Assessment of the Impact of Ozone Air Pollution on Agricultural Resources of the Fraser Valley, B.C. : Sources of Uncertainty and Risk Assessment Methodology

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FOREWORD

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Abstract

Air quality monitoring in the Fraser Valley east of Vancouver has demonstrated that the Canadian air quality objectives for ozone are regularly exceeded during the agricultural crop growing season. Agricultural resources represent one class of potentially sensitive receptors in this region. It appears that observed ozone levels may be resulting in "invisible" yield reductions of some or several crops, although evidence of this is largely circumstantial at this time. This is because our knowledge of dose-response relationships for local cultivars and growing conditions is at present very limited; only potato and pea dose-response relationships are presently being studied.

This paper describes the major sources of uncertainty involved in predicting the effect of ozone pollution on agricultural productivity. It also proposes a risk assessment methodology for describing the uncertainty associated with the use of secondary dose-response information; that is, dose-response information for cultivars and growing conditions not common to the Fraser Valley.

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1. INTRODUCTION AND OBJECTIVES

Although much of the public concern about ozone is presently focussed upon its depletion in the stratosphere, its elevated levels near the earth's surface in the vicinity of urban **centers** represent one of our most important air pollution problems today. As a result of society's increasing use of fossil fuels, and the widespread use of the internal combustion engine, the concentration of ozone's precursors, the oxides of nitrogen and reactive hydrocarbons, have increased so that photochemical reactions leading to ozone formation are common in the lower atmosphere during the warmer months. Although ozone is a highly reactive gas, **it** may be transported over considerable distances depending upon meteorological conditions. Hence it often moves away from its urban origins into rural areas.

Past research has shown that ozone results in visible symptoms of injury to sensitive vegetation when the ambient ozone level exceeds a threshold of about 40 ppb, maintained for at least one hour. Research has also clearly shown that important chronic exposure effects may occur, which may or may not involve visible symptoms, but which lead to impairment of plant growth and hence productivity. It is this latter awareness that has led to much of the present effects research that is being conducted; for example, the large National Crop Loss Assessment Network (NCLAN) program of the U.S. Environmental Protection Agency (Heck et al., 1984a).

Air quality monitoring in the Fraser Valley east of Vancouver has demonstrated that the Canadian air quality objectives for oxidants (ozone) have been regularly exceeded during the summer months, and that research is needed to determine the potential magnitude of the problem (Wilson et al., 1984). Based on effects documented under similar oxidant conditions in other regions, agricultural resources have been identified as one of the potentially sensitive receptor groups in the Fraser Valley. An assessment of the impact of oxidants on agricultural resources in the Fraser Valley requires two types of information:

(a) Continuously monitored air quality data collected during the growing season within important agricultural areas; and

(b) Dose-response information for locally important crops.

Figure 1 shows the location of air quality monitors in the Fraser Valley. It can be seen that the majority of the monitors are located in the urban Greater Vancouver Regional District. Monitors in important agricultural areas east of the GVRD include Pitt Meadows (T16), Surrey (TM), Abbotsford (T11) and Chilliwack (T12). Operation of these four monitors east of Vancouver has shown that ozone air quality in rural agricultural areas frequently exceeds the National Air Quality Objectives for oxidants (ozone), but that the number of exceedances per growing season has been decreasing over the period of record.
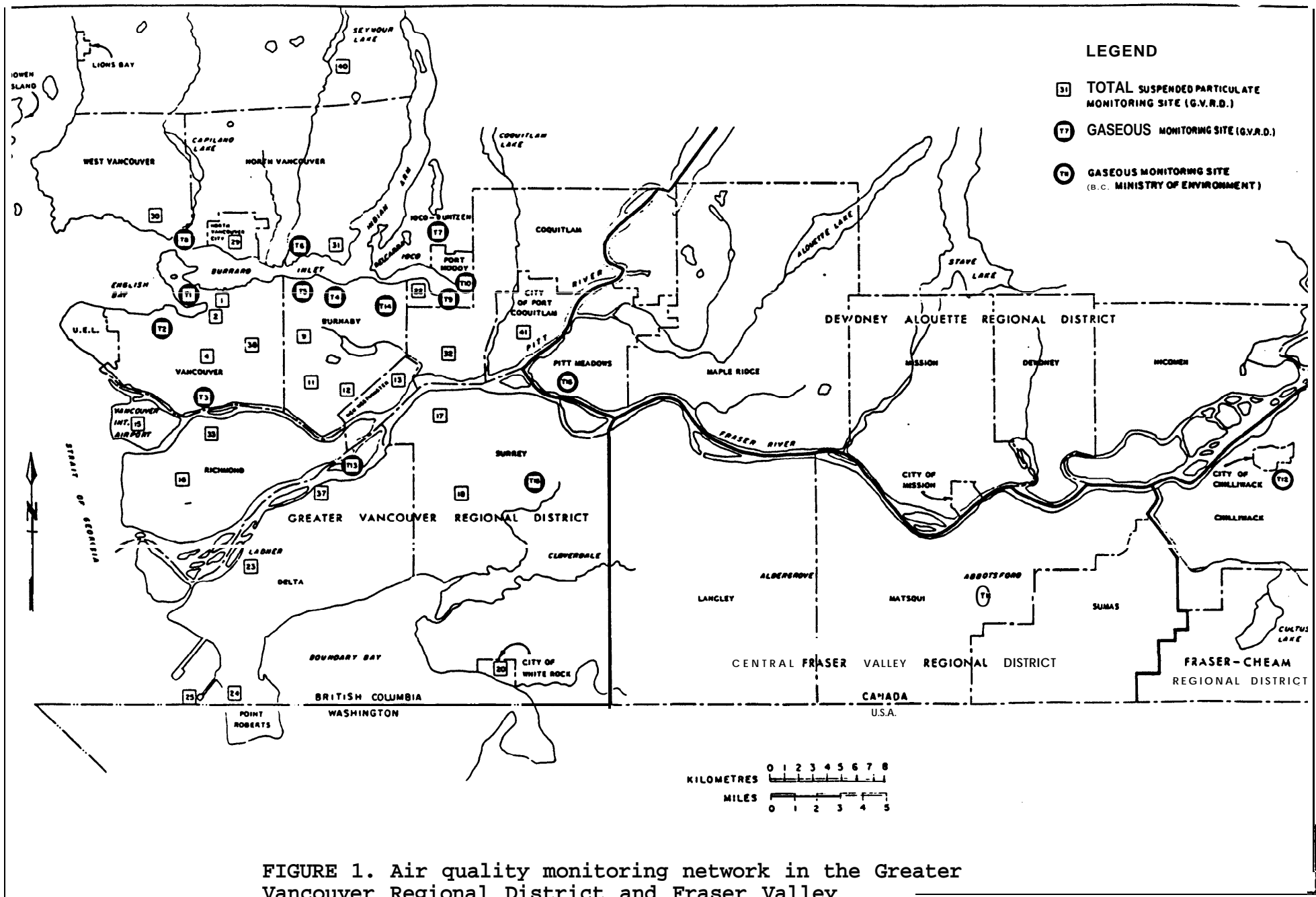
FIGURE 1. Air quality monitoring network in the Greater
Vancouver Regional District and Fraser Valley

This may be observed form the data in Table 1, which is the "growing season ?-hour (9 am to 4 pm) daily mean ozone concentration" at various locations for the period of record. The seasonal 7-hour mean was one summary statistic originally proposed by NCLAN (Heck et al, 1984a) for use in agricultural crop dose-response experiments.

