure 4) is a composite of several factors:

Figure 5. Time series of ring mass (wood production) calculated for a single tree of Douglas-fir from interior Canada.

1. Geometric: the same quantity of wood yields narrower rings as the tree enlarges.
2. Changes in wood allocation along the stem: ring width is usually greatest near the branches with the most foliage (Fritts 1976).
3. Physiological effects due to maturation and changes in total tree photosynthesis and net carbon balance, including effects of competition from other trees.

Other trends ascending or declining, may be due to other factors such as:

1. Long term climatic trends.
2. Fire history.
3. Progressively increasing air pollution.
4. Growth enhancement by CO_2 (if any), acting in the opposite direction from most of the above.
5. Other yet unidentified influences.

Dendroclimatologists ordinarily remove the long-term trend because it is primarily an age growth trend and non-climatic in nature. This trend is usually removed through empirical curves such as the exponential (Fritts 1976). In this investigation, however, primary interest centers on the trend. If all other factors contributing to the trend can be removed, any residual trend is presumably due to the CO_2 effect. Complete removal is of course not possible, but partial control of some contributing factors will aid in assessing trend differences.

The principal analytic procedure will include comparisons of growth trends of tree-ring chronologies of "affected" and "control"

trees of similar ages. Affected trees are those for which growth rates are calculated at a particular tree age for a period of time up to the present, during the span of CO_2 buildup. Control trees are of a comparable age but grew during a period prior to 1860 under pre-industrial CO_2 concentration. Sample pairings of affected and control trees should be taken from the same site or from trees that grew under similar conditions.

Changes in growth rates of old trees also will be examined. Trees more than 300 years of age, with growth trends that are essentially flat for the last 200 or more years, will be compared with respect to the periods before and after 1860. Any measured increase in growth in the senescent years would not be expected physiologically but rather would be expected to result from extrinsic sources, particularly a rise in CO_2 and/or a related climatic shift.

Another strategy for removing the influence of localized factors in isolating the presence of a global CO_2 response involves averaging ring-mass chronologies from many geographical regions. This approach should dampen year-to-year (i.e., climate) and short-term (i.e., single stand events) trend signals of uncommon variance, while accentuating the communality of globally or uniformly distributed responses, such as the hypothesized CO_2 effect.

9. Summary and Conclusions

During the past century there has been a worldwide increase in atmospheric CO_2 , with a marked increase during the past several decades. There is speculation that this increase in atmospheric CO_2

since the start of the industrial revolution already has had a measurable worldwide effect on growth of crops and forests. The purpose of this project is to test this hypothesis by measuring tree growth, particularly tree-ring width, density and mass.

Tree growth is the end product of the tree's environment and its genetic composition. Trees are useful instruments for recording environmental conditions because they respond to climate and other environmental conditions, they are recorders of time, they are widely distributed and they are long-lived.

Radial growth in the stem of the tree produces discernible annual rings for many species, particularly temperate-zone conifers. The intra-ring density, from pith to bark, can be measured on these trees to produce ring density and ring width chronologies. Intra-annual, annual, short-term and long-term fluctuations in environmental conditions are recorded in these chronologies.

Total ring width and maximum ring density are two parameters that have been found to be highly correlated with environmental conditions. Other intra-ring variables such as earlywood width, latewood width, minimum ring density and total ring density also provide additional information about environmental conditions.

A tree-ring parameter that should be useful to assess the hypothesized fertilizer effect of CO_2 is annual ring mass. If CO_2 fertilization increases tree growth, it must be through augmented production of photosynthate that is translocated from leaves to woody parts and converted to new xylem tissue. The additional xylem increases the mass of the tree, especially the bole. A useful method

to measure the mass of the bole is intra-ring density analysis because this technique measures both width and density from which mass can be calculated.

There is general agreement that X-ray densitometry, at this time, is the best method for measuring intra-ring density. The X-ray densitometry facility at ORNL will produce detailed intra-ring data including width, density and mass. The problems and approaches associated with operating an X-ray wood densitometry facility at ORNL are the topics dealt with in this report.

The history and development of X-ray densitometry in tree-ring research is documented. Wood and tree characteristics are considered as they relate to obtaining useful intra-ring data. Methods in X-ray densitometry are examined and alternative approaches considered. Four currently-operating X-ray densitometry laboratories were described. Applications of X-ray densitometry in dendrochronology are listed and some detail is given to the various ways that it has been used in Canada. The environmental and genetic factors affecting tree-ring responses are described.

There is an interaction between genetic and environmental factors to produce the end results of tree growth. The environmental factors include climate and other "natural" forces such as floods or forest fires. In addition to the natural influences, there are factors of human disturbance such as logging and air pollution.

At this point in time, the human species has the power to drastically alter the earth's environment. One way that this is being done is by increasing the level of CO_2 in the atmosphere. The

objective of this project is to determine whether or not there is a measurable fertilizer effect of elevated levels of CO_2 on tree growth. To do this, all of the other factors that may influence tree growth must be considered, measured and eliminated from the data series.

Several of the approaches to be taken are to: (1) apply X-ray densitometry techniques that will rapidly and accurately produce extensive and detailed intra-ring data; and (2) collect and process tree-ring samples from many, widely-distributed sites.

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