Forests as an Ecological Monitoring Tool for Catastrophic Events

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A Manuscript Report Prepared for the
Canadian Environmental Assessment
Research Council
March 1990

ACKNOWLEGEMENTS

The work contained within this paper has been partially supported by the Canadian Environmental Assessment Research Council (CEARC) through a Graduate Student Research Contract Award. The author gratefully acknowledges the CEARC Secretariat for their support, assistance and patience. Finally I would like to express my appreciation to Dr. R. Revel, University of Calgary, Dr. A. Legge, University of Calgary and Dr. S. Titus, members of my supervisory committee, who provided invaluable advice throughout the completion of this project.

PREFACE

The Alberta Forest Service gave "support in principle" for the research conducted and described within this manuscript. However, the project was conducted separately from the agency therefore, **all statistical interpretations, discussion and recommendations presented within are the opinion of the author not the agency.**

Following completion of this document a 1984 Energy Resource Conservation Board publication was found which stated that flow rates from the Lodgepole well had been measured and indicated that rates were likely twice as high and possible three or more times as high as the original estimates (ERCB 1984(2)). At a rate three times higher than the original estimate the volume of condensate released would have been between 50 and 60 million litres making this spill volume greater than the volume of crude released during the Exxon Valdez spill (42 million litres). Although the author acknowledges that the spill environment, impacts and events surrounding the two spills are substantially different, the comparison is made to illustrate the potential release which may accompany well blowouts. All pollutant concentrations discussed within this document are those of the original estimates.

Although it is important to realize that the spill volume may be three times that originally estimated, all environmental affects discussed within this document may be a result of pollutant concentrations three time those originally discussed.

ABSTRACT

A stem analysis analytical methodology was used to evaluate growth impacts on White Spruce (*Picea glauca* (Moench)) resulting from the 1982 Lodgepole sour gas well blowout. The results and methodology are discussed in the context of Environmental Impact Assessment monitoring in Canada.

Growth reductions at the two sites closest the wellhead were statistically significant for five post-blowout years. Growth at these condensate impacted sites was reduced to 9.8 % and 38.1 % in 1983. Differences in growth reductions reflect a gradient of effects and a dose-response relationship. Recovery of surviving trees was been rapid but is leveling off at approximately 80 % of pre-blowout growth. Growth reductions were greater and recovery rates slower than those previously predicted by other authors.

Statistically significant differences in height profile growth responses were limited to the upper portions of the trees. Growth rates over a tree height profile ranged from 10 % less to 50 % more than growth rates observed at a 1.3 metres. Analytical methodologies detected and described growth differences over a height profile but a larger sample size was desirable.

Criteria are proposed for the development of Environmental Impact Assessment (EIA) monitoring tools. Stem analysis methodologies are discussed in terms of these criteria and in a general EIA context. Used in conjunction with contaminant, bioaccumulator and nutrient cycling monitoring, stem analysis methods have significant potential for use in EIA monitoring where forest resources or productivity are at risk.

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CHAPTER ONE: PROJECT OVERVIEW

INTRODUCTION

This paper describes and discusses the use of a detailed sampling program and analytical methodology to evaluate growth impacts to coniferous trees resulting from an abnormal pollution event known as the Lodgepole Blowout. Subsequently the paper discusses the methodology and its potential for future use in Environmental Impact Assessment (E.I.A.) in Canada. The analytical work is described in detail within a Masters Degree Project prepared by the author for the Faculty of Environmental Design at the University of Calgary.

PROJECT ORIGIN

In fall 1982, a sour gas well located in the Parkland Boreal Forest transition zone of central Alberta blew out of control. Pollutants including hydrogen sulphide, sulphur dioxide and approximately 120,000 barrels of condensate were released into the environment during the 67 day event.

Due to the severity of the event the Energy Resources Conservation Board held the Lodgepole Blowout Public Inquiry and prepared a report on their findings. Within that report was a recommendation that the Alberta Forest Service (AFS) monitor the potential effects on the forested ecosystem within a ten kilometre radius. The AFS developed and initiated a monitoring program known as the Lodgepole Blowout Forest Ecosystem Monitoring Project (LBFEMP). The LBFEMP utilized a series of monitoring stations downwind and upwind of the well head. Information was collected on a broad range or forest ecosystem parameters during 1985 and 1986. Preliminary stem analysis studies done in 1985 revealed substantial growth reductions at one of the monitoring stations. It was also observed that growth reductions varied throughout a tree and that radial measurements taken at one height did not accurately reflect growth effects within a tree, Baker (1986). In 1987 the LBFEMP was discontinued due to budget constraints.

In an effort to elaborate on stem analysis research the author initiated a new research effort as a master degree project at the U of C. Although the AFS gave support in principle for the research, all stem analysis work described with the Masters Thesis and within this paper was accomplished separately from the AFS project.

INCREMENTAL GROWTH STUDY

Past studies of pollution impact on coniferous growth have concentrated on revealing growth trends by analyzing a sample (2 or 3) of tree cores usually taken at 1.3 metres from the point of germination, from 10 - 20 trees/site (Fox et. al. 1985, Jaques 1983, Legge 1980). These methods allow sampling at a large number of sites but assume that entire tree growth can be estimated from one or two cores. Dendrochronological studies have shown significant growth variation throughout a tree with patterns dependent on a range of parameters such as; crown development, individual tree translocation and storage dynamics, stand spatial dynamics,

mechanical damage, climate and pollutants (Clyde and Titus 1985, Trimmer and Verch 1983, Fritts 1976).

The project described in this paper is based on the use of detailed stem analysis techniques for measuring coniferous growth at five sites on a Nw to Se gradient through the forest surrounding the Lodgepole Blowout. Four of the sites used were forest ecosystem monitoring stations of the LBFEMP. An additional site midway between the first and second closest sites to the Lodgepole Blowout well head was added in 1987. The stem analysis sampling strategy has also allowed for determination of growth trends over a height profile within any tree.

PROJECT OBJECTIVES

The following project objectives briefly define the research conducted within this project:

1) to conduct detailed stem analysis on Picea glauca (Moench) Voss, from five sites near the Lodgepole Blowout;

2) to determine the nature and extent of pollutant impact on conifer growth over a 10 km downwind gradient;

3) to determine if individual trees affected but not killed by blowout pollutants are experiencing a post-blowout growth recovery;

4) to evaluate growth impact and recovery over a height profile within individual trees;

5) to discuss applications of these monitoring techniques to Environmental Impact Assessment in Canada.

PROJECT RELEVANCE TO ENVIRONMENTAL IMPACT ASSESSMENT IN CANADA

Environmental Impact Assessment can be broadly described as a formal process or component of planning which reviews social and ecological implications of development activities (CEARC 1986). On federal lands the E.I.A. process is directed by the Federal Environmental Review Office (F.E.A.R.O.); on provincial lands the process is regulated by provincial authorities. As a result there is some interprovincial variability in E.I. A. methodologies, strategies and techniques. The methodology used within this report will be discussed primarily within the context of the federal E.I.A. methodology with reference to Alberta's E.I.A. process where applicable.

Abnormal pollution events can be described as events which have a low probability of occurrence but may have high environmental consequence (Hunsaker and Lee, 1987). Although large scale development project E.I.A. often address the probability and magnitude for change from such events, small projects often provide little detail on the environmental implications of

such events. This is partially a result of problems in specifying quantitatively the risk involved, and impact significance should such an event occur. There is also a perceived lack of importance or regulated requirement with smaller scale projects. These factors have resulted in post impact assessment which by definition cannot be carried out under ideal conditions or research plans. Impact assessment and response to abnormal events occurring during routine or small scale projects is predominantly reactionary and speculative in nature and is based on hypothesized normal conditions. Background information and baseline data are not readily available thereby complicating the overall nature and approach to impact assessment. These pitfalls reveal the need for specialized tools or methodologies which can be used to quantitatively evaluate environmental impact when abnormal events occur.

The following criteria are based on those proposed by Ausmus (1982) and are proposed for evaluating monitoring tools.

- Monitors should establish cause/effect, dose-response relationships which relate to exposure.
- Monitors must possess enough sensitivity to detect effects.
- Monitors should provide time dependant data both past and present and lend themselves to prediction.
- Monitoring parameter spatial and temporal variation must be comparable or allow standardization.
- Monitoring parameters must be wide spread there by allowing spatial sampling over areas of potential impact.
- Monitors should allow evaluation of economic costs of contamination.

The methodology employed in this project promotes the derivation of in-situ pre-impact biological information to ascertain baseline data or patterns. Once pre-event data is reviewed and analyzed attempts can be made to predict post-event data based on pre-event patterns. Subsequently, pre-event, post-event predictions and actual post-event patterns may be compared. The strengths and weaknesses of this approach are reviewed in detail in the conclusion of this report.

In this case the methodology is being applied to the impact assessment of an abnormal event. These techniques also have potential for use as a component of impact assessment monitoring projects or post-project environmental audit. The technique should not be considered a stand alone methodology for impact assessment but as a monitoring tool or component for monitoring projects in evaluating impacts from large scale point source pollutant emission projects.

CHAPTER TWO: BACKGROUND INFORMATION

THE LODGEPOLE BLOWOUT

On October 17, 1982 a well being drilled for AMOCO Canada Ltd. at 13-12-48-12-W5, blew out of control. This situation persisted for 67 days until the well was successfully capped December 23, 1982 (Alberta 1984(l)). During the event three major environmental pollutants were released. Prior to accidental ignition, the primary pollutants were hydrogen sulphide and condensate. During control efforts the gas release was accidentally ignited on two occasions and during these burning phases the primary pollutant was sulphur dioxide (Alberta 1984(l)). Baker (1989) after reviewing the potential impact of pollutants, concluded that of the three pollutants condensate had the greatest potential for being a vector of environmental damage. This conclusion was based on the timing of the blowout, estimates of pollutant concentration and dispersion, pollutant characteristics and observations of infield pollutant damage symptoms.

POLLUTANTS OF CONCERN

Of additional importance was a similar well blowout (1977) two kilometres southwest of the 1982 blowout site which created the potential for overlap of impacted areas. This blowout was out of control for 28 days during December and January 1978/1979. Blowout pollutants were similar with condensate, hydrogen sulphide and sulphur dioxide forming the main components. Blowout effects were assessed the following summer by Hogan and Malhotra (1978). They found that condensate caused irreversible injury to 60 % of the total forest vegetation within a radius of 400 - 800 metres. Injury was mainly due to destruction of buds, cambium and procambium and physical coating of foliage. No injury could specifically be attributed to sulphur dioxide (Monenco 1983).

Condensate

During the 1982 Lodgepole blowout an estimated 100,000 - 140,000 barrels of hydrocarbons were released into the atmosphere and deposited on the forest surrounding the well head (Jaques 1983). Fires that occurred on the well site during two occasions burned a portion of the condensate and ameliorated condensate concentrations. Following blowout control, Ecostat Geobotanical Surveys Inc. measured condensate adhering to spruce foliage samples from 62 coniferous sites (Jaques 1983) . Subsequently, a map delineating light, moderate and heavy deposition zones was produced. Figure 1 illustrates the 1982 deposition zones. Also illustrated are the condensate deposition zones of the 1977 well blowout.

Monenco employed false colour infrared aerial photography and ground truthing of 90 sites to identify the extent of visible forest damage and presence of condensate (Monenco 1983). Figure 2 illustrates the visible zone of damage described. Although this approach did not attempt to quantify pollutant deposition it was found to accurately represent the forested area visibly affected. For comparative purposes, condensate deposition zones determined by Jaques are shown on the Monenco map.