The other primary source of data needed for impact assessment is dose-response information for locally important crops. The effects of ozone at the individual plant level are documented for several agricultural species that are important in the southern and eastern U.S., but there is at present no direct experimental data for ozone effects on important agricultural species in British Columbia. Thus, our understanding of local dose-response relationships is at present very poor, although experiments currently being conducted by researchers from the Department of Plant Science at UBC will produce dose-response data for locally important cultivars of potato and pea. Unfortunately, there has not been a lot of support available for such research, suggesting that additional dose-response information will at best be slowly accumulated.

Under these circumstances, if impact assessment is desired, it must utilize secondary data. For example, considerable dose-response information is available for California crops, and for crops grown in other parts of the United States that have problems with oxidants. The important question is whether and to what extent such information is relevant to British Columbia, as plant response varies between cultivars, and because local growing conditions greatly affect plant response to air pollution.

TABLE 1

Seasonal Seven-Hour (9 am - 4 pm) Ozone Dose by Year and Site
(parts per billion)

Year	T7 Anmore	T13 Annacis	T11 Abbotsford	T12 Chilliwack	T15 Surrey
1986	28.2	23.3	30.4	25.1	25.1
1985	36.3	NA	40.1	39.1	46.2
1984	28.4	23.9	39.0	37.6	34.5
1983	32.4	25.8	25.9	NA	NA
1982	59.9	38.2	34.3	NA	NA
1981	45.7	NA	24.4	26.7	NA
1980	53.1	NA	37.1	32.3	NA
1979	52.6	NA	43.3	38.9	NA
1978	52.2	NA	37.3	NA	NA
Average	43.2	27.8	34.6	33.3	35.3

Note: these figures are not true growing season means because when they were calculated 1986 data were only available until the end of July. The above means for all years are thus for the 3-month period May, June, July. True seasonal means would also include August and part of September.

Under these circumstances, a risk assessment methodology which utilizes expert judgments about the applicability of "foreign" dose-response data is needed. In other words, the use of objective data requires subjective judgments about its applicability. Subjective probability distributions elicited from experts on dose-response contain information about two types of uncertainty (i) scientific and measurement uncertainty related to the original objective data, and (ii) uncertainty related to use of objective probability distributions for different conditions than those associated with the objective probability distribution.

This report is divided into two major sections as follows. Section 2 describes sources of uncertainty in our scientific understanding of ozone effects on agricultural crops, and offers suggestions on how some of these uncertainties may be reduced in future research. The information in Section 2 was originally presented in a paper delivered at the 1986 annual meeting of the Air Pollution Control Association, in Minneapolis (Runeckles and Brown, 1986).

Section 3 presents a risk assessment methodology which involves the use of expert judgments about probabilistic dose-response relationships for locally important agricultural crops.

2. SOURCES OF UNCERTAINTY IN RISK ASSESSMENT

Although risk assessment provides a means for dealing with uncertainty, the preferred method for improving decisions is by reducing uncertainty. In this respect there is no substitute for scientific research, which is the only means by which we can improve our knowledge base of the system under study. In ozone/agricultural crop research, our knowledge base has been greatly enlarged in recent years by major research efforts, and scientific uncertainty has been reduced.

Although our knowledge of the effects of ozone on **agro-**ecosystems is relatively good, significant sources of uncertainty remain. Some of these cannot easily be dealt with, as they are inherently **unpredictable** due to the stochastic nature of ecosystems. On the other hand, the potential exists to reduce uncertainty associated with several aspects of ozone effects on agro-ecosystems, as discussed below.

2.1 General Sources of Uncertainty

Uncertainty refers to absence of knowledge of the system under study, and degree of uncertainty refers to that proportion of the information about a system not known. Interest is focused on those uncertainties which affect our ability to simulate the outcome of a particular action. Collectively, these may be referred to as "predictive" uncertainties, of which there are many types, as described in Table 2.

TABLE 2

General Categories of Types of Uncertainty

Stochastic uncertainty: is related to prediction of events which by their very nature are uncertain because of their random behaviour, e.g., the values of meteorological parameters at specific future times. In general, further research will not reduce this type of uncertainty.

Scientific uncertainty: includes both descriptive and measurement uncertainty. "Descriptive" uncertainty arises from lack of information, knowledge or scientific agreement on cause-effect relationships. "Measurement" uncertainty arises both from random error and measurement error. Statistical methods can quantify measurement uncertainty due to random events.

External uncertainty: refers to lack of knowledge of external factors or decisions which may affect the system, but are outside the realm or control of the particular decision group, e.g., changes in social tastes and preferences, and changes in technology.

Analytical uncertainty: is due to the fact that predictive models are simplified versions of the real world, and cannot accurately represent all the nuances of the system under study. Examples include meteorological models and empirical dose-response models.

Source: Turner (1985)

2.2 Uncertainty in Ozone Effects Research

2.2.1 <u>Scientific Uncertainty</u>

According to the definitions given in Section 2.1, scientific uncertainty includes measurement and descriptive uncertainty, both of which may be reduced by research.

(a) Measurement Uncertainty

The most important sources of measurement uncertainty in ozone/ecosystem research are: (i) the inherent variability of natural systems, and (ii) measurement error.

<u>Variability</u> <u>of Natural Systems</u>

Measurement uncertainty is introduced due to the stochasticity of natural systems, as described by Krupa and Teng (1982):

> Uncertainty is an accepted phenomenon when modelling biological systems. This uncertainty arises from the stochastic nature of many biological stimulus-response relationships and is a reflection of the inherent stochasticity of both the biological system itself and the environment that drives that system... (this) makes it almost impossible to predict a response that is deterministic, i.e., without variation.

Since seasonal fluctuations and long-term climatic cycles contribute to natural conditions, defining an adequate control requires many years of baseline data. The major challenge today is to distinguish the signal created by low level, anthropogenic pollutant stress from the background "noise" inherent in the system.

Measurement Error

This source of uncertainty is inherent in all scientific investigations. In ozone/ecosystem research, major sources of measurement error include incorrect or inaccurate measurement of response, or the use of inaccurate equipment (e.g. air pollution monitors). An example of the measurement of an inappropriate response variable would be measurement of foliar injury, if information on yield reduction was desired, because foliar injury is not a reliable indicator of yield reduction (Jacobson, 1982).

An important component of measurement uncertainty relates to the choice of experimental method to be used to obtain dose-response data. In much of the early work, little appreciation was shown for, and little attention paid to, the natural dynamics of air movement around vegetation in field situations. As a result, although much of the experimentation employing various types of growth chambers and modified greenhouses provided information about the effects of ozone on plants, it provided little of direct use in determining the dose-response to be expected in the field. This element of measurement uncertainty, related to choice of experimental method, persists in today's research.

The large NCLAN study and many others have adopted the open-top chamber approach (Heagle et al, 1973; Mandl et al, 1973). In this approach, plants growing in the field are treated with various regimes of ozone additions to the ambient air within the confines of the chambers. One serious flaw in their use is the inability to eliminate the confounding between treatment and

chamber: the former cannot be provided without the latter. In particular, it is impossible to evaluate (treatment) x (chamber) interactions, although considerable effort has been expended in an attempt to show that this flaw may not invalidate certain conclusions respecting effects on final yield.

