MEASURING THE TANGIBLE BENEFITS OF ENVIRONMENTAL IMPROVEMENT: AN ECONOMIC APPRAISAL OF REGIONAL CROP DAMAGES DUE TO OZONE

by

CLIVE LAURENCE SPASH

B.A. Hons. (Econ.), University of Stirling, Scotland, 1984

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ARTS

in

THE FACULTY OF GRADUATE STUDIES (Department of Resource Management Science)

We accept this thesis as conforming to the required standard

UNIVERSITY OF BRITISH COLUMBIA

June, 1987

© Clive Laurence Spash, 1987
In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Resource Management Science
The University of British Columbia
1956 Main Mall
Vancouver, Canada
V6T 1Y3

Date June, 1987
ABSTRACT

The main purpose of this thesis is to empirically calculate the welfare changes which might be expected to result from potato yield reductions caused by ambient ozone loadings in the Lower Mainland of British Columbia. The objectives of the research are: (1) to review the scientific literature pertaining to the effects of ozone loadings on agricultural crops; (2) to review the methodologies employed in previous regional economic assessments of ozone damages; and (3) to apply an economically defensible technique to the analysis of welfare losses due to ozone.

Ozone in the Lower Mainland may be pictured as being restricted laterally by the mountain ranges surrounding Vancouver, and vertically by stagnant high pressure systems. Land/sea breezes aid in transporting ozone and its precursors from Vancouver up the Fraser Valley towards important crop growing regions. The highest levels of ozone occur during spring and summer coinciding with the most active season for many crops.

Seasonal ambient ozone dose, measured as hours-ppm>0.10ppm was found to be high in rural areas, especially Abbotsford, during the late 1970's and early 1980's, dropping to low levels in more recent years. Potatoes are one of the economically important crops in the Lower Mainland known to be sensitive to
ozone. Potato tuber weight reductions are estimated to have reached 16.5 percent in the Abbotsford region in 1981 at seasonal ambient ozone loadings.

An aggregate supply/demand model is set up for potato production in B.C. based upon prior estimates of supply and demand elasticities. This model assumes the price in the B.C. market is set exogeneously by U.S. imports. Thus, all policy relevant welfare changes affect producers' quasi-rent alone. Sensitivity of the model to import price, and the price elasticity of supply is tested. A range of welfare estimates is reported for a variety of ambient ozone loadings.

The total damages to potato producers, assuming all regions of B.C. are affected by the same seasonal dose as Abbotsford, are calculated to be around one million dollars at ambient ozone loadings in four out of eight years. A peak occurred in 1981 at 2.4-2.9 million dollars total damages. Damages may be overestimated because 20-30 percent of potato production takes place outside the Lower Mainland, Abbotsford often appears to receive higher ambient ozone loadings than other regions, and not all potato cultivars grown in the Lower Mainland are as sensitive to ozone as that employed here. However, there are also reasons to be cautious over discounting these estimates as too large. Potato response to ozone is restricted to tuber weight reductions while other important effects may include increased plant stress and damage to crop quality. In addition, missing air quality information for some years and stations, suggests that actual ozone dose could be higher than calculated.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF APPENDIX TABLES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>x</td>
</tr>
<tr>
<td>LIST OF APPENDIX FIGURES</td>
<td>xi</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>xii</td>
</tr>
</tbody>
</table>

## CHAPTER

### I INTRODUCTION

1.1 Background Information

1.1.1 Agriculture in the Lower Mainland

1.1.2 Crop Selection

1.2 Objectives

1.3 Research Procedure

1.3 Outline

### II SCIENTIFIC ASPECTS OF OZONE DAMAGE TO AGRICULTURAL CROPS

2.1 Introduction

2.2 Sources of Ozone

2.2.1 Natural Ozone

2.2.2 Anthropogenic Ozone

2.3 Ozone Formation and Transportation

2.3.1 Ozone Formation

2.3.2 Seasonal and Diurnal Cycles of Urban Ozone

2.3.3 Ozone Transportation, Dispersion and Removal

2.4 Ozone in the Lower Mainland

2.4.1 Atmospheric Conditions

2.4.2 Ambient Ozone Concentration and Potato Damage

2.5 Biological Response of Agricultural Crops

2.5.1 Factors Affecting Plant Response to Air Pollution
### 2.5.2 Methodologies for Deriving Dose-Response Functions

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5.2</td>
<td>46</td>
</tr>
</tbody>
</table>

### 2.5.3 The Research Programme of the NCLAN

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5.3</td>
<td>50</td>
</tr>
</tbody>
</table>

### 2.5.4 Characteristics of Response Functions Applied in Economic Crop Loss Assessments

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5.4</td>
<td>52</td>
</tr>
</tbody>
</table>

### 2.5.5 Economically Important Response Characteristics

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5.5</td>
<td>55</td>
</tr>
</tbody>
</table>

### 2.6 Conclusion

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6</td>
<td>57</td>
</tr>
</tbody>
</table>

### Footnotes

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footnotes</td>
<td>58</td>
</tr>
</tbody>
</table>

### III METHODOLOGIES AND APPLICATIONS IN THE REGIONAL ECONOMIC ASSESSMENT OF OZONE EFFECTS ON AGRICULTURAL CROPS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>65</td>
</tr>
</tbody>
</table>

### 3.2 Methodologies for the Valuation of Agricultural Crop Yield Changes: With Reference to Air Pollution

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>69</td>
</tr>
</tbody>
</table>

#### 3.2.1 The Traditional Model

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.1</td>
<td>69</td>
</tr>
</tbody>
</table>

#### 3.2.2 Optimization Models

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.2</td>
<td>71</td>
</tr>
</tbody>
</table>

#### 3.2.3 Econometric Models

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.3</td>
<td>72</td>
</tr>
</tbody>
</table>

### 3.3 Microtheoretic Approaches to Modelling Agricultural Production Decisions

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td>75</td>
</tr>
</tbody>
</table>

#### 3.3.1 Duality Models and Environmental Changes

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3.1</td>
<td>75</td>
</tr>
</tbody>
</table>

#### 3.3.2 Duality Models Applied to Agricultural Crop Production

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3.2</td>
<td>76</td>
</tr>
</tbody>
</table>

### 3.4 A Review of Recent Regional Economic Assessments of Ozone Effects on Agricultural Crops

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4</td>
<td>81</td>
</tr>
</tbody>
</table>

#### 3.4.1 A Traditional Study

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4.1</td>
<td>81</td>
</tr>
</tbody>
</table>

#### 3.4.2 Quadratic Programming Approaches

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4.2</td>
<td>86</td>
</tr>
</tbody>
</table>

#### 3.4.3 Econometric Approaches

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4.3</td>
<td>90</td>
</tr>
</tbody>
</table>

#### 3.4.4 A Duality Study

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4.4</td>
<td>95</td>
</tr>
</tbody>
</table>

### 3.5 Issues in Economic Models of Ozone Induced Crop Loss

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>97</td>
</tr>
</tbody>
</table>

#### 3.5.1 Modelling the Impact of Airborne Pollutants on Agricultural Inputs

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5.1</td>
<td>97</td>
</tr>
</tbody>
</table>

#### 3.5.2 Cross-Crop Substitution

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5.2</td>
<td>99</td>
</tr>
</tbody>
</table>

#### 3.5.3 The Distribution of Benefits

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5.3</td>
<td>103</td>
</tr>
</tbody>
</table>

### 3.6 Conclusion

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6</td>
<td>112</td>
</tr>
</tbody>
</table>

### Footnotes

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footnotes</td>
<td>113</td>
</tr>
</tbody>
</table>
III AN ECONOMETRIC MODEL OF THE AGRICULTURAL SECTOR IN BRITISH COLUMBIA

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>196</td>
</tr>
<tr>
<td>The Theoretical Model</td>
<td>196</td>
</tr>
<tr>
<td>Cost Function</td>
<td>198</td>
</tr>
<tr>
<td>Behavioural Assumptions</td>
<td>198</td>
</tr>
<tr>
<td>The Econometric Model</td>
<td>199</td>
</tr>
<tr>
<td>The Multiple-Output Multiple-Input Translog</td>
<td>201</td>
</tr>
<tr>
<td>Cost Function</td>
<td>201</td>
</tr>
<tr>
<td>Variable Definitions and Data Description</td>
<td>203</td>
</tr>
<tr>
<td>Empirical Results</td>
<td>205</td>
</tr>
<tr>
<td>Cost Function for B.C. Agriculture</td>
<td>205</td>
</tr>
<tr>
<td>Scale Economies</td>
<td>206</td>
</tr>
<tr>
<td>Elasticities of Substitution</td>
<td>210</td>
</tr>
<tr>
<td>Marginal Cost</td>
<td>218</td>
</tr>
<tr>
<td>Conclusion</td>
<td>219</td>
</tr>
<tr>
<td>Footnotes</td>
<td>220</td>
</tr>
</tbody>
</table>

IV COST FUNCTION INPUT AND REVENUE SHARE EQUATION ESTIMATES

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>223</td>
</tr>
</tbody>
</table>
LIST OF TABLES

1. Percentage of Provincial Cash Receipts from Agriculture in the Districts Closest to Vancouver, in 1981. ................................. 3
2. Crops Generating Over One Million Dollars Per Annum in the Lower Mainland. .............................................................. 5
3. Susceptibility to Ozone of Crops Grown in the Lower Mainland. .................................................................................. 7
4. Oxidant Precursor Emissions in the Lower Mainland for 1978. ...................................................................................... 18
5. Air Quality Monitoring Stations of the Lower Mainland. ......................................................................................... 34
6. Ambient Ozone Concentrations at Rural Monitoring Stations in the Lower Mainland ......................................................... 38
7. Predicted Percentage Tuber Weight Reduction in the Lower Mainland. ................................................................. 39
8. Factors Affecting Plant Sensitivity to Air Pollutants. ........................................................................................... 42
9. Details of Ozone Exposure in 23 Studies of Effects on Crop Productivity. ............................................................... 44
10. Measures of Ozone Occurrence Used in Studies of Effects on Crop Productivity. ......................................................... 45
11. Main Source(s) of Response Functions Used in 15 Recent Economic Studies of Ozone Effects on Agriculture. .... 53
12. Processes and Characteristics of Crop Plants that may be Affected by Ozone. ............................................................ 56
13. Methodologies for the Economic Evaluation of Crop Loss 75
14. Applications of the Profit Function in Agricultural Economics. ............................................................................. 78
15. Applications of the Cost Function in Agricultural Economics. ............................................................................. 81
16. Summary of Recent Regional Studies of the Economic Losses Due to Ozone Pollution. ....................................................... 83
17. Crops Included in Regional Assessments. ........................................................................................................... 84
18. Price Elasticities of Demand Reported for Potatoes. .......................................................................................... 129
19. Potato Producer Loss Due to Ozone: Scenario Analysis. ..................................................................................... 142
20. Total Damages to Potatoes Based Upon Ozone Dose at Abbotsford Monitoring Station.................................................. 149
LIST OF APPENDIX TABLES

A3.1 Parameter Estimates for Translog Cost Function of Agriculture in B.C. ................................................. 207
A3.2 Product-Specific and Ray Economies of Scale for Agriculture in B.C. ....................................................... 209
A3.3 Product-Specific and Overall Scale Economies Reported by Ray.............................................................. 210
A3.4 Translog Cost Function Estimates of Partial Elasticities of Substitution.................................................. 212
A3.5 Sample Mean Elasticities of Substitution in Agricultural Cost Function Studies........................................ 213
A3.6 Translog Cost Function Estimates of Own Price Elasticities for B.C. Agriculture........................................ 215
A3.7 Own Price Elasticities in Agricultural Cost Function Studies.................................................................... 216
A3.8 Expected and Estimated Input Parameters......................................................................................... 217
LIST OF FIGURES

1. Photolytic Cycle and Ozone Production.......................... 20
2. Seasonal and Diurnal Cycles of Urban Ozone...................... 22
3. Inversions...................................................................... 26
4. Schematic Diagram of Land/Sea Breeze Over Vancouver......... 29
5. Box Model of a Stagnant High Pressure System Over Vancouver.................................................. 31
6. The Air Quality Monitoring Network in the Lower Mainland................................................................ 33
7. Diurnal Ozone Cycle in Vancouver..................................... 35
8. Conceptual Model of Factors Involved in Air Pollution Effects on Vegetation...................................... 41
9. Representation of Agricultural Crop Producing Activities................................................................. 67
10. The Traditional Model.......................................................... 86
11. Supply Shift Due to Ozone Decrease................................. 102
12. Supply Intercept Assumptions........................................... 107
13. Parallel Versus Rotation Supply Shift............................... 110
14. Spatial Equilibrium............................................................ 122
17. Lower Mainland and B.C. Potato Production 1964-1984... 127
18. Consumer and Producer Welfare Areas.............................. 132
19. Base Scenario Total Damage Function for Potatoes............. 136
20. Supply Scenario Total Damage Function for Potatoes......... 139
21. Import Scenario Total Damage Function for Potatoes........ 141
<table>
<thead>
<tr>
<th>Appendix</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1.1</td>
<td>Dupuit Consumer Surplus</td>
<td>168</td>
</tr>
<tr>
<td>A1.2</td>
<td>Marshallian Consumer Surplus</td>
<td>171</td>
</tr>
<tr>
<td>A1.3</td>
<td>Compensating and Equivalent Variations</td>
<td>178</td>
</tr>
<tr>
<td>A1.4</td>
<td>Relationship Between Ordinary and Compensated Demand Curves</td>
<td>179</td>
</tr>
<tr>
<td>A1.5</td>
<td>Willig Approximation</td>
<td>184</td>
</tr>
<tr>
<td>A2.1</td>
<td>Producer Surplus</td>
<td>190</td>
</tr>
<tr>
<td>A2.2</td>
<td>Quasi-Rent</td>
<td>190</td>
</tr>
<tr>
<td>A2.3</td>
<td>Producer Surplus and Non-elastic Factor Supply</td>
<td>192</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

Foremost amongst those who have aided the completion of this thesis are my parents, who have provide moral and financial support throughout. I also feel indebted to Alistair Dow, Professor of Economics at Stirling University in Scotland, who gave me early encouragement to pursue my chosen fate. In the actual execution of this study I wish to thank Gordon Brown for discussion and advice on the scientific, especially biotic, aspects of ozone pollution, and helping in the analysis of air quality data. I am indebted to Vinay Kanetkar for advice and help throughout the many runs of the duality model. Finally, I would like to thank Angus Bell for providing the entertainment. The blame for errors, if they dare occur, is to be placed at my door and mine alone.
CHAPTER I

INTRODUCTION

Several types of air pollution result from fossil fuel combustion causing many types of damages. This thesis describes the effects of one such pollutant, ozone, upon agricultural crops. Methodologies and applications in the regional assessment of economic crop loss due to ozone are reviewed. An attempt was made to set up a model of B.C. agriculture to assess the aggregate impacts of ozone in the Lower Mainland. Serious problems were encountered and an alternative approach was chosen; namely, to concentrate upon damages to potatoes. Producer quasi-rents were used to measure the effect of ambient ozone loadings on potato farmers. This study is restricted to only one aspect of the potential damages from ambient ozone loadings and therefore does not reflect the full tangible benefits of control.

1.1 Background Information

1.1.1 Agriculture in the Lower Mainland

Approximately one third of the provincial cash income from crops originates from the Lower Fraser Valley, which produces the majority of the provincial small fruit, vegetable, potato and horticultural crops. The high capability arable lands of the
Mainland Agricultural Reporting Region are the most suitable lands in the Province in terms of yield potentials and crop diversity. The region has the highest yield estimates for many vegetables, berry, grain and root crops; the only group of crops not suitable for the region is tree fruits.\(^2\)

In December 1972 the importance of this area was confirmed when the government set up an Agricultural Land Reserve to prevent highly productive land being removed from agricultural use.\(^3\) Land was selected on the basis of either being taxed as farmland, zoned for agriculture, or rated in the top four land classification classes of the British Columbia Land Inventory.\(^4\) The Agricultural Land Reserve showed that the best agricultural land of Mainland British Columbia was concentrated in the areas closest to Vancouver.

In Chapter 2 ozone episodes are shown to occur under anticyclonic inversions, which combined with the surrounding mountain ranges restricts the dispersion of air pollutants within an almost closed area of the Lower Fraser Valley i.e., a "box model" is hypothesised. On this basis the areas of prime susceptibility to high ozone concentrations are to the south and east of Vancouver. Three agricultural districts surround Vancouver, namely Abbotsford, Chilliwack and Cloverdale. A large area of Cloverdale district which extends beyond the North Shore mountains can therefore be assumed to be unaffected.\(^5\) However, only a relatively small amount of agricultural crop production takes place outside the Greater Vancouver region of the Cloverdale district, e.g., the GVRD accounts for 99 percent of
the area under berry cultivation and 93 percent of potato production.\(^6\)

In 1981 the three districts received cash receipts of approximately 30 million dollars from the production of each of the following: (1) small fruits (mainly berries), (2) field vegetables, and (3) floriculture/nursery products. Field crops were relatively unimportant contributing only 0.6 million dollars. Table 1 shows the relative contribution of the three agricultural districts to total provincial cash receipts from each of these production activities. The three regions are responsible for 74, 79 and 67 percent of provincial cash receipts from small fruits, field vegetables and floriculture/nursery, respectively.

<table>
<thead>
<tr>
<th>Products</th>
<th>Cloverdale</th>
<th>Abbotsford</th>
<th>Chilliwack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Fruits</td>
<td>25.59</td>
<td>44.45</td>
<td>4.14</td>
</tr>
<tr>
<td>Field Vegetables</td>
<td>30.86</td>
<td>23.43</td>
<td>24.82</td>
</tr>
<tr>
<td>Floriculture/Nursery</td>
<td>14.67</td>
<td>31.56</td>
<td>20.75</td>
</tr>
</tbody>
</table>


Floriculture/nursery may be impacted by ozone, but was not analyzed because: (a) the plants are largely grown indoors (in greenhouses) and therefore ambient ozone levels may not reflect the actual dose, (b) variations in the greenhouse environment could be important in determining the response of plants, and (c) an initial literature survey showed no dose-response functions available for such crops.
1.1.2 Crop Selection

The criteria for crop selection were the economic importance of the crop and the sensitivity of the crop to ozone.

(a) Economic Significance

Numerous varieties of vegetable and berry crops are grown in the Lower Mainland with production ranging from potatoes to Chinese vegetables. Initial selection was restricted to those crops which generated an average annual revenue over one million dollars during the ten-year period from 1975-1984, in constant 1981 dollars. Table 2 shows the fifteen crops which qualified, together with the annual cash receipts from each for the ten-year period. These fifteen crops account for approximately 83 percent of Lower Mainland and 70 percent of provincial farmgate revenue from vegetable and berry crops. The revenue from these crops has averaged approximately 72 million dollars, with a peak in 1982 of 95 million (1981 dollars).

Mushrooms have become increasingly important relative to other crops as production and revenue quadrupled in the ten year period. Potatoes have for a long time been an important contributor to farm revenue, but in the last five years revenue declined some four million dollars. Besides these two vegetables the most important source of revenue in the Lower Mainland has been small fruit production, mainly raspberries, strawberries, cranberries and blueberries. Production of all four berry crops has increased. In particular, raspberry production has doubled since 1975, and revenue from this crop in recent years has only been exceeded by mushrooms. These two vegetable and four berry
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>mushroom</td>
<td>7269</td>
<td>8880</td>
<td>10957</td>
<td>12146</td>
<td>12755</td>
<td>14918</td>
<td>22380</td>
<td>18910</td>
<td>26478</td>
<td>29021</td>
<td>16371</td>
</tr>
<tr>
<td>raspberry</td>
<td>4996</td>
<td>6340</td>
<td>11518</td>
<td>16716</td>
<td>16499</td>
<td>7758</td>
<td>12380</td>
<td>19308</td>
<td>12302</td>
<td>15661</td>
<td>12348</td>
</tr>
<tr>
<td>potato</td>
<td>10407</td>
<td>10899</td>
<td>9457</td>
<td>8624</td>
<td>11478</td>
<td>12279</td>
<td>7701</td>
<td>9462</td>
<td>8751</td>
<td>7965</td>
<td>9702</td>
</tr>
<tr>
<td>strawberry</td>
<td>5014</td>
<td>4525</td>
<td>5584</td>
<td>6074</td>
<td>6352</td>
<td>8161</td>
<td>7274</td>
<td>8736</td>
<td>841</td>
<td>5358</td>
<td>6592</td>
</tr>
<tr>
<td>cranberry</td>
<td>2504</td>
<td>3354</td>
<td>4580</td>
<td>4531</td>
<td>4693</td>
<td>4793</td>
<td>8115</td>
<td>9815</td>
<td>6529</td>
<td>5662</td>
<td></td>
</tr>
<tr>
<td>blueberry</td>
<td>2555</td>
<td>4384</td>
<td>7921</td>
<td>7150</td>
<td>5254</td>
<td>5024</td>
<td>3791</td>
<td>9227</td>
<td>6552</td>
<td>4082</td>
<td>5612</td>
</tr>
<tr>
<td>pea</td>
<td>3522</td>
<td>2361</td>
<td>3635</td>
<td>2471</td>
<td>2595</td>
<td>2176</td>
<td>2103</td>
<td>3698</td>
<td>2734</td>
<td>3701</td>
<td>2900</td>
</tr>
<tr>
<td>lettuce</td>
<td>1574</td>
<td>2701</td>
<td>1629</td>
<td>2260</td>
<td>2810</td>
<td>1850</td>
<td>2001</td>
<td>2045</td>
<td>2528</td>
<td>2630</td>
<td>2203</td>
</tr>
<tr>
<td>sweet corn</td>
<td>2024</td>
<td>1867</td>
<td>1425</td>
<td>1887</td>
<td>2270</td>
<td>1570</td>
<td>1342</td>
<td>3586</td>
<td>1966</td>
<td>1947</td>
<td>2000</td>
</tr>
<tr>
<td>brussels</td>
<td>1672</td>
<td>1101</td>
<td>1466</td>
<td>1961</td>
<td>1622</td>
<td>1995</td>
<td>1216</td>
<td>2745</td>
<td>1551</td>
<td>894</td>
<td>1622</td>
</tr>
<tr>
<td>broccoli</td>
<td>801</td>
<td>652</td>
<td>1245</td>
<td>1449</td>
<td>1668</td>
<td>1850</td>
<td>2221</td>
<td>2681</td>
<td>1590</td>
<td>1926</td>
<td>1608</td>
</tr>
<tr>
<td>cauliflower</td>
<td>795</td>
<td>680</td>
<td>735</td>
<td>1484</td>
<td>2010</td>
<td>2064</td>
<td>1329</td>
<td>3031</td>
<td>1485</td>
<td>1723</td>
<td>1534</td>
</tr>
<tr>
<td>cabbage</td>
<td>1337</td>
<td>1195</td>
<td>969</td>
<td>1384</td>
<td>1477</td>
<td>1732</td>
<td>1176</td>
<td>1374</td>
<td>2283</td>
<td>1767</td>
<td>1469</td>
</tr>
<tr>
<td>onion</td>
<td>1757</td>
<td>818</td>
<td>1361</td>
<td>1566</td>
<td>1529</td>
<td>1455</td>
<td>1084</td>
<td>1388</td>
<td>1395</td>
<td>733</td>
<td>1309</td>
</tr>
<tr>
<td>green bean</td>
<td>1223</td>
<td>593</td>
<td>1081</td>
<td>1237</td>
<td>1227</td>
<td>900</td>
<td>1029</td>
<td>1106</td>
<td>859</td>
<td>1334</td>
<td>1059</td>
</tr>
</tbody>
</table>

| TOTAL        | 47450 | 50350 | 63563 | 70941 | 74240 | 68708 | 75141 | 95001 | 89132 | 85270 | 71980         |
| TRLM         | 57200 | 58552 | 74197 | 83609 | 87427 | 81093 | 87122 | 107040 | 97754 | 92840 | 82683         |
| TRBC         | 79099 | 75300 | 91921 | 105733 | 106926 | 102773 | 107735 | 128585 | 125040 | 112834 | 103595         |

TRLM is the total revenue for all vegetable and berry crops grown in the Lower Mainland. TRBC is the total revenue for all vegetable and berry crops grown in British Columbia. Source: Ministry of Agriculture and Food. Production of Berry Crops, Grapes and Filberts Together with an Estimate of Farm Value (Victoria: Ministry of Agriculture, various annual issues); Ministry of Agriculture and Food. Production of Vegetable Crops Together with an Estimate of Farm Value (Victoria: Ministry of Agriculture, various annual issues).
crops have consistently been the largest revenue earners in the Lower Mainland since 1975.