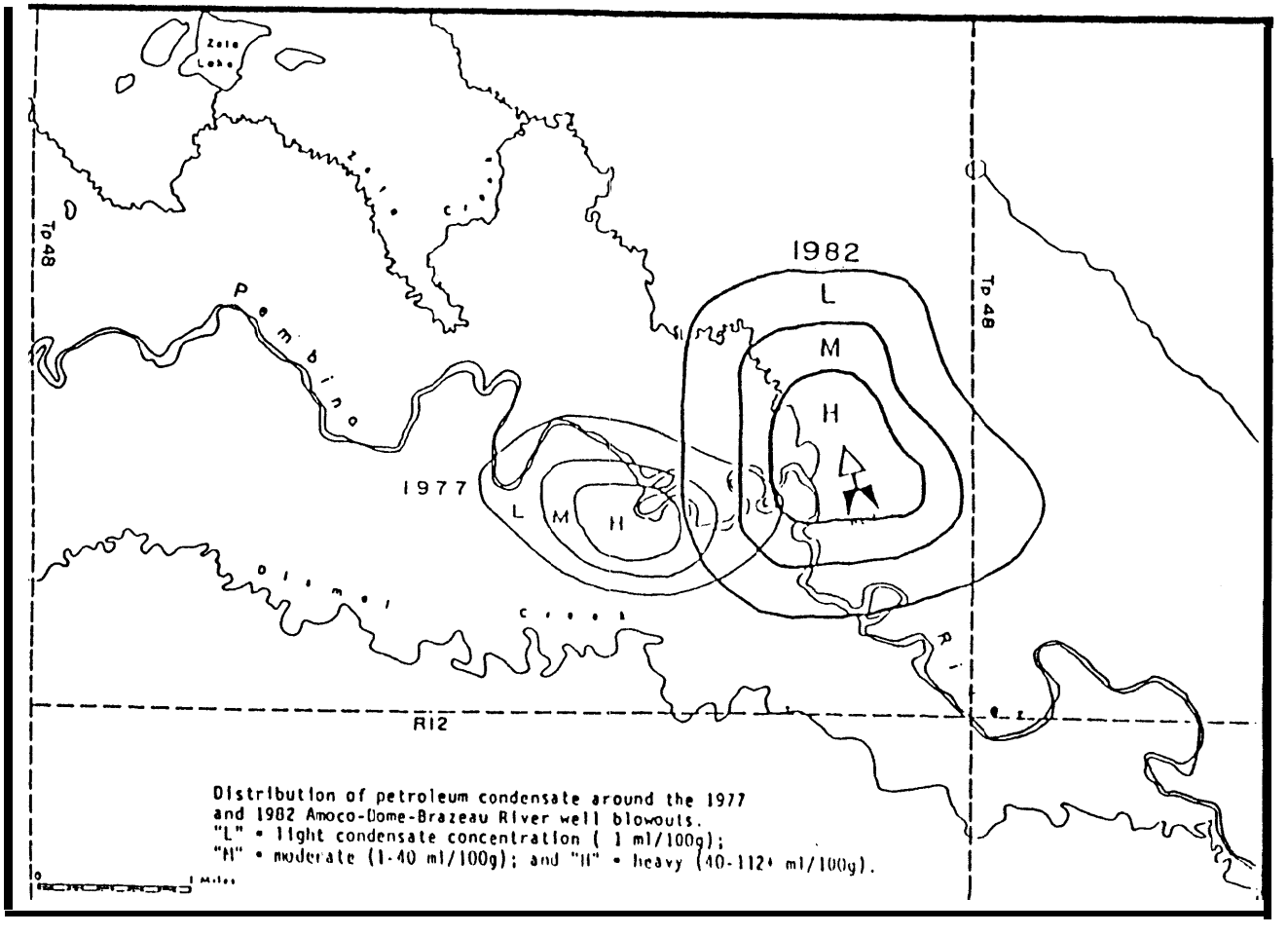

Figure 1.
Condensate Deposition Maps Prepared by Jacques (1983).

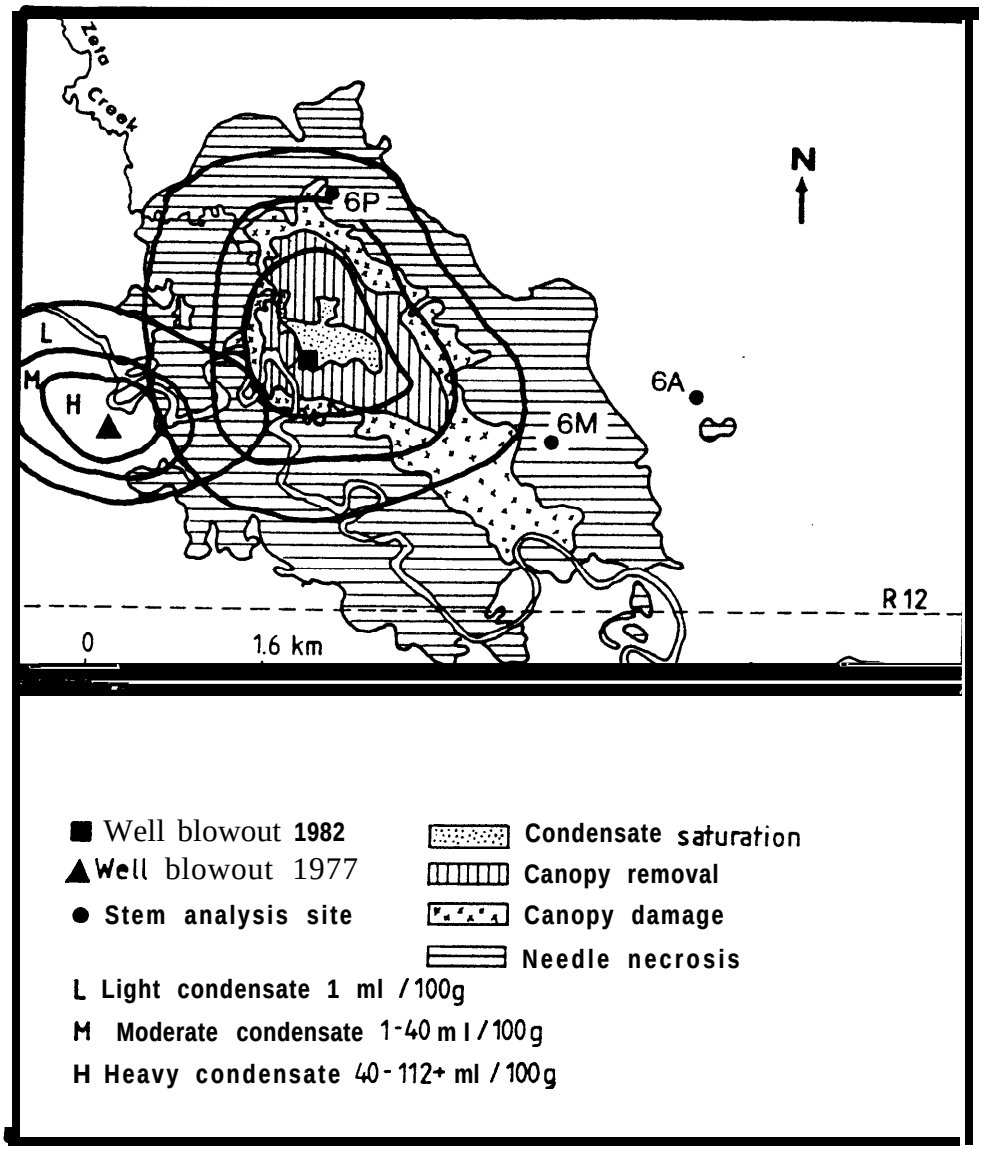

Figure 2.
Zones of Visible Damage Prepared by Monenco (1983), Condensate deposition zones determined by Jacques are also shown.

Table 3.
Residual Mean Squares for Selected Polynomials and Three Step Filters.

p = polynomial
n = number of points on curve
df = degrees of freedom
st3 = 3 step filter 3, 5, 7 year running mean
p5 = 5th degree polynomial
* = smallest residual mean square

tree	curve	p	n	df	sum of squares	res. mean square	
6p01	st3	3	54	50	10.9201	0.2194	*
6p01	p4	4	54	49	21.5046	0.4387	
6p08	st3	3	51	47	8.0192	0.1706	*
6p08	p9	9	51	41	6.4872	0.1582	
6p06	st3	3	46	42	10.9535	0.2607	*
6p06	p5	5	46	40	18.3700	0.4592	
6p06	p7	7	46	38	14.0160	0.3688	
6p04	st3	3	46	42	6.2591	0.1490	*
6p04	p4	4	46	41	20.2539	0.4940	
6p05	p5	5	46	40	18.3700	0.4592	
6r06	st3	3	48	44	5.0968	0.1158	*
6r06	p7	7	48	40	5.4404	0.1360	
6r06	p8	8	48	39	4.8444	0.1242	
6r06	p9	9	48	38	4.2841	0.1127	
6r07	st3	3	44	40	12.1470	0.3036	*
6r07	p5	5	44	38	17.4527	0.4592	
6r07	p9	9	44	34	11.8998	0.3499	
6r08	st3	3	41	37	5.9099	0.1597	*
6r08	p5	5	41	35	7.3285	0.2094	
6r10	st3	3	38	34	4.8257	0.1419	
6r10	p5	5	38	32	6.1889	0.1934	

PLOT CHRONOLOGY DEVELOPMENT

Following standardization pre-blowout ring width indices were averaged for each base disk with the mean ring width index series representing a tree chronology. Cross-correlation functions were calculated between tree chronologies for each plot with correlations calculated up to lags of seven. Subsequently, plot chronologies were calculated by averaging all tree chronologies within a given plot. This series represents a historical plot chronology. Historical plot chronology similarities were evaluated using cross-correlation techniques and by graphical inspection.

Incremental Volume Calculations

Implementation of detailed stem analysis techniques allow the calculation of incremental volume based on measurements throughout a tree. Calculated in this fashion, incremental volume growth is a more explicit descriptor of overall tree growth. A Fortran program was written to convert radial growth and sampling height into incremental volume. Volume calculations were based on the stump being of cylindrical form, thereafter section volumes were considered to be frustoms of a cone with the last segment volume being calculated as a cone. All equations used in volume calculation were taken from Husch et al (1971).

Three volume increment series for each tree were calculated and subsequently average to produce a tree volume increment time series. One-way ANOVA was used to compare differences in yearly growth per tree. As with raw radial measurement, variability in incremental volume growth between trees was found to be extensive thus preventing compilation of data into plot series. In order to overcome this problem volume increments were standardized to make variation relative, thereby allowing compilation of plot volume indices.

STANDARDIZATION OF INCREMENTAL VOLUME DATA

Since this technique was used to evaluate blowout impact within and between plots, it became essential to use techniques which allowed prediction of post-blowout growth based on pre-blowout growth. Curve fitting was accomplished by least mean squares fit of linear, exponential power and logarithmic equations though a set of data points. Equations for pre-blowout data could then be used to predict expected post-blowout growth. Predicted post-blowout values were used to standardize raw post-blowout data.

Standardized incremental volume time series for each tree and plot were compared using cross-correlation functions. One-way ANOVA was used to test statistical significance of growth trends from year to year within a plot chronology, and for individual years between plots.

INDIVIDUAL TREE PROFILE RESPONSES

The sampling strategy employed in this project allows for the investigation of tree response patterns which may vary over height. Variability of radial growth with height requires that the individual tree height profiles be standardized prior to compilation into a plot chronology. Standardization of tree height profile data was accomplished by determining a normal height profile based on five year pre-blowout mean growth at a given height. Subsequently post-blowout profiles were standardized by dividing by the five year pre-blowout profile. Compilation of tree and plot height profile series for any given post-blowout year was then possible. In addition, analytical differences from one year to another were investigated graphically and by ANOVA.