The other approaches to acquiring dose-response data of direct applicability to field assessments dispense with enclosures completely. One approach is the open-air release system typified by the **Zonal** Air Pollution System (ZAPS), first extensively used in the Colstrip, Montana studies of the effects of sulphur dioxide on a grassland ecosystem (Lee et al., 1975). The basis of the approach is the release of the gaseous pollutant from a perforated pipe manifold supported above or within the vegetation, in order to supplement that present in ambient air. This approach has seen very limited use in ozone/ecology research. Unfortunately, ZAPS also has certain inherent sources of uncertainty, largely related to the adequacy of the distribution and mixing of the released gas. In turn, adequate description of the air quality achieved requires a high intensity of monitoring, in order to obtain an adequate description of the short-term fluctuations in concentration, and to provide assurance that distributions of concentrations obtained over plots to which pollutant is added to that present in the ambient air resemble those occurring when the ambient air itself reaches such concentrations (Krupa, 1984).

A second outdoor no-chamber approach exploits the variations in overall air quality to be found within an **airshed**. Where the general climatological and meteorological conditions are reasonably comparable over an area in which proximity to an area source of ozone dictates the ambient ozone concentration, sites for experimental plots are selected along the downwind pollutant gradient. By standardizing the soil, fertility, and water regimes, and by monitoring the ambient air at each site, **dose**-response curves for test species can be developed. This approach has been used to study the effects of ozone **on** alfalfa and other crops in the South West Coast Basin in California (Oshima et al, 1976). Again, uncertainties directly ascribable to the methodology still exist, particularly with respect to the effects of uncontrolled variables on response, for example differences in local soil and climatic conditions.

Uncertainty related to the appropriate description of dose is deferred to Section 2.2.2, since its importance bears directly on analytical (modelling) uncertainty.

(b) Descriptive Uncertainty

The main sources of scientific (descriptive) uncertainty are lack of understanding and lack of information, each of which includes several components.

Lack of <u>Understanding</u>

At the heart **of** the uncertainty of the effects of ozone on plants is the lack of a clear understanding of the physiological mechanisms responsible for plant response, including **detoxifi-**

cation and repair (Tingey and Taylor, 1982). Increased knowledge

of such mechanisms would allow development of models with much

improved capabilities.

Another uncertainty source relates to the relationship

between ambient dose and effective dose (Runeckles, 1974). Air

quality monitoring data only provide us with the indirect

evidence of the probability of a response, a phenomenon first

reported by Macdowall et al. (1964) in their studies of the

relationship of tobacco leaf injury to ambient ozone. Attempts

to relate conventional assessments of dose based solely upon

concentrations and duration failed to yield a satisfactory

response curve. However, when the method of expressing dose was

modified to include a measure of the crop's capability for

absorbing ozone from the ambient air (based upon transpiration

and other measurements), a significantly improved dose-response

relationship was obtained. An alternative approach to

determining the integrated effects of ambient dose and vegetation

receptivity is found in the use of selected, sensitive species of

plants as biological monitors, as practiced in the Netherlands

(Posthumous, 1982) and elsewhere. Such biological monitors act

as integrators of all local conditions, including air quality.

As such they provide better evidence of whether or not ambient

pollutant exposures are resulting in plant injury or damage.

A third area of uncertainty is related to the value of the

natural background level of ozone that should be assumed for the

purposes of predicting anthropogenic impacts. The assumption by

NCLAN (Heck et al, 1984a) that the natural background level of

ozone is 25 ppb is somewhat arbitrary. Background levels of ozone will differ over time and space and in some cases will be substantially different from 25 ppb. In such cases, impacts calculated assuming this background level will be erroneous.

There are several additional needs for better general understanding of the many variables which influence plant response to ozone. These include pollutant-environment interactions, variation among and within species, interactive effects of pollutant mixtures and sequential exposures, acclimation and predisposition, stimulatory effects under low ozone doses, and differing growth stage susceptibilities (Bennett et al., 1974; Runeckles, 1986). Ongoing research is gradually reducing the uncertainty related to many of these relationships.

Lack of Information

This category of descriptive uncertainty refers to information deficiencies resulting from practical limitations to the amount of data that can be collected, e.g., site-specific air quality data and dose-response models. In order to predict impacts at such sites, expert judgements are required to extrapolate from indirect data bases, as described in Section 2.2.

2.2.2 Analytical Uncertainty

Analytical uncertainty refers to uncertainty introduced by the use of simplified models which simulate real systems. Two issues are relevant in this regard: (a) validity of the model in terms of representing the system, and (b) choice of the model's functional form.

(a) Validity of the Model

There are four major sources of uncertainty related to model validity:

- deciding which independent variables to include,
- the need to obtain response data from plants exposed under real-world conditions,
- the difficulty in determining the appropriate measure of ozone dose, and
- number of ozone treatment levels.

Each of these sources of analytical uncertainty is discussed below.

Variables in the Model

A dose-response model which accurately represents reality would be of the form:

Plant Response = ozone dose + (all others factors affecting plant response to ozone dose)

Such a predictive model, which captures the entire system relationship, is in practice impossible to achieve. A major consideration is the extent to which the effect of the several important non-pollutant factors that modify plant response to ozone should be incorporated into the model. Incorporation of most or all of these factors into the response model would be an admirable undertaking, but one which in reality is probably not worth the cost and effort, considering the heterogeneity of conditions over time and space. (In theory an infinite number of such models would be required to define all possible functional

relationships). Thus for practical purposes, the number of explanatory variables in any model is restricted to those which are most important in determining plant response. For example, NCLAN is explicitly incorporating only ozone and effects of plant water stress (which potentially reduces plant response to ozone) at this time, although incorporation of other factors such as pollutant interactions is planned *(Heck* et al., 1984a) .

It is not always possible to define the most important variables. Obviously, independent information may tell us that a particular environmental variable may have a large effect on growth and performance and hence we tend to feel we must include such a variable in our model. Numerous other variables may influence response less dramatically. In particular, individual variables may fail to reach an acceptable level of statistical significance in experiments in which their influence is tested, and thus are excluded. Unfortunately, the excluded variables **may** collectively have a large effect on response, and hence reduce the validity of a model by their omission.

A satisfactory model that incorporates the influence of developmental stage on ozone sensitivity (e.g. the three dimensional response surface envisaged by Krupa and Teng, 1982), has not yet been developed. Several years' experimental data would, of course, implicitly incorporate this relationship. Since NCLAN is maintaining records of ozone concentrations and associated crop development stage, the functional relationship between co-occurrences of critical ozone concentrations and development stage as it affects final yield may eventually be defined (Heck et al., 1984a).

However, to develop a more generally useful understanding of this relationship requires the application of the various methods of plant growth analysis, in order to reveal the effects of short-term dose on the dynamics of growth and differentiation (Hunt, 1982; Runeckles, 1984).

Exposure Under Natural Conditions

Past studies have demonstrated that plant response under natural field conditions is significantly different from response under laboratory conditions, given the same pollutant dose (Heck, , 1982). For this reason, most experimental studies today involve exposure of test plants under field conditions. Ideally only ozone exposure is controlled while all other variables that affect plant response are uncontrolled but can be explained. As discussed in Section 2.2.1, this ideal has yet to be attained, but trials over time and space (i.e., different locations and seasons) permit us to gain some understanding of the variation imposed by local conditions.