Peas have maintained a relative position above the remaining crops, followed by lettuce and corn. The other six crops have rarely contributed more than two million dollars each in any one year. In Table 2 the crops are ranked in order of the average annual cash receipts from each between 1975-1984. While this picture of relative importance may alter considerably from year to year, a definite division exists between the revenue contribution of the first six crops and that of the other nine. A weaker division can be drawn between peas, lettuce and corn and the remaining six crops.

(b) Crop Sensitivity to Ozone

The literature on plant response to ozone was reviewed in order to discover the relative susceptibility of each of the fifteen crops in Table 2. No information could be found on the response of blueberries, cranberries, raspberries, mushrooms or brussel sprouts. The remaining ten crops may be characterised as either susceptible, intermediate or tolerant to ozone, as shown in Table 3. This categorization is helpful in as far as showing the general results of previous research. However, the rankings may be misleading due to the wide variety of responses possible across cultivars.

While the evidence is that strawberries are almost certainly tolerant, with seven cultivars commonly grown in California found to be tolerant, a general ranking is not always easy with different cultivars showing different susceptibilities to ozone.
Table 3. Susceptibility to Ozone of Crops in the Lower Mainland

<table>
<thead>
<tr>
<th>Susceptibility to Ozone</th>
<th>Crop</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitive</td>
<td>Potatoes</td>
<td>1, 2, 3, 6</td>
</tr>
<tr>
<td></td>
<td>Lettuce</td>
<td>1, 2, 5</td>
</tr>
<tr>
<td></td>
<td>Sweet Corn</td>
<td>2, 3</td>
</tr>
<tr>
<td></td>
<td>Onions</td>
<td>1, 3</td>
</tr>
<tr>
<td></td>
<td>Green Beans</td>
<td>2, 6</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Peas</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Cabbages</td>
<td>3</td>
</tr>
<tr>
<td>Tolerant</td>
<td>Strawberries</td>
<td>1, 3</td>
</tr>
<tr>
<td></td>
<td>Broccoli</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Cauliflower</td>
<td>4</td>
</tr>
<tr>
<td>Unknown</td>
<td>Blueberries</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cranberries</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Raspberries</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mushrooms</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brussel Sprouts</td>
<td></td>
</tr>
</tbody>
</table>

Key: 1. California Department of Food and Agriculture (1986)
2. Stern et al. (1973)
6. Heggestad and Bennett (1984)
Indeed a crop may be ranked differently by different sources. For example, lettuce is shown as sensitive in Table 3 based upon the response of head lettuce and leaf lettuce, but lettuce has also been stated to be resistant. The rankings as shown in Table 3 give a higher ranking where a discrepancy was found so as to emphasise the possibility of damage. For example, green beans are categorised as sensitive but, in a four-year study at Beltsville, Maryland investigations showed two of four cultivars were tolerant. Obviously, the actual cultivars grown in a region and their relative importance need to be assessed to fully account for crop susceptibility.

On the basis of the above analysis, potatoes were chosen as the crop to be analysed. In the Lower Mainland the six common potato cultivars are Gem Russet, Warba, Norland, Norgold Russet, Keenebec and Norchip. These have been given ozone susceptibility rankings by U.S. studies as follows: Norland and Norchip sensitive, Keenebec intermediate, Norgold Russet and Gem Russet tolerant, and Warba unknown.

1.2 Objectives

The main objective of this thesis is to calculate the welfare changes which might be expected to result from potato yield increases caused by the reduction of ambient ozone loadings in the Lower Mainland of British Columbia. The main sub-objectives are:

1. Review of the scientific literature pertaining to the effects of ambient ozone loadings on agricultural crops.
2. Review of the economic literature on the methodologies
employed when regional air pollution assessments are to be made.

3. The estimation of a cost function for B.C. for the assessment of changes in economic welfare due to aggregate crop damage from ambient ozone loadings.


5. The use of scenario analysis to evaluate the sensitivity of consumer and producer welfare to changes in important model parameters.

6. To draw policy conclusions, and identify areas for future research and possible improvements in regional economic crop damage estimates.

1.3 Research Procedure

Two major tasks were undertaken in this thesis. Firstly, the calculation of potential physical damage to regionally important crops due to ambient ozone loadings in the Lower Mainland of B.C. Secondly, to employ the findings of the first area of research to perform an economic estimation of ozone induced crop damage. More emphasis was placed upon the second area in order to achieve subobjectives 2 to 5.

This involved surveying the literature on ozone formation and transportation in recent journal articles and books. Reports by government agencies in Canada and the United States of relevance to ambient ozone loadings, and related issues were sought. Reports specific to the Vancouver region were of particular interest. The surveys of work carried out by the National Crop
Loss Assessment Network of the United States were collected. Dose-response information and relationships were obtained from the California Department of Agriculture and Food. The engineering division of the Greater Vancouver Regional District was contacted for information on ambient ozone loadings and the operations of their air quality monitoring network.

The second sub-objective also involved a literature survey. This survey fell into two parts; namely reviewing economic methodologies for crop loss assessment, and studying applications of such methodologies in relation to ozone pollution. Environmental and agricultural economics, and pollution related journals were searched for articles attempting or discussing economic crop loss assessment. The bibliographies of all such reports were checked for further references. This literature was used to identify a methodology which could be employed in the assessment of crop loss due to ozone in the Lower Mainland, and to identify issues important to conducting such an assessment.

This identified the dual approach as a theoretically well founded method of modelling agricultural production which had been applied to regional ozone crop loss assessment. A multiple-output, multiple-input cost function model of the B.C. agricultural sector was developed using the translog functional form. Data on the B.C. agricultural sector were collected from Statistics Canada. Econometric estimation of the model was achieved using the Statistical Analysis System (SAS) available on the main U.B.C. computing network. In particular, the SAS's systems regression procedure was used with three-stage least
squares. This method was required because the cost function, input share and revenue share equations were estimated together. This approach increases the efficiency of parameter estimation compared to estimation of the cost function alone. Due to the limited time-series information available, increased efficiency in the estimation procedure was important.

Failure to achieve sub-objective 3 required the selection of another methodology by which to perform an economic assessment of ozone damages to crops. A crop-specific analysis of damages was performed. Information on specific crops produced in B.C. and the Lower Mainland had already been obtained from provincial government publications and the B.C. Department of Agriculture and Food. Studies related to potato production and consumption were sought. On the basis of a previous econometric study of the B.C. potato industry, supply and demand functions were calculated. A model was set up to include the percentage reduction in yield predicted by a dose-response function, and using SAS a total damage function was derived and marginal damages calculated. The results were then compared to total and marginal damages calculated under various scenarios.

1.3 Outline

Chapter Two describes the sources of ozone, its formation and transportation. Ambient ozone loadings in the Lower Mainland and their potential physical damage to potato production are outlined. The second part of the chapter reviews the factors affecting the response of plants to air pollution and the methodologies for deriving dose-response functions. The chapter
finishes with a look at certain requirements of response function proposed for use in economic assessments.

Chapter Three opens by describing the methodologies available for the valuation of agricultural crop yield changes induced by air pollution. This is followed by a review of recent applied work in the regional economic assessment of the effects of ozone upon agricultural crops. The chapter concludes with an analysis of specific issues relevant to the economic assessment of air pollution which were raised by the literature review.

Chapter Four concerns the attempt at estimating a multiple-output, multiple-input translog cost function model of B.C. agriculture. The data are described and the parameter estimates presented. The results for ray and product-specific economies of scale are given, along with the estimates of input substitution. The problems encountered with regard to parameter estimates are summarised.

Chapter Five develops an alternative to the aggregate analysis attempted in Chapter Four. A model of the potato market in British Columbia is presented. Supply and demand functions are specified and the spatial equilibrium of the market described. Several scenarios are then employed to analyse the effects of changes in ambient ozone concentrations on potato production in the Lower Mainland. The sensitivity of the model to changes in import prices, and supply and demand elasticities, is analysed. Finally, the results are discussed in Chapter Six.
Footnotes


2 Ibid, p.93.


4 Land in the first three classes is defined as capable of sustained production of common cultivated crops, and those in the fourth are marginal for sustainable agriculture. In order for land to be rated in the top classes it must meet certain climatic and soil quality criteria. See, B.C., Legislative Assembly, SSCA. Land Productivity in B.C..

5 This concers with work done in California where mountain ranges have been assumed to provide protection for crop areas. See, S. K. Leung, W. Reed and S. Geng "Estimation of Ozone Damage to Selected Crops Grown in Southern California" Journal of Air Pollution Control Association Vol.32 No.2 (February, 1982) p.160-164.


7 California, Department of Food and Agriculture. Air Pollution Manual (1986).


9 California, Department of Food and Agriculture. Air Pollution Manual.

10 S. Bialobok, "Controlling Atmospheric Pollution" in M. Treshow (ed.) Air Pollution and Plant Life (Chichester: John Wiley and Sons, 1984).

11 H.E. Heggestad and J.H. Bennett, "Impact of Atmospheric Pollution on Agriculture" in M. Treshow (ed.) Air Pollution and Plant Life (Chichester: John Wiley and Sons, 1984).


13 H.E. Heggestad and J.H. Bennett, "Impact of Atmospheric Pollution on Agriculture"; and California, Department of Food and Agriculture. Air Pollution Manual.
CHAPTER II

SCIENTIFIC ASPECTS OF OZONE DAMAGE
TO AGRICULTURAL CROPS

2.1 Introduction

Photochemical oxidants is the term used to describe ozone and other compounds consisting of oxidised organics such as ketones, aldehydes, peroxyacetyl nitrates (PAN) and peroxo compounds. They are capable of causing plant damage, affecting human health, disrupting ecosystem structure and stability, and reacting with a number of nonbiological materials (e.g., rubber), as well as forming a visibility-reducing blue haze. Oxidant air pollution mixtures consist of three phytotoxic (i.e. toxic to plants) compounds: ozone, oxides of nitrogen, and PAN. The PAN are the most phytotoxic, but occur in relatively small concentrations. Nitrogen oxides are of concern for three reasons, namely: (a) phytotoxicity, (b) as precursors to ozone, and (c) as precursors to acid precipitation.

Ozone is the most prevalent photochemical oxidant, has been studied most extensively, and is used as the basis for photochemical oxidant air quality standards in both the United States and Canada. Injury to plants from photochemical smog was first noted in the mid-1940's, when stippling and glazing or
bronzing of the leaves of vegetables were discovered in the Los Angeles basin, California. Tropospheric (the lowest 10-15 kilometers of the atmosphere) ozone concentrations alone or in combination with sulphur dioxide and nitrogen dioxide have since been identified as the major source of crop losses caused by air pollution in the United States.

In this chapter the pathway of tropospheric ozone through the environment, from sources to receptors, is described and characterized. The first two sections discuss the factors which determine the amount of ozone at a site; namely the nature of relevant emissions and the state of the atmosphere. The final section covers some of the main issues concerning the biological response of agricultural crops to ozone. The effect of various ozone concentrations has been summarised in biological dose-response functions for certain crops and most economic assessments of crop losses are dependent upon this information. An understanding of the limitations of the dose-response information base is therefore important.
2.2 Sources of Ozone

Ozone in the lower atmosphere has two sources, namely anthropogenic and natural. Ozone is not released directly into the atmosphere but is formed from precursor emissions. The most important precursor emissions for natural and man-made tropospheric oxidant formation have been identified as hydrocarbons and oxides of nitrogen. All hydrocarbons present in the atmosphere are not significant oxidant precursors, but only non-methane hydrocarbons. Of the eight oxides of nitrogen found in the atmosphere, the main contributors to oxidant formation are nitrogen dioxide and nitric oxide.

2.2.1 Natural Ozone

The concentration of natural ozone in the troposphere is the result of stratospheric (upper atmospheric layer beginning approximately six miles above earth's surface) transfers and photochemical reactions involving naturally occurring precursors. The major source of atmospheric hydrocarbons is the natural decomposition of organic material. Sources of natural oxides of nitrogen include decomposition in the soil and oceans, stratospheric photochemistry, and lightning. The photochemical production of ozone from natural hydrocarbons and nitrogen oxides has been estimated to make only a minor contribution to natural ozone levels in the troposphere, which can thus be largely attributed to stratospheric transfer. The meteorological and climatological conditions for this transfer will therefore determine the levels of naturally occurring ozone.

Background ozone concentrations in the troposphere are
generally about 0.02 or 0.03 ppm (parts per million).\textsuperscript{15} Monitoring has shown natural ozone to have a seasonal pattern, being at its highest in spring, then winter.\textsuperscript{16} Also natural ozone concentrations increase with latitude in the northern hemisphere.\textsuperscript{17} In southern Canada, springtime high background ozone levels are estimated at 0.04 to 0.05 ppm, decreasing to a low of 0.02 ppm in late summer and fall.\textsuperscript{18} Despite these latitudinal and seasonal variations, a constant natural ozone level of 0.025 ppm has been assumed in experiments to determine the response of plants to ozone in the United States.\textsuperscript{19}

2.2.2 Anthropogenic Ozone

Anthropogenic precursor emissions are dominant in and around urban centres where the most severe oxidant problems occur, e.g., in Canada, Vancouver, Quebec City, Montreal and Toronto.\textsuperscript{20} Anthropogenic production of hydrocarbons is small compared to natural releases, but the compounds are highly reactive and important in the formation of ozone.\textsuperscript{21} Hydrocarbons are produced during fossil fuel combustion and the evaporation of gasoline, and hydrocarbon emissions are closely related to traffic density. The principal anthropogenic sources of oxides of nitrogen are vehicles, coal and natural gas burning, and fertilizer and explosives factories.\textsuperscript{22}

The transportation sector has been identified as the primary source of anthropogenic ozone precursor emissions in the United States.\textsuperscript{23} Since the transportation sector is a population-dependent activity, most areas with a high population density are areas with high hydrocarbon and oxides of nitrogen emission
Precursor emissions due to residential heating, fuel wood combustion and solid waste incineration are also population dependent, which explains the urban nature of severe oxidant problems.

A breakdown of anthropogenic hydrocarbon and oxides of nitrogen emissions for the Lower Mainland is given in Table 4. The total oxides of nitrogen emitted in the Lower Mainland in 1978 was 68,800 tonnes while the total for British Columbia was 176,500 tonnes. Total emissions of hydrocarbons (i.e., including non-methane hydrocarbons) in the Lower Mainland were estimated to be 95,700 tonnes in 1978. Gasoline powered vehicles are the predominant source of ozone precursor emissions, contributing 49 percent to total hydrocarbons and 44 percent to total oxides of nitrogen in the Lower Mainland.

Table 4. Oxidant Precursor Emissions in the Lower Mainland for 1978 (Tonnes)

<table>
<thead>
<tr>
<th>Precursor Source</th>
<th>Hydrocarbons (95,700 tonnes)</th>
<th>% of Total</th>
<th>Nitrogen Oxides (68,800 tonnes)</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline Powered Vehicles:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light-Duty Vehicles</td>
<td>37.6</td>
<td>34.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy-Duty Trucks</td>
<td>6.2</td>
<td>5.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium-Duty Trucks</td>
<td>4.7</td>
<td>6.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stationary Fuel Combustion</td>
<td>0.5</td>
<td>16.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off-Highway Mobile Sources</td>
<td>2.0</td>
<td>9.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petroleum Refining</td>
<td>12.3</td>
<td>3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline Marketing</td>
<td>13.8</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel Powered Engines</td>
<td>1.9</td>
<td>22.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applications of Surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coatings</td>
<td>7.6</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>13.4</td>
<td>3.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.3 Ozone Formation and Transportation

2.3.1 Ozone Formation

The formation of photochemical smog in the troposphere is a complex process involving the reactions of hundreds of primary precursors in the presence of ultraviolet sunlight to generate ozone.\(^{27}\) Figure 1 shows the basic processes involved. Oxygen atoms (O) are derived principally from the dissociation of nitrogen dioxide (NO\(_2\)) by solar radiation.\(^{28}\)

\[
\text{NO}_2 + \text{Ultra-Violet Sunlight} \rightarrow \text{NO} + \text{O}
\]

This atomic oxygen reacts rapidly with molecular oxygen (O\(_2\)) to form ozone (O\(_3\)).

\[
\text{O} + \text{O}_2 \rightarrow \text{O}_3
\]

Ozone in turn reacts with nitrogen oxide (NO) to form nitrogen dioxide again.

\[
\text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2
\]

These three equations make up the naturally occurring nitrogen dioxide photolytic cycle. In the absence of reactive hydrocarbons there is no significant ozone production, because ozone and nitrogen oxide are formed and destroyed constantly with no net production. Reactive hydrocarbons released by vehicle exhausts unbalance the cycle by converting nitrogen oxide to nitrogen dioxide without consuming an equivalent amount of ozone.\(^{29}\) A complex series of chemical reactions follow which create a wide range of secondary pollutants of which ozone is quantitatively the most important.\(^{30}\) Photochemical smogs are characterised by a distinctive odour, and a yellow-brown haze (due to NO\(_2\)).\(^{31}\)
Figure 1

Photolytic Cycle and Ozone Production

Ultra-Violet Light

Source: Adapted from A.C. Stern et al. Fundamentals of Air Pollution (1984) Figure 11-4 p.169
2.3.2 Seasonal and Diurnal Cycles of Urban Ozone

The necessity for high intensity short-wave radiation to initiate the phytolytic cycle gives variations in photochemical smogs distinct diurnal and annual cycles. Figure 2(a) shows the annual patterns of ozone concentrations in Los Angeles and Denver, using a monthly average of the mean daily maximum one hour average concentration. Sunlight is a limiting factor in Denver creating a mid-summer peak, while in Los Angeles the peak is in late summer and autumn when cloud cover is least and winds are weak. The seasonal peak for ozone will vary depending upon local conditions, but outside the tropics the occurrence of photochemical smogs tends to be restricted to summer.