Through the application of this methodology it is expected that project objectives 1 to 4 can be addressed and discussed. It is not expected that this approach will answer all potential questions. Broad conclusions regarding the extent and severity of growth reductions and recovery response over the entire area impacted by the Lodgepole Blowout is not possible. To accomplish this would require a more extensive network of sampling stations and additional post-blowout data. The following section presents and discusses results of the methodology described within this section.

CHAPTER FOUR: RESULTS, DISCUSSION, PROJECT CONCLUSIONS

CROSS DATING

Manual cross dating procedures were adequate for this project. Signature years were identified for 1936, 1961, 1977 and 1982. Some difficulty was experienced identifying post-blowout growth rings due to missing rings, growth reductions and incomplete ring development. These problems were overcome through careful identification of pre-blowout years and by applying the following assumptions:

1) Trees surviving blowout impact would progressively increase their radial growth.
2) Post-blowout growth could be cross dated backwards with the year of harvest constituting the first post-blowout radial growth within the cambium. Previous years were formed progressively within the first growth ring.

Cross dating was particularly difficult at sites close to the blowout. Often no late wood was distinctive but a shortening of tracheid width corresponding to late wood in a different portion of the disk was observed. At times this pattern could not be observed even when late wood appeared to have grown in different portions of the stem. In these situations it became necessary to assume that if annual growth could not be identified, all observed growth occurred during one year.

HISTORICAL PLOT CHRONOLOGIES

Historical plot chronologies developed from base disk radial measurements are illustrated in Figure 5. As expected variability of growth patterns is greatest in the first half of the chronologies and progressively lessens with age. Throughout the chronologies synchronous occurrences of peaks and troughs were observed. Peaks occur in 1948, 1961 and 1978, troughs occur in 1941, 1961 (cross dating signature year) and 1968. Although these anomalies were not specifically linked to any environmental or anthropogenic phenomena, they do indicate the similarity of the sites in their growth response to regional factors, thereby strengthening the notion of comparative sites.

A notable stabilization of variance can be seen from 1968 to 1982 as the frequency and magnitude of erratic deviations of peaks and troughs decrease. This is a normally occurring phenomena as trees age (Fritts 1976). During this time the only major deviation (positive) noted across all sites occurred in 1978. Although this aberration occurred one year after the 1977 well blowout there is no evidence indicating the two events are related.

Cross-correlation functions amongst the historical plot chronologies are illustrated in Table 4. All plot chronologies are similar with the strongest cross-correlations occurring when lags of zero are evaluated. The hypothesis that no similarities between series exist was tested by examining cross-correlation functions. The hypothesis is rejected for all possible combinations of two time series at the 95%, 99% and 99.9% confidence level.

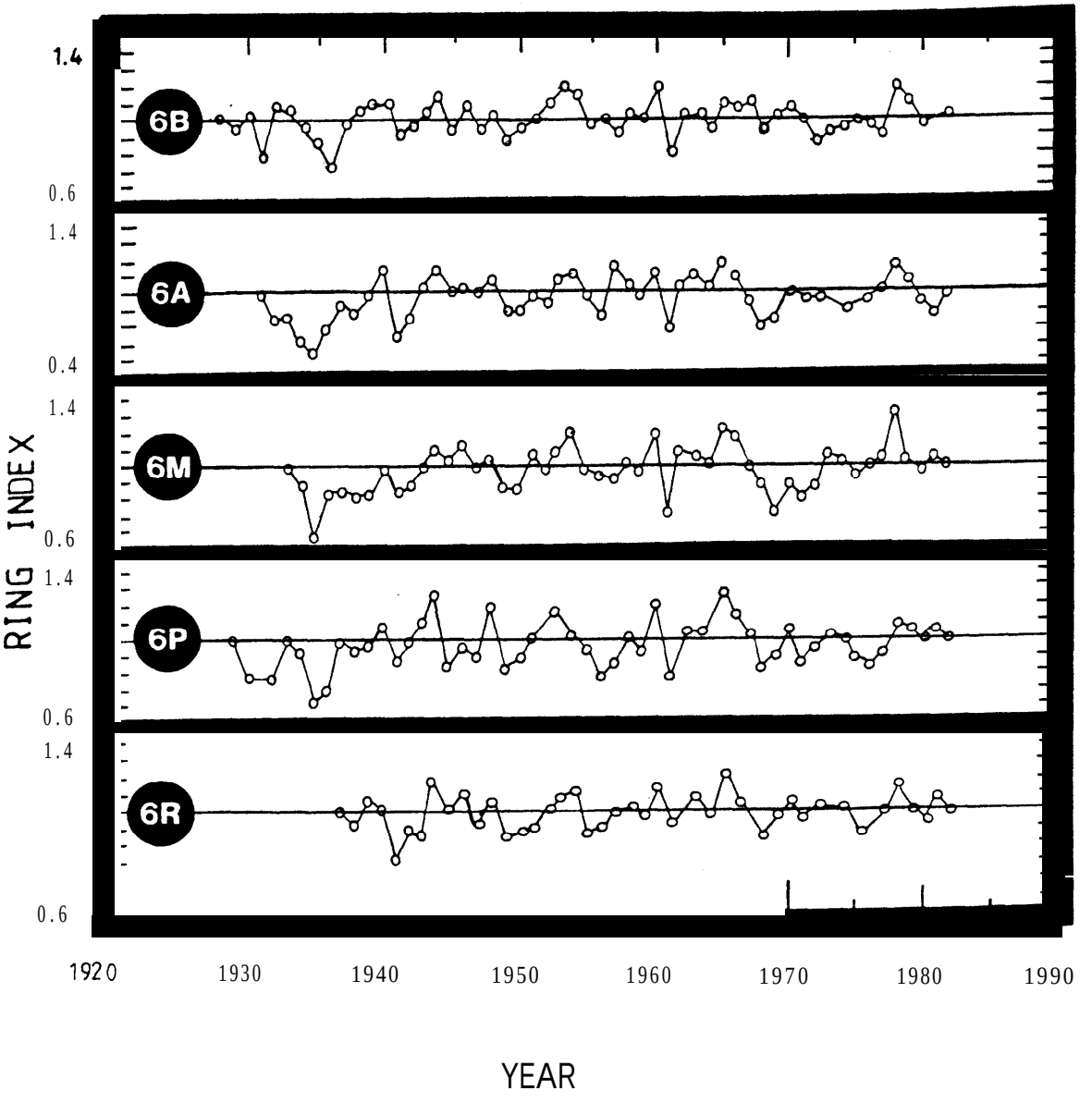

Figure 5.
Historical Plot Chronologies.

Plot chronology cross-correlation functions indicate strong similarities in growth patterns between plots. It is postulated that differences between chronologies reflect influences of site and microclimate. Similarities also indicate that regional aberrations in climate should be reflected across all sites. Therefore, departure from these regional patterns indicate aberrations that are a result of site specific factors or localized influences.

Table 4.
Plot Chronology Cross-Correlation Functions 1938 - 1982.

Ho: p=0 Ha: p=0 n=44 df=42
ci = 95.0% / 2 critical value Of r=.297
ci = 99.0% / 2 critical value of r=.389
ci = 99.9% / 2 critical value of r=.484

Plot/Plot	6R	6P	6M	6A	6B
6R	1.0	.709	.637	.714	.642
6P		1.0	.633	.642	.702
6M			1.0	.698	.524
6A				1.0	,577
6B					1.0

INCREMENTAL VOLUME ANALYSIS

Analysis of raw data or data subsequent to log transformation was found inadequate for this project. Emphasis was therefore placed on standardizing data to allow for pooling of within plot tree data.

Curve Fitting for Incremental Volume Index Creation

Based on the strength of correlation with the raw data linear, exponential, power or logarithmic equations were used for curve fitting and the creation of volume indices. No single curve type was adequate in all situations. In general one curve type best described growth trends within a tree but could not be uniformly used across or within plots. This is not an uncommon problem in dendrochronology. Different curve types have been used for standardization by Brubaker (1980) and Thompson (1981). Since this technique was to be used to predict post-blowout expected volume increments, it was essential to use curves with the highest correlation coefficients in the standardizing procedure.

Cross-correlation functions were calculated for all within plot combinations of pre-blowout tree volume chronologies (1966-1982). Table 5 illustrates cross-correlation results which were used to evaluate within plot similarities of pre-blowout time series. Between series correlation for each pair, and variation of time series, was examined by testing the hypothesis that correlations between trees indicated no association (r=O). Variability in volume index chronologies resulted in the application of 75 %, 90 % and 95 % confidence intervals in hypothesis testing .

Table 5.
Cross-correlation of Tree Volume Chronologies.
Chronologies from 1966 - 1982.

Plot	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10
6R01	1.000	0.631	0.863	0.774	0.420	0.532	0.725	0.746	0.827	0.678
6R02		1.000	0.542	0.498	0.819	0.660	0.431	0.748	0.626	0.7%
6R03			1.000	0.674	0.427	0.362	0.567	0.616	0.652	0.525
6R04				1.000	0.218	0.505	0.748	0.669	0.783	0.476
6R05					1.000	0.442	0.287	0.642	0.371	0.596
6R06						1.000	0.714	0.723	0.752	0.510
6R07							1.000	0,696	0.909	0.451
6R08								1.000	0.821	0.623
6R09									1.000	0.693
6R10										1.000
6P01	1.000	0.592	0.579	0.199	0.601	0.488	0.615	0.777	0.500	0.663
6P02		1,000	0.749	0.541	0.766	0.815	0.762	0.451	0.761	0.724
6P03			1.000	0.631	0.753	0.787	0.696	0.655	0.666	0.750
6P04				1.000	0.739	0.866	0.678	0.498	0.675	0.755
6P05					1.000	0.892	0.656	0.590	0.829	0.915
6P06						1.000	0.789	0.605	0.865	0.875
6P07							1.000	0.708	0.737	0.761
6P08								1.000	0.520	0.684
6P09									1.000	0.856
6P10										1.000
6M01	1.000	0 .300	0.820	0.608	0.844	0.588	0.735	0.889	0.919	0.911
6M02		1.000	0.661	0.641	0.430	0.689	0.595	0.393	0.438	0.597
6M03			1.000	0.789	0.864	0.812	0.775	0.864	0.832	0.922
6M04				1.000	0.632	0.780	0.843	0.709	0.636	0.699
6M05					1.000	0.712	0.619	0.954	0.854	0.875
6M06						1.000	0.707	0.725	0.648	0.686
6M07							1.000	0.726	0.727	0.795
6M08								1.000	0.870	0.875
6M09									1.000	0.950
6M10										1.000
6A01	1.000	0.812	0.281	0.320	0.753	0.656	0.643	0.276	0.525	0.270
6A02		1.000	0.378	0.334	0.529	0.512	0.808	0.214	0.472	0.109
6A03			1.000	0.914	0.088	0.238	0.410	0.588	0.500	0.292
6A04				1.000	0.172	0.233	0.443	0.643	0.662	0.422
6A05					1.000	0.691	0.638	0.176	0.481	0.517
6A06						1.000	0.691	0.322	0.677	0.438
6A07							1.000	0.233	0.740	0.344
6A08								1.000	0.545	0.459
6A09									1.000	0.649
6A10										1.000
6B01	1.000	0.625	0.567	0.135	0.846	0.806	0.216	0.823	0.721	0.223
6802		1.000	0.784	0.140	0.611	0.792	0.165	0.804	0.903	0.075
6B03			1.000	0.226	0.650	0.652	0.264	0.822	0.746	0.152
6B04				1.000	0.2'40	0.171	0.626	0.079	0.006	0.755
6B05					1.000	0.836	0.370	0.824	0.668	0.356
6B06						1.000	0.193	0 .902	0.813	0.092
6B07							1.000	0.273	0.290	0.727
6B08								1.000	0.842	0.220
6B09									1.000	0.076
6810										1.000

Table 6 presents results of hypothesis testing. The hypothesis was rejected for all pre-blowout chronology pairs (75 % confidence interval) for plots 6R, 6P and 6M. This trend was not observed for plots 6A and 6B. These plots could be readily divided into two groups where comparison within, but not between groups resulted in a rejection of the hypothesis. Pre-blowout volume index chronologies of tree 1, 2, 5, 6, 7 and 9 of group 6A correlated well with one another (range r=.531 to .859). Chronologies of trees 3, 4, 8, 9 and 10 of plot 6A correlated well with one another (range r=.264 to ,914) but not with the other group. Chronologies for trees 1, 2, 3, 5, 6, 8, and 9 of plot 6B correlated well with one another (range r=.567 to . 902). Chronologies for 6B trees 4, 7 and 10 correlated well with one another (range r = .626 to .755) but poorly with the remainder. Environmental reasons for this apparent stratification of growth trends are unknown. Cross-correlations using time lags up to 7 did not improve the correlation of time series in any reoccurring pattern. Therefore, this trend was attributed to natural variation of tree growth within a plot.