Pollution Exposure Statistic

A third difficulty in terms of model validation relates to defining a biologically meaningful ozone exposure statistic. Ambient air quality is conventionally defined in terms of average concentrations, calculated from frequent "instantaneous" monitor readings. The use of averages results in a loss of information about the fluctuations of concentration and, more importantly, the peak concentrations which may occur. Nevertheless, the attractive simplicity of a single summary dose statistic is

undeniable, especially from the point of view of regulation and control (Heck et al 1984b). Unfortunately, its use in dose-response modelling increases rather than decreases uncertainty since the process involves two independent components, each of which has its own uncertainties: (i) the choice of expression used to define the ambient dose, and (ii) biological response.

The NCLAN study has investigated the relationships between several simple exposure statistics and is currently focussing on 7-h and 12-h daily means, while recognizing that more than one statistic may be inevitable to provide an adequate description of dose from a biological perspective (Heck et al., 1984b). A partial solution to this problem may be the use of the effective mean concentration parameter proposed by Larsen and Heck (1984), which, by using a power function of the ozone concentration, gives additional weight to peak concentrations. Use of this parameter predicts higher injury (yield reduction) at sites with more pollutant variation, over sites experiencing the same arithmetic mean exposure, but with less variation.

One model which minimizes the uncertainties of overall dose-response is that of Nosal (1983), although it is achieved only through the utilization of more complex exposure parameters. This is a mixed multivariate polynomial-Fourier regression, in which response is related to three "dose" parameters:

- Total cumulative exposure dose over the growing season,

- Peak concentration of individual episodes, and

- Total number of episodes above a certain threshold over the growing season.

This model thus interrelates directly the key features of the episodicity and fluctuations in ambient air quality over time with response, rather than attempting to define a simple summary dose statistic.

<u>Treatment Levels in Experimental Design</u>

A fourth difficulty related to model validity is that the number of treatments in most experimental designs is insufficient (Krupa and Teng,1982; Nosal, 1983). Thus a high R-square value does not necessarily reflect a high degree of fit of the model, but is theoretically guaranteed as the consequence of the limited number of regression points. This is a very serious shortcoming which is common to most air pollution effects dose-response modelling at present.

(b) Choice of Model Functional Form

The second major category of analytical uncertainty is related to choice of model functional form. The following discussion is restricted to empirical dose-response models, the vast majority of which are fitted to data using a least-squares regression approach. Popular model forms include linear, plateau-linear, quadratic, Weibull and others. Each model has certain strengths and weaknesses; the most important criterion for selection of model form is goodness-of-fit.

Linear models are desirably simple but they cannot represent threshold levels below which no yield reduction occurs. Many exposure-response relationships are non-linear. Both the log-normal (Larsen and Heck, 1984) and Weibull (Heck et al. 1984a)

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models have been used, although they cannot easily incorporate the effect of low level pollutant stimulations. The quadratic model accommodates both low level stimulation, and injury at higher doses.

It is essential to **recognize** the limitations of empirical models. Any particular model should not, in theory, be extrapolated. Separate models should be developed for individual cultivars in time and in space; thus a large number of such models is theoretically needed to predict future impact over large agricultural regions. Since this is obviously not possible, scientific judgement is necessary to select the various experiments that will be conducted in any particular assessment (see Section 2.2). A related issue is the recognition that results cannot be directly extrapolated beyond the range of pollutant concentrations modelled. Such extrapolations must be based on scientific judgement, they must have a strong biological basis and, since uncertainty is involved, they should be probabilistic.

3. DEALING WITH UNCERTAINTY: RISK ASSESSMENT METHODOLOGY

The previous section described various sources of uncertainty in ozone/agricultural crop research and offered suggestions on how uncertainty could be reduced in future research. However, there are limits to the ability of science to reduce uncertainty. There will always be uncertainty, due largely to the inherent variability and stochasticity of natural systems, and the difficulty in **predicting** the value of future variables which may affect plant response.

This section describes a risk assessment methodology for dealing with one major source of uncertainty - the response of crops to ambient ozone for which specific experimental data are not available. This section proposes a methodology which involves the use of expert judgments to generate probabilistic dose-response relationships. The risk assessment methodology proposed here is intended to produce **an** information base which not only makes full use of the existing scientific data base, but **also characterizes** the magnitude of uncertainties **associated** with the data base. The methodology is not intended **as a** substitute for scientific research, rather it is intended to maximize the information **available** and usefulness of existing knowledge.

3.1 Need and Rationale for Expert Judgments Regarding Dose-Reponse

One of the early proponents of environmental risk assessment utilizing expert judgments was Morgan, who in 1978 argued that

> Good analysis must recognize that physical truth
> may be poorly or incompletely known. Its objective
> is to evaluate, order, and structure incomplete
> knowledge so as to allow decisions to be made with
> as complete an understanding as possible of the
> current state of knowledge, its limitations, and
> its implications. (Morgan et al 1978).

The National Academy of Sciences (1977) pointed out that two kinds of judgment are involved in environmental policy-making, namely cognitive judgment based on scientific data, and evaluative judgment based on policy considerations. Identification and assessment of risks to ecosystems requires cognitive judgments because of unavoidable sources of uncertainty, while determination of the acceptability of risk is an evaluative task for the political process.

The methodology proposed here deals specifically with the use of cognitive judgments by scientists of uncertain dose-response relationships. These are uncertain for many crops and growing conditions because of lack of empirical data. Where dose-response information is available, it represents specific experimental conditions and may not be an accurate model of what may happen under different conditions. Cognitive judgments are required to evaluate the applicability of specific models to conditions other than those under which the experiment was conducted.

With experimental data, statistical methods are used to **characterize** the uncertainty associated with random variability, measurement and sampling error. In situations where experimental data are sparse and only indirectly relevant (**e.g.**, differences in crop cultivar, growing conditions, or representation of dose term), this experimental variability may represent only a small portion of the scientific uncertainty about the dose-response relationship being investigated. In other words, the use of objective evidence requires subjective judgments. In this regard the following quote was originally published in 1959:

> A knowledge about past instances or about statistical samples, while indeed providing valuable information, is not the sole and sometimes not even the main form of evidence in support of rational assignments of probability values. In fact the evidential use of such _prima_ _facie_ evidence must be tempered by reference to background information, which frequently may be intuitive in character and have the form of a vague recognition of underlying regularities, such as analogies, correlations, or other conformities whose formal rendering would require the use of predictions of a logical level higher than the first....(Experts have) at their disposal a large store of mostly inarticulated background knowledge and a refined sensitivity to its relevance, often enabling production of trustworthy personal probabilities regarding hypotheses in the particular area of expertise (**Helmer**,1983).

Helmer suggests that an expert's subjective estimate of the probability of a particular event, given certain evidence, may be taken as an estimate of the probability in question.

Dressler (1972) suggested that subjective capability can be thought of as a continuum consisting of three areas. At one end is knowledge - assertions for which there is a great deal of evidence. At the other end is speculation, for which there is

little or no evidential backing. In the middle is opinion, which

represents material for which there is some basis for belief.

Although the dividing line between these three areas is vague,

the 3-way split concept "guards against a tendency to dismiss

whatever is not knowledge as mere speculation".

3.2 Probabilities as Measures of Uncertainty

The National Academy of Science, referring to decision

making in the U.S. Environmental Protection Agency, stated

> it is improper for (scientists) to fail to
> &lain clearly the limits of their knowledge, the
> margin of uncertainty in their estimates, and the
> gaps that might be closed by further research
> (NAS, 1977).