Three factors create the diurnal ozone cycle: (a) the temporal variation of precursor emissions, (b) atmospheric dispersion capacity, and (c) the intensity of solar radiation. The diurnal cycle for ozone is characterized in Figure 2(b), which shows one day's variation of nitrogen oxide and dioxide, and ozone for Los Angeles. Peak precursor emissions occur in the early morning, with rush hour traffic, when dispersion and solar intensity are weak. Exhaust products such as nitrogen oxide and hydrocarbons rapidly accumulate, leading to the production of nitrogen dioxide. Increasing solar radiation intensity and nitrogen dioxide levels cause a rapid increase in ozone, which reaches a peak at midday. Meanwhile, precursor emissions drop, atmospheric instability increases aiding dilution, and other reactions alter the nature of essential smog chemicals. In the afternoon, ozone concentrations decrease with radiation.
Figure 2
Seasonal and Diurnal Cycles of Urban Ozone

(a) Annual Ozone Variations in Denver and Los Angeles

(b) Classic Diurnal Ozone Cycle in Los Angeles

Source: T.R. Oke, Boundary Layer Climates (1978) Figure 9.14 p.296
intensity, dilution continues and ozone is removed by reaction with atmospheric constituents (nitrogen oxides and hydrocarbons) and surface receptors such as plants.\textsuperscript{34}

This general pattern may be modified as a parcel of air moves across a region accumulating more pollutants. For example, in the Los Angeles Basin oxidant pollution is highest in downwind communities, and in the late afternoon. Diurnal peaks occur at midday in West Los Angeles, 1300 hours in downtown, and 1400 hours in Azusa where ozone concentrations are higher than the upwind locations despite lower local precursor emissions.\textsuperscript{35} The multiple input of pollutants in this manner (i.e., due to the random alignment of sources) is called cumulative loading. The cumulative loading of reactive chemicals can cause downwind (e.g., rural) areas to receive high ozone, or other secondary pollutant, concentrations not apparent at upwind (e.g., urban) monitoring stations.\textsuperscript{36}

2.3.3 Ozone Transportation, Dispersion and Removal

(a) The Role of Wind

Wind diffuses (dilutes) pollution in the along-wind direction, and by turbulent diffusion in the across-wind and vertical directions.\textsuperscript{37} Turbulent diffusion is the dilution of material in the atmosphere as a result of random or irregular fluctuations in the wind. Wind fluctuations may cover an arc of 30-40 degrees centered upon the mean wind direction. The mean direction determines the path followed by pollutants. Wind speed is responsible for forward stretching and the distance pollutants are transported. Weak winds curtail both horizontal transport and
turbulent diffusion, and allow local circulation systems to develop. Local circulation systems are not good pollution diffusers because of low wind speeds, closed circulation and diurnal reversal in the direction of flow.\textsuperscript{38}

(b) Dispersion and Inversion

Dispersion of pollutants is achieved when turbulence causes them to mix with clean air. Turbulence is the result of mechanical overturning of near-surface layers by frictional contact with rough surfaces, and thermal instability produced by vertical temperature structure. Mechanical instability is relatively unimportant above 100 meters or with weak air flow. Thus, the vertical temperature structure is of prime concern when considering regional air quality.\textsuperscript{39}

The stability of a parcel of air is determined by the variation of temperature with height. In general, if the parcel of air has a higher temperature than the air above, it will be able to rise and is "unstable". A "stable" parcel of air has a lower temperature than the air above and may sink. Days with good surface heating are characteristic of instability (the depth affected by this heating is called the "mixing layer") which enhances dispersion.\textsuperscript{40}

Inversions are particularly important to dispersion and exist when warm air overlies cooler air.\textsuperscript{41} Inversions may be due to (a) cooling from below, such as on nights with little or no cloud cover when the ground cools; (b) warming from above, most importantly due to subsidence inversion; or (c) advection of warmer or cooler air, due to weather fronts or sea breeze.
Advection due to weather fronts occurs when cold air is wedged under warm air by a cold front or warm air over-rides colder air in a warm front, as shown in Figure 3(a). Frontal inversions are normally short-lived and not important to air pollution. However, exceptions may occur with slow moving warm fronts, and when pockets of cold air are trapped in valley bottoms by warm air behind a front. Advection may also occur due to the sea breeze (see below), when land cools at night and warmer air flows inland from the sea.  

Large scale subsidence in an anticyclone is of particular concern for the concentration of ozone because it combines an inversion with clear skies which allow high levels of solar radiation at ground level. As an anticyclone (high pressure area) moves into an area of low pressure the air flow is "divergent," as shown in Figure 3(b). The diverging air is replaced by air from above as it subsides. The subsiding air is warmed as it becomes compressed owing to increasing pressure, as the mass of air above the air parcel increases. This warming may cause the air some distance above the surface to be warmer than near-surface air, not participating in the subsidence, creating a temperature inversion.  

In general, the most unfavourable dispersion conditions occur with weak air flow and a shallow mixing layer, conditions characteristic of anticyclonic weather. As air becomes stagnant pollutant concentrations may increase with time. Thermal breezes circulate the air around inside an almost closed box. Additional topographical confinement of the source area can restrict lateral
Figure 3
Inversions

(a) Frontal Inversions

Cold Front

<table>
<thead>
<tr>
<th>COLD</th>
<th>WARM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td></td>
</tr>
</tbody>
</table>

Warm Front

<table>
<thead>
<tr>
<th>WARM</th>
<th>COLD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td></td>
</tr>
</tbody>
</table>

(b) Subsidence Inversion

<table>
<thead>
<tr>
<th>WARM</th>
<th>Base</th>
<th>Divergence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: After T.R. Oke, Boundary Layer Climates (1978) Figure 9.3 (a) and (b); Figure 9.2 (a) p.275.
spreading, and further enhance pollutant concentration.\(^{44}\)

(c) **Removal**

Over one or several hours, chemical reactions involving precursors can generate significant amounts of ozone which, if not quickly destroyed, can be transported over great distances before removal from the atmosphere. Long range transportation of ozone and its precursors can cause high ozone concentrations to occur in rural areas hundreds of kilometres from precursor sources.\(^{45}\) Ozone may persist overnight in rural areas where there are fewer reactive compounds (such as NO), or in parts of the atmosphere where there are few removal mechanisms.\(^{46}\)

Primary processes removing pollutants from the atmosphere are chemical transformation, gravitational settling (dry deposition), adsorption (impaction) and precipitation scavenging.\(^{47}\) Precipitation scavenging is not considered a major sink for ozone because ozone is relatively insoluble in water, and forms under warm, dry, stagnant conditions.\(^{48}\) However, nitrogen dioxide may be removed by this process, affecting the potential for smog production. Adsorption by soil and vegetation surfaces represents a major sink for pollutants introduced into terrestrial ecosystems, and especially for ozone.\(^{49}\) Pollutant transfer from the atmosphere to a sink is expressed as a flux (pollutant uptake) rate, and is defined as the weight of pollutant removed by a given surface area per unit of time. Factors determining flux rates include atmospheric conditions (wind, turbulence, temperature, and humidity), pollutant nature and concentration, sink surface geometry and moisture, and other parameters.\(^{50}\)
2.4 Ozone in the Lower Mainland

2.4.1 Atmospheric Conditions

Vancouver experiences its worst air quality in summer under anticyclonic conditions. Local features which contribute to the formation and accumulation of ozone in the Lower Mainland are similar to those found in the Los Angeles Basin\(^{51}\). They are:

1. Anticyclonic conditions found in summer, providing high solar radiation, and a lack of precipitation.
2. Subsidence inversion associated with anticyclonic conditions, preventing vertical mixing.
4. Land/sea breezes, which develop in light winds, and are associated with anticyclonic conditions.

Land/sea breeze circulations are essentially closed and completely reverse their flow from day to night, thus minimizing the net transportation out of a region. This system may be augmented by others (e.g. mountain/valley winds). Figure 4 characterizes the circulation of the land sea breeze in Vancouver. At night the breeze can take pollutants off-shore. The vertical exchange rate over the Pacific is very weak, so that ozone and its precursors are not rapidly destroyed or absorbed by the sea surface.\(^{52}\) These pollutants can then be returned to the city the next day as the circulation reverses.

Hay and Oke\(^{53}\) have characterised the occurrence of a summer stagnant high pressure system over Vancouver in terms of a "box" model. The Fraser Valley is enclosed by mountain walls on either side and a lid, provided by a subsidence inversion, below the top of the valley sides. When the airflow system is of the
Figure 4

Schematic Diagram of Land/Sea Breeze Over Vancouver

(a) DAY

(b) NIGHT

Source: J.E. Hay and T.R. Oke, The Climate of Vancouver Figure 17 (a) p. 37.
closed circulation type the ends of the box may be considered closed, as shown for Vancouver in Figure 5.

The box is restricted to a small volume. At night in Vancouver the base of the inversion layer is about 100 meters above the surface, due to heat from the city and the warm waters of the Burrard Inlet. In the rural areas of the valley the base is essentially zero. On a good heating day the mixing layer may reach 300 to 500 meters, but this is still below the height of the valley walls (i.e., approximately one kilometer). When pollutant removal is weak, the continual emissions from the floor of the box will cause the concentration of pollutants to build up. Such periods of anticyclonic weather often last two to four weeks in the late summer and fall.

The Lower Mainland area is susceptible to transboundary pollutants due to its proximity to the United States. Determining the transboundary nature of oxidant problems in Vancouver was the prime objective of a study carried out for the Environmental Protection Service by Concorde Scientific Corporation. The study concluded that there was no indication that the long range transport of ozone or its precursors is a factor that contributes to ozone episodes in Greater Vancouver or the Lower Fraser Valley.

In summary, ozone and its precursors travel up the Fraser Valley from the Burrard Inlet, towards major agricultural crop growing areas. During the day, sea breezes transport precursor emissions from the high density commercial and traffic areas of Vancouver eastwards. These winds, combined with the restricted
Box Model of a Stagnant High Pressure System Over Vancouver

Source: J.E. Hay and T.R. Oke, The Climate of Vancouver (1973) Figure 19 p.45.
atmospheric dispersion within the topographic setting of the Burrard Inlet, create conditions virtually ideal for the concentration of air pollution at areas east towards the Fraser Valley.57

2.4.2 Ambient Ozone Concentration and Potato Damage

Several air quality monitoring stations have been operating in the Lower Mainland, providing ambient ozone concentration and meteorological data since 1977. The location of the stations is shown in Figure 6 and their GVRD codes and descriptions are given in Table 5. Rural sites now exist at Surrey East, Pitt Meadows, Chilliwack and Abbotsford, and a new station was set up in 1986 at Richmond South. All other stations are in urban areas of the GVRD (Greater Vancouver Regional District).58

The National Air Quality Objectives for ozone define Maximum Desirable, Maximum Acceptable and Maximum Tolerable one hour concentrations of 0.051, 0.082 and 0.153 ppm respectively.59 The acceptable level is defined as providing "adequate protection" against adverse effects on soil, water, vegetation, materials, animals, visibility, personal comfort and well-being.60 Spring (April to June) has the highest ozone levels, but the greatest number of exceedances of the acceptable level occur in summer (July and August). Diurnal patterns for ozone and its precursors are shown, for station T7, in Figure 7, and in spring and summer follow the classic pattern as outlined earlier. At T7 there is a peak in nitrogen oxide and hydrocarbon levels in the morning between 0800 and 1000 and, after a lag, nitrogen dioxide levels rise. However, all these species peak later in the day at T7 than
Table 5. Air Quality Monitoring Stations of the Lower Mainland

<table>
<thead>
<tr>
<th>Station Description</th>
<th>Station Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robson Square - Robson and Hornby</td>
<td>Vancouver T1</td>
</tr>
<tr>
<td>Rocky Point Park - 2294 West 10th Avenue</td>
<td>Vancouver T2</td>
</tr>
<tr>
<td>Marpole - 250 West 70th Avenue</td>
<td>Vancouver T3</td>
</tr>
<tr>
<td>Kensington Park - 6400 East Hastings St.</td>
<td>Vancouver T4</td>
</tr>
<tr>
<td>Confederation Park - Willingdon &amp; Penzance</td>
<td>Burnaby T5</td>
</tr>
<tr>
<td>Second Narrows - 75 Riverside Drive</td>
<td>N. Van. T6</td>
</tr>
<tr>
<td>Anmore - Sunnyside Road</td>
<td>Anmore T7</td>
</tr>
<tr>
<td>Lions Gate - West end of Welch Road</td>
<td>W. Van. T8</td>
</tr>
<tr>
<td>Rocky Point Park - Murray Street</td>
<td>Port Moody T9</td>
</tr>
<tr>
<td>Eagle Ridge - 475 Guilford Way</td>
<td>Port Moody T10</td>
</tr>
<tr>
<td>Abbotsford Airport -</td>
<td>Abbotsford T11</td>
</tr>
<tr>
<td>Chilliwack Airport -</td>
<td>Chilliwack T12</td>
</tr>
<tr>
<td>Annacis Island - Derwent Way</td>
<td>Delta T13</td>
</tr>
<tr>
<td>Burnaby Mountain - Ring Road, SFU</td>
<td>Burnaby T14</td>
</tr>
<tr>
<td>Surrey East - 1900 blk. 72nd Avenue</td>
<td>Surrey T15</td>
</tr>
<tr>
<td>Pitt Meadows - Pitt Meadows Airport</td>
<td>T16</td>
</tr>
<tr>
<td>Richmond South - Williams and Aragon</td>
<td>Richmond T17</td>
</tr>
</tbody>
</table>

SFU = Simon Fraser University
Source: Personal communication with Greater Vancouver Regional District, Engineering and Operations Department (March, 1987).
Figure 7
Diurnal Ozone Cycle in Vancouver
Station T7 August 1981

Source: Environmental Protection Service, Vancouver Oxidant Study: Air Quality Analysis (1982). Fig.7.3 p.172.
for stations T4 and T2, with ozone peaking approximately one hour later, around 1400 hours. This suggests the transportation of precursors from upwind sites makes a significant contribution.

Despite low oxides of nitrogen concentrations at station T7 relatively high ozone levels are found there, again implying precursor transportation from upwind (west) of the station. Rural stations T11 and T12 experience peaks even later in the afternoon, between 1500 and 1700 hours, with Abbotsford reaching a peak approximately one hour after Chilliwack. The indication from other stations is clearly that precursors are transported by westerly flows, away from T1, T2, T3 and T8, which have high precursor concentrations but relatively infrequent episodes, towards T7 and points east.

During the period from 1978-1981 the maximum tolerable one hour concentration was exceeded in two or more years at stations T4, T5, T7, T9, T10 and T11. Oxidant levels in the Lower Mainland were frequently in excess of the acceptable level for ozone. For example, station T7 consistently recorded the greatest number of exceedances with 134, 84, 191 and 215 exceedances of the maximum acceptable level for ozone in 1978, 1979, 1980 and 1981 respectively. Station T7, at the eastern end of the Burrard Inlet, has also consistently recorded the highest annual mean ozone levels. The two rural stations which were operational during this period (T11 and T12) have also recorded relatively high ozone concentrations. Abbotsford (T11) consistently recorded the second or third highest annual mean, while the annual mean for Chilliwack (T12) ranked between second and fifth highest.
In more recent years ozone concentrations have been significantly lower. Information from the rural monitoring stations was obtained from the GVRD Air Quality Monitoring Network, and analysed in order to assess the potential for impacts on potato yields for the entire period from 1977 to 1985. Table 6 reports two seasonal ozone dose measures for the four rural stations, and includes one urban station T7. As Table 6 shows, the rural monitoring sites have often recorded higher ambient ozone loadings than the urban site, especially for ppm-hours>0.10ppm. These measures were calculated for the 124 day period from May 15th to August 15th, which coincides with the busiest potato growing season. The number of valid days (ranging from 29-124) shows how much data are missing. The seasonal seven hour mean incorporates hourly readings between 9 a.m. and 4 p.m., and is included to allow comparisons with U.S. studies. The ppm-hours>0.10ppm includes all readings in a 24 hour period, and is compared below with the potato dose-response function of the "Air Pollution Manual" of the California Department of Agriculture and Food. Dose-response relationships and exposure statistics are discussed in section 2.5.

As mentioned in Chapter I, of the six common potato cultivars grown in the Lower Mainland experimental data from the U.S. shows three to be susceptible to ozone, two tolerant and one unknown. The dose-response function from the Air Pollution Manual is for a sensitive cultivar (Centennial). The percentage reduction in potato tuber weight is given by the formulae:

\[
\text{Percentage Reduction} = 0 + (1.03 \times \text{Dose}),
\]

where Dose is calculated in ppm-hours>0.10ppm for a 120 day
Table 6. Ambient Ozone Concentrations at Rural Monitoring Stations in the Lower Mainland

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dose&gt;0.10ppm</td>
<td>0</td>
<td>0</td>
<td>1.025</td>
<td>0</td>
<td>0</td>
<td>0.408</td>
<td>0</td>
<td>0.117</td>
<td>0.107</td>
</tr>
<tr>
<td></td>
<td>hrs&gt;0.10ppm</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>7hr seasonal av. ppm</td>
<td>0.045</td>
<td>0.027</td>
<td>0.036</td>
<td>0.030</td>
<td>0.021</td>
<td>0.035</td>
<td>0.024</td>
<td>0.037</td>
<td>0.037</td>
</tr>
<tr>
<td></td>
<td>Number of valid days</td>
<td>29</td>
<td>94</td>
<td>111</td>
<td>103</td>
<td>119</td>
<td>82</td>
<td>114</td>
<td>107</td>
<td>107</td>
</tr>
</tbody>
</table>

**Anmore**

**Abbotsford**

**Chilliwack**

**Surrey**

**Pitt Meadows**

NA = no data available because station not operational.
period. The source document does not justify the assumption of no plant damage below 0.10ppm, and may therefore under estimate actual reductions. In addition, if such a threshold exists it may be lower for other crops and cultivars.

Table 7. Predicted Percentage Reduction in Potato Tuber Weight for the Lower Mainland

<table>
<thead>
<tr>
<th>Ozone Dose (ppm-hrs&gt;0.10ppm)</th>
<th>Potato Tuber Weight Reduction (percentage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>0.103</td>
</tr>
<tr>
<td>0.20</td>
<td>0.206</td>
</tr>
<tr>
<td>0.40</td>
<td>0.412</td>
</tr>
<tr>
<td>0.80</td>
<td>0.824</td>
</tr>
<tr>
<td>1.00</td>
<td>1.030</td>
</tr>
<tr>
<td>3.10</td>
<td>3.193</td>
</tr>
<tr>
<td>5.59</td>
<td>5.758</td>
</tr>
<tr>
<td>6.52</td>
<td>6.716</td>
</tr>
<tr>
<td>8.46</td>
<td>8.714</td>
</tr>
<tr>
<td>16.00</td>
<td>16.480</td>
</tr>
</tbody>
</table>

Ozone dose (from Table 6) and the corresponding percentage potato yield reduction are shown in Table 7. Extrapolating the linear response function over a wide range of ozone doses would not seem justified, as the rate of damage is hypothesised to increase and then decline. However, over the relatively small range of ozone doses of concern here the linear function is adequate. In 1985, 1984, and 1983 no substantial potato damage is predicted. Although, substantial missing data at Abbotsford, the only operational rural site in 1983, makes reductions possible for that year. The predicted yield reductions for Abbotsford in the years 1978, 1979, 1980, 1981, and 1982 are approximately 9, 3, 6, 16.5, and 7 percent respectively. The reductions for 1982 are based on 47 days data, and those for 1979 on 36 days, instead of the full 124 day season, and may therefore be higher.
2.5 Biological Response of Agricultural Crops

2.5.1 Factors Affecting Plant Response to Air Pollution

(a) Environmental and Biological Factors

A conceptual model of air pollution effects on vegetation is shown in Figure 8 and the biotic, climatic and edaphic factors are defined in Table 8. Inherent genetic resistance has been cited as probably the most important factor influencing plant response to air pollutants. Plant response to ozone varies among species of a given genus (e.g., potato) and varieties or cultivars (e.g., Netted Gem) within a given species.65

Ozone, as with other air pollutants, damages a plant after entering the stomatal leaf opening.66 Thus, factors affecting stomatal size and opening determine pollutant uptake and the potential for damage. For example, reduced moisture or increased temperature can cause reduced stomatal apertures and higher resistance to air pollution.67 Plants under no such stresses, growing under favourable conditions, may therefore be more susceptible to damage. In general, plants are more able to cope with exposure to ozone at night because stomata are closed, and at lower temperatures and relative humidity; and are more susceptible to ozone damage when the leaves are mature, due to the increase in cell gaps.68

Farm practices may also alter plant response to air pollution. For example, attempts to improve growing conditions (e.g., irrigation) and reduce plant stress, could increase ozone susceptibility. The mixture of production inputs is a factor often ignored in the derivation of dose-response functions under
Figure 8
Conceptual Model of Factors Involved in Air Pollution Effects on Vegetation

Source: adapted from S.N. Linzon, W.W. Heck, and F.D.H. Macdowall "Effects of Photochemical Oxidants on Vegetation" in National Research Council of Canada, Subcommittee on Air, Photochemical Air Pollution: Formation, Transportation and Effects (Ottawa: Environmental Secretariat, 1975) Figure 4-3 p.128.
Table 8. Factors Affecting Plant Sensitivity to Air Pollutants

| Botanic:          | Genetic Composition                  |
|                  | Stage of Plant Development           |
| Climatic:        | Light Quality                        |
|                  | Light Intensity                      |
|                  | Precipitation                        |
|                  | Temperature                           |
|                  | Relative Humidity                     |
|                  | Carbon Dioxide                        |
| *Edaphic:        | Soil Moisture                         |
|                  | Soil Type                             |
|                  | Soil Nutrients (salinity, nitrogen and other nutrients' availability) |
| Biotic:          | Insects                               |
|                  | Biological Pathogens                  |
| Other:           | Pollutant Mixtures                    |

*Edaphic factors will be subject to alteration due to irrigation, fertilization and cultural management practices.

experimental conditions. Cultural and input variations between regions make dose-response functions which have been derived in one area inappropriate for use in another area. Even when the same inputs and cultivars are used in two different regions, all the other factors in Table 8 would have to concur before a dose-response function derived in one region could be used to accurately predict the yield loss in the second region.

(b) Ozone Dose

The ambient ozone concentration, the length of time a particular concentration persists, and the frequency of occurrences combine to form a measure of the dose of an air pollutant to which a plant is exposed; the "exposure dose". Other characteristics of plant exposure may also be important determinants of the nature and magnitude of the effects of ozone on plants --- the length of time between exposures, the time of day of exposures, their sequence and pattern, and the total flux of ozone to the plant as it is affected by canopy characteristics and leaf boundary layers. However, as Table 9 shows, ozone studies have defined exposure dose in terms of concentration, duration and frequency to the exclusion of other factors.

Certain factors imply the concentration of gas surrounding a plant or the dose may not accurately reflect the cellular dose to which the plant actually responds. Thus, an alternative to exposure dose was suggested by Runeckles, and called the "effective dose". The effective dose is the amount of an air pollutant that enters a plant, as opposed to that in the air surrounding the plant. The use of effective dose excludes
response variability due to pollutant uptake and thus focuses upon physiological differences in plant sensitivity. A major drawback of the effective dose measure is the inability to calculate it directly from available air monitoring data. Thus exposure dose has remained the common measure used in studies of the effects of ozone on crop productivity.