Master Volume Index Chronologies

Tree volume index chronologies for each plot were averaged with resulting plot series being called the master volume index chronology. Master chronologies are presented in Figure 6.

Master chronologies have a tendency to average out non synchronous and emphasize synchronous peaks and troughs. The smoothing of a time series was particularly evident in plot 6A and 6B where cross-correlations of individual trees revealed time series dissimilarities. Master chronologies from these plots are similar in appearance with a period of relative stabilized variation between 1968 and 1977 followed by increasing variation. This observation is a result of the differences in tree time series discussed above. Combination of all trees from these plots has resulted in a general smoothing of the master chronology. In contrast, correlations of tree chronologies within plots 6R and 6P was high, therefore master plot chronologies have retained year to year volume index variability.

The 6M pre-blowout chronology is similar to that of 6A and 6B. However, the post-blowout chronology illustrates a pronounced growth reduction followed by a recovery from 1984 through 1987. In 1986 the recovery trend appears to be leveling off below the predicted growth curve with only slight recovery in 1987 to an index of .81. Although the 6P pre-blowout chronology does not appear similar to that of the chronologies for 6M, 6A or 6B, the post-blowout chronology shows a similar trend to that of 6M. The primary difference is that the volume index reduction is greater and the recovery is not as dramatic for 6M. This trend reflects increased pollutant effect at 6P.

Post-blowout volume chronology of the reference site (6R) indicates a reduction of volume index occurred in 1984 and 1985 with a minor recovery in 1986. This deviation is the largest which occurred over the 20 year volume index chronology but it cannot be positively linked to any specific factor. This site, located 15.82 km Nw of the well head, is outside the zone of condensate deposition. However, the site lies within a zone of sulphur fumigation and sulphur deposition determined by Promet Environmental Group and Monenco. It had been speculated

Table 6.
Cross-correlation of Tree Volume Chronologies.
Chronologies from 1966 - 1982.

Ho:p=0 Ha:p=0 n=17 df=15
critical value .25/1,15=.176 Ho acceptance .
critical value .10/1,15=.327 Ho acceptance **
critical value .05/1,15=.412 Ho acceptance • **,

Plot	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10
6R01	.	.	.	.	.	.	.	.	.	.
6R02										
6R03						•••				
6R0Y					••					
6R05							••		mm-	
6R06										
6R07										
6R08										
6R09										
6R10										
6P01	.	.	.	••						
6P02										
6P03										
6P04										
6P0S										
6P06										
6P07										
6P08										
6P09										
6P10										
6M01	.	••								
6M02										
61703										
6M04										
6M05										
6M06										
6M07										
6M08										
6M09										
6M10										
6A01	.	.	••	••				••		••
6A02			•••	•••				••		
6A03					•	••	•••			••
6A04						••				
6A05										
6A06								••		
6A07								••		•••
6A08								••		
6A09										
6A10										
6B01	.	.	.				••			••
6B02				•			•			•
6803				••			••			•
6B04					••					
6B05							mm-			*
6B06							••			•••
6B07								••	••	
6B08										••
6B09										•
6B10										

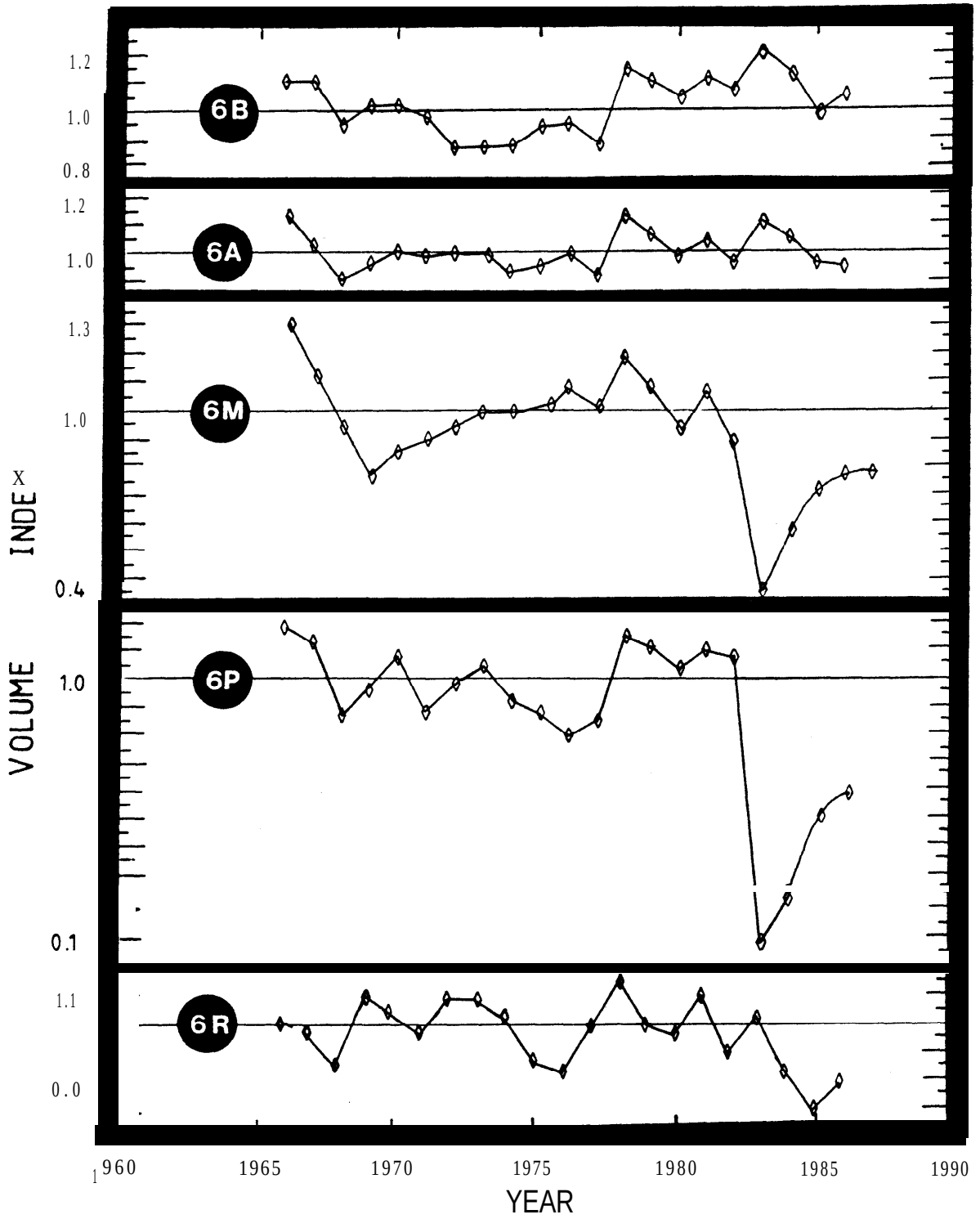

Figure 6.
Master Volume Index Chronologies.

that at this site, blowout effects were insufficient to cause a detectable coniferous growth response. At the present time it is not possible to determine if the observed reduction is a result of the Lodgepole Blowout or other unknown natural and/or anthropogenic factors.

Regrouping of Tree Chronologies for Plots 6A and 6B

In an effort to improve the sensitivity of master chronologies from plots 6A and 6B, tree chronologies for each site were divided into two groups. Subsequently, each group was used to develop two master chronologies for each plot. Division of tree chronologies into groups was based on results of individual tree cross-correlation and hypothesis testing as previous discussed. Cross-correlation functions were recalculated to examine the degree of similarity of the additional master chronologies. The hypothesis of no association was tested using these newly calculated cross-correlations. Results are presented in Tables 7 and 8.

Table 7.
Cross-correlation of all Pre-blowout Master Chronologies

PLOT	6R	6P	6M	6A	6A1	6A2	6B	6B1	6B2
6R	1.000	.514	.079	.504	.391	.544	.148	.098	.302
6P		1.000	,430	.760	.739	.540	.752	.756	.204
6M			1.000	.702	.811	.257	,416	.347	.373
6A				1.000	.942	.763	.688	.619	.511
6A1					1.000	.505	,736	.654	.580
6A2						1.000	.340	.317	.226
6B							1.000	.981	.365
6B1								1.000	.191
6B2									1.000

Table 8.
Summary of Hypothesis Testing Cross-correlation of all Pre-blowout Master Chronologies.

Ho: p=0 Ha: p=0 n=17 df=15
critical value .25/1,15 = .176 Ho acceptance *
critical value .10/1,15 = .327 Ho acceptance **
critical value .05/1,15=.412 Ho ● ccqamce ***

PLOT	6R	6P	6M	6A	6A1	6A2	6B	6B1	6B2
6R			.		• **		*	*	**
6P									**
6M						**		***	***
6A									
6A1									
6A2								**	**
6B									***
6B1									• *.

Results of master chronology comparison indicated that most comparisons of whole plot chronologies were statistically significant at the 75 % confidence level (with the exception of 6R to 6M and 6B). It was also noted that little was to be gained by splitting plots 6A and 6B into two master chronologies. Table 9 presents a summary of significance tests for final master chronologies. Results indicated that statistical tests of year to year growth should be limited to within plot comparisons since the cross-correlation of across plot 17 year pre-blowout chronologies were not consistent.

Table 9
Summary of Hypothesis Testing Cross-correlation of Final Pre-blowout Master Chronologies.

Ho: p=0 Ha: p=0 n=17 df=15
critical value .25/1,15=.176 Ho acceptance *
critical value .10/1,15=.327 Ho acceptance **
critical value .05/1,15=.412 Ho acceptance • **

PLOT	6R	6P	6M	6A	6B
6R			*		*
6P					
6M					
6A					
6B					

GROWTH REDUCTION and RECOVERY

Five Year Pre-blowout Master Chronology Comparison

A similarity of pre-blowout volume chronologies over a five year period immediately preceding the blowout was observed. The strength of the similarity was tested by calculating cross-correlation functions of a five year pre-blowout volume chronology. Correlations at a lag =0 are presented in Table 10 and show an increase in correlation for all plots. In fact, these correlations were found to be significant for all comparisons at the 90 % confidence level.