For the responsible use of science in decision making, it is

important for decision makers to know not only what is known, but

also what is not known (Clark, 1985). Unfortunately, it would

appear that uncertainty related to predictions of environmental

effects is in general not being explicitly reported to the extent

it should be. In Clark's words:

> Unfortunately, it is precisely in communicating
> assessments of incomplete scientific knowledge that
> the scientific community remains least effective in
> providing usable knowledge to decision makers....
> Most technical policy studies of the last decade
> have paid more or less elaborate lip service to
> these cental issues of uncertainty... but very few
> analysts have moved beyond arm waving and
> mathematical exhibitionism to the systematic,
> synoptic, and useful analysis of uncertainties and
> their policy implications (Clark, 1985).

The words "**odds**", "probability", "**likelihood**", and
"frequency" may be used to quantitatively represent
uncertainties.   There are two schools of thought regarding the
definition of probability (Mock and Vertinsky, 1985):

(a) Statistical probability, also called objective probability or
the **frequentist's** approach, is the relative frequency of a given
class of events within a larger population of such events.
Objective probabilities are often determined from properly
designed experiments.

(b) Subjective probability refers to personal beliefs;
probability in this case is a measure of an individual's
confidence in the truth of a particular proposition.

Both objective and subjective probability distributions for
events denote a quantitative representation of uncertainties.
The use of subjective probabilities is the only alternative for
obtaining a probability distribution when empirical or
theoretical models are not directly applicable or available.
Subjective probability distributions are intended to capture
statistically-based uncertainty (due to random variability,
measurement and sampling error) as well as uncertainty about how
the specific experimental results might generalize to a different
situation.

3.3 A Conceptual Model of Human Judgment

Social judgment theory provides a conceptual framework for describing how individuals combine multiple pieces of information into a single judgment (Adelman and Mumpower, 1979). Most judgments are the result of comparisons with various cues as originally **conceptualized** by the psychologist **Brunswik** in his **"lens** model", which is depicted in Figure 2. Judgments are made about an uncertain event on the basis of cues A,B,C . . . F. The person must identify these cues from the information that is available. The relationship between the judgment and the cues are represented by the lines between the "person" box and the cues. The relationship between the cues and the uncertain event are shown on the environmental side of the model.

Accuracy of judgment depends on the extent to which the relationships on both sides of the lens are the same. The importance of **Brunswik's** lens model is to stress the following (Hogarth, 1980):

(a) Judgment results from a series of operations on information which is related to other items of information or events;

(b) Such interrelationships in the human mind have an anlogue in nature;

(c) Judgment will be accurate to the extent that the individual's picture of reality and judgmental rules match those of reality;

(d) Judgment takes place in a probabilistic environment. The relationships between cues in the environment and the target outcome cannot be represented by strict functional rules, because they are not exact in all cases;

(e) Judgmental accuracy is a function of both individual characteristics and the structure of the task environment.

Disagreement among people occurs when they use the same information in such a manner that they arrive at different judgements. In the social judgement theory approach, four major parameters describe the relationships between proximal cues and distal variables as follows (Adelman and Mumpower, 1979):

(a) The relative weight (or importance) that a person places on each proximal cue when making judgments;

(b) The function form (linear or nonlinear) that describes the shape of the relationship between a person's judgments and the values of a cue;

(c) The organizational principle (additive or nonadditive) which the individual uses for combining all the information from multiple cues into an overall judgment;

(d) The consistency with which an individual uses information in making judgments.
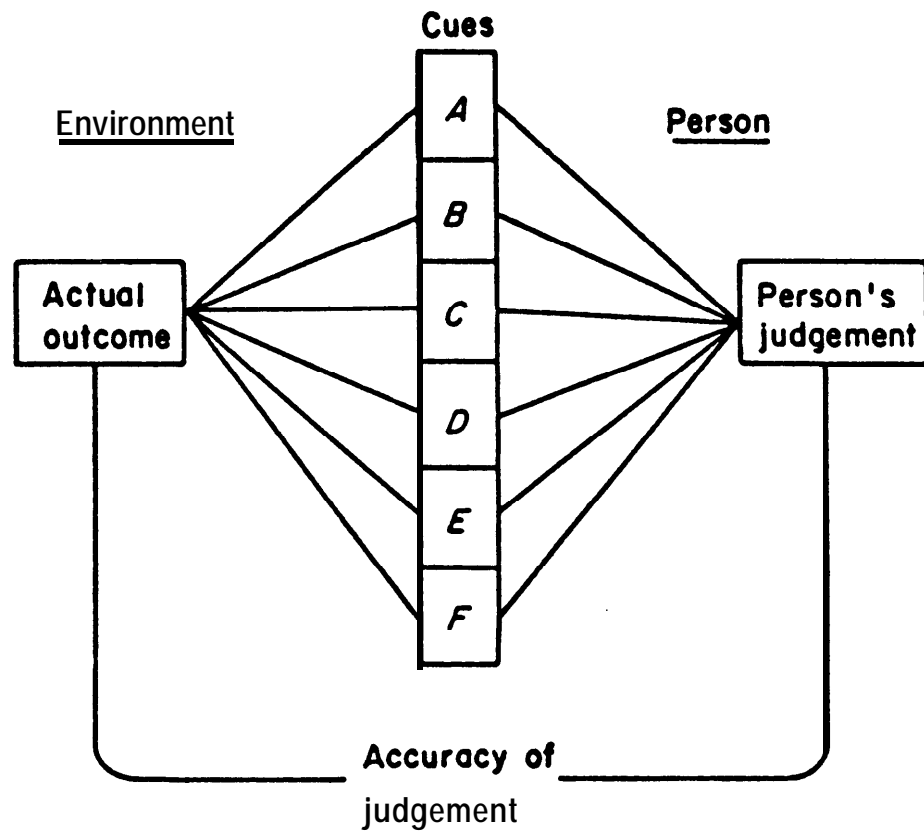
FIGURE 2: Brunswik Lens Model of the Human Judgment Process

Source: **Hogarth,** 1980

Quantitative models incorporating the above parameters have been constructed using multiple regression analysis techniques. Individuals made numeric judgments (the dependent variable) for a number of cases in which the values of the relevant cues (the independent variables) varied. Through the use of such models the basis for judgments are made explicit (Adelman and Mumpower, 1979).

## 3.4 Eliciting Expert Judgments Regarding Dose-Response

The previous subsection described a conceptual model of judgment processes and described how such processes could be modelled. Elicitation of expert judgments regarding probabilistic dose-reponse relationships is not concerned with judgmental processes but with the judgments themselves. In this case what is ultimately desired is a cumulative distribution function (CDF) representing the expert's opinion of the probability of various response levels (in this case yield reductions of a specific crop type) at a given pollutant concentration or dose. A probabilistic dose-response relationship can be obtained by eliciting from the expert points on the CDF (e.g., .01,.25,.50,.75, .99 fractiles) representing probable responses at a given dose. Additional CDF's are "probability encoded" for different pollutant levels. Thus a probabilistic dose-response relationship may be developed.

Methods for eliciting probabilities from experts have been developed primarily within the area of decision analysis. Methods used widely today in business applications were developed

some time ago by Spetzler and Von Holstein (1975) and are still being refined (Morgan et al., 1985). The method will not be discussed here as it is thoroughly described in the above references as well as in various textbooks (e.g., Holloway, 1980).