Table 9. Details of Ozone Exposure in 23 Recent Studies of Effects on Crop Productivity

<table>
<thead>
<tr>
<th>Details Provided</th>
<th>Number of Publications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration</td>
<td>23</td>
</tr>
<tr>
<td>Duration</td>
<td>18</td>
</tr>
<tr>
<td>Frequency</td>
<td>16</td>
</tr>
<tr>
<td>Time Between Exposures</td>
<td>13</td>
</tr>
<tr>
<td>Time of Day</td>
<td>6</td>
</tr>
<tr>
<td>Fluctuation of Concentrations</td>
<td>3</td>
</tr>
<tr>
<td>Pattern (sequence)</td>
<td>0</td>
</tr>
<tr>
<td>Flux</td>
<td>0</td>
</tr>
</tbody>
</table>


Several types of exposure dose measures have been employed in ozone studies, as is shown in Table 10. An extensive project on crop damage due to ozone has been conducted by the National Crop Loss Assessment Network (NCLAN) of the United States Environmental Protection Agency (E.P.A.). NCLAN has employed a seasonal seven-hour/day mean ozone concentration exposure statistic in all its published dose-response functions. This mean is calculated upon the seven hours judged to be the most susceptible for plants; that is, between 0900 and 1600 hours. The daily means for the seven-hour period are then averaged over the
entire growing season.

Table 10. Measures of Ozone Occurrence Used in Studies of Effects on Crop Productivity

<table>
<thead>
<tr>
<th>Measure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean values for 1, 3, 6, 7, or 24 hours</td>
<td>Maximum hourly average concentrations</td>
</tr>
<tr>
<td>Diurnal variation of hourly average concentrations</td>
<td>Number of hourly average concentrations exceeding 0.05, 0.10, 0.15 ppm</td>
</tr>
<tr>
<td>Frequency distribution of hourly average concentrations</td>
<td>Cumulative dose (ppm-h) greater than 0.10 ppm-h</td>
</tr>
</tbody>
</table>


The seasonal seven-hour mean statistic combines a large number of ozone concentration observations. However, it should be noted that:

There is no consensus on an exposure statistic(s) that will best relate to the potential response of plants to varying $O_3$ concentrations over a growing season. It is generally accepted that the degree of plant response is affected more by differences in concentration than by differences in duration of exposure. Thus a given seasonal mean concentration that includes many high $O_3$ concentrations could cause greater effects than would the same mean that includes few high $O_3$ concentrations. This hypothesis is untested for $O_3$. Possibly no single exposure statistic will be adequate for all crops under all environmental conditions.

The implication is that high ozone concentrations may be lost in the statistic but could be an important explanation of crop loss which should not go unobserved. Thus NCLAN has also discussed the use of alternative exposure statistics such as the peak (maximum) daily seven-hour mean ozone concentration occurring during the growing season; the seasonal mean of the daily maximum one hour mean ozone concentrations; and the peak (maximum) one hour mean
ozone concentration occurring during the season.\textsuperscript{77}

The measure of dose used must be compatible with ambient air quality data to enable the development of useful predictive models.\textsuperscript{78} In Canada, the annual one hour peak ozone concentration is used to set ozone standards, whose primary concern is with the threshold for acute damage to human health.\textsuperscript{79} In order to use a different exposure statistic for a standard and a response model, the distribution of ozone in the ambient air needs to provide a basis for using one statistic as a surrogate for another.\textsuperscript{80} For example, assume a seasonal average concentration is discovered at which there is no crop loss, and this seasonal average is never exceeded when a certain hourly peak ozone concentration is not exceeded. Under these circumstances it is reasonable to assume crops are protected when the hourly peak is not exceeded.\textsuperscript{81} Unfortunately, the seasonal mean can vary widely while the peak value remains constant, and is unlikely to always remain at or below a certain value. The implication for ozone standards is that they should employ concentration measures which relate to chronic, as well as acute, damage.

\subsection*{2.5.2 Methodologies for Deriving Dose-Response Functions}

Three main approaches have been employed to derive dose-response relationships for ozone ---foliar injury models, secondary data and experimentation.
(a) **Foliar Injury Models**

Early studies assumed a threshold below which no damage was presumed to occur and related this to visible, normally foliar, injury. These foliar injury models can be misleading as signs of yield loss because tubers, roots, and dry weight, among other factors, can be affected without visible damage. Conversely, foliar injury may overestimate damage because some plants can suffer severe leaf damage without loss of photosynthetic ability, and recovery from visible injury can be quick. Generally, three types of response to air pollution can be defined; visible injury symptoms, growth responses, and quality changes. Foliar injury models ignore "hidden injury", which may occur with the latter two responses.

Hidden injury may include: (1) reduced photosynthetic activity, (2) accumulation of a pollutant or its byproducts within a leaf, (3) an overall unhealthy appearance without necrotic lesions, (4) reduced growth or yield, and (5) increased susceptibility to disease, particularly insect invasion.

Recent studies with soybeans, tomatoes, annual ryegrass, spinach, wheat, lettuce and potatoes have demonstrated that foliar-symptom production is not a reliable index of ozone effects on plant growth or yield.

(b) **Secondary Response Data**

This technique has been employed in two recent studies of regional economic crop losses from ozone. Cross sectional analysis of crop yield data is used to obtain dose-response functions via regression techniques. This requires information on the existing outdoor variations in air pollution and actual crop yields, and other environmental factors. This approach can save
time and money compared to the chamber study approach. 88

Leung et al. (1982) obtained statistically significant results for nine crops using this technique, but the results were not always consistent with experimental chamber studies, and ozone levels in the study region were high. 89 Rowe and Chestnut (1985) attempted to derive dose-response functions for ten crops but could only obtain significant results for four of these. 90 They found the success of the approach was generally dependent upon the effort made to measure and incorporate non-air pollution variables in the yield functions. Generally, their results suggested that ozone was causing yield losses but the secondary data regression approach only captured the effects for the most sensitive crops; i.e., those which experienced high rates of damages at low ozone levels such as dry beans, cotton, grapes and potatoes.

Rowe and Chestnut used their results in comparison with other similar studies to define the conditions under which the secondary data regression approach might be most appropriately employed.

The approach has the most chance of being successful when there are high O_3 levels in the study area, for example regular exposures of 72 pphm (0.12 ppm) and higher, so that there may exist significant O_3 induced damage to detect; when crops known to be "very sensitive" are being studied in moderately high O_3 environments; or as a relatively inexpensive means to identify potentially sensitive crops to be more carefully examined with chamber studies.
(c) **Experimentation**

Several experimental approaches have been developed in studies of ozone effects on crops; these include the use of greenhouses, field chambers (open-top or close-top), unenclosed field plots and the pollution gradient approach. Each approach varies in the design of the exposure system, but for use in economic assessments, the environmental and exposure conditions occurring on actual farms should be replicated, with only air pollution concentration being modified. While general responses to ozone of plants grown in different environments may be similar, the quantitative relationships between dose and response are clearly affected by environmental conditions.

The different experimental designs may affect the environment, and so plant response to air pollutants. Plant response may vary with differences in:

1. wind conditions: speed, variability;
2. ozone flux;
3. plant density; and
4. other environmental conditions.

Crops grown in the field may experience wide fluctuations in temperature, wind conditions, rain, and crowding which are not imposed on experimental plants. In particular, air flow alterations can be important to pollutant uptake.

Open-top field chambers have been the method preferred by NCLAN because they closely simulate actual field conditions, only affecting air flow. Closed-top chambers affect air flow and precipitation, and greenhouses affect the total environment. Thus, all these approaches suffer in varying degrees from
"chamber effects", with field-grown plants showing different susceptibilities to pollutant injury. An alternative approach is the use of unenclosed field plots such as zonal air-pollution systems (ZAPS). ZAPS expose plants by releasing gaseous pollutants from a perforated pipe manifold supported above or within the vegetation, and thus supplementing ambient ozone concentrations. Problems with this approach include adequately describing the air quality achieved and uncertainty as to the distribution and mixing of released gases.

The pollution gradient approach was employed by Oshima et al. to develop a dose-response function for ozone damage to alfalfa in Southern California. An area source of ozone supplies the exposure dose with standardised field plots being set up downwind. This method also has problems, similar to the secondary data approach, particularly with regard to the effects of uncontrolled variables upon response.

2.5.3 The Research Programme of the NCLAN

A major source of experimentally derived ozone dose-response information in recent years has been the United States National Crop Loss Assessment Network (NCLAN) run under the Environmental Protection Agency. The primary objectives of NCLAN are to define the relationship between yields of major agricultural crops and ozone exposure; to assess the national economic consequences resulting from the exposure of agricultural crops to ozone; and to advance the understanding of the cause and effect relationships that determine crop responses to pollutant
exposure. Although originally other air pollutants were to be studied, the main focus has been on ozone because alone, or in combination with sulphur dioxide and nitrogen, ozone is the main cause of crop losses in the United States due to air pollution.

The NCLAN open-top chambers attempt to simulate actual farm input conditions, because farmers are more likely to set variable inputs at levels which minimize the cost of producing a given output, rather than providing plants with optimal conditions. The NCLAN has several experimental sites, namely in New York, North Carolina, Maryland, Illinois, California, and Oregon. The sites were selected on the basis of differing climatic conditions, distribution of crop species and the existence of established research groups. Maintaining sites in major U.S. crop growing regions means environmental factors will be similar to those on the actual farms producing the main U.S. cash crops, which should facilitate the accuracy of economic crop loss assessments.

NCLAN has conducted multi-year studies at the regional sites deriving dose-response functions for corn, soybean, kidney bean, peanut, lettuce, turnip, winter wheat, tomato, barley, clover/fescue, tobacco, red clover/timothy, cotton and alfalfa. The results of the seven year research programme provide the most comprehensive review yet of the effects of ozone on major agricultural crops.
2.5.4 Characteristics of Response Functions Applied in Economic Crop Loss Assessments

Response functions derived from each of the methodologies reviewed above have been applied in economic assessments of air pollution damage to agricultural crops. Early work in this area depended upon trained field observers to use their judgement to estimate crop damage from visible symptoms. These subjective estimates (often arbitrarily converted into monetary values) were replaced by foliar injury models. In turn, foliar injury models have been found deficient in several aspects and response functions derived from scientific field experimentation are now commonly applied in economic assessments.

Economic assessments of ozone in the U.S. have in recent years concentrated on the use of response functions derived from field experiments. As Table 11 shows, ten out of fifteen studies since 1982 have relied upon NCLAN response data as their main source. All six studies recently carried out at the national level (for the United States) have used the NCLAN data. At the regional level a mixture of data sources is often used. For example, the two studies using secondary data, discussed above, also make use of experimental data for some crops. NCLAN data is a primary source of response information but has so far been restricted to major U.S. agricultural crops. Thus the research of other scientists is employed for important regional crops.
Table 11. Main Source(s) of Response Functions Used in 15 Recent Economic Studies of Ozone Effects on Agriculture

<table>
<thead>
<tr>
<th>Source of Dose-Response Data</th>
<th>Number of Publications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimentation: NCLAN</td>
<td>10</td>
</tr>
<tr>
<td>Other</td>
<td>3</td>
</tr>
<tr>
<td>Secondary</td>
<td>2</td>
</tr>
<tr>
<td>Foliar Injury</td>
<td>1</td>
</tr>
<tr>
<td>Field Observation</td>
<td>0</td>
</tr>
</tbody>
</table>

While the derivation of response functions used in economic assessments has improved, the application of the functions has sometimes been both technically and economically deficient (the economic issues are fully discussed in Chapter 3). Serious errors can arise from extrapolating from a limited data base. For example, the Organisation for Economic Cooperation and Development (OECD) performed a cost-benefit analysis of sulphur oxide which included the benefits expected from crop loss reductions under various scenarios. A dose-yield relationship was developed from information on the response to sulphur dioxide of rye grass (Lolium perenne), and applied to all crops throughout Europe. Major criticisms of this study included:

1. Ignoring crop and cultivar sensitivities: rye grass being one of the most sensitive crops to sulphur dioxide, resulting in overestimation of damages;

2. Ignoring differences in soil sulphur content: the rye grass studies used gave the plant nutritionally adequate supplies, again leading to overestimation of damage, because nutrient deficient soils actually benefit from sulphur deposition.

3. Overestimation was created by extended extrapolation beyond
plant threshold and background pollutant levels, thus creating the illusion of damages when they would not occur or would be irrelevant to the control of anthropogenic sources;

4. The research into rye grass used was mostly from laboratory or greenhouse experiments. This can give results widely varying from plant response to sulphur oxide under field conditions.¹¹¹

This kind of extrapolation and use of response functions ignores the limits of the data base. The application of one set of results to other crops, cultivars, regions and countries ignores variations in plant sensitivity and environmental conditions. However, this does not mean certain extrapolation is not justified. In the case of ozone, data are not available for many regionally important crops and cultivars, and so far, experimental results are largely derived for the major crop growing regions of the United States. In the absence of alternative data, "surrogate" response functions have been used for crops judged to be of similar sensitivity. For example, Howitt, Gossard and Adams studied the economic effects of ozone on thirteen crops.¹¹² They used NCLAN data for seven crops and derived five "surrogate" response functions. Such use of response data relies upon the judgement of researchers, and implicitly involves the subjective estimation of uncertainty.¹¹³ This type of probabilistic estimation requires explicit explanation of the areas of uncertainty so that the accuracy of, and possible bias in, the final results are clear.
2.5.5 Economically Important Response Characteristics

In performing an economic assessment of crop loss the response changes of interest are those related to both the costs of production and the marketability of a product. That is, there are two routes via which pollution-induced crop damage can influence the welfare of consumers and producers. First, a reduction in crop damage, expressed as an increase in yield, which will reduce costs and therefore reduce the minimum price the producer must receive to supply a given quantity. Secondly, altered levels of air pollution may affect the attributes of a crop, thus changing the consumers' willingness to pay and the welfare derived from the consumption of a given quantity of a crop. The change in cost implies a supply response, while the change in quality a demand response.

Recent studies conducted on ozone crop damage have tended to concentrate upon yield, and therefore are only relevant to the supply response. Research upon the potential crop quality changes has apparently not been emphasised. Yet, there is evidence that such quality changes result from ozone pollution. Examples of quality changes which have been found are shrivelling in kernels of corn, reduction in the size of tomatoes, and alterations in chemical composition that affect cooking quality of potatoes and nutritional values of alfalfa. Table 12 clearly shows that there is a wide range of possible crop responses to ozone. Research is required to estimate the importance of these responses. This may be a difficult problem to resolve where consumer tastes are concerned, requiring objective
characteristics to be associated with economic values in order to allow the derivation of dose-response functions appropriate for economic benefit assessments. However, without work in this area economic assessments cannot be made of the full range of possible economic impacts.

Table 12. Processes and Characteristics of Crop Plants that may be Affected by Ozone

<table>
<thead>
<tr>
<th>Growth Rate</th>
<th>Development</th>
<th>Yield</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flowering</td>
<td>Number</td>
<td>Appearance: size, shape, colour</td>
<td></td>
</tr>
<tr>
<td>Branching</td>
<td>Mass</td>
<td>Storage life</td>
<td></td>
</tr>
<tr>
<td>Fruit set</td>
<td></td>
<td>Texture and cooking quality</td>
<td></td>
</tr>
<tr>
<td>and development</td>
<td></td>
<td>Nutrient content</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Viability of seeds</td>
<td></td>
</tr>
</tbody>
</table>

2.6 Conclusion

The dose which a particular target crop will receive in a given growing season is a function of precursor emission levels, and meteorological, climatological and topographical factors. In the Lower Mainland high levels of precursor emissions are directed towards important agricultural areas due to restricted atmospheric dispersion within the Fraser Valley. When certain meteorological conditions prevail, high ozone concentrations may result. The highest ozone levels occur during the spring and summer months coinciding with the growing season for many agricultural crops. Comparison of the ambient ozone dose at rural sites in the Lower Mainland with response information from California shows the potential for sensitive varieties of potato to suffer tuber weight reductions of up to 16.5 percent in certain years.

Crop damage is a function of the ozone dose, crop species and cultivar, and biological, climatic, edaphic, production and other factors. The interaction of these variables makes accurate crop loss assessment, especially over large areas, an error prone task. Results from field experiments, especially those of NCLAN, have increased the accuracy with which the economic consequences of plant damage caused by ozone can be estimated. Where crop or region specific information is lacking, qualified approximations to actual response can be made using surrogate functions. Finally, current economic assessments of crop loss from ozone are restricted by a lack of information as to the importance crop quality responses, and must therefore concentrate upon supply response alone.
Footnotes


3 Ibid.

4 Howard E. Heggestad, and Jesse H. Bennett, "Impact of Atmospheric Pollution on Agriculture" in Michael Treshow (ed.) Air Pollution and Plant Life (Chichester: John Wiley and Sons, 1984) p. 357.

5 Walter W. Heck et al., "Assessment of Crop Loss from Ozone" Journal of Air Pollution Control Association Vol. 32 No. 4 p. 353 (April, 1982).

6 Another ozone problem was discovered in the late 1970's; namely, ozone depletion in the stratosphere (the upper layer of the atmosphere approximately six miles above earth's surface) which threatens to increase ultra-violet radiation to lethal proportions [6]. Stratospheric ozone is not of concern here beyond the contribution it makes to natural background ozone concentrations in the troposphere. The discovery of this problem is fully discussed in L. Dotto, and H. Schiff, The Ozone War, (New York: Doubleday & Co., 1978)


10 Ibid.

11 Ibid.

12 Oke, Boundary Layer Climates p. 272.

13 Benkowitz, "Characteristics of Oxidant Precursors".

15 Heggestad and Bennett, "Impact of Atmospheric Pollution on Agriculture" p.360.


17 Ibid

18 Wilson et al., Assessment of Oxidants in the Lower Mainland, p.7.

19 The seasonal seven hour mean and other exposure statistics are discussed in section 2.5.1(b); also see, Heck et al., "Assessing Impacts of Ozone on Agricultural Crops: I" p.731.


21 Oke, Boundary Layer Climates p.272.

22 Ibid.

23 Benkowitz, "Characteristics of Oxidant Precursors".

24 Ibid.


28 Ibid; see also, Wilson et al., Assessment of Oxidants in the Lower Mainland, p.7


30 Oke, Boundary Layer Climates p.283.

31 Ibid.

59
32 Ibid.
33 Ibid pp.297-298.
34 Oke, *Boundary Layer Climates* p.298; and Whitten "The Chemistry of Smog Formation".
35 Oke, *Boundary Layer Climates* pp.298-300.
36 Ibid p.280.
39 Ibid.
40 For a full discussion on the various types of inversion see Oke, *Boundary Layer Climates* pp.274-278.
41 Ibid.
42 Hay and Oke, *The Climate of Vancouver* p.41.
43 Oke, *Boundary Layer Climates* p.298.
46 William H. Smith, "Pollution Uptake by Plants" in Michael Treshow (ed.) *Air Pollution and Plant Life* (Chichester: John Wiley and Sons Ltd., 1984).
48 Smith,"Pollutant Uptake by Plants" p.428.
49 Ibid.
50 Ibid.
52 Ibid p.53.
53 Hay and Oke, *The Climate of Vancouver*.

54 Ibid, pp.44-45.

55 Ibid.

56 Canada, Environmental Protection Service, *Vancouver Oxidant Study*.


58 The stations at Langley and Pitt Meadows were set up in 1982 and 1985 respectively. The one at Richmond was set up in 1986.

59 The National Air Quality Standards are given in micrograms/cubic meter, and discrepancies may arise when converting to ppb. The maximum acceptable level for ozone is 160 micro-grams/cubic meter for one hour, and this is normally taken as equivalent to 80 ppb. Telephone conversation with E.P. Witushek, Manager Air Programmes, E.P.S. Pacific Region, 9th July 1986.


61 Canada, Environmental Protection Service, *Vancouver Oxidant Study* p.108.

62 Canada, Environmental Protection Service, *Vancouver Oxidant Study*, p.1. Note maximum acceptable standard is given as 82 ppb, see footnote 62 above.

63 Information on the monitoring stations and air quality in the Lower Mainland was obtained on magnetic tape from Al, J. Percival, Monitoring Supervisor, Pollution Control, Engineering and Operations Department, GVRD.

64 California, Department of Food and Agriculture. *Air Pollution Manual* (1986).


66 Holdgate, *Environmental Pollution*, p.130


68 Ibid.

70 Jacobson, "Ozone and Agricultural Crops", p.298.


74 Ibid.


76 Ibid.

77 Ibid.

78 Heck, "Measuring the Acute Dose-Response of Plants to Ozone".


81 Ibid.

82 Medeiros and Moscowitz, "Quatifying Effects of Oxidant Pollutants on Crops"


84 Ibid, p.31.


88 Rowe and Chestnut, "Economic Assessment of the Effects of Air Pollution on Agricultural Crops in the San Joaquin Valley" p.729.

89 Leung et al., "Economic Assessment of the Effects of Air Pollution on Agricultural Crops in Southern California".

90 Rowe and Chestnut, "Economic Assessment of the Effects of Air Pollution on Agricultural Crops in the San Joaquin Valley".

91 Ibid, p.731.


94 Ibid.

95 Unsworth, "Exposure to Gaseous Pollutants".

96 Heck et al., "Assessment of Crop Loss from Ozone".

97 Martha Smith and Deborah Brown, Crop Production Benefits From Ozone Reduction: An Economic Analysis, (Indiana: Agricultural Experimentation Station, Purdue University, 1982) Station Bulletin No.388, p.2.