Table 10.
Cross-correlation of Tree Volume Chronologies for the Five Year Period Immediately Preceding the Blowout (1977- 1982).

Ho: p=0 Ha: p=0 n=5 df=3
critical value .10/1,3 =.687

PLOT	6R	6P	6M	6A	6B
6R	1.000	.726	.928	.886	.830
6P		1.000	.892	.903	.932
6M			1.000	.983	.932
6A				1.000	.841
6B					1.000

Volume Reductions Based on Raw Data

Post-blowout volume reduction was evaluated by comparing mean pre-blowout volume increment (annual mean for 1978 - 1982) to annual post-blowout volume increment at each site. Post-blowout comparison was made as a percentage of the mean of pre-blowout annual increment (1978 1982). Results are presented in Figure 7 and Table 11.

Table 11.
Growth Reduction by Plot, Expressed as % of Pre-Blowout Volume Growth.

PLOT	1983	1984	1985	1986	1987
6R	102.867	83.237	68.843	116.917	na
6P	9.862	21.601	48.875	66.439	na
6M	38.184	56.337	72.041	79.765	81.395
6A	112.514	107.141	97.782	95.724	na
6B	110.090	104.245	90.313	97.299	na

Figure 7 illustrates significant reduction of coniferous growth beginning in 1983 at the sites closest the well head (6P and 6M). At the five and 10 kilometre sites, 6A and 6B, no reduction of growth was observed. As previously stated the reference site illustrates an interesting decrease in volume growth in 1984 and 1985 followed by a subsequent sharp increase in 1986. A number of potential causes, including blowout effect, could be responsible for this aberration.

Blowout effects are more pronounced at site 6P (1.28 km N.) then at 6M (2.2 km Ese) with reduction in 1983 being 90.2 % and 61.9 % respectively. It is speculated that this observation reflects a dose response relationship. Site 6P lies within the Jaques (1983) low condensate deposition zone (Figure 1) low condensate deposition = 1 mg condensate/ 100mg coniferous foliage). Site 6M is located outside Jaques condensate deposition but within Monenco's zone of needle necrosis (Figure 2). This observation emphasizes the potential for growth reductions in ares where condensate deposition is difficult to quantify,

Volume increment recovery is evident in post-blowout years (Figure 7) but insufficient data is available to determine if complete recovery to pre-blowout rates will occur. The slope between years of the plot recovery lines indicates that site 6M recovery was greatest (slope .18 15) in the first year and is progressively lessening (slope .0163 in 1987). In 1987 volume increment was still only 81 % of pre-blowout rates with recovery appearing to level off indicating it may be many years before pre-blowout growth rates are observed. The recovery situation is similar for plot 6P but highest recovery rates occurred in 1984. It is clear that future post-blowout growth data is necessary to determine if and when pre-blowout growth rates will be resumed.

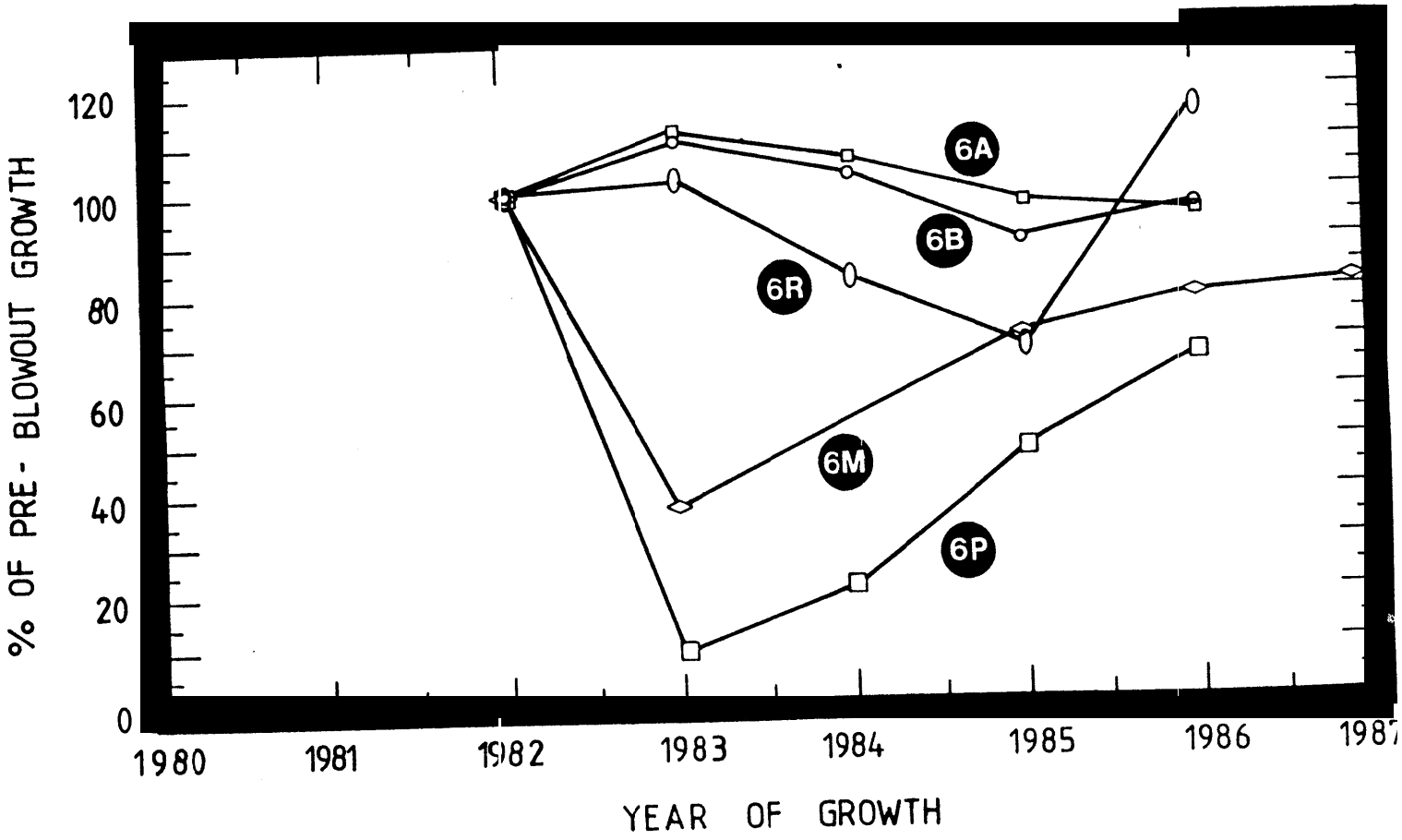

Figure 7.
Post Blowout Growth Reductions (Percentage of 5 year Pre-blowout Growth).

Significance of Growth Reductions - One Factor ANOVA

Significance of post-blowout growth reduction was evaluated by comparing post-blowout volume indices to a five year pre-blowout period on a plot by plot basis using one factor ANOVA and Scheffe's multiple range test. The hypothesis of homoscedacity was accepted for plots 6R, 6A and 6B at the 99 % confidence level with plot 6P also being accepted at the 99.9 % confidence level. Fmax was largest at plots affected by blowout pollutants, reflecting an increase is growth variability due to pollutant effects and tree response.

Table 12 indicates that for all plots the hypothesis of equal group means is rejected at significance levels of as high as p = .001 . Only at site 6B is the hypothesis rejected at a level of p = .0001. The magnitude of the F statistic reveals the strength of rejection. Rejection of the hypothesis at the reference site was unexpected and indicates that some factor has affected growth at this site. Figure 7, illustrates that this reduction (mean index 1985 = .6937) is the greatest observed in the reference sites 20 year volume index chronology. The cause of this reduction is unknown but it is interesting to note that the reduction appears in 1984, two years after the blowout. Growth at this site in 1983 (mean index=0.192) was equal to the predicted value. Whether the response observed is that of a lagged blowout effect is uncertain but no other causal factors have been identified,

Table 12.
ANOVA Results by Plot of Five Year Pre and Post-blowout Years.

Ho: u=u=u=u=u Ha: u=u=u=u=u
critical value .05/1,4,150 = 2.44

PLOT	F	PROBABILITY
6R	50.1511	.0000
6P	326.4761	.0000
6M	83.0189	.0000
6A	8.4089	.0000
6B	6.4526	.0001

Scheffe's multiple range tests, Table 13, indicated that low growth rates observed at the reference site are significant (p=.001) for 1984, 1985 and 1986 when compared to the pre-blowout period and 1983. Post-blowout growth rates for plot 6P and 6M are statistically significant (p = .001) when compared to the pre-blowout period. Figure 7 illustrates the post-blowout growth response observed for plots 6P and 6M. Post-blowout growth rates at plot 6A and 6B were not statistically significant when compared to the pre-blowout period. This evidence leads to the conclusion that post-blowout growth at these sites was unaffected by the Lodgepole Blowout.

After a period of rapid recovery, growth rates at sites 6P and 6M are leveling off below that predicted for the trees in the standardization procedure. Post-blowout response of trees is rapid

with statistically significant difference in volume index being observed over the five year post-blowout period. Although this trend indicates that complete tree recovery may occur, additional data is required to substantiate the recovery trend.

Table 13.
Scheffe's Multiple Range Test.

p=.05@, p=.01*, p=.001**, p=.0001 ● **. ns - not significant, na - not available

PLOT	GROUP	PRE-BLOWOUT	1983	1984	1985	1986	1987
6R	PRE		ns	***	***	***	na
	1983			• **	***	***	na
	1984				**	ns	na
	1985				---	ns	na
	1986					---	na
	1987						---
6P	PRE		***	***	•	***	na
	1983			*	***	***	***
	1984			---	***	***	***
	1985				---	ns	na
	1986					---	---
	1987						
6M	PRE	---	• . .	. . .	•	***	•
	1983		---	• **	***	• **	***
	1984			---	@	***	***
	1985				---	ns	ns
	1986					---	ns
	1987						---
6A	PRE	---	ns	ns	ns	ns	na
	1983		• *.	ns	•	**	na
	1984			---	ns	ns	na
	1985				---	ns	na
	1986					---	na
	1987						---
6B	PRE	---	ns	ns	ns	ns	na
	1983			ns	**	@	na
	1984			---	@	ns	na
	1985				---	ns	na
	1986					---	na
	1987						---

HEIGHT PROFILE RESPONSE

Height profile responses for the two sites affected by blowout pollutants (6P and **6M)** are illustrated in Figures **8** and 9. As expected growth reduction and subsequent recovery is not uniform over a height profile in any given tree. Tables 14 and 15 contain descriptive statistics for height profile indices for all years for both sites. Generally, growth reductions are not as great in the crown (with the exception of the last 1 to 2 metres) and below 2.5 metres. The upper portion of the crowns often have 10 - 50 % greater growth than the bole at a height of 1.30 metres or less. Growth measured at 1.30 metres is generally 3-10 % greater than growth in the bole below the active crown. These results illustrate the potential for over or under estimating growth based on radial measurement taken at one height.