Since continuous CDF's are desired and only several discrete points representing the various fractiles on each CDF are elicited, a method for interpolating between encoded points is needed. One such method has been suggested by Whitfield and Wallsten (1984) and Keeney et al. (1984), in human health risk assessments of lead and carbon monoxide, respectively. These analysts suggested fitting "normal-on-log-odds" distribution functions, which generally seem to fit the typically sigmoidal probabilistic dose-response functions very well. The normal-on-log-odds distribution is obtained by fitting a normal distribution to the natural log of the odds implied by the response (crop reduction) rate. A separate normal-on-log-odds distribution function can be fitted to the elicited CDF's at each pollution dose. For the judgments by health experts encoded by Whitfield and Wallsten (1984) and by Keeney et al. (1984), the normal-on-log-odds distribution described the encoded judgments very well, with R-square values of .95 to .99.

A hypothetical family of probabilistic relationships about the fraction of a crop yield that will be lost at each air pollution dose is shown in Figure 3. Each curve in Figure 3 represents the judgmental probability that the crop yield loss (a fraction between 0 and 1) will be less than or equal to a particular value Z at each of three pollutant concentrations (or
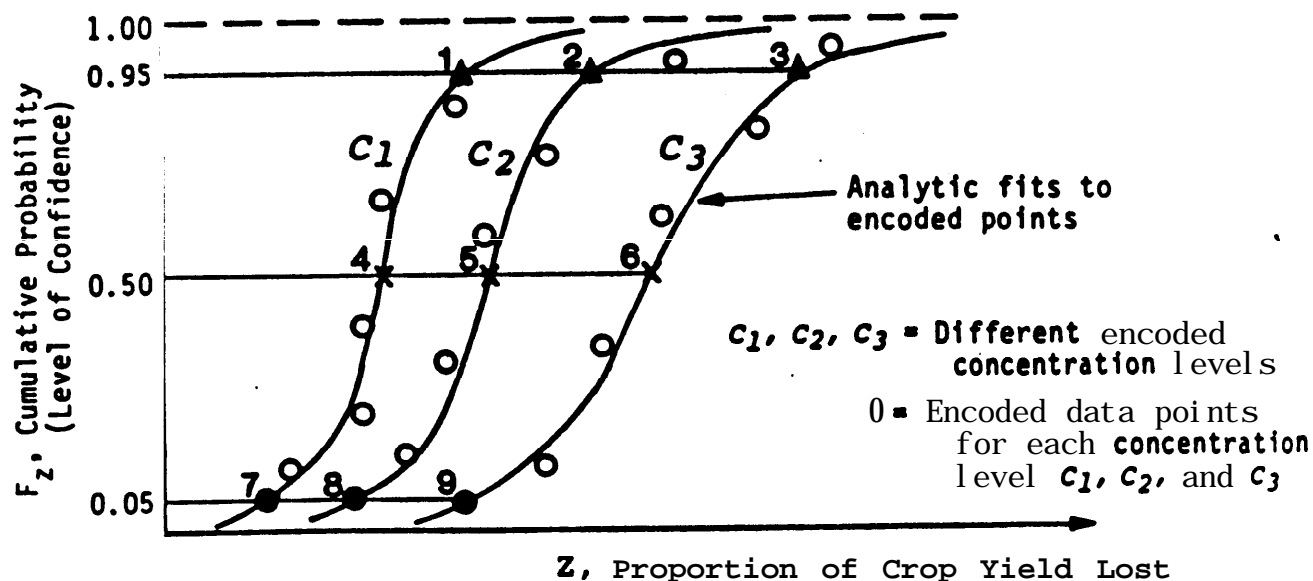
(a) Encoding results
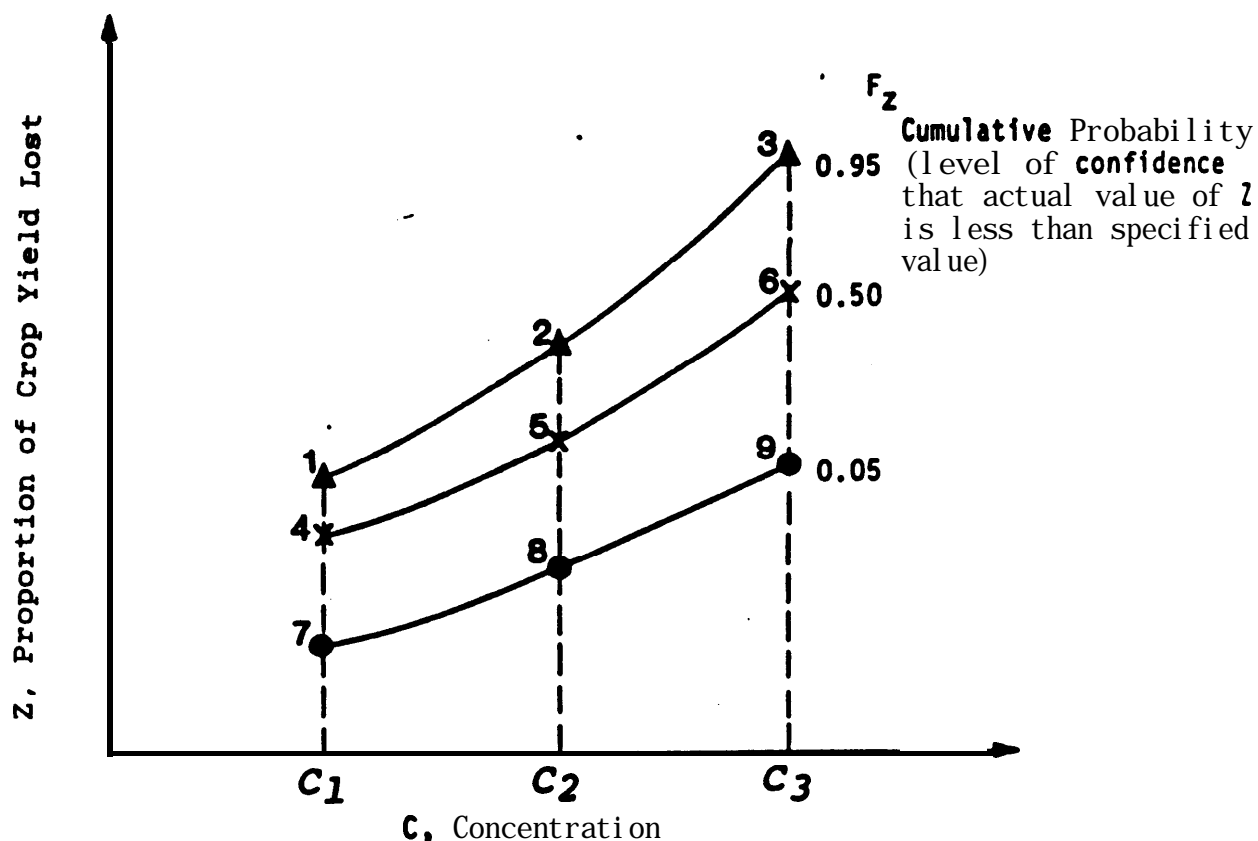
(b) Exposure-response relationship [inversion of encoding data in (a)]

FIGURE 3:   Probabilistic Dose-Response Relationship for Crop Yield Reduction at Three Pollution Levels

Source: Adapted from U.S. Environmental Protection Agency (1986)

doses) C1, C2, C3. The mathematical functions **Fz**(Z,C) shown in Figure **3a** can be inverted to yield the dose-response relationship Z(C,**Fz**) shown in Figure 3b. In this case, for three probabilities (.05, .50, .95) crop reduction fractions are determined for each encoded pollutant concentration level.