100 Ibid.


107 Heck et al., "Assessment of Crop Loss from Ozone".


109 The regional assessment of the economic effects of ozone on agriculture is discussed in Chapter 5.


115 Jacobson, "Ozone and Agricultural Crops".
CHAPTER III

METHODOLOGIES AND APPLICATIONS IN THE REGIONAL ECONOMIC ASSESSMENT OF OZONE EFFECTS ON AGRICULTURAL CROPS

3.1 Introduction

The problem of measuring and interpreting the benefits to society from air pollution reduction is given a consistent conceptual framework by applied welfare economics. Most economic assessments of policy issues now measure benefits in terms of the economic surplus accruing to consumers and producers,\(^1\) a stance which is supported by recent literature.\(^2\) This literature and the theoretical issues surrounding the development of consumer and producer surpluses as measures of welfare are discussed in Appendix I and II. The correct generation and use of economic surplus information requires some understanding of the behavioural assumptions of individual decision makers, e.g., farmers and consumers. Detailed coverage of these issues can be found in the intermediate/advanced economics literature.\(^3\)

The economists' production function is a concept somewhat analogous to the biologists' dose-response function, and has traditionally been used by agricultural and resource economists to assess farm level decision problems.\(^4\) A change in pollution
levels alters the elements in, and form of, the set of alternatives which bound production choices and so affect the decisions of the firm in the pursuit of maximum profits. The assessment of the benefits resulting from such a change requires the analysis of biological processes, technical possibilities, their interactions with producer decisions, and the effect of resulting production changes on consumer welfare.

Biological or production response data provide a link between pollutant dose and the performance parameters of a crop system. The response relationship, as discussed in Chapter 2, may be quantified directly from biological experimentation, indirectly from observed producer output and behavioural data (secondary data), or from some combination of data sources. Procedures based upon producer data, for example production or cost functions, are preferable from the viewpoint of economic analysis. Cost and production functions have been applied in the regional assessment of crop losses from ozone, but data and statistical difficulties have prevented their use across large geographical areas. At present, dose-response functions are commonly applied in economic assessments of environmental stress to agriculture.

Agricultural production is affected by inputs from the natural system outside the farmer's control and typically results in multiple outputs from a single firm. Ozone is only one element in the set of potentially important variables affecting agricultural production processes. Figure 9 illustrates the types of choices, regarding technology and output mix, facing the profit maximizing crop farmer. The quality of the soil and the type of climate define the feasibility constraints for crop
Figure 9. Representation of Agricultural Crop Producing Activities

Nature's Inputs
Sunlight, length of growing season, precipitation, ground water, and other climatic factors (e.g., wind)

Factor Inputs and Prices

<table>
<thead>
<tr>
<th>Nature's Inputs</th>
<th>Sunlight, length of growing season, precipitation, ground water, and other climatic factors (e.g., wind)</th>
</tr>
</thead>
</table>

Crop Production Operations

<table>
<thead>
<tr>
<th>Unit Operations/Other Production Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Crop Mix, e.g., field corn, barley, vegetables.</td>
</tr>
<tr>
<td>2. Crop Rotation Pattern and Schedule, e.g., continuous corn, corn-corn-alfalfa-corn.</td>
</tr>
<tr>
<td>3. Tillage Method, e.g., minimum tillage, no tillage, shallow plow, harrow, disk.</td>
</tr>
<tr>
<td>4. Plowing Practices, e.g., contouring, grading rows, ridge planting.</td>
</tr>
<tr>
<td>5. Fertilization Practices --- mix of fertilizers; application rates, methods, and schedules.</td>
</tr>
<tr>
<td>7. Irrigation Methods/Systems, if any, e.g., sprinklers, line canals.</td>
</tr>
<tr>
<td>9. On-site Crop Processing, e.g., washing and packaging.</td>
</tr>
<tr>
<td>10. Other.</td>
</tr>
</tbody>
</table>

Product Output

<table>
<thead>
<tr>
<th>Crops Harvested</th>
<th>Product Outputs either:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field Corn for all purposes e.g., for grain for silage.</td>
<td></td>
</tr>
<tr>
<td>Soybeans for all purposes e.g., seed grain, silage.</td>
<td></td>
</tr>
<tr>
<td>Wheat for grain e.g., canning</td>
<td></td>
</tr>
<tr>
<td>Other small vegetable, oil grains</td>
<td></td>
</tr>
<tr>
<td>Hay</td>
<td></td>
</tr>
<tr>
<td>Peanuts</td>
<td></td>
</tr>
<tr>
<td>Tobacco</td>
<td></td>
</tr>
<tr>
<td>Potatoes</td>
<td></td>
</tr>
<tr>
<td>Vegetables</td>
<td></td>
</tr>
<tr>
<td>Orchard Crops</td>
<td></td>
</tr>
<tr>
<td>Greenhouse products</td>
<td></td>
</tr>
<tr>
<td>Other Crops</td>
<td></td>
</tr>
</tbody>
</table>

growing, and given these constraints, the farmer selects the input sets, crop mixes and rotation patterns that, based upon factor prices and output market values, maximize profits. Air pollution concentrations can be an important variable in this decision making process.

The individual's decision problem is to modify his or her choices so as to maximize the gains from pollution reductions and to minimize losses from pollution increases. The complete economic concept of pollution control benefits embodies the physical and biological changes in the receptors of interest (crops, buildings, human health), as well as the adaptive responses of individuals and institutions (including markets) to these changes.

In addition to the direct economic impacts of air pollution on producers and consumers, indirect impacts can also be important. Indirect impacts are those changes induced by alterations in the pollutant-affected product which occur in other markets and sectors of the economy, e.g., the disruption of livestock production as a result of ozone damage to forage crops. A comprehensive economic model would include all such indirect welfare changes in the assessment of benefits.
3.2 Methodologies for the Valuation of Agricultural Crop Yield Changes: With Reference to Air Pollution

Various methods have been applied to the valuation of the benefits from the reduction of crop losses. Three main categories can be defined; namely, traditional type models, optimization models and econometric models.

3.2.1 The Traditional Model

The "traditional" type model is a simple method of approximating a monetary value for crop yield changes. The model has various names in the literature, --- the historical approach, the naive model, the biologist's approach, and the ad hoc approach. Until the late 1970s the traditional model was the most prevalent type of crop loss assessment reporting dollar losses. The model multiplies estimates of a physical crop change, based on current acreage in production, by the current price of the crop. This implies a simple response assumption that resource use and prices, and thus consumer surplus, do not change.

In regional crop loss assessments, assuming the market price will not be affected by yield increases may be particularly tempting because the size of the increase is assumed to be small relative to the national market. However, this can cause serious errors in benefit estimates where the crop in question is regionally concentrated in production; for example, a substantial increase in corn yield in the Corn Belt area of the United States could not realistically be assumed to leave prices unaltered. Unlike other methodologies, the traditional model cannot drop the constant price assumption, cannot measure changes in consumer
surplus and thus ignores distributional impacts.

Despite this, Kopp et al. (1984) have claimed that the approach of the traditional model "... may be justified as a first order approximation to the change in consumers' surplus arising from a policy change, and is hence not totally devoid of economic content." However, studies comparing the traditional model and more comprehensive techniques have found the former to overestimate benefits by 20-100 percent. Since the traditional model can only measure quasi-rent (see Appendix II for definition), not consumer surplus, the difference is even more dramatic. When considering only producer effects, the estimates of the traditional procedure are up to four times greater than other economic techniques. As Adams et al. (1982) state,

The comparison between the traditional and the more comprehensive approach reported here suggests a substantial divergence in estimates. Further, shifts in cropping patterns within and across regions, as well as distributional effects of environmental degradation, seem likely to be of considerable interest to policy makers. The traditional analysis is incapable of capturing them.

The advantage of the traditional model is that the informational requirements are relatively modest, allowing a quantitative measure of damages to be calculated quickly and inexpensively. Yet, the results from, and the procedure of, the model are largely discounted by economists as being an unrealistic abstraction that ignores well documented price effects and is incapable of addressing distributional consequences. As Adams and McCarl (1985) have stated, "... one should resist the temptation to resort to such simple minded models in future assessments for the sake of expediency".
3.2.2 Optimization Models

There are two types of optimization model — Linear Programming (L.P.) models and Quadratic Programming (Q.P.) models. They require extensive data sets and are normally established as computer programmes due to their complexity. Both L.P. and Q.P. are similar in their approach. They both require an objective function capable of being maximized, or minimized; alternative methods or processes for obtaining the objective; and resource and other constraints. They describe the world as it should be given certain assumptions; that is, they are normative models.

The L.P. model can be set up as cost minimizing or profit maximizing. In the former case, the cost minimizing set of production activities is selected to produce specific goods given constraints on critical inputs (e.g., land). The basic assumptions of the L.P. model are:

1. Linear production relationships; i.e., constant input-output coefficients.
2. Linear relationships are inequalities; a productive activity can use less than or equal to, but not more than the amounts of resources available.
3. Linear objective function.
4. Specification of process relationships; as opposed to estimation in an econometric model.
5. Additivity.
6. Perfect divisibility of inputs and outputs.
7. Finiteness; there is a limit to the number of alternative activities and resource restrictions that can be allowed.
8. Single-value expectations; i.e., certainty.
In L.P., biological dose-response functions can be used to alter the quantity of output produced for the set of inputs required for each production activity, and so can mimic the effect of varying air pollution (e.g., ozone) concentrations. Both L.P. and Q.P. assume an infinitely elastic supply curve for variable inputs and constant returns to scale. The quantity demanded is exogeneously fixed when cost minimization is the objective of L.P., and price is exogeneously fixed when profit maximization is the objective. In Q.P. price and quantities are endogeneously determined. This forms the main difference between the two models.

Optimization models can give details on benefit distribution and model the complex interrelationships of an economy, allowing indirect effects to be considered. However, if discrepancies arise between the model solutions and reality, it is never certain if they are a result of incorrect or inaccurate modelling of production activities, improper constraints, or just the fact that the real world operates suboptimally due to market interference or distortions. Optimization models are generally poor predictive tools, but can be improved in this respect by recursive programming.

3.2.3 Econometric Models

In contrast, to the normative optimization models, econometric models, by the very nature of the data base used to develop them, reflect historical reality over space and time. This is not to deny that ideological bias creeps into the very selection of questions investigated, or the inferences drawn from
factual evidence. These matters do not prevent applied work from being normative in the sense that the results can be rigorously examined using accepted scientific and statistical methods.24

Econometric models cannot capture the effects of new technologies developed outside of the time (or space) span of the data; nor can they estimate the effect on production of institutional rearrangements which are not translated into changes in market prices.25 The institutional setting is taken as given. Three categories of econometric model for assessing crop loss from air pollution can be defined, namely, Aggregate supply/demand models, Microtheoretic supply/demand models, and Neoclassical econometric production, cost, or profit function models.

Aggregate supply/demand models require little in the way of theory, except for some general specification of the variables affecting price and a conceptualization of the aggregate system as either simultaneous or recursive in the estimation step.26 The model may be recursive in that each equation of the system can be solved in turn because they have an ordering in time and the solved value can enter the next equation as a predetermined variable. For example, a farmer may use current production methods and crop mixes to help determine next year's production; that is, production is determined first and then prices are determined; the model is not simultaneous.27

Microtheoretic supply/demand models specify an objective function for the firm, under perfectly competitive conditions, which is then estimated empirically. This Neoclassical theoretic
basis requires that microtheoretic approaches strictly adhere to economic theory. Microtheoretic approaches capture both the physical engineering aspects of production and the behavioural aspects of producers. The parameters of the model can be made functions of pollution concentrations so that changes in those concentrations are reflected by changes in the parameters and shifts in the supply function. The Microtheoretic approach has the ability to incorporate biological information, or to estimate the parameters of biological functions directly from observed producer behaviour; in the latter case the approach becomes a Neoclassical econometric model. Since the economic model presented in Chapter 4 is of the general microtheoretic category, a more detailed discussion follows. Table 13 summarises the main characteristics of each of the methodologies which have been discussed.
<table>
<thead>
<tr>
<th>Methodologies for the Economic Evaluation of Crop Loss</th>
<th>Normative or Positive Model</th>
<th>Economic Theory of the Firm</th>
<th>Biological Dose-Response Functions</th>
<th>Output Demand Conditions</th>
<th>Benefit Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Traditional Model</td>
<td>?</td>
<td>None</td>
<td>Required as initial condition</td>
<td>Exogenously fixed prices</td>
<td>Producer surplus</td>
</tr>
<tr>
<td>2 Optimization Models</td>
<td>(A) Linear Programming</td>
<td>Normative</td>
<td>Cost min. or profit max. subject to constraints</td>
<td>Exogenously fixed quantities (cost min.) or prices (profit max.)</td>
<td>Net producer and consumer surplus</td>
</tr>
<tr>
<td></td>
<td>(B) Quadratic Programming</td>
<td>Normative</td>
<td>Net social benefit max. subject to constraints</td>
<td>Endogenously determined price/quantity surplus</td>
<td>Net producer and consumer surplus</td>
</tr>
<tr>
<td>3 Econometric Models</td>
<td>(A) Aggregate Supply/Demand Duality Models</td>
<td>Positive</td>
<td>Some recognition of symmetry conditions on cross price terms</td>
<td>Endogenously determined price/quantity surplus</td>
<td>Net producer and consumer surplus</td>
</tr>
<tr>
<td></td>
<td>(B) Microtheoretic Supply/Demand</td>
<td>Positive</td>
<td>Fully consistent with optimization theory via duality theorems</td>
<td>Endogenously determined price/quantity surplus</td>
<td>Net producer and consumer surplus</td>
</tr>
<tr>
<td></td>
<td>(C) Neoclassical Econometric (Production, Cost or Profit Function)</td>
<td>Positive</td>
<td>Fully consistent with optimization theory via duality theorems</td>
<td>Not required reflected in producer choices</td>
<td>Endogenously determined price/quantity surplus</td>
</tr>
</tbody>
</table>

3.3 Microtheoretic Approaches to Modelling Agricultural Production Decisions

3.3.1 Duality Models and Environmental Changes

Several methodologies exist for the estimation of production technologies and the derivation of supply curves. In recent years the primal approach has been criticised as too restrictive, requiring the prior specification of the production technology, and the dual approach has offered an alternative which avoids many of the estimation problems of the former. Assume the production unit is a firm which employs \( n \) input factors to produce \( m \) outputs, given a specific technology, which specifies the physical transformation of inputs into outputs, i.e., a production function. The primal technology set (PT) is of fundamental importance since any physical effects upon production, attributable to an environmental variable (e.g., air pollution) must impact production through an alteration in the technology set.

The production function picks out the maximum outputs as a function of inputs while the transformation function picks out the maximum net output vector. The transformation function \( T \) can serve as a measure of technical inefficiency. Given a transformation function \( T \) which meets certain conditions, PT may be defined in terms of \( T \). In this way a duality exists between the technology set and the transformation function. This duality insures that any impact realized upon the technology set PT due to the effect of an environmental set of variables will be mirrored in the transformation function. In addition, the production possibilities of a firm facing a multiple output
technology can be fully described by a transformation function. Two dual approaches to production which have been applied to agricultural crops are the profit function and the cost function.

3.3.2 Duality Models Applied to Agricultural Crop Production

(a) Profit Functions

The profit function of the firm gives the maximum profits as a function of prices for inputs and outputs of the firm. The analysis assumes firms act according to certain decision rules, including profit maximization given the price regime for outputs and variable inputs, and the quantities of fixed inputs. In the short run the profit function is restricted in that the quantities of some inputs are fixed. Every concave production function has a dual which is a convex profit function, and vice versa. The firm's supply function and input demand functions can be derived without reference to the production function. Thus, the behaviour of a profit maximizing, price-taking firm can be analysed by considering the profit function alone, without any explicit specification of the corresponding production function.

Table 14 summarises the main features of some recent profit function studies applied to agriculture. A variety of flexible functional forms have been employed to specify the profit function in agricultural studies --- Cobb-Douglas, Translog and Generalized Leontief. (Any equation that gives a second-order Taylor's approximation to an arbitrary functional form is termed flexible.) The earlier studies which employed the Cobb-Douglas
Table 14. Applications of the Profit Function in Agricultural Economics

<table>
<thead>
<tr>
<th>Author(s)/Year</th>
<th>Country/Region</th>
<th>Functional Form</th>
<th>Input Factors</th>
<th>Fixed</th>
<th>Output(s)</th>
<th>Data</th>
<th>Returns to Scale</th>
<th>Comments</th>
</tr>
</thead>
</table>
specification have since been criticised. Chand and Kaul (1986) have outlined some of the reasons for criticism and "... suggest caution in the use of some of the results quoted by the studies conducted by Lau and Yotopolous, Sidhu, and others."  

Sidhu and Bannante used the Translog formulation in their 1981 study and found it preferable to their earlier use of the Cobb-Douglas. The translog may under certain conditions collapse to the Cobb-Douglas specification and can thus be used to test for the type of technology underlying the production process. A major advantage of the translog is that behavioural assumptions such as profit maximization can be tested. In comparison with both the Cobb-Douglas and the Generalized Leontief formulations, the translog has been found to be the most reliable.  

The earlier profit function studies assumed only one output, and therefore implicitly assumed nonjointness. A nonjoint commodity is produced by a decision process separate from the decisions about other commodities, and the supply of the nonjoint product can be studied without regard to other product prices. As Shumway (1983) has shown, nonjointness can be tested for using the translog specification.  

More recent studies have looked at multioutput firms and increased the number of variable inputs included, from one to five or more. Table 14 does not show all the input groups of all the studies but only the main categories, e.g., labour may be split into family and hired labour. All the profit function studies are restricted (i.e., short run) except for that by Lopez (1984). Common variable inputs include labour, machinery and
fertilizer, and the main fixed input is land. Many of the profit function studies have been carried out using a cross-sectional data base. The studies using cross-sectional data have recently been criticised, with only Flinn et al. (1982), of the pre-1984 studies avoiding most of the problems.

(b) Cost Functions

A variant of the restricted profit function is the cost function. Production is characterized as a cost minimizing process in which the firm chooses the optimal quantities of variable factors given fixed output and factor prices. At the minimum cost a firm is both technically efficient (i.e., on the transformation function frontier) and allocatively efficient (i.e., has the correct factor intensities). The transformation function $T$, efficient input-output combinations and primal technology set $PT$, can be retrieved from the cost function. Differentiation of the cost function with respect to each output produces a set of interdependent marginal cost functions. Given the assumptions of perfect competition these marginal cost functions can be used to characterize the supply responses of individual production units and thus provide another means for benefit calculation.

Table 15 summarises some recent studies of agriculture using the cost function. As opposed to the profit function studies the translog is the main functional form used and time series information is the data base. All the studies have been performed for the long run and thus input factors are not split into fixed and variable.
### Table 15. Applications of the Cost Function in Agricultural Economics

<table>
<thead>
<tr>
<th>Author(s)/ Year</th>
<th>Country/ Region</th>
<th>Functional Form</th>
<th>Input Factors</th>
<th>Output(s)</th>
<th>Data</th>
<th>Returns to Scale</th>
<th>Comments</th>
</tr>
</thead>
</table>
3.4 A Review of Recent Regional Economic Assessments of Ozone Effects on Agricultural Crops

The majority of recent economic assessments of ozone damage to crops have been at the regional level,\textsuperscript{47} and these have employed most of the economic modelling techniques outlined above.\textsuperscript{48} The work done in this area before circa 1982 was scientifically orientated and concentrated upon the accuracy of physical estimates of ozone damage to crops. Where monetary values of damages were given, the traditional model was employed without regard for the overestimation this technique can cause.

Recent studies have concentrated on two main regions of the United States; namely, the Corn Belt (Illinois, Indiana, Iowa, Ohio, and Missouri) and California. These areas have a good supply of data on crop response and air quality, and are nationally important crop growing regions. Only one study could be found which gave an economic assessment of ozone crop damages in Canada, and this used the traditional method. In all, nine regional studies are reviewed, and the discussion is summarised in Table 16. A list of the crops covered by each study is given in Table 17.