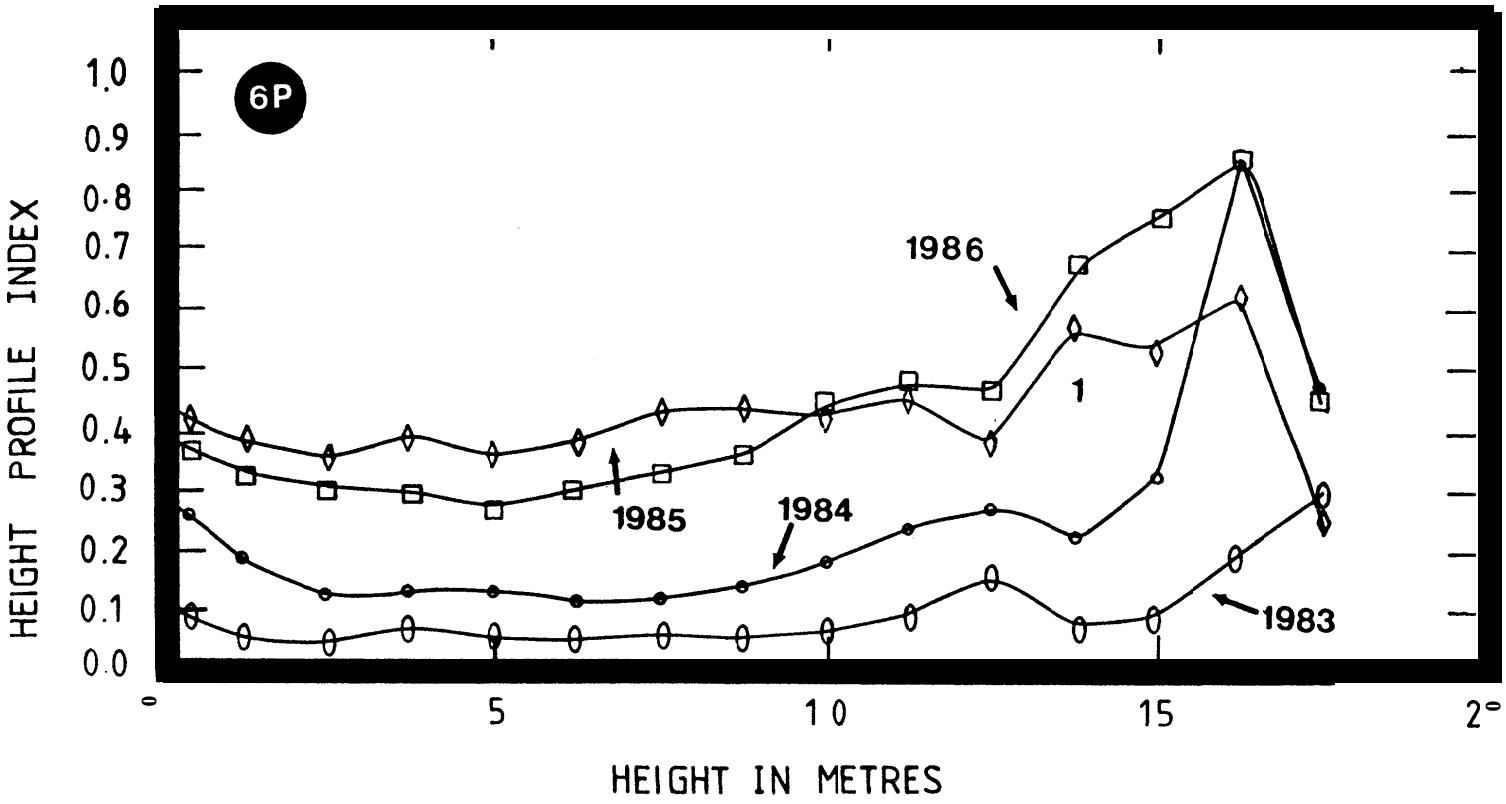

Figure 8.
Height Profile Graph of Site 6P.

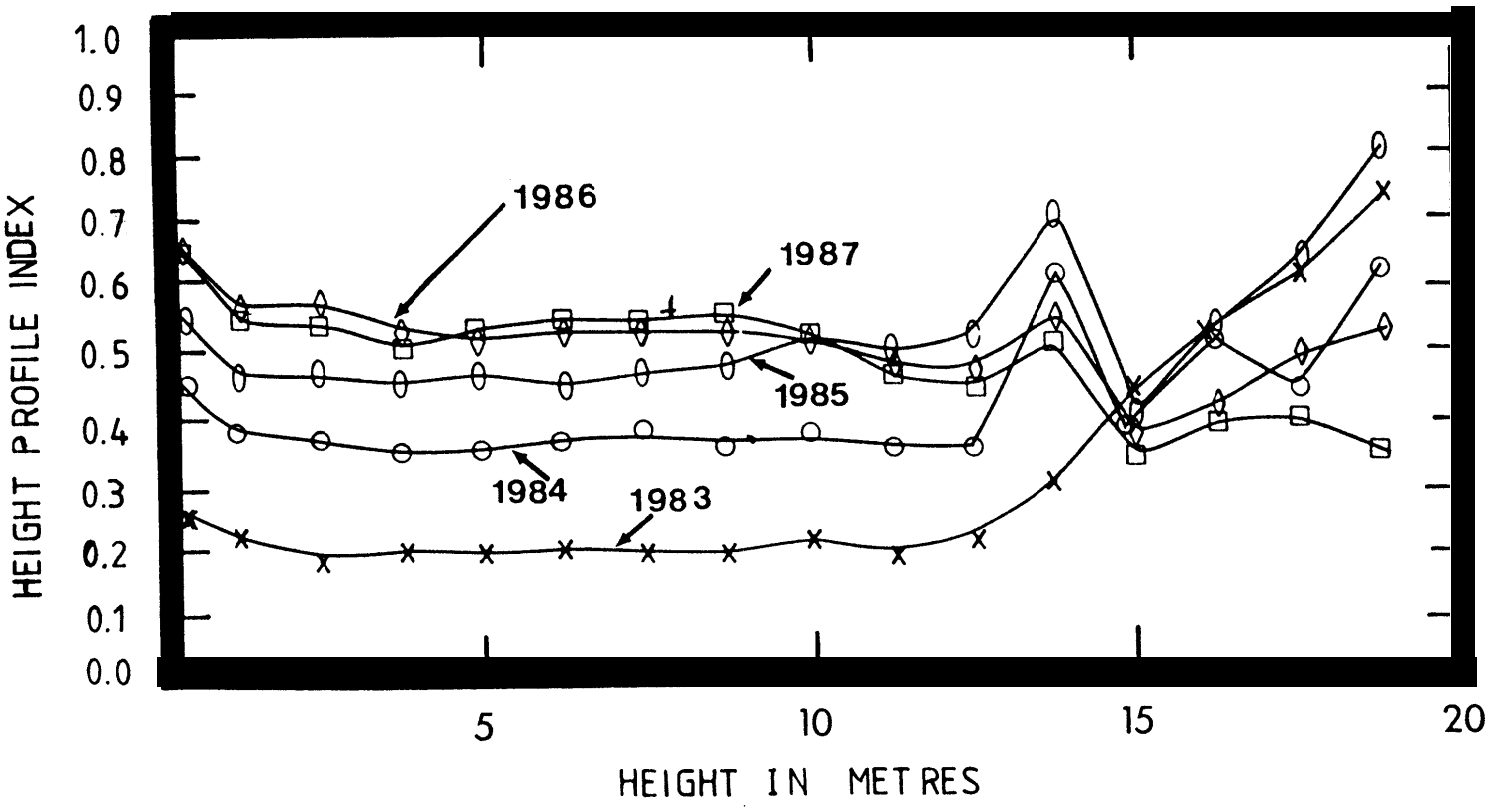

Figure 9.
Height Profile Graph of Site 6M

Table 14.
Height Profile Mean, Standard Deviation and Sample Size for 6P.

HEIGHT	1983			1984			1985			1986		
m	$\bar{x}$	σ	n	$\bar{x}$	σ	n	x	σ	n	x	σ	n
00.30	.093	.181	10	.268	.113	10	.380	.230	10	.431	.057	5
01.30	.053	.092	10	.182	,085	10	.330	.191	10	,383	,096	5
02.50	.048	.075	10	.130	.106	10	.304	.186	10	.353	.130	5
03.75	.074	.120	10	.132	.100	10	.302	.214	10	.398	.130	5
05.00	.045	.068	10	.135	.074	10	,274	,180	10	.362	.239	5
06.25	.047	.068	10	.122	.092	10	.304	.191	10	.391	.251	5
07.50	.066	.075	10	.117	,068	10	.335	.207	10	,435	.187	5
08.75	.056	.066	10	.141	.083	10	,359	.208	10	.441	.131	5
10.00	.060	.071	10	.182	.137	10	.447	.253	10	,432	.087	5
11.25	.087	.098	10	.237	.195	10	.480	.229	10	.462	.155	5
12.50	.162	.192	9	,298	.340	9	,515	.271	9	.468	.194	4
13.75	.069	.094	7	.222	.077	7	.679	,170	7	.575	.185	3
15.00	.091	.091	7	.331	.082	7	.755	.206	7	.529	.233	3
16.25	.199	.187	6	.861	.461	6	.854	.282	6	.630	.185	2
17.50	.378	.048	3	.642	.268	3	.601	,232	3	.498	.000	1

Table 15.
Height Profile Mean, Standard Deviation and Sample Size for 6M.

HEIGHT	1983			1984			1985			1986			1987		
m	$\bar{x}$	σ	n	$\bar{x}$	σ	n	$\bar{x}$	σ	n	x	σ	n	$\bar{x}$	σ	n
00.30	.361	.074	10	.557	,140	10	.672	.115	10	.759	.090	10	.762	.090	10
01.30	.326	.070	10	.485	.141	10	.576	.110	10	.671	.118	10	.662	.128	10
02.50	.289	.083	10	.472	.147	10	,576	.139	10	.682	.160	10	.649	.170	10
03.75	.303	.088	10	.454	.136	10	.555	.105	10	.632	.145	10	.611	.138	10
05.00	.303	.087	10	.461	.155	10	.573	.147	10	.625	.148	10	.642	.182	10
06.25	.308	.076	10	.467	.163	10	.559	.132	10	.643	.134	10	.651	.181	10
07.50	.302	.086	10	.484	.177	10	.571	.156	10	.642	.171	10	.655	.205	10
08.75	.302	.080	10	.464	.164	10	.588	.197	10	.639	.236	10	.663	.246	10
10.00	.319	.092	10	.480	.187	10	.626	.238	10	.625	,145	10	.627	.168	10
11.25	.307	.100	10	.467	.165	10	.605	.135	10	.583	,108	10	.564	.112	10
12.50	.305	.118	9	.494	.210	9	.658	.154	9	,603	.143	9	.573	.139	9
13.75	.361	.191	9	.706	.369	9	.807	.268	9	.714	,302	9	.675	.283	9
15.00	.524	.303	5	.643	.341	5	.795	.281	5	.774	.280	5	.757	.250	5
16.25	.261	.207	2	.406	.132	2	,605	.006	2	,601	.010	2	.578	.015	2
17.50	.328	.082	2	.589	.084	2	.624	.050	2	.628	.013	2	.587	.022	2
18.75	.446		1	.694		1	.824		1	.939		1	,789		1

Table 14 and 15 illustrate results of height profile analysis of variance. Although statistical significance was found for differing height profile indices for 1983 to 1985 at site 6P, Duncan's multiple range test revealed that significance was found only for the last few height levels. Anova results for site 6M were not statistically significant. Although it had been postulated that growth profile indices would show statistical significance throughout a greater portion of the tree this hypothesis could not be demonstrated. It is speculated that the cause of this observation is a result of extensive tree to tree variability in height profile responses and a samples size too small to detect subtle differences which occurred as a result averaging out differences in the compilation of entire plot height profiles.

TABLE 16
ANOVA of Height Profile Indices.