Probabilistic dose-respose relationships based on expert judgments have been or are being developed for effects of various air pollutants on human health (Morgan et al., 1985; Keeney et al., 1984; Whitfield and Wallsten, **1984**), for the effects of acid deposition on fisheries (Peterson and Violette, **1983**), and for effects on forests and aquatic resources (North et al, 1985). At present the U.S. Environmental Protection Agency is conducting an ozone health risk assessment which will involve subjective expert judgments (U.S. E.P.A. 1986).

Probability encoding protocols used in the above studies varied significantly in procedure and sophistication. In general, the elicitors emphasized the need to ensure that the experts carefully review relevant information and data prior to encoding, and that they understand the exact definitions of response and air pollution measures. All probability encoding for the above projects involved personal interviews with no feedback of the opinions of others, thus preserving independence of opinion.

In a research project of the risks to Canadian forests from air pollution, a Delphi approach was used to elicit expert judgments. The Delphi approach involves feedback of opinions of others to each expert and allows revision of personal judgments based on the opinions of others, in an effort to achieve consensus.

This type of approach was criticized by Sackman (1975) who stated:

> (It) rewards conformity and penalizes individuality, and profers non-independent iterative results as authentic expert consensus... (it) deliberately manipulates responses toward minimum dispersion of opinion in the name of consensus.

The Delphi approach involving feedback and revision of opinion is thus not compatible with the risk assessment methodology proposed here, which requires knowing to what extent independent judgments concur. This is because secondary uncertainty is said to exist regarding the modelling of primary uncertainty related to the event in question (Feagans and Biller, 1981). Such information would be useful to decision makers, who would have greater confidence in estimates where secondary uncertainty is minimal.

It should be kept in mind that even so-called independent judgments are not completely independent, to the extent that experts share the same information and knowledge base through common training and reading of the same scientific publications. Additional comments are made on this in Section 3.6.

Another concern related to the Delphi approach is the anonymity assured to experts. Sackman (1975) believes this guarantees protection against individual accountability, which may promote vested interests or other biases. If this is true, it may be difficult to remedy the situation, since experts may not wish to risk reducing their credibility through subjective pronouncements that are made public. For this reason if experts

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are not assured anonymity, some may refuse to participate in the risk assessment.

3.5 Accuracy of Expert Judgments

Strictly speaking, a subjective probability assessment cannot be evaluated in that it is simply **a** statement of the expert's personal opinion (Hogarth, 1980). The basic criterion of what constitutes a good probability assessment is coherence, i.e. the assessment should obey the laws of probability. An assessment is coherent if probabilities assigned to a set of mutually exclusive and exhaustive events sum to 1.0.

In addition to coherence, assessments should also be consistent over time (assuming the expert does not get new information), and should be consistent between different assessment methods. Beyond this there are measures related to both substantive expertise, which refers to knowledge that an expert has related to what is being assessed, and normative expertise, which refers to the skill of the assessor on expressing his or her beliefs in probabilistic form (Morgan et al., 1979).

Substantive expertise can be measured by how well a set of assessments predicts the actual outcomes; a substantive expert should generally assign high probabilities to those events that occur frequently, and low probabilities to those that do not occur frequently. This is a measure of the accuracy of the expert's judgments. Calibration, on the other hand, also known as reliability, is the measure of normative expertise. An expert is well-calibrated if the assessed probability of events

corresponds well with their empirical frequency. Obviously for judgments about dose-response relationships, substantive experts are necessary, otherwise the elicitation will mean nothing no matter how well calibrated the expert is.

There is an alarming lack of information in the environmental risk assessment literature pertaining to the accuracy of expert judgments. This is presumably because true dose-response relationships were not known. (If they were known, there would have been no need for subjective assessments.) These risk assessments involved effects on human health, forests, and aquatic systems; in general, science has to date not been able to explain the precise relationships between air pollution dose and response measures for these receptors.

On a relative basis much more knowledge has been accumulated concerning the effect of elevated levels of ozone on agricultural crops, and it should be possible to evaluate the accuracy of an expert's predictions of dose-response. The expert's predicted dose-response function could be compared with an actual dose-response function as determined from experiments. It would be necessary to ensure the expert had not seen the data prior to the elicitation session. Recent experimental data that has not yet been published could be used for evaluation of the accuracy of the expert's judgments.

It would be useful if there were data available regarding the accuracy of dose-response judgments, because research has shown that people are subject to significant cognitive biases which can significantly affect their judgment (Tversky and

Kahneman, 1974). In particular there is a strong tendency toward over-confidence in subjective assessments, with the result that subjective probability distributions are "tighter" than actual distributions. There is a bias in our culture in favor of confident statements; for example, politicians presumably prefer to deal with "one-armed scientists" who do not say "On one hand..., but on the other hand . . . . " (David, 1975).

The following list summarizes various biases and sources of bias which may contribute to errors in elicitation of expert judgments (Hogarth, 1980):

(a) Avoidance of uncertainty: The notion of uncertainty is uncomfortable. By failing to face up to uncertainty, people do not acquire mechanisms for dealing with it explicitly.

(b) Representativeness: People tend to ignore whether they have sufficient information to make predictions, and seldom consider the possibility of surprise or unusual events. Hence assessed distributions are often too tight.

(c) Availability: We may tend to be overly biased by recent or memorable events.

(d) Anchoring and adjustment: In any particular judgment, adjustment from an initial value (the anchor) is usually insufficient.

(e) Internal coherence: People tend to diminish the importance of events which are inconsistent with their beliefs.

(f) Unstated assumptions: Judgments are often made against a background of assumptions which are not made explicit.

Some analysts conducting expert elicitations have attempted to ameliorate the effect of these sources of error by describing them to the experts prior to elicitation (e.g. Morgan et al., 1985). Unfortunately it is difficult to determine whether simply making experts aware of potential biases helps them to avoid making errors.

An indirect indication of the accuracy of judgments is related to the extent to which independent assessments concur. In a risk assessment of health effects from air pollution (Morgan et al., 1985) it was found that the independent judgments by atmospheric scientists of sulfur oxidation rates were in good agreement. Conversely the health experts predictions differed dramatically. Although there is no guarantee the meteorologists predictions were accurate (they may have all been wrong), a decision maker should have more confidence in the accuracy of the median meteorologist& prediction than in the accuracy of the median value predicted by health experts.

3.6 Selection of Experts

There is a paucity of published information concerning systematic means of selecting experts for risk assessment, even though the importance of this step has been widely acknowledged. The quality of the judgmental data collected depends clearly and crucially on the competence of the experts that are selected.

According to Morganstern (1973) the competence in question has two components:

(a) Substantive expertise in the relevant **area** of science or technology; and

(b) Intuitive judgment.

Since good intuitive judgment is an elusive personality characteristic, an investigation of the necessary attributes of expertise must focus primarily on the attributes of substantive expertise.

The lack of research into environmental expert selection may be because past researchers believed selection could be done on the basis of straightforward, obvious criteria and that valuable time and resources should be expended on other aspects of the risk assessment. The methodology proposed here takes the opposite view; that is, that expert selection is a very important component of the risk assessment and that significant effort should be expended at this task.