3.4.1 A Traditional Study

Linzon et al. (1984), analysed fifteen crops in two regions of Ontario, Canada.\textsuperscript{49} Yield reductions were estimated for each crop using the experimental results of other researchers. No damage was assumed to occur at 0.03 ppm or lower (seven hour seasonal average). The traditional model was used to calculate monetary equivalents of the approximated crop losses. Increased
Table 16. Summary of Recent Regional Studies of the Economic Losses Due to Ozone Pollution

<table>
<thead>
<tr>
<th>Study Number</th>
<th>Study Authors</th>
<th>Study Date</th>
<th>Economic Model</th>
<th>Number of Crops</th>
<th>Type of Dose-Response Information</th>
<th>Benefits Estimated</th>
<th>Nature of Supply Shift</th>
<th>Inclusion of Cross-Crop Substitution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Linzon, Pearson, Donnan, Durham</td>
<td>1984</td>
<td>Traditional</td>
<td>15</td>
<td>Experimental Data (NCLAN and other)</td>
<td>Producer</td>
<td>Parallel</td>
<td>Not Included</td>
</tr>
<tr>
<td>2</td>
<td>Adams, Crocker, Thanavibulchai</td>
<td>1982</td>
<td>Quadratic Programming</td>
<td>14</td>
<td>Foliar Injury Models</td>
<td>Producer</td>
<td>Uncertain</td>
<td>Included</td>
</tr>
<tr>
<td>3</td>
<td>Howitt, Gossard, Adams</td>
<td>1984</td>
<td>Quadratic Programming</td>
<td>13</td>
<td>Experimental Data (NCLAN)</td>
<td>Producer</td>
<td>Rotation</td>
<td>Included</td>
</tr>
<tr>
<td>4</td>
<td>Rowe, Chestnut</td>
<td>1985</td>
<td>Quadratic Programming</td>
<td>16</td>
<td>Field and Experimental Data</td>
<td>Producer</td>
<td>Rotation</td>
<td>Included</td>
</tr>
<tr>
<td>5</td>
<td>Adams, McCarl</td>
<td>1985</td>
<td>Quadratic Programming</td>
<td>3</td>
<td>Experimental Data (NCLAN)</td>
<td>Producer</td>
<td>Uncertain</td>
<td>Included</td>
</tr>
<tr>
<td>6</td>
<td>Benson, Krupa, Teng, Welsch</td>
<td>1982</td>
<td>Aggregate Supply/Demand</td>
<td>4</td>
<td>Experimental Data</td>
<td>Producer</td>
<td>Parallel</td>
<td>Not Included</td>
</tr>
<tr>
<td>7</td>
<td>Leung, Reed, Geng</td>
<td>1982</td>
<td>Aggregate Supply/Demand</td>
<td>9</td>
<td>Secondary Data</td>
<td>Producer</td>
<td>Rotation</td>
<td>Not Included</td>
</tr>
<tr>
<td>8</td>
<td>Page, Arbogast, Fabian, Ciecka</td>
<td>1982</td>
<td>Aggregate Supply/Demand</td>
<td>3</td>
<td>Experimental Data</td>
<td>Producer</td>
<td>Rotation</td>
<td>Not Included</td>
</tr>
<tr>
<td>9</td>
<td>Mjelde, Adams, Dixon, Garcia</td>
<td>1984</td>
<td>Neoclassical Econometric Production Function</td>
<td>3</td>
<td>Secondary Data</td>
<td>Producer</td>
<td>Uncertain</td>
<td>Not Included</td>
</tr>
</tbody>
</table>
Table 17. Crops Included in Regional Assessments

<table>
<thead>
<tr>
<th>Frequency of Crop Occurrence in Studies</th>
<th>Crop Type</th>
<th>Regional Assessment Study (referred to by number assigned in Table 16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Wheat</td>
<td>* * * * * * * * * *</td>
</tr>
<tr>
<td>6</td>
<td>Field Corn</td>
<td>* * * * * * *</td>
</tr>
<tr>
<td>5</td>
<td>Lettuce</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>5</td>
<td>Tomatoes</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>5</td>
<td>Potatoes</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>4</td>
<td>Alfalfa</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>4</td>
<td>Soybean</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>3</td>
<td>Celery</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>3</td>
<td>Cotton</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>3</td>
<td>Onions</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>2</td>
<td>Barley</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>2</td>
<td>Beans</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>2</td>
<td>Carrots</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>2</td>
<td>Grain Sorghum</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>2</td>
<td>Grape</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Avocado</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Broccoli</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Cantaloupe</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Cauliflower</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Cucumber</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Grain Hay</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Green Bean</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Lemon</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Lima Bean</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Orange</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Rice</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Pasture</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Rutabage</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Radish</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Safflower</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Silage</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Strawberry</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Sugar Beet</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Sweet Corn</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Spinach</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>Tobacco</td>
<td>* * * * * *</td>
</tr>
<tr>
<td>1</td>
<td>White Bean</td>
<td>* * * * * *</td>
</tr>
</tbody>
</table>

| Total Number of Crops in Study | 15 | 14 | 13 | 16 | 3 | 4 | 9 | 3 | 3 |

** Means two types of same crop studied.
yields, due to pollutant reduction, were multiplied by a current producer benefit estimate. The constancy of price assumption was justified by (a) the small magnitude of crop production from the region relative to total market production, and (b) by the existence of supply management and Marketing Boards.

In Figure 10 the implicit assumptions of the traditional model are shown. A constant price level is assumed to exist at P0. The aggregate demand curve D0 is perfectly elastic (i.e., horizontal), because the quantity of the crop produced, before and after ozone concentrations are altered, is assumed to sell at the same price. The original quantity supplied is Q1 at high ozone concentrations, and shifts to Q2 when concentrations are reduced; and the respective aggregate supply curves are S0 and S1. Instead of the normal upward sloping supply curve equal to marginal cost (under perfect competition), the model assumes marginal cost is zero up to the quantity being produced and infinite thereafter; that is, supply is perfectly elastic up to Q2 and then price inelastic.

The fact that aggregate supply curves are normally positively sloped was ignored by Linzon et al., and so the disjointed function of the traditional model was implicitly accepted. As has been discussed the traditional model seems certain to grossly overestimate the gain to producers from ozone reductions. This study estimated the average gain to producers of reducing ozone from current levels (the highest regional category being 0.05 ppm, 7hr. seasonal mean) to 0.03 ppm as $15 million per annum, with a range of $9 to $23 million (1980 dollars). Five crops accounted for over 80 percent of the estimate due to their
Figure 10
The Traditional Model

sensitivity to ozone—namely, potatoes, soybeans, tobacco, wheat and white beans.

3.4.2 Quadratic Programming Approaches

Four economic regional studies of ozone crop losses published since 1982 have used the price endogeneous Q.P. approach. Three of these were based on the agricultural crop growing regions of California, and employed similar models. The fourth study generated welfare estimates via a micro-macro model, using farm models to derive the effects of regional production changes on national markets.

Adams et al. (1982) studied fourteen field crops in four regions of southern California. The dose-response functions are a major weakness of the study, being calculated from foliar injury models which have been converted to reflect yield loss (see Chapter 2). This approach showed broccoli, cantaloupes, carrots, cauliflower, and lettuce to be ozone resistant, with little or no damage occurring. Lettuce in particular seems to be incorrectly classified, with evidence existing which states it to be an ozone sensitive crop (see Chapter 1). The optimal crop mix after ozone concentrations were reduced showed a very significant decrease in the production of these air pollution tolerant crops, due to their substantially reduced profitability relative to crops that were more sensitive to ozone.

Linear inverse demand functions were assumed for each crop, i.e., price as a function of quantities. The supply functions for all production inputs were assumed to be perfectly price elastic. The Willig Approximation conditions were invoked (see Appendix I)
so that any differences between ordinary and compensated consumers' surplus was assumed to be trivial. This invocation was justified because neither income elasticities nor expenditures as a percentage of income seemed likely to be large for the crops being studied.

The model (calibrated to 1976) was set up to maximize the sum of producer and consumer surpluses. Reducing ozone levels to 0.08 ppm, the state standard, would have increased 1976 producer quasi-rents by $35.1 million and consumer surplus by $10.1 million. Production changes induced by altering ozone concentrations were assumed to leave the input mix constant. Changes in ozone concentrations from 1976 levels were reflected by changes in the optimal mix of outputs. Due to the variety of demand price elasticities across crops, the distribution of benefits was a function of the mix of demand curves and resultant crop proportions in the solution. For example, the removal of cotton from the study causes the balance between consumer and producer surpluses to be reversed. Cotton has an elastic demand curve, thus the benefits from ozone reduction are largely producer quasi-rents. The exclusion of cotton reduces the producer gain to $9 million and leaves the consumer gain almost unchanged at $10 million.

Although mitigation was allowed for by cross-crop substitution, the authors felt the use of fixed 1976 production coefficients and resource levels potentially constrained the possible producer mitigative adjustments on the input side. Thus, they warn that the subsequent programming results and welfare
effects might be overestimated, although this seems unlikely in the case of ozone as is discussed in section 3.5.1. They also suggest, among other things, that improvements could be made by allowing for non zero, cross-price elasticities, widening the scope to include effects in other regions and markets and studying a greater variety of crops.

Howitt et al. (1984) studied thirteen crops, also in the state of California. They employed the NCLAN experimental results to derive dose-response functions for seven of the crops and other experimental results for one other crop. The remaining five crops were given "surrogate" response functions. The California Agriculture Resources Model (C.A.R.M.) was used to calculate consumer and producer surplus. This Q.P. model allowed for constrained cross-crop substitution, and included twenty-seven other crops which were assumed unaffected by ozone concentrations. The model was similar to that used by Adams et al. (1982) above but was calibrated to 1978 instead of 1976.

Three ozone scenarios were compared with a base case for 1978. The total welfare gain from a reduction in ambient ozone of approximately 25 percent (to 0.04 ppm, seasonal seven-hour average) was $35.8 million per annum, and the welfare loss from an increase in ozone levels by approximately 33 percent (to 0.08 ppm, seasonal seven hour average) was $157.3 million. Reductions in ozone concentrations cause a "downward shift" of the supply function, which is shown graphically as a rotation, i.e., the price intercept does not change.

Rowe and Chestnut (1985) used the CARM, as used by Howitt et al. (1984), to study sixteen crops in the San Joaquin Valley,
California. Although thirty-three crops were included in the economic model only sixteen were judged to be affected by ozone, or could be supplied with dose-response functions. The study analysed the use of field data regression to derive dose-response functions, but only obtained statistically significant results for four crops --- dry beans, cotton, grapes and potatoes (see Chapter 2). As a result, NCLAN functions were used for six other crops, and a further six were derived from other sources and by the use of "surrogate" functions. Three ozone scenarios were studied (0.12, 0.10 and 0.08 ppm seasonal hourly maximum) and results were given for both consumers and producers. Sulphur dioxide was also included in the study, but over 98 percent of the economic value of the agricultural damages was attributed to ozone. If an ozone standard at which little or no crop damage was expected (defined as 0.08 ppm seasonal hourly maximum) had been met in 1978, the estimated gain to consumers would have been $30.3 million and the gain to producers $87.1 million.

Adams and McCarl (1985), studied three crops in the Corn Belt region of the United States, with a Q.P. model calibrated to 1980. The dose-response functions were taken from NCLAN results for 1980-1982, and were Illinois specific. The model analysed the changes occurring throughout the agricultural sector at the national level as a result of the adjustments in Corn Belt output, ceteris paribus. This was achieved by characterising regional agricultural production using twelve representative farm models. These representative farms were then used to generate supply adjustments in the national level model. Consumer and
producer surpluses were calculated under two scenarios. An improvement in air quality of 25 percent (a reduction of ozone from 0.12 ppm to 0.08 ppm one hour seasonal average) gave total benefits of $688 million (1980); a loss to producers of $1,411 million and a gain to consumers of $2,079 million. The other scenario took a 50 percent degradation in air quality (an increase in ozone from 0.12 ppm to 0.16 ppm one hour seasonal average) and gave a total loss of benefits of $2,225 million; a reduction of consumer surplus by $4,986 million and an increase of producer surplus by $2,761 million. Increases in crop supply were found to favour consumers and reductions in crop supply favoured producers. These distributional consequences are a result of supply shifts in the face of a price inelastic demand curve.

3.4.3 Econometric Approaches

Several econometric approaches have been applied to the assessment of crop damage due to ozone pollution, including a dual model which is reviewed in the next section. In this section we discuss two models which analyse producer surplus and one which one includes both producer and consumer surplus. Each model has distinctive features and makes different assumptions about the nature of agricultural crop supply curves and production responses.

Benson et al. (1982), studied four crops in Minnesota. Originally, six crops were to have been studied but dose-response functions could not be calculated for soybeans and oats, so they were dropped. Dose-response for the four remaining crops was
calculated using experimental data reported by other researchers. The dose-response functions allowed for episodic (as opposed to chronic or acute) exposure by breaking the exposure into multiple time periods over the growing season. The functions were applied to Minnesota using actual or simulated county level ozone data. This was used to derive a range of yield losses under different ozone concentrations.

The economic analysis, using a comprehensive econometric model of U.S. agriculture, was carried out under two separate conditions --- (a) crop loss was restricted to Minnesota alone and Minnesota and United States production levels were estimated; (b) the same rate of loss as occurred in Minnesota was assumed to occur over the entire United States, and again Minnesota and national production levels were estimated. A range of producer welfare estimates was derived with the worst case ozone level (0.12 ppm hourly concentration with ten occurrences per week) causing a loss of $30,366,409 under assumption (a) compared to 1980 production. The worst case estimate under assumption (b) gave a gain to producers of $67,540,745 compared to 1980 production.

The explanation for the gain under (b) is that price rises as output is restricted and the "price effect" dominates, whereas under (a) the "production effect" dominates. The increase in the total value of production as ozone increases is due to the price inelastic nature of demand for the commodities studied. This "gain" to producers is in fact misleading in that: (1) costs have risen due to ozone pollution, and so a loss of comparative advantage is suffered by all affected farmers (the gain is at
best a short-run phenomenon as competition from other sources would drive high cost producers out of the industry; as the authors note, scenario (a) is more likely in the long run). (2) Focusing on the "gain" to producers ignores the dynamics of consumer and producer welfare. Benson et al. do not calculate consumer surplus, therefore the net change in societal welfare, and the distribution of welfare changes, are unknown. In addition, scenario (b) is highly dubious because of the assumption that regional dose-response/ozone estimates can be extrapolated to the national level.

Although a detailed national level model was used the economic analysis is similar to that of the traditional model. A comprehensive econometric model of the United States agricultural sector (calibrated to 1980) was used to capture crop supply and demand across multiple domestic and foreign markets.

The production level estimates for various ozone concentration/frequencies were used as data input to a national crop-livestock model which considers the interrelationships of the commodities and estimates a price for each production level. These prices were then multiplied by the production level estimate in order to estimate the value of production.

Thus, despite accounting for national level changes, the regional model remains simplistic in that quantity is being multiplied by price in order to estimate the "value" of production (namely producer quasi-rents). Also, cross-crop substitution is ignored as a mitigative strategy.

Leung et al. (1982) studied nine crops in the south coastal region of California. Linear dose-response functions for each crop were calculated from secondary data. No yield reductions
were found for celery which was therefore excluded. Yield reductions were estimated by calculating the difference between actual yields with 1975 ozone levels and yields predicted by the dose-response functions at zero ozone levels. The use of zero ozone levels risks overestimation of benefits by including ozone from natural sources as anthropogenic. The predicted percentage yield changes predicted were used to rotate the supply curve for each crop individually allowing no cross-crop substitution. The best fit aggregate econometric supply curves were linear, and the demand curves were power functions.

Both ordinary consumer surplus and producer quasi-rents were calculated. The ordinary consumer surplus was assumed to equate approximately with true consumer surplus because the marginal utility of income was expected to be nearly constant; this assumes the commodities in the study commanded only a small proportion of consumer income (see Appendix I). The resulting estimates were $57.3 million in lost producer surplus and $45.7 million in lost consumer surplus (1975 dollars). An input-output model was used to translate these losses into direct income effects and indirect economic effects. The direct losses within the south coastal region were $117 million, and $14.1 million for the rest of the state. Indirect effects were estimated to cause a loss of $276 million within the region and $36.6 million in the rest of California.

Page et al. (1982) studied three crops in the Ohio River Basin (which includes all of Kentucky, and portions of Illinois, Indiana, Ohio, West Virginia and Pennsylvania). Linear dose-response functions were taken from a previous study on the
region, which was itself based on the experimental data of other researchers. Errors may have arisen from these data because they were originally derived for areas outside the Ohio River Basin and may include cultivars not grown in the study area. In addition, the dose-response functions overestimate crop yield reductions when compared to the results from NCLAN.

Producer surplus was estimated under three scenarios which involved different characterizations of future energy and fuel use. Under the "business as usual" scenario, the net present value of probable total cumulative crop loss, for twenty-four years (1976-2000), from sulphur dioxide and ozone, was approximately $7002 million. The losses attributable to sulphur dioxide were 0.7 percent of the total, ozone being responsible for the other 99.3 percent.

Aggregate econometric supply curves (convex, with constant price elasticities over the relevant producer surplus estimate range) were derived for each crop. Price was assumed to remain constant, which may be a serious omission considering the Ohio River Basin is a major producer of the crops studied, and a substantial change in the regional yields would most certainly affect market price, and so consumer welfare (see the Q.P. study by Adams and McCarl (1985) above). The authors felt the normally negative intercept of the supply curve made the notion of producer surplus "vacuous", and therefore adjusted their empirical results to give supply curves with zero intercepts. The problem with the position of the intercept is not mentioned in any of the other studies. Some studies use negative intercepts,
e.g., Howitt et al. (1984), Rowe and Chestnut (1985), and others positive intercepts, e.g., Leung et al. (1982). Page et al. do not explain the logic underlying their decision to assume a zero intercept. The dose-response functions were used to rotate the supply curve of each crop in turn to simulate ozone damage, and thus cross-crop substitution was excluded.

3.4.4 A Duality Study

Mjelde et al. (1984) employed the Neoclassical econometric model with a profit function. Duality models are not dependent upon an explicit dose-response function to estimate the welfare changes from a change in crop yield. However, experimental data are required to frame the initial hypothesis, and to cross-check the resulting estimates. The profit function, which includes ordinary economic variables and environmental variables (as fixed inputs), shows the effects of varying ozone concentrations on farm profits.

Pollution which is deleterious to the production process will exert an exogenous force upon producer decisions. Producers may respond, even if they are not aware of the phenomenon causing the observed effects, by varying input mixes.

A profit function that has air quality as an input can be used directly to determine the producer's loss in profit and how other inputs are adjusted in response to a change in air quality. A dose-response function, while useful in establishing cause and effect relationships, does not provide this latter type of information. Furthermore, the change in the supply of a crop can be computed directly and this response is the net effect in agricultural output, i.e., the response incorporates producer adjustments triggered by price and yield effects.

Part of this theoretical advantage may not be of benefit in the case of ozone as producer adjustments should not include a change
of input mix, as will be discussed in section 3.5.1. In order to compare the results of a dual study with experimental results, such as those of NCLAN, the mix of variable inputs is assumed constant. However, producers may adjust their output mix, and this is not allowed for in the study.

The study analysed three crops in Illinois. Detailed farm level cost and production information was made available by the Illinois Association of Farm Business Farm Management which provided a rich source of individual farmer data not available in many other states. The study found increased ozone levels depressed output and reduced the marginal productivity of variable inputs so that less were used. Ozone resulted in an aggregate loss in profits to Illinois farmers of approximately $50 million (1980). The assumption of a constant price ignores consumer surplus, and may be unjustified because Illinois is a major grain producer. Also if ozone reduction improved crop yields throughout the Corn Belt, both consumers and producers would be expected to benefit. As the study states:

These loss figures should be interpreted with extreme caution. They are computed under the assumption that price remains constant. Such an assumption is not valid if ambient ozone levels increased in other grain producing regions. If this latter case occurs then the supply curve of feed grains would shift to the left. Given an inelastic demand curve (which is typical of demand in the short run), the corresponding price rise may leave producers better off than before the ozone increase. However, consumers would be worse off than before. This illustrates the importance of analyzing both producer and consumer interactions in drawing conclusions about the impact of any pervasive environmental change.
3.5 Issues in Economic Models of Ozone Induced Crop Loss

3.5.1 Modelling the Impact of Ozone on Agricultural Inputs

Kopp et al. (1984) have summarised the theory pertaining to the incorporation of air pollution in an agricultural production model. The primal technology set $PT$ is altered by changes in environmental variables, such as ozone, so that, $PT$ is a function of $E$, where $E$ is a vector of environmental influences. This implies a transformation function of the form where $E$ impacts the manner in which $x$ is transformed into $y$, that is, inputs are transformed into outputs. The link between $E$ and the $x$, $y$ transformation can be made by the use of experimental natural science information (the approach chosen in this thesis), or from observed nonexperimental data (as done by Mjelde et al.).

The manner in which $E$ affects the $x$, $y$ transformation determines how it should be modelled within the $T$ function. Given the transformation function:

$$T(x, y, E) = 0,$$

the imposition of functional separability gives the impact of $E$ on $T$ as,

$$T(x, y, E) = G*[H(x, y) + (E)] = 0.$$

This implies that the frontier transformation function is neutrally displaced inward and outward as the components of $E$ change. Alternatively, the productivity of factor inputs may be biased causing a non-neutral production function shift. For example, crop fungicide retention may be reduced by acid precipitation, ceterus paribus. Thus, reducing acid precipitation can cause the productivity of fungicides to increase relative to
other inputs. In the case of the effects of ambient ozone upon the productivity of pre-harvest agricultural production factors, "neutral factor productivity enhancement" is hypothesised. That is, the optimal mix of factors of production (i.e., their ratios) is invariant with respect to ozone concentrations, and agricultural production functions are shifted in a neutral fashion. If this hypothesis holds, the underlying production function for a single output firm can be written as,

\[ Y = \ast(E) f(x_1, \ldots, x_n), \]

and the corresponding cost function written as,

\[ C = [C(P, Y) \ast(E)], \]

where \( P \) is an \( n \)-vector of input prices. Given a fixed vector \( x \), \( \ast(E) \) can be interpreted as a dose-response function, and experimentally derived functions can be used as proxies to the true function \( \ast(E) \).

If ozone were hypothesised to differentially impact factor productivity, implying a non-neutral production function shift, then experiments would need to be designed so as to systematically vary input quantities in addition to ozone. This would lead to the derivation of dose-input functions, as well as dose-yield functions. Thus, neutral factor productivity enhancement is an implicit assumption of all those studies employing dose-yield functions without dose-input functions. Of the studies reviewed in the previous section, only the duality model of Mjelde et al. (1984) is free of the neutral factor productivity enhancement assumption, because experimentally derived dose-response functions are not required. Yet in order to
compare the results of the model with those from NCLAN, the mix of variable inputs was assumed constant. Hence all the regional studies of ozone damage to agricultural crops have conformed to the neutral production function shift implying a neutral cost function shift, which determines the shift in agricultural supply functions.70

3.5.2 Cross-Crop Substitution

The potential to change output mix has been noted as an important producer mitigative strategy in the face of ozone damage to crops.71 Given the wide range of sensitivities of crops to ozone concentrations, substantial yield reductions could be expected to cause farmers to react so as to minimize their losses by adopting more resistant crop types. The potential to employ alternative, ozone resistant, crops (or cultivars) in the face of damages will be affected by climate and soil characteristics, technical constraints and institutional factors. This is an empirical issue and has been analysed by Smith and Brown, and Kopp et al.72

Smith and Brown (1982) assessed in detail the importance of acreage shifts between differentially sensitive crops in response to ozone induced yield changes. They studied corn, soybeans, and wheat in Indiana. Demand was assumed to be infinitely elastic, that is, market price was assumed constant. A L.P. model was employed to calculate producer quasi-rents based upon a representative farm. Four yield improvement scenarios were compared with a base case. The conclusion was that allowing for cross-crop substitution could increase the estimated economic
gain to farmers from reductions in ozone concentrations by up to 20 percent, depending upon the region and yield loss estimates. This was due to substantial acreage shifts to the relatively more ozone sensitive crop, soybean.