PLOT	YEAR	DEGREES FREEDOM	F RATIO	F PROBABILITY
6P	1983	14, 117	2.7210	.0017
	1984	14. 117	9.2679	.oooo
	1985	14, 117	5.2173	.0000
	1986	14, 48	.6816	.7803
6M	1983	15, 112	1.4757	.1263
	1984	15. 112	1.2018	.2808
	1985	15, 112	1.7092	.0588
	1986	15, 112	.9506	.5117
	1987	15, 112	.7886	.6878

The methodology employed to compile height profile indices is based on the assumption that compilation can occur with all trees at any given plot. Following analysis is was found that extensive variability of indices over a height profile created analytical problems in the upper portions of the height profile. As a result trees from each plot were regrouped into three similar height categories and the analysis rerun. No improvement in results were obtained using this methodology. This observation is primarily due to the reduced sample size of each group and extensive variability of the individual blowout response profiles. Future application of these techniques must employ greater sample sizes and restrict sampling to trees with similar height and crown development.

Although the approaches employed in the analysis of height profile did not provide expected results, variability of growth reductions and recovery trend over a height profile within individual trees is evident. Figures 10 and 11 illustrate the extensive variability observed and emphasize the need for sampling over a height profile. If an accurate evaluation of growth is required, growth sampling of growth trends from one height low on the stem misrepresent overall growth trends.

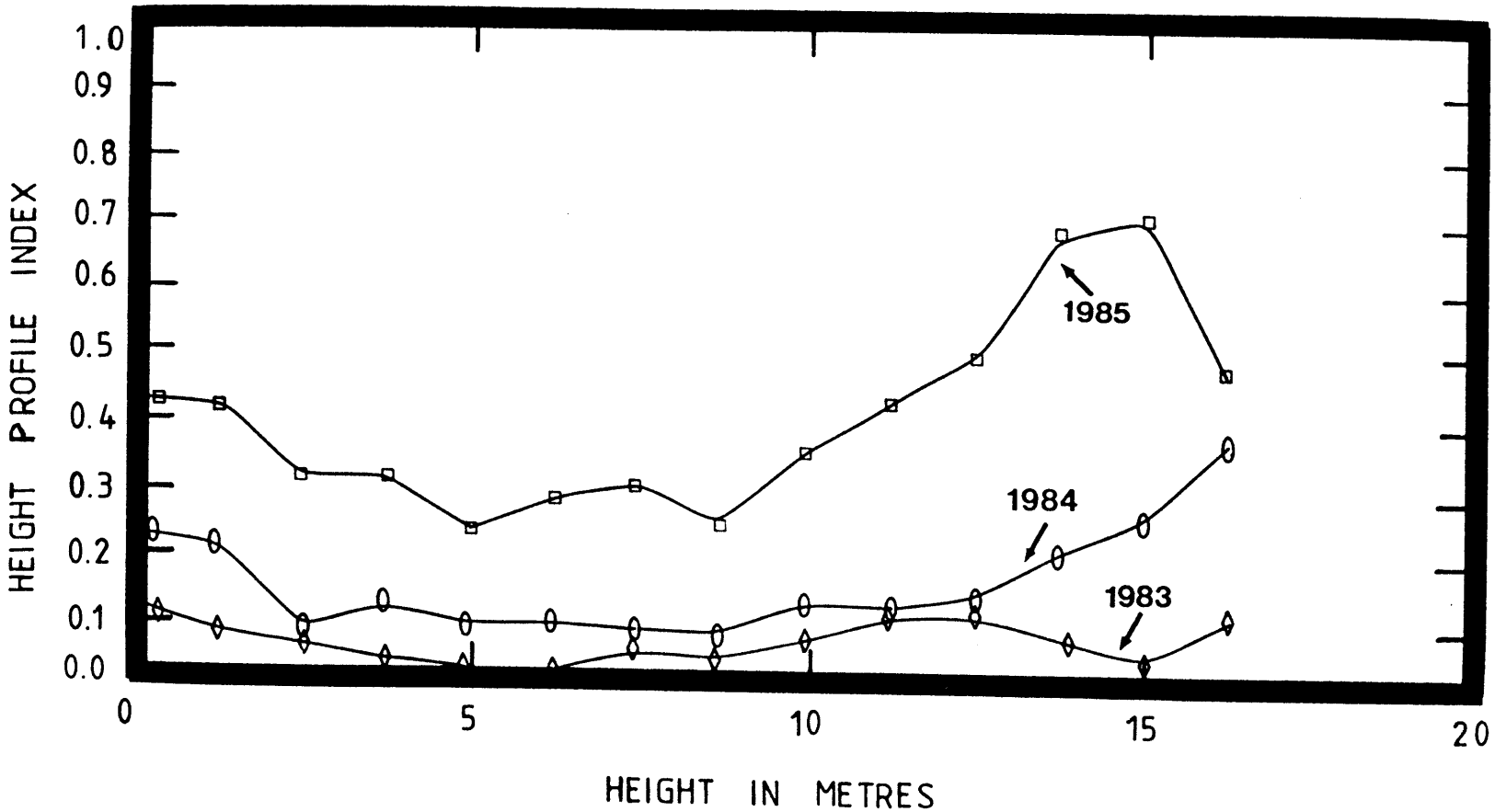

Figure 10.
Height Profile Graph of Tree 2 Site 6P.

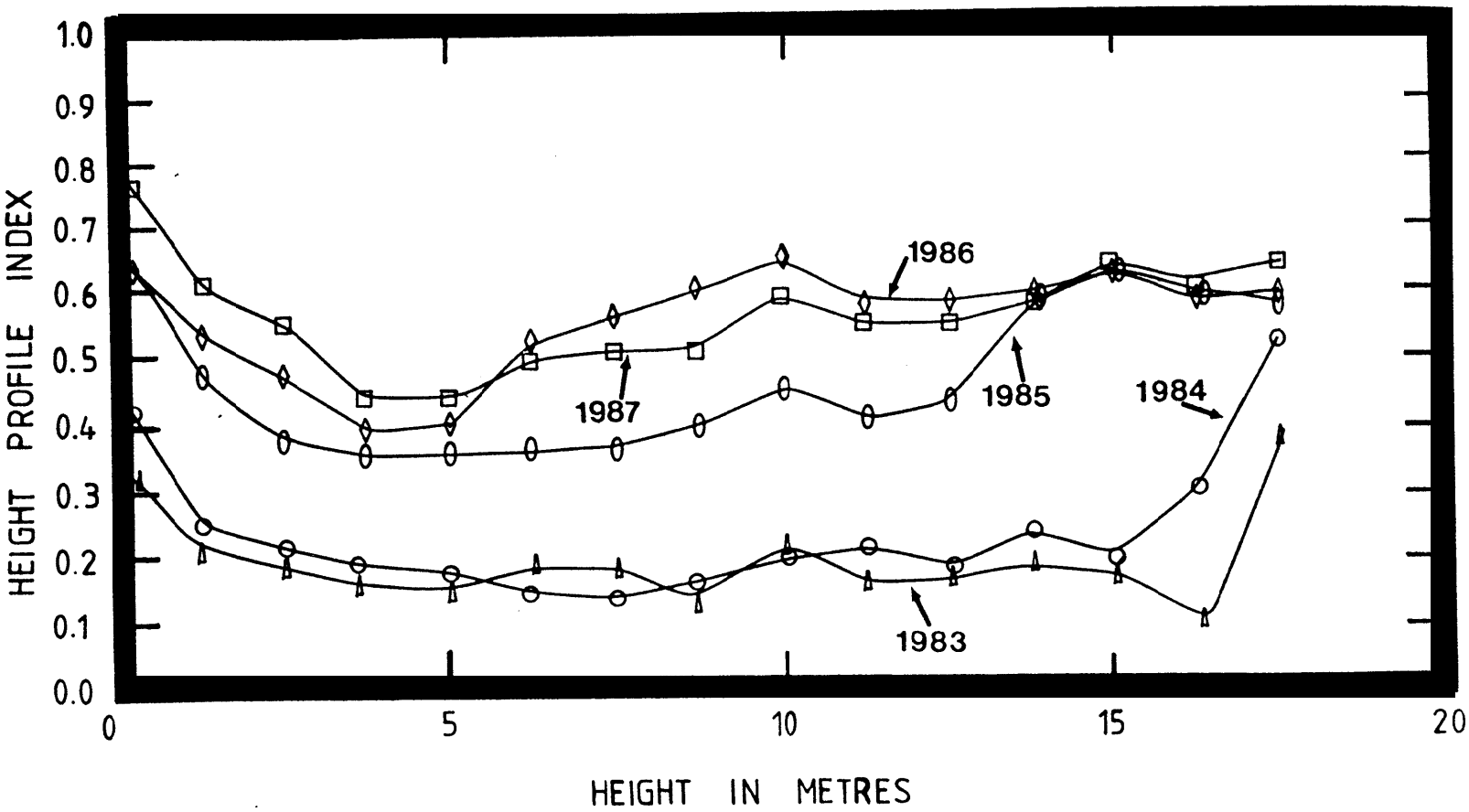

Figure 11.
Height Profile Graph of Tree 9 Site 6M.

PROJECT CONCLUSIONS

The Lodgepole Blowout has had a significant impact on coniferous growth in forested areas surrounding the wellhead and clear cut. Statistically significant growth reductions were found at the sites closest to the wellhead for all five years of post-blowout data. Growth in 1983 on sampled trees was reduced to 9.8 % and 38.1 % at site 6P (1.2 km Ne) and 6M (2.2 km Se) respectively. No growth reductions were observed at the 5 and 10 km downwind sites which are located outside the zone of visible damage described by Monenco.

Differences in growth reductions observed reflect a dose-response relationship. Growth reductions were greatest at site 6P which is located within the low condensate deposition (1 ml/100g) zone described by Jaques. Site 6M is located outside of Jaques low deposition zone in an area where condensate deposition could not be quantified. This observation leads to the conclusion that significant growth reduction in conifers can occur in areas where condensate deposition is very light ($\leq$ 1 ml/100g). It also emphasizes the difficulties in defining boundaries of impact when pollutant concentrations are low.

Recovery of surviving trees has been rapid with 66.4 % and 79.8 % of the five year pre-blowout growth rates being attained at sites 6P and 6M respectively by 1986. Recovery rates are now decreasing. Growth at site 6M increased by only 1.6 % in 1987 to a current rate of approximately 80 % of the pre-blowout growth rates. Further research is required to determine if growth rates at these two sites will eventually experience full recovery.

Growth reductions observed were greater and recovery rates slower than those predicted by Jaques (1983). Jaques's predictions were based on observed reductions from a similar 1977 well blowout where blowout effects and growth reductions were not as severe. Growth reductions were also found outside Jaques's predicted zone of light growth reduction.

Growth reductions and recovery rates were variable between trees and over individual tree height profiles. Statistically significant differences in growth responses were found over a height profile. Although statistically significant growth reduction was limited to the upper portion of the crown, growth rates observed throughout the tree ranged from 10 % less to 50 % more than that observed at a sampling height of 1.3 metres. The sampling strategy employed was sufficient to detect and describe differences over a height profile within individual trees. However, a larger sample size of trees of the same height and crown development would improve results of plot height profile description and the detection of statistically significant differences.

It is evident from this study that the effects of condensate released by the 1982 Lodgepole Blowout continue to manifest themselves through reduced productivity of White Spruce at distances as great as 2.2 km from the wellhead. Whether forest productivity will continue to improve until pre-blowout growth rates are attained and what time frame will be required for such a recovery are questions worthy of further investigation.