The first and most obvious criterion of substantive expertise is specific knowledge related to what is being assessed. The reason for this was articulated by Helmer (1983):

> We resort to an expert precisely because we expect his information and the body of experience at his disposal to constitute an assurance that he will be able to select the needed items of background information, determine the character and extent of their relevance, and apply these insights to the formulation of the required personal probability judgments.

The difficulty, of course, lies in determining which experts have a sufficient and appropriate knowledge base. In some of the early research into the Delphi technique, attempts were made to identify the relative competence of panelist by asking them to rate their expertise in the area being examined. The results were disappointing in that the expert groups with the high self ratings did not do any better than the "non-expert" groups (Martino, 1972). A possible explanation for this was offered by Morganstern et al. (1973) who suggested that:

> (Scientists) might be too eager or too reluctant, for various reasons, to admit incompetence. They might be reluctant because they are ignorant or biased in judging their expertise; or they might be eager to escape from a difficult job (ie providing subjective probabilities) (comment in brackets added).

In more recent environmental risk assessments, a common means of identifying experts has been to obtain a list of recommended individuals from an appropriate agency or establishment. For example, health experts recommended by the Environmental Protection Agency were selected by Morgan et al. (1985), Keeney et al. (1984) and, it would appear, Whitfield and Wallsten (1984). This selection method is susceptible to the bias of the particular agency.

A more objective approach was used by Peterson and Violette (1985) in a risk assessment of acid deposition on fisheries in the Adirondacks (1985). They compiled a list of authors from recent relevant scientific literature. Weighting for selection was assigned on the basis of (i) the number of recent publications, and (ii) the amount of work performed in the Adirondack Mountain region.

Experts used in the Delphi assessment of the impact of air pollution on Canadian forest productivity were selected using a nomination procedure. The experts selected were those that were nominated the most number of times by their peers (Fraser et al., 1985).

Helmer (1983) suggested that expert choice should initially be made on the basis of past performance in the area being investigated; that is, experts' past judgments should have been shown to have been reliable and accurate. Secondly, expert choice should be made on the basis of personal qualifications and achievements, such as education, experience, publications, status among peers, and so on.

Regarding Helmer's first criterion, it was pointed out in Section 3.5 that the accuracy of expert judgments about dose-response have not been evaluated, although it should be possible in the future to evaluate the accuracy of judgments about ozone effects on agricultural crops. Unfortunately, this a posteriori type of evaluation obviously cannot be conducted until experts have been selected in the first place, and have presented their judgments.

Thus, for initial expert selection, we are generally restricted to the use of a priori type criteria related to qualifications and achievements. Once again, however, it is not clear how to proceed since the relationship between measures of these attributes and the ability to make reliable, accurate predictions does not appear to have been systematically investigated and reported. There are probably several strategies for investigating such a relationship but, in general, the

following primary criteria are recommended:

(a) The attributes of expertise and their relative importance should be determined by scientific peers;

(b) A properly designed questionnaire or survey should be used to obtain opinions from peers on the attributes of expertise;

(c) The survey should ask respondents to quantitatively evaluate various objective indices such as education, experience, publications, scholarly research, awards, personal characteristics (e.g. judgment), and so on;

(d) The survey should ask respondents to rank themselves in terms of relative expertise for the proposed task;

(e) The survey should ask respondents to nominate experts for the proposed task.

The results of a properly conducted survey should allow objective <u>a</u> <u>priori</u> selection of experts, and weighting of their relative expertise, for risk assessment. Once the judgments have been selected, <u>a</u> <u>posteriori</u> evaluation, as described previously for judgments about ozone dose-agricultural crop response, would constitute a very useful and interesting investigation of the feasibility and value of expert judgments for air pollution risk assessment.

Another question related to the selection of experts concerns how many experts should be contained in the sample. There has been some empirical research into this question by

decision analysts, as well as by theoretical statisticians (Winkler and Makridakis 1983; Hogarth 1978; Ashton 1986). Empirical work by Ashton and Ashton (1985) showed that forecast error decreased as additional individuals' forecasts about advertising pages for Time magazine were included in the aggregate, but that only 2 to 5 individuals must be included to achieve much of the total improvement available from combining the forecasts of up to 13 individuals.

In the previously mentioned risk assessment of health effects from air pollution by Morgan et al. (1985), the results showed that only a few atmospheric scientists' predictions were required due to the consensus of opinion of this group. (One or two scientists predicted nearly the same probabilities as the aggregate opinion of the larger group.) On the other hand, due to disagreement among health experts, a considerably larger sample of experts would be required to determine the true opinions of this population.

One final comment should be made regarding the value of an objective expert selection procedure. Such a methodology would allow the weighting of experts in terms of their relative< "expertise". Thus, in the case of divergent judgments, more weight could be given to those opinions elicited from the individuals with greater expertise, as determined from the survey. The resulting "consensus distribution" should be compared with other methods of aggregating opinions, ranging from simple averaging of the distributions to more complex and formal Bayesian revision processes such as those described by Winkler (1981, 1986). It is worth noting that one of these consensus

models allows for dependence among the experts sample (Winkler, 1981). It was developed on the basis that experts have common and similar education and experience, resulting in some sort of stochastic dependence among their errors of estimation.

4. CONCLUSIONS AND RECOMMENDATIONS

Environmental impact/risk assessment is a tool that may be used to assist in making difficult decisions about the environment, because such decisions always involve uncertainty. The importance of identifying and understanding the sources and magnitude of uncertainty in environmental policy decision making has long been recognized. Unfortunately, however, there has been relatively little effort to date to explicitly incorporate uncertainty analysis into environmental risk assessments. Thus, in an attempt to allow the improvement of impact assessments related to the effect of ozone pollution on agricultural crop productivity, this report had two major objectives:

(i) To describe sources of uncertainty in the evaluation of the effect of ozone on agricultural productivity (Section 2); and

(ii) To describe a risk assessment methodology for the use of secondary dose-response information, i.e. information for other cultivars or growing conditions than those common to the Fraser Valley of B.C. (Section 3).

Several approaches to reducing uncertainty were suggested in Section 2, but it was pointed out that significant improvements in our knowledge base will require a major research effort and will require several years at least. Thus, if an impact assessment is desired at this time in order to gain an appreciation of the magnitude of the problem, secondary dose-response data will have to be used.

The proposed risk assessment methodology involves elicitation of subjective, probabilistic dose-response estimates for important crops of the Fraser Valley. Subjective probability distributions represent and include uncertainties related to both the original relationship as determined from an experiment, (e.g. scientific uncertainties) as well as uncertainty about how specific experimental results might generalize to a different situation.

One particularly important component of the risk assessement involves selection of experts. This is because the quality of the subjective judgments is directly related to the substantive expertise of the scientists that are providing opinions, as well as their intuitive capability, their ability to provide true representations of their opinions of uncertainty, and so on. It was recommended that an objective approach be used for defining the relevant attributes of expertise, and for selection of experts. Such a methodology would also allow the weighting of expert judgments in terms of the relative "expertise" of the experts, which is an important step in the specification of a consensus probability distribution.

One obvious limitation related to the past use of experts is that the accuracy of their judgments could not be evaluated, because the real relationships were not known. The proposed methodology should allow evaluation of the accuracy of subjective probabilistic dose-response relationships. This should be possible by asking experts to predict dose-response relationships for species for which experimental data has been obtained, but the experts have not seen.

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