Figure 11 explains the reasoning behind the results of Smith and Brown. The crop shown in the figure is assumed to be relatively resistant to ozone concentrations. In part (a) acreage is assumed not to change with differences in ozone concentrations. The aggregate demand curve is D, the aggregate supply curve shifts from S0 to S1 as ozone is reduced, the price drops from p0 to p1, and the quantity supplied increases to q1 from q0. In part (b) farmers are allowed to alter their acreage devoted to a particular crop. As before the supply curve may initially shift from S0 to S1, but now as ozone concentrations fall farmers can substitute crops which are relatively sensitive to ozone. As this happens the acreage of the more resistant crops falls and the supply curve shifts to S2. In (a) the change in consumer surplus was p0,A,B,p1 and in (b) is this area minus area p2,C,B,p1. Smith and Brown state that cross-crop substitution could move the supply curve back to, or beyond, S0. Thus, the change in consumer and producer welfare can be overestimated (underestimated) when acreage is assumed to remain constant for relatively ozone resistant (sensitive) crops in the face of a fall in ozone concentrations.

In contrast to the findings of Smith and Brown (1982), Kopp et al. (1985) found the potential for bias from not accounting for cross-crop substitution to be small. Kopp et al. studied
Figure 11
Supply Shift Due to Ozone Decrease

(a) No Cross-Crop Substitution

(b) Allowing for Cross-Crop Substitution

Source: Martha Smith and Deborah Brown, *Crop Production Benefits from Ozone Reduction: An Economic Analysis* (Indiana: Purdue University, Agricultural Experimentation Station, 1982) p.15 Figures 3 and 4.
corn, soybeans and wheat in the U.S. Corn Belt, which includes Indiana, using a partial equilibrium econometric model. Ozone induced welfare changes were calculated allowing for cross-crop substitution and compared to those crop mix constant. The maximum change in acreage in response to changes in ozone concentrations was equivalent to 4 percent of total corn belt acreage (1978). Assuming prices were constant, Kopp et al. found the benefit gains from a reduction of ozone (to 0.09 ppm) were understated by 2 percent and losses from an increase in ozone (to 0.15) overstated by 4 percent compared to a fixed crop mix model. Both Kopp et al., and Smith and Brown showed that if output prices were to change in response to cross-crop substitution, the benefit errors from assuming a fixed crop mix were substantially reduced. In Kopp et al. the errors became a 0.1 percent overestimate of welfare losses from the increase in ozone and a 0.2 percent underestimate of welfare gains from the decrease in ozone.

Thus, the potential error from excluding cross-crop substitution as a mitigative strategy remains uncertain. Given price changes the problem may be small and, in addition, there may be transactions costs which restrict output substitution. For example, specialised machinery (with a zero opportunity cost) may be made obsolete encouraging a farmer to remain in production as long as it is operational (assuming variable costs are covered). Certain farmers may have traditionally grown a specific crop and may not even realize the potential for substitution, or may wish to maintain consistency and avoid uncertainty. Crops and cultivars grown in a particular region are normally selected.
because they are those best suited to the environmental and production requirements (e.g., processing or fresh markets). In addition, the adoption of ozone resistant cultivars can be at the expense of yield reductions, because the resistant strains are less productive. Producers of perennial crops may follow a fixed crop mix pattern due to the added expense of changing output mix. Similarly, farmers whose crops take several years before bearing first fruit may find themselves committed to a fixed output mix.

All the Q.P. models reviewed included cross-crop substitution, and all of the other models have failed to do so (see Table 16). While the potential for a 20 percent error in benefit estimates may make this a serious exclusion, this conclusion is far from clear. The flexibility of farmers in switching their output mix should be assessed before including cross-crop substitution, because errors may arise from assuming farmers are more flexible than in reality. This may be a particular problem where perennial crops and those requiring a long time to first fruit are concerned.

3.5.3 The Distribution of Benefits

Benefits may be distributed between groups, such as producers and consumers, across geographical areas and amongst different sectors of the economy. Where the area being analyzed is relatively large, such as the U.S. Corn Belt or the entire United States, the geographical distribution of welfare changes may form the central focus of attention. Similarly, where important crop growing regions are being studied, the indirect effects can be
significant. However, only Leung et al., of the studies reviewed above, have included a calculation of the latter, indirect effects, and no attempt is made to do so in this thesis. The main concern here is for the distribution of welfare changes between producers and consumers. Varying assumptions concerning the position of both supply and demand functions, and the nature of the response of supply functions to changes in ozone levels will result in wide variations in welfare estimates.

(a) Demand Characteristics

The distribution of welfare changes between consumers and producers is dependent upon the price elasticities of supply and demand. A numerically large value for demand price elasticity implies that the quantity demanded is proportionately very responsive to price changes. Generally, when the demand price elasticity is large the good is a luxury, and when small a necessity. Agricultural products are usually closer to the latter with inelastic, short-run aggregate demand curves.

A perfectly elastic demand curve was assumed by four of the studies reviewed; namely, Linzon et al. (1984), Benson et al. (1982), Page et al. (1982), and Mjelde et al. (1984). As has been mentioned, this assumption may be justified when the change in the yield of a crop is not expected to be large enough to induce a demand response, or when some institutional arrangement fixes a rigid price, preventing market forces from operating. However, this assumption has also been employed as a method of simplifying the study so as to focus attention upon other issues besides policy orientated benefit estimates. For example, in Mjelde et
The main goal was to test the dual approach not previously applied to air pollution benefit assessments. The benefits estimated by such studies ignore the dynamics of consumer and producer surpluses, and cannot therefore be taken as measure of the net societal welfare change. The benefits obtained may also be contrary to other evidence or unrealistic, such as the results of Benson et al.

(b) Supply Characteristics

The price elasticity of supply is a similar concept to that for demand; that is, a measure of the responsiveness of supply to price changes. Supply responsiveness is dependent upon the technical characteristics of production and the underlying input cost structure. Normally, the supply curve will be positively sloped and between the extremes of perfectly elastic and perfectly inelastic and, excepting the two traditional type models (Linzon et al. and Benson et al.), all the studies reviewed concur with this. However, two main differences occur among the supply characteristics assumed by different studies; (a) the positioning of the intercept, and (b) the nature in which the supply curve is shifted.

Page et al. mention that the notion of a negative intercept as typical in agricultural supply curves makes the notion of producer surplus "vacuous". Without any further expansion upon the matter, this leads them to assume a zero intercept. In Figure 12, S0 has a negative intercept, S1 has a zero intercept and S2 a positive intercept. The supply function S0 implies some quantity q0 will be produced when the market price is zero; that is, the
Figure 12
Supply Intercept Assumptions

Price of Crop

S2

S1

S0

p2

B

A

0

q0

Quantity of Crop
cost of producing q0 is zero. S1 implies nothing will be produced until the price is positive and S2 requires a price of at least p2 before production commences. While S0 is counter-intuitive, Adams et al. (1984) suggest a zero intercept may also be unrealistic. They suggest, where the supply function is locally estimated, it may be appropriate to truncate the function rather than extrapolate to the intercept. A supply function such as S0AB might result. However, this procedure will underestimate the increase in producer surplus from a yield increase due to a reduction of ozone (unless supply actually truncates). Therefore, in the analysis of Chapter IV the function is not arbitrarily altered, but is left with a negative intercept.

(c) The Nature of Supply Response to Ozone Reduction

Two types of supply function "shifts" have been used in ozone crop loss studies and discussions, (a) the parallel shift, and (b) the rotation, see Table 16. Several studies have assumed that the supply curve is rotated so that the price intercept (vertical axis) remains fixed, Howitt et al. (1984), Page et al. (1982), Leung et al (1982), Rowe and Chestnut (1985). However, some studies and discussions have also assumed the supply curve is shifted in a parallel fashion, the analysis of cross-crop substitution by Smith and Brown (1982), and a review paper by Eidman and Benson,79 and it is implicit in the traditional type models of Linzon et al. (1984), and Benson et al. (1982). Although each supply response implies different assumptions which affect the resulting producer surplus, the underlying logic of
each has not been explained in any of the papers above.

The parallel shift of the supply function (as in Figure 11) changes the price intercept while maintaining a constant slope. That is, for a reduction in ozone, the average cost is reduced while the marginal cost remains constant. This implies that costs are reduced by an equal amount for every unit produced. The cost of producing the first unit is reduced by $A$, the second by $B$, the third by $C$, and so on, where $A=B=C$. Alternatively, this can be stated as implying that an extra fixed quantity of the crop in question will be supplied at any price equal to or above that at the original intercept.

A dose-response function gives a predicted percentage change in quantity as a result of a change in the concentration of ozone. The absolute amount of the change will depend upon the quantity of the crop exposed. For example, assume that a specific reduction of ozone causes a 50 percent increase in the weight of potato tubers. If 1 unit of potatoes was being produced now there will be one and a half units, if two then now there will be three, if three then now four and a half, and so on. The reduction in cost is greater as the quantity increases, thus in the above example $A<B<C$. The gain in production at a given price is dependent upon the quantity produced at that price and exposed to ozone, before a change in the concentration of ozone. Thus, assuming a fixed quantity of crop is added over a wide range of prices is contrary to the underlying biological dose-response functions, and thus the parallel shift is an inappropriate characterisation of supply response.

Figure 13 shows the effects of the parallel shift and the
Figure 13
Parallel Verses Rotation Supply Shift
(a) Price Elastic Demand

(b) Price Responsive Demand
rotation upon consumer surplus. Part (a) shows the effects of a reduction in ozone upon a crop under the two response assumptions given an infinitely price elastic demand function $p_d, D$. Supply is originally $S_0$ and moves to $S_P$ under the parallel shift, and $S_R$ under the rotation. Producer surplus is given by the area above the supply curve and below the price line. The original surplus $p_0, p_d, A$ is increased by $p_0, A, B$ by the rotation and by $p_1, p_0, B$ by the parallel shift. Thus, the parallel shift overestimates the gain in producer surplus by $p_1, p_0, B$.

When the demand function is downward sloping, $D_D$ in Part (b), the equilibrium for the parallel shift is at a lower price and greater quantity than for the rotation. The same change as in Part (a) takes place, but this time the price falls from $p_d$ to $p_r$ under the rotation and to $p_p$ under the parallel shift. Area $a$ is lost, area $d$ remains unchanged and area $e$ is gained under both response assumptions. The difference in producer surplus between the two cases is then dependent upon the relative size of areas $b$, $c$ and $f$. The lower relative price under the parallel shift means a greater loss in surplus by area $b$ and that area $c$ is not gained, while the gain is greater by $f$. Producer surplus due to the parallel shift will exceed that due to a rotation when area $f$ exceeds areas $b$ plus $c$. This seems likely even when the demand curve is perfectly inelastic, i.e., the dotted line through $A$ in Part (a). Thus, the parallel shift is both counter factual and likely to cause biased welfare estimates.
3.6 Conclusion

Several methodologies are available for crop loss assessment and have been applied to the analysis of welfare changes due to alterations in ozone pollution levels. Among these the microtheoretic econometric models provide a theoretically rigorous structure and have become a common approach to studying the agricultural sector. In conceptualizing agricultural crop production changes, neutral factor productivity enhancement is unanimously accepted, while output substitution will depend upon particular circumstances. Demand functions must be estimated if credible welfare estimates are to be obtained. Finally, the supply function characteristics used in recent studies have not been fully explained and may cause unjustified bias in benefit estimates.
Footnotes


6 Ibid.


9 Ibid.


11 Ibid.


13 Adams et al., Economic Effects of Ozone on Agriculture p.7; and Adams, "Assessing Economic Benefits Ozone Control".

14 Kopp et al., Agricultural Sector Benefits Ozone p.52.

Adams, "Assessing Economic Benefits Ozone Control".

Adams et al., "Economic Assessment Air Pollution Damages to Crops" p.57.


Adams, and McCarl, "Effects Acid Deposition on Agriculture" p.23.


Leung et al. Valuation of Agricultural Crop Yield Changes.

The dichotomy of positive and normative is not as clear cut as is often suggested, especially by economists. For an excellent discussion of these issues see Mark Blaug, The Methodology of Economics (Cambridge, U.K.: Cambridge University Press, 1982) Chapter 5.


Ibid, p.16.


31 Varian, Microeconomic Analysis pp.9-10.

32 The transformation function must be continuous, monotonic and quasi concave in every subset of input cross output.

33 Kopp et al., Agricultural Sector Benefits Ozone pp.22-23.

34 Varian, Microeconomic Analysis p.21.


36 Ibid.

37 Ibid.


Varian, Microeconomic Analysis p.21.

Kopp et al., Agricultural Sector Benefits Ozone.

Ibid.


Adams et al., Economic Effect of Ozone on Agriculture gives a review of national level studies.


Adams et al., "Economic Assessment Air Pollution Damages to Crops".


Adams et al., Economic Effect of Ozone on Agriculture p.10 gives these percentage estimates.

Howitt et al., "Effects of Ozone and Response Data on Economic Assessments".


Adams, and McCarl, "Effects Acid Deposition on Agriculture".

E.J. Benson, S. Krupa, P.S. Teng, and P.E. Welsch, "Economic Assessment of Air Pollution Damages to Agricultural and Silvicultural Crops." (Final report to Minnesota Pollution Control Agency, 1982).

Ibid.


61 Howitt et al., "Effects of Ozone and Response Data on Economic Assessments"; Rowe, and Chestnut, "Economic Assessment of the Effects of Air Pollution on Agricultural Crops in the San Joaquin Valley"; Leung et al., "Estimation of Ozone Damage to Selected Crops Grown in Southern California". Mjelde et al., "Using Farmers' Actions to Measure Crop Loss Due to Air Pollution".

62 Mjelde et al., "Using Farmers' Actions to Measure Crop Loss Due to Air Pollution" p.361.


64 Ibid.

65 Adams et al., Economic Effect of Ozone on Agriculture.

66 Mjelde et al., "Using Farmers' Actions to Measure Crop Loss Due to Air Pollution".

67 Ibid.

68 Kopp et al., Agricultural Sector Benefits Ozone.

69 Ibid.


71 Adams et al. Economic Effect of Ozone on Agriculture.

72 Martha Smith, and Deborah Brown, Crop Production Benefits from Ozone Reduction: An Economic Analysis. Station Bulletin No.388 (Indiana: Purdue University, Agricultural Experimentation Station, 1982). Kopp et al. "Implications of Environmental Policy".

73 Smith and Brown, Crop Production Benefits from Ozone Reduction p.32.

74 Kopp et al. "Implications of Environmental Policy".
75 H.E. Heggestad and J.H. Bennett "Impact of Atmospheric Pollution on Agriculture" in M. Treshow (ed.) Air Pollution and Plant Life (Chichester: John Wiley and Sons, 1984).

76 Demand/supply price elasticity is the proportionate rate of change of the quantity of a product demanded/supplied divided by the proportionate change of price, with the price of other goods and income held constant.


78 See review of Mjelde et al. above, especially the last quote.

CHAPTER IV

OZONE POLLUTION IN THE LOWER MAINLAND
AND THE WELFARE FROM CROP
YIELD CHANGES

4.1 Introduction

In this chapter a model of the potato industry in B.C. is presented and employed to analyze the potential benefits from reducing ambient ozone levels in the Lower Mainland. The sensitivity of the predicted welfare estimates of the model is tested using various scenarios. These scenarios include changes in the price of U.S. imports, and price elasticity of supply.

Originally, as suggested in Chapter 3, an aggregate dual model of crop production was intended for use in an aggregate analysis of the response of producers and consumers to alterations in ambient ozone loadings. However, attempts to estimate a translog cost function model with two outputs and three inputs for the agricultural sector in B.C. were unsuccessful. The best model estimated from available data showed serious parameter errors. Appendix III presents the data base and parameter estimates of the final model. Data availability restricted the usefulness of this approach.
The dual approach has several advantages over the econometric supply/demand approach employed here, some of which were noted in Chapter 3. The duality model has a sound theoretical basis. The duality model allows analysis of industry structure and gives valuable insights into both input and output interdependencies. For example, the damage to crops due to ozone may affect livestock production, and the dual approach allows tests for jointness between livestock and crop outputs. Disadvantages of the dual approach include the data requirements, and the stringency of underlying assumptions.

The data requirements of the dual approach exclude its use for individual crops in B.C. Aggregation is to a higher level than that required for this study. Aggregating crops in this fashion has the disadvantage that details of individual markets are lost and cannot be analysed. Also, dose-response functions become difficult to apply since most dose-response functions are crop (and cultivar) specific. NCLAN has done some work on aggregate functions. However, aggregation is a problem which must be tackled at some stage if commodity-specific, policy applicable results are to be obtained. Thus, the analysis of potatoes which follows, while indicative of the ozone damages in the Lower Mainland, may be less than a more complete study which covers a broader range of crops.
4.2 The Economic Model

4.2.1 Spatial Equilibrium Theory

The market for potatoes in B.C. can be characterised as a situation in which two regions trade, and supply and demand functions for these two regions determine a price, i.e., a spatial equilibrium model is appropriate. Two regions, i.e., the U.S. and B.C., produce and consume a homogeneous product, and are separated but not isolated by transfer costs. The problem is to determine the equilibrium levels of production, consumption and prices in each region and the equilibrium trade flows.

A geometric exposition of this problem, is presented in Figure 14. The first and third graphs show the known supply and demand curves of region 1 (U.S.) and region 2 (B.C.) respectively. If no trade were allowed the equilibriums would be $q_1, p_1$ in region 1 and $p_2, q_2$ in region 2. Allowing trade means that the low cost producers of region 1 can sell some output at a higher price than $p_1$, and consumers in region 2 will be able to buy output at a price below $p_2$. The amount producers in region 1 offer at prices above $p_1$ is called the excess supply function (ES), and the quantity the consumers of region 2 demand at prices below $p_2$ is the excess demand function (ED). The intersection of these two functions gives the equilibrium level of trade.

If there are no transfer costs the equilibrium price under trade will be $p_T$ the same in both regions. However, if transfer costs do exist the excess supply function is shifted to the left. The price in region 2 will now be higher than $p_T$, at $p_{T2}$. While the price in region 1 is lower than before, at $p_{T1}$, with a greater quantity being supplied to the home market. The price in
Figure 14. Spatial Equilibrium
region 2, set exogeneously, will reflect both transportation costs and any tariff which might be enforced.

4.2.2 The Potato Market in B.C.

Data for potato production at the farm level were collected from annual reports of the B.C. Ministry of Agriculture and Fisheries. The information includes data on potatoes sold to the processing industry, at the roadside and to the fresh market. Data on the quantity and value of fresh potato imports was obtained from the External Trade Reports of the B.C. Ministry of Industry. All values and prices were deflated, 1981=100.

The per capita consumption of fresh potatoes at the farm level in B.C. was calculated as the sum of net imports plus B.C. production (for processing, fresh and roadside markets) divided by the population. This per capita demand shows a distinct decline in the last ten years, see Figure 15. A downward trend in the demand for fresh potatoes is characteristic across Canada and is hypothesised to be income related, i.e., fresh potatoes are an inferior product. In B.C. the mean quantity of potatoes demanded per capita was approximately 99 pounds for the 21 year period 1964-1984, but the minimum level was reached in 1984 at 72 pounds.

B.C. production of potatoes has declined, while the quantity of imports has shown a slight increase. Figure 16 shows the increasing importance of imported potatoes relative to B.C. production. Competition is almost entirely from the United States, and in particular Washington, California and Idaho. Imports averaged 30 percent of the total quantity sold in B.C.
Figure 15. Consumption of Potatoes in B.C. 1964-1984

Total Quantity (lbs per capita)

YEAR
64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84
Figure 16. Net Potato Imports into B.C. 1964-1984

Quantity (lbs per capita)

B.C. Production

Imports

YEAR
over the period 1964-1984, but in 1981 reached a peak of 51 percent. In the ten years from 1975-1984 imports have supplied 36 percent of the market. The other main production trend has been the increased relative importance of Lower Mainland production. Under 40 percent of the quantity produced in B.C. was from the Lower Mainland in 1965, but by 1980 this had reached 83 percent. The production of the Lower Mainland is compared to that of B.C. as a whole in Figure 17. Since the early 1970's the influence of the Lower Mainland on total output trends has been strong, and has grown stronger as the production from other areas has diminished.

4.2.3 Potato Supply and Demand in B.C.

Estimates of the price elasticity of demand for potatoes in British Columbia were calculated in an econometric study by Stodola and McNeill. They estimated the price elasticity of demand for fresh potatoes generated from annual data as -0.14. The demand equation used for this estimate took the form:

\[ Q_d = f(\text{wholesale prices, price of substitutes, income}), \]

where \( Q_d \) is per capita potato demand. Although this is a wholesale level demand estimate it is taken as representative of farm level demand. This is equivalent to treating the wholesale and farm levels as one, and can be justified because of the role played by the vegetable marketing boards.

Nuckton has reviewed past vegetable demand studies and provides a summary of several studies which include potato demand estimates. The estimated price elasticities of demand reported by Nuckton for potatoes are shown in Table 18. The demand price
Figure 17. Lower Mainland and B.C. Potato Production 1964-1984

- **Quantity Produced (lbs per capita)**

  - **Lower Mainland Production**: Shows a steady increase from 1964 to 1984.