CHAPTER FIVE: STEM ANALYSIS AS A MONITORING TOOL

MONITORING IN EIA

Within the last decade considerable emphasis has been placed on employing the science of ecology to Environmental Impact Assessment in Canada, Beanlands and Duinker (1983). Through the use of scientific methodologies it is hoped that EIA will conduct investigative studies with analytical themes designed to produce predictions which are specific and valuable for use in the decision making process. Beanlands and Duinker (1983) also recommended that emphasis be placed on the use of monitoring as a formal and integral component of the EIA process. Accomplishing these goals requires that monitoring have its foundations in science and ecology.

In general, monitoring is carried out to test impact predictions and hypotheses and evaluate the success of mitigative measures (Beanlands and Duinker 1983). As such, monitoring is an integral link amongst a series of EIA components and is critical to the implementation of successful EIA. Even though biophysical monitoring is understood to be a useful tool in EIA, some authors feel it has not developed to the level of utility originally expected. The reason for this shortcoming is difficult to determine but Sors and Wiersma (1981) felt that the problems might lie with the difficulties in designing and operating meaningful monitoring programs. In order to be meaningful, monitoring must allow quantification of ecological change. Since impacts are seldom specific to one environmental variable, monitoring programs must be designed to evaluate changes for any array of variables. Success in monitoring therefore lies in the monitoring design and approaches used to investigate specific variables. Effective monitoring must provide insight into the inter relation and integration of a broad spectrum of variables and production of a tangible understanding of overall effect and mitigative success.

In this context environmental effects monitoring within the framework of Canadian EIA is a broad and complex subject. The objective of this paper has been to take a detailed look at the use of stem analysis as a component or tool for use in EIA monitoring. As such the inclusion of stem analysis within a larger framework of monitoring is discussed. The stem analysis methodology offers a tangible technique for evaluating development impacts where air borne pollutants of an acute or chronic nature have had or may have an affect on forest ecosystems. The strengths and weaknesses of this methodology are evaluated and discussed in this chapter.

MONITORING IN AN ENVIRONMENTAL CONTEXT

Monitoring in environmental impact assessment can be divided into the broad fields of Social Impact Assessment (SIA) and Environmental Impact Assessment. This report is restricted to a discussion of monitoring within the environmental context. An in depth discussion of SIA and the linkage of SIA and EIA is presented by Krawetz et al (1987).

Definitions and interpretations of what monitoring is are variable. Krawetz et al (1987) reviewed definitions from three authors and suggests that a common definition is needed. Broad

definitions may promote continuity between EIA monitoring projects but specific monitoring principles must also be applied to projects which have similar environmental impacts and monitoring requirements.

Since this project has reviewed the effects of pollutants in a forested environment, the stem analysis methodology will be discussed in terms of monitoring of pollutants or contaminants. Ausmus (1982) has proposed that pollution monitoring in the biophysical system should include the following three monitoring types; contaminant, biological effects and ecological effects. Contaminant transport and fate is the most common type of terrestrial monitoring. Biological effects monitoring examines the uptake or physiological response of selected plant or animal species to pollutants. Biological effects can be monitored through the use of bioindicators or natural resource indicators. Bioindicators demonstrate physiological sensitivity or accumulatory characteristics, natural resource indicators have special resource value to society. Ecological effects monitoring emphasizes the examination of net response of biotic-abiotic interactions due to pollutant inputs. The stem analysis techniques discussed within this report can be described as a natural resource indicator of biological effect.

CRITERIA FOR BIOLOGICAL MONITORS

In order for biological and ecological monitors to have utility within monitoring programs they must meet several criteria. The following criteria are based on those suggested by Ausmus (1982):

- Monitors should establish cause/effect, dose-response relationships which relate to exposure.
- Monitors must possess enough sensitivity to detect effects.
- Monitors should provide time dependant data both past and present and lend themselves to prediction.
- Monitoring parameter spatial and temporal variation must be comparable or allow standardization.
- Monitoring parameters must be wide spread thereby allowing spatial sampling over areas of potential impact.
- Monitors should allow evaluation of economic costs of contamination.

Finding and employing biological and ecological monitors which meet all criteria is an improbable task. However, the utilization of several monitoring parameters which when unified meet these criteria is an attainable goal. The remainder of this chapter discusses the stem analysis methodology in terms of these criteria and in the context of EIA monitoring in Canada.

STEM ANALYSIS AS A MONITORING TOOL

Forest Productivity as a Valued Ecosystem Component

Beanlands and Duinker (1983) have emphasized that EIA should identify valued ecosystem components to provide a focus for subsequent EIA activities. Forest growth and productivity is an easily recognizable valued component. In 1986 the softwood, hardwood and pulp industries in Canada were valued at $ 11 billion with employment in the softwood industry alone equalling 91,000 individuals Canada (1988). Thus the discussion of contaminant effects in economic terms is possible. The importance of forest ecosystem health to overall environmental quality is more difficult to determine but is arguably of greater long term utility than that of forest products harvested from within.

As such, development projects which may directly or indirectly affect forest ecosystems should consider incorporating forest productivity monitoring as a component of EIA. Industrial developments in forested areas which produce air pollutant emissions such as oxides of sulphur and nitrogen should employ forest productivity studies as part of long term monitoring programs. Large scale hydrocarbon processing facilities, such as Alberta's Syncrude and Suncor plants, or uranium refineries, such as the Eldorado Refinery, are examples of the type of industries with the potential to affect forest productivity.

Stem analysis methodologies also have application to projects where abnormal or accidental events may adversely affect forest ecosystems. An example of circumstances requiring environmental monitoring include gas pipeline ruptures on projects such as the Alaska Highway Gas Pipeline. Under these circumstances the stem analysis methodology discussed within this report can form an important part of a monitoring program employed after the fact, as was the case with the Lodgepole Blowout.

Ecological basis for Monitoring Stem Analysis

Growth of an individual tree is dependant on a large array of biochemical, environmental and genetic variables. Defining which organisms, or ecosystem components should be evaluated as biological monitors is a difficult task. Though considerable research has been conducted on pollutant effects on vascular plants, soils, and soil microbiology, pinpointing cause and effect relationships of pollutants in the environment is rarely simple Legge and Crowther (1987), Mayo (1987), Visser et al (1987), Laishley and Bryant (1987), Turchenik et al (1987).

This project has clearly demonstrated the ability for stem analysis techniques to detect a cause/effect relationship. Correlation of the stem analysis methodology with accurate pollutant deposition information has the potential to determine dose-response relationships in forests. Standard stem analysis procedures were used for this work. However, the potential exists for more powerful applications of stem analysis techniques. Dendrochronological techniques include x-ray densitometry, stable isotope research and an array of time series analytical approaches including the development of response and transfer functions Jozsa et al (1984), Long (1982),

Wigley (1982), Guiot et al (1982), Lofgren (1982). Tree ring analysis has been conducted on a large number of species throughout the world with chronologies as long as 8000 years being developed.

Although studies of growth within trees are good indicators of forest productivity and do give insights into overall ecosystem health, stem analysis alone is not a particularly sensitive technique for evaluating ecosystem well being. It is recognized that tree species are not the forest organisms most susceptible to pollution. As such it is important to recognize that symptoms of contaminant toxicities may be found in other species long before they are found in trees. Legge and Crowther (1987) present a comprehensive review of air pollutants and their affects on an array of vascular plants. From this perspective it is recommended that forest productivity studies be accompanied by the use of bioaccumulators, such as lichen, to monitor pollutant impacts. Case (1982) provides a general review of the strengths and weakness of lichen biomonitoring in Alberta. In addition to bioaccumulators Ausmus (1982) has suggested that nutrient cycling monitoring is essential to evaluation of long-term ecosystem changes resulting from anthropogenic contaminant input.

To determine cause and effect relationships, monitoring in forested ecosystems must include contaminant transport and fate evaluation, examination of bioindicator species and investigations of ecological effects at the population, community and/or ecosystem level. Forest productivity studies provide a measuring stick for detecting long term and acute temporal change in forested ecosystems. The power of stem analysis lies in its ability to extract information subsequent to an event, which can be linked with statistically valid cause/effect predictions for tree growth.

Study Design and Quantification

Beanlands and Duinker (1983) have emphasized that EIA be based on scientific methodologies whenever possible. They emphasize the implementation and design of frameworks for ecological EIA which involve the formulation of hypotheses, the use of statistically based designs, and the testing of hypotheses and assumptions. As a monitoring tool, stem analysis lends itself to these approaches. Quantification of natural patterns, variability and impacts to growth can be measured and tested statistically in spatial and temporal terms.

The Lodgepole blowout stem analysis project was based on the sampling of trees at five sites. It is not possible to draw broad conclusions as to boundaries of well blowout effects with this number of sites. To successfully establish overall impacts to the forest it is necessary to stratify areas of potential impact into zones of similar effect. Subsequently, a stem analysis sampling program can be used in conjunction with forest inventory information to identify the extent of growth perturbations over broad areas and evaluate overall modification of volume yields. The use of modeling to project inventories into the future allows for the determination of overall potential impacts.

Stem Analysis as a Time Dependant Variable

Perhaps the greatest strength of stem analysis is its use as a time dependant variable which maintains a chronological record of past conditions and variability. Through standardization and time series analysis it is possible to establish detailed baseline data for use in prediction of future trends. In relation to impact prediction, it allows for confident prediction of unaffected post development growth trends for which subsequent measurement can be used to evaluate deviations from the norm. In this sense stem analysis has the ability to provide background data after the fact.

This factor is particularly useful in cases where EIA involves projects where abnormal pollutant events are possible. The remote probability of such events occurring make expensive background studies difficult to justify. If unexpected releases occur in forested areas stem analysis techniques provide a method for deriving baseline data for use in prediction and evaluating environmental impacts. Other projects with the potential for significant abnormal releases include the pipeline transmission of gases or condensates.

Prediction and Monitoring

Prediction of potential environmental impacts is the cornerstone of monitoring in EIA. It is also the most difficult EIA component to confidently determine. Stem analysis has the potential to predict growth patterns which should occur under normal circumstances and can also be used to evaluate observations and impacts after the fact. The potential for comparative work, such as the Lodgepole Blowout work conducted by Jaques (1983) may help to make impact predictions for projects under consideration. However, it is not possible to use stem analysis to predict potential impacts, just measure those that have already occurred.

Prediction of net pollution impact on forest ecosystems requires other techniques. For example, the analysis of potential impacts from air pollutant point sources must employ emission and dispersion modeling and rely on subjective determination of potential impact once pollutant concentration, frequency, ecosystem adsorption potential, buffering capacities and species susceptibilities have been quantified. Once predictions are made stem analysis can be employed within a larger monitoring program to verify and evaluate impact predictions to forest productivity.

A large number of computer models have been developed for use in forest growth studies. Models already developed include: individual tree models, whole stand models, fertilization and genetic improvement models, and several for evaluating the effects of insects and diseases and anthropogenic disturbances. An array of these models are discussed within the proceedings of the International Union of Forestry Research Organizations Conference on Forest Growth and Modeling (Ek et al 1988). Further research into the use and application of forest growth modeling for EIA purposes should be conducted.

SUMMARY

This paper has demonstrated that stem analysis has utility as an EIA monitoring tool, particularyly when used in the context of a multifaceted monitoring program. Even though forest productivity is not the most sensitive indicator of environmental impact, this project has shown that cause/effect and dose response relationships can be detected. As a variable for EIA monitoring, forest productivity can be readily defined in economic and ecological terms as a valued ecosystem component. From a scientific perspective stem analysis data can be defined in statistical terms and promotes the proposal and testing of hypotheses. The greatest strength of the methodology is in its ability to examine historical trend and variance in an "after the fact" situation. The chronological record contained within trees promotes analysis in temporal and spatial dimensions within which predictions may be tested. Future EIA in forested regions where forest productivity is at risk should incorporate stem analysis methodolgies within monitoring programs.

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