**YEAR**

- 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84
elasticity derived by Stodola and McNeill appears very inelastic when first compared with these estimates. However, estimates of wholesale and farm level demand are expected to be more inelastic than at the retail level, due to the greater possibilities for substitution at the latter. Stodola and McNeill's estimate compares to that of George and King for U.S. farm level demand. The estimate of Canadian price elasticity of demand at the retail level of -0.85 found by Hassan is also consistent with a lower farm level elasticity e.g., -0.14. Hee found several considerably more elastic price elasticity estimates at the farm level but this can be attributed to the disaggregation of potatoes by growing season, thus allowing for greater substitution.

Combining Stodola and McNeill's demand price elasticity estimate with the price and quantity data described above gives a demand function for the base model. The mean quantity demanded per capita over the period 1964-1984 was 99.34 pounds (lbs.), and the mean price was 8.67 cents (constant 1981=100). This gives the demand function for B.C. at the mean of the data as:

$$Q_d = 113.25 - 160.48P_d$$  \hspace{1cm} (4.1)

The short run supply price elasticity estimate given by Stodola and McNeill for fresh potatoes generated from yearly data is 0.343. This estimate is combined with mean values for B.C. quantity supplied and price, to derive the supply function for the base model. The mean quantity supplied by B.C. from 1964-1984 was 70.22 lbs per capita, and the mean price per lb was 8.67 cents. This gives the B.C. potato supply function as:

$$Q_s = 46.13 + 277.92P_s$$  \hspace{1cm} (4.2)
Table 18. Price Elasticities of Demand Reported for Potatoes

<table>
<thead>
<tr>
<th>Author/Date</th>
<th>Period</th>
<th>Potatoe Type</th>
<th>Market</th>
<th>Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blaich 1963</td>
<td>1957-1961</td>
<td>Frozen</td>
<td>U.S. Farm</td>
<td>-0.20 to -2.00</td>
</tr>
<tr>
<td></td>
<td>1957-1960</td>
<td>Canned</td>
<td>U.S. Farm</td>
<td>-0.20 to -2.50</td>
</tr>
<tr>
<td>Hee 1967</td>
<td>1947-1960</td>
<td>Various*</td>
<td>U.S. Farm</td>
<td>-0.21 to -2.63</td>
</tr>
<tr>
<td>Siebert 1967</td>
<td>1956-1966</td>
<td>Fresh</td>
<td>California</td>
<td>-1.20</td>
</tr>
<tr>
<td>George and King 1971</td>
<td>Estimate to 1980</td>
<td>Fresh</td>
<td>U.S. Farm</td>
<td>-0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>U.S. Retail</td>
<td>-0.31</td>
</tr>
<tr>
<td>Martha and Schrimper 1974</td>
<td>1949-1972</td>
<td>Fresh</td>
<td>U.S. Retail</td>
<td>-0.50</td>
</tr>
<tr>
<td>Clevenger and Geithman 1977</td>
<td>1957-</td>
<td>Fresh</td>
<td>U.S.</td>
<td>-0.83</td>
</tr>
<tr>
<td>Hassan 1978</td>
<td>1974</td>
<td>Fresh</td>
<td>Canada Retail</td>
<td>-0.85</td>
</tr>
</tbody>
</table>

*Hee classified potato types by growing season and obtained seven elasticities for fresh and stored farm level potatoes for food -0.21, -2.63, -0.59, -1.88, -0.67, -0.52, -0.48.

The data on price and quantity given by Stodola and McNeill were not used because it only covered the period from 1961-1976. The analysis conducted in the following sections is based upon ozone doses for the period 1978-1985. Thus, an updated data base is important for the analysis of recent changes.

4.2.4 The Market Equilibrium for Potatoes

Combining demand and supply functions 4.1 and 4.2 allows the market equilibrium to be calculated. In absence of imports the equilibrium quantity would be approximately 88.68 lbs per capita at a price of 15.31 cents per lb. However, as explained U.S. imports are assumed to set the price on the B.C. market. The U.S. import price is therefore assumed to equal the mean Lower Mainland farm price (1964-1984) of 8.67 cents per lb. At this price the quantity of potatoes imported is 29 lbs per capita. That is, instead of the quantity demanded equalling that supplied by B.C. producers it exceeds local supply by the amount of imports. The quantity supplied by B.C. producers is 70.22 lbs and the quantity consumed 99.34 lbs per capita.

In the following sections the effects of a range of ozone doses upon producer welfare is analysed. Firstly, the areas of consumer and producer surplus, and the changes in producer surplus under the assumption of a constant price are described. Next the annual total and marginal damages from a reduction in potato yield due to various seasonal ozone doses are calculated. These damages are recalculated under two scenarios; (a) involving an alternative, more inelastic, supply elasticity, and (b) a higher import price. Finally, the results are discussed.
4.3 Economic Assessment of Potato Damage Due to Ozone in the Lower Mainland

4.3.1 Net Welfare Areas

In order to calculate the welfare changes which will occur under various ambient ozone loadings the areas shown in Figure 18 (a) and (b) must be calculated. In part (a) net consumer surplus is the shaded area between the price lines \( p_0 \) and \( p_1 \), and bounded by the demand function \( DD \). If the original price was \( p_0 \) then an increase in ozone levels which shifts the supply curve, ceteris paribus, would increase price to \( p_1 \). The price change impacts consumer welfare. (This assumes the demand function does not shift i.e., that ozone does not affect the quality of potatoes.) In the case of B.C. the price of potatoes is set by the much larger U.S. market and therefore no change in the consumer surplus area is expected to occur when ambient ozone loadings in the Lower Mainland change since there is no price change in the B.C. market for this local damage.

Part (b) illustrates the net producer welfare for an increase in ozone which reduces yield and shifts the supply function, but assuming the price does change. The quasi-rent (or producer surplus, see Appendix II) is the area bounded by the price line and the supply function. The original supply function \( S_0 \) is rotated, about its intercept with the price axis, to \( S_1 \). When the price is impacted by this supply shift there is a price increase from \( p_0 \) to \( p_1 \). The area \( C \) is lost by consumers and gained by producers, while area \( B \) is lost to producers. Area \( A \) is common to both situations. Thus, the net change in producer welfare is given by area \( C \) minus area \( B \). The overall effect upon producers'
Figure 18. Consumer and Producer Welfare Areas

(a) Net Consumer Surplus

(b) Net Producer Quasi-Rent Price Change

(c) Net Producer Quasi-Rent Constant Price
welfare will depend upon the price elasticities of supply and demand.

Assuming the price is fixed, and set in the U.S. market, as is the case for potatoes in B.C., means area C disappears. The situation is now as shown in part (c) of Figure 18. The original area of producers surplus is given by area A plus area B. When the supply curve shifts to S1 area B is lost by potato producers, and the new surplus is area A alone. The prime determinant of the loss to producers from a given reduction in potato yield is the price elasticity of supply. Under a fixed market price, potato producers will always lose from increases (and gain from reductions) in ambient ozone loadings which cause yield reductions.

4.3.2 Approach to Economic Assessment

The equilibrium situation of the base model can be regarded as the production level under which no ozone damage occurs. This is justified by the nature of ambient ozone loadings in the Lower Mainland. As shown in Table 6, the ozone dose in rural areas is not constant but varies widely between seasons from levels expected to cause no damages to levels causing 16.5 percent yield reductions. Thus, characterising ozone in the Lower Mainland as having to be reduced from a high dose to a low dose would be unrepresentative of actual ambient ozone loadings. The problem is more accurately seen as the potential for yield reductions in any given year compared to the production that would occur in the absence of damage. The alternative approach, of regarding the problem as starting from a high ozone dose, implies ozone
reductions and supply shifts to the right. The approach adopted here implies ozone increases, causing a shift of the supply function to the left.

Mendelsohn has noted the failure of economic air pollution damage assessments to derive marginal damage functions. All the ozone studies reviewed in Chapter 3 (except for Page et al.) have assessed the total damages occurring at ambient ozone levels in a specific year and compared this with total damages expected at one or two other levels and/or background levels. Typically this approach is adopted to allow the assessment of damages at proposed government standards. However, economic theory suggests that the optimal level of pollution is where the marginal damages equal the marginal costs of controlling the pollutant. Thus, economic assessments should be concerned with estimating marginal damages, i.e., the price of the pollutant. The analysis here does not therefore follow previous studies, but rather presents total damage functions and marginal damage estimates.

4.3.3 Base Model Welfare Estimation

Starting from the equilibrium obtained above the supply function is rotated according to the predicted percentage changes in the quantity produced at different ozone doses. This involves introducing a yield reduction term into 4.2 so that it becomes:

\[ Q_s = (46.13 + 277.92P_s)(1-R/100), \]

where \( R \) is the percentage reduction in quantity derived from the seasonal ozone dose. \( R \) is calculated from the dose-response function presented in Chapter 2, and taken from the "Air Pollution Manual" of the California Department of Food and
Agriculture. When \((1-R/100)\) is greater than one, yield is increased (R is negative), since this implies that ozone dose is decreased. When \((1-R/100)\) is less than one, yield is reduced. When \((1-R/100)\) is equal to one, the quantity is constant and the equation 4.3 is the same as 4.2. Thus, for example, if \(R=-0.5\) then \((1-R/100)=1.5\) and the quantity has increased by 50 percent; conversly if \(R=0.5\), then \((1-R/100)=0.5\) and the yield has decreased by 50 percent.

In order to calculate the quantity of potatoes which will be supplied when yield changes occur, the supply equation 4.3 replaces 4.2. The ozone dose can then be adjusted and equilibrium price and quantity calculated. Starting with the seasonal ozone dose at zero (\(R=0\)) the quantity demanded is 99.34 lbs per capita, and the quantity supplied by B.C. is 70.22 lbs per capita. The ozone dose is then adjusted to a higher level, \(R\) increases, B.C. supply shifts and information on the price and the quantity of potatoes supplied by B.C. producers is used to calculate quasi-rents. Net producer welfare is calculated by subtracting the quasi-rent at zero hours-ppm>0.10ppm ozone from that at the new seasonal ozone dose. Repeating this process gives a range of the total seasonal damages expected at various ambient ozone dose levels.

Figure 19 shows the results of this process. Net producer welfare from potatoes is shown as dependent upon the level of the seasonal ozone dose (hours-ppm>0.10ppm). The vertical axis measures the loss incurred by producers in thousands of constant 1981 dollars. The producer welfare loss was calculated on a per capita basis, with 1984 being the base year, and then multiplied
Figure 19. Base Scenario Total Damage Function for Potatoes

Producer Welfare Loss (Thousands of dollars)

Ozone Dose (hours-ppm>0.10ppm)
by the population of B.C. The range of ozone doses was chosen to represent the range of actual ambient seasonal ozone dose in the Lower Mainland. For example, if the seasonal ozone dose was 16 hours-ppm>0.10ppm (Abbotsford, 1981) in all potato growing areas, producers are estimated to lose 2.4 million dollars; approximately 19 percent of farm cash receipts in 1981.

The total damage function of Figure 19 gives the marginal damage function when differentiated once with respect to dose. The linear nature of the total damage function means that the marginal damage function is constant. If ozone is measured in units of dose hours-ppm>0.10ppm, the marginal damage is 0.15 million dollars per unit of ozone. The marginal damage in this model is also equal to the average total damage. For example, 10 units of ozone causes 1.5 million dollars damage.

4.3.4 Sensitivity Analysis

In order to judge the accuracy of the above annual ozone damage estimates, their sensitivity to changes in the underlying model is tested. Two scenarios are chosen; (a) a more inelastic supply price elasticity, and (b) a higher import price. The demand elasticity estimate was not varied as was the supply elasticity. Changes in the demand elasticity would not affect the producer welfare losses because of the constant price assumption. The more inelastic supply scenario was chosen because this was presented as an alternative estimate by Stodola and McNeill, and no alternative supply elasticity estimates were found, preventing a more comprehensive comparison as conducted for the demand elasticity above. The import price is an import determinant of
the monetary value of the final damage estimates. This price has increased in real terms in the 1980's compared to the twenty-year mean. Thus, the import scenario takes a price reflecting this later period.

(a) Welfare Sensitivity to Supply Elasticity

A search of the literature revealed no studies for comparison of supply price elasticities for potatoes. However, the short run supply price elasticity of 0.343 reported by Stodola and McNeill, is one of two estimates they calculated. The other estimate was from a different formulation of the supply equation and gave the price elasticity of supply as 0.263.

In order to test the sensitivity of the base case welfare estimates to this more inelastic estimate, a new supply function was estimated at the mean. The supply function derived from the price elasticity of 0.263 is:

\[ Qs = 51.75 - 213.10Ps \]  

(4.4)

where \( Qs \) is quantity supplied per capita and \( Ps \) is price per lb.

The total damage function, as shown in Figure 20, is shifted to the left. At a dose of 16 \((\text{hours-ppm}>0.10\text{ppm})\) the inelastic supply model predicts a loss to producers of 2.51 million dollars while the base model predicted 2.40 dollars. The more inelastic the supply curve the larger the loss to producers, and vice versa. Marginal damages are also larger at 0.16 million dollars.

(b) Welfare Sensitivity to Imports

In recent years the import price in the B.C. market has been considerably higher than the mean for 1964-1984. This implies
Figure 20. Supply Scenario Total Damage Function for Potatoes
some change may have occurred in the U.S. market, and/or perhaps transportation costs have increased. This change to a higher price level has caused a loss in consumer surplus and an increase in producers' surplus relative to that of the twenty year base period. This producer surplus area is then subject to the changes due to varying ambient ozone loadings. Reworking the equilibrium equation to allow for an import price of 10 cents per lb, instead of 8.67 cents per lb., gives the quantity of imports as 23.27 lbs per capita (as opposed to 29 lbs previously). At this higher exogenous price, quantity demanded falls to 97.2 lbs per capita and quantity supplied by B.C. producers increases to 73.93 lbs per capita.

The net result is a rise in the estimated welfare loss to producers from increases in the seasonal ozone dose, as shown in Figure 21. This is as expected due to the higher quantity produced by B.C. under the import scenario as compared to the base scenario. The total damage function is shifted to the right at the new import price. At a seasonal dose of 16 (hours-ppm>0.10ppm) the loss to producers is now approximately half a million dollars more at 2.85 million dollars. Marginal damages have also increased, to 0.18 million dollars per unit of ozone dose.
Figure 21. Import Scenario Total Damage Function for Potatoes
4.3.5 Summary and Discussion of Results

Table 19 summarises the results of increases in ambient ozone loadings on potato yield and the effects on producer welfare under each of the scenarios described above. The ozone dose is measured as hours-ppm>0.10ppm, which causes a percentage reduction in potato tuber weight $R$. The seasonal ozone dose reported in Table 19 extrapolates beyond the highest dose calculated in the Lower Mainland of 16 hours-ppm>0.10ppm. The base scenario with inelastic demand and supply gives the lowest damage estimates. The marginal damages range from 149,768 to 178,322 dollars.

<table>
<thead>
<tr>
<th>Ozone Dose (hrs-ppm&gt;0.1ppm)</th>
<th>Potato Tuber Weight Reduction (%)</th>
<th>Total Damages Under Scenarios: (thousands $ deflated 1981)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>More Inelastic Supply Higher Import Price</td>
</tr>
<tr>
<td>20.00</td>
<td>20.6000</td>
<td>2995.35 3139.97 3566.44</td>
</tr>
<tr>
<td>19.00</td>
<td>19.5700</td>
<td>2845.59 2982.97 3388.12</td>
</tr>
<tr>
<td>18.00</td>
<td>18.5400</td>
<td>2695.82 2825.97 3209.80</td>
</tr>
<tr>
<td>17.00</td>
<td>17.5100</td>
<td>2546.05 2668.97 3031.48</td>
</tr>
<tr>
<td>16.00</td>
<td>16.4800</td>
<td>2396.28 2511.98 2853.16</td>
</tr>
<tr>
<td>15.00</td>
<td>15.4500</td>
<td>2246.51 2354.98 2674.83</td>
</tr>
<tr>
<td>14.00</td>
<td>14.4200</td>
<td>2096.75 2197.98 2496.51</td>
</tr>
<tr>
<td>13.00</td>
<td>13.3900</td>
<td>1946.98 2040.98 2318.19</td>
</tr>
<tr>
<td>12.00</td>
<td>12.3600</td>
<td>1797.21 1883.98 2139.87</td>
</tr>
<tr>
<td>11.00</td>
<td>11.3300</td>
<td>1647.44 1726.98 1961.54</td>
</tr>
<tr>
<td>10.00</td>
<td>10.3000</td>
<td>1497.68 1569.98 1783.22</td>
</tr>
<tr>
<td>9.00</td>
<td>9.2700</td>
<td>1347.91 1412.99 1604.90</td>
</tr>
<tr>
<td>8.46</td>
<td>8.7138</td>
<td>1267.03 1328.21 1508.61</td>
</tr>
<tr>
<td>6.52</td>
<td>6.7156</td>
<td>976.49 1023.63 1162.66</td>
</tr>
<tr>
<td>5.59</td>
<td>5.7577</td>
<td>837.20 877.62 996.82</td>
</tr>
<tr>
<td>3.10</td>
<td>3.1930</td>
<td>464.28 486.70 552.80</td>
</tr>
<tr>
<td>1.00</td>
<td>1.0300</td>
<td>149.77 157.00 178.32</td>
</tr>
<tr>
<td>0.80</td>
<td>0.8240</td>
<td>119.81 125.60 142.66</td>
</tr>
<tr>
<td>0.40</td>
<td>0.4120</td>
<td>59.91 62.80 71.33</td>
</tr>
<tr>
<td>0.10</td>
<td>0.1030</td>
<td>14.98 15.70 17.83</td>
</tr>
<tr>
<td>0.00</td>
<td>0.0000</td>
<td>0.00 0.00 0.00</td>
</tr>
</tbody>
</table>
The information presented in Table 19 can be expanded upon, as included in Table 20 presented in Chapter 5, to give a perspective on actual ambient ozone doses in the Lower Mainland. For example, in 1981 the seasonal ozone dose at Abbotsford was 16.00 hours-ppm>0.10ppm causing a 16.5 percent reduction in potato tuber weight. This potato loss caused a loss to potato producers between 2.4 and 2.9 million dollars which was 19 to 23 percent of the farm cash receipts from potatoes for 1981. In other years the seasonal ozone dose has been very low, and in 1984 was zero. The lowest non-zero seasonal ozone dose was in 1983 at 0.22 hours-ppm>0.10ppm. This caused a 0.2 percent potato tuber weight reduction, and between 0.03 and 0.04 million dollars total damage or a 0.3 percent reduction in farm cash receipts from potatoes in 1983.

The import scenario has the largest effect upon estimated damages. The import price imposed in the base model is likely to be lower than in recent years. Thus the import scenario may be a more accurate reflection of the expected losses incurred by farmers in the Lower Mainland from ambient ozone loadings. In this case the estimates of the base scenario would be underestimates of actual damages. The position of the base model below the other damage estimates implies under-estimation. However, there are underlying assumptions to the above analysis which suggest that the damages reported may in fact be overestimated.

Underlying the above analysis are three assumptions which can result in biased estimation of damages. Firstly, the entire B.C. crop is assumed to be affected while damages have only been
substantiated for the Lower Mainland. However, as was shown in Figure 17, Lower Mainland production has been steadily increasing as a percentage of total production accounting for between 70 to 80 percent of the total crop in recent years. The problem here is that aerometric data are currently only available within the confines of the Lower Fraser Valley, as shown in Figure 6. The dose received by the other major potato growing regions is unknown. If the remainder of the B.C. crop were unaffected by ambient ozone doses, then the damages reported above would be overestimated.

A related problem is that all areas are assumed to be affected by the same ozone dose. Table 6 showed that the rural areas of the Lower Mainland do not receive similar ozone doses but that measurements may differ substantially. If a specific dose is assumed to occur across all regions, the resulting bias will depend upon the distribution of actual doses around that level. The doses measured at Abbotsford have often been higher than at other stations, and therefore when the dose there is 16 (hours-ppm>10ppm) it would be expected to be lower elsewhere. If this were the case, overestimation of damages would result because the highest reading is taken as uniform. However, if a lower reading is taken as more representative, underestimation of damages may result. This problem may be resolved by the increased number of monitoring stations now existing in rural areas of the Lower Mainland, and by employing aerometric modelling techniques. Other studies have also assumed a uniform dose across regions e.g., Adams and McCarl (1985) assumed the same ozone dose across the entire Corn Belt.
Finally, all cultivars are assumed to be equally sensitive to ozone. In Chapter 1 the main varieties of potato grown in the Lower Mainland were identified and given susceptibility rankings, i.e. sensitive, intermediate, tolerant and unknown. The dose-response function employed here is for a sensitive cultivar, and thus the resulting damage estimates will be biased upward because not all potato cultivars in the Lower Mainland are sensitive. One cultivar has been used to represent the response of all those grown in a region in several of the regional economic studies of ozone reviewed in Chapter 3. e.g., Benson et al. (1982), Rowe et al. (1984), Howitt et al. (1984), This simplifying assumption is required due to the limited information available on cultivar response.
Footnotes


2 British Columbia, Ministry of Agriculture and Food. Production of Vegetable Crops Together with an Estimate of Farm Value (various annual); and British Columbia, Ministry of Agriculture and Food. Production of Berry Crops Together with an Estimate of Farm Value (various annual).


5 British Columbia, Ministry of Agriculture and Food. Vegetable Marketing Guide.


7 The vegetable marketing boards handle washing, packaging and transportation of farm produce to retail outlets. They replace the role played by a wholesale merchant. They operate so as to promote the products under their jurisdiction on behalf of the farmer.


10 California, Department of Food and Agriculture. Air Pollution Manual (1986).

CHAPTER V

SUMMARY AND CONCLUSIONS

There is a growing body of evidence that ozone affects crop yields at ambient ozone loadings resulting in millions of dollars of damage. The formation of ozone via the interaction of several chemicals in the atmosphere in the presence of ultra-violet light is a complex process. Precursor emissions, of nitrogen oxides and hydrocarbons, alone are not sufficient to insure ozone formation. The dose of ozone received by agricultural crops during a growing season also depends upon atmospheric and topographic factors.

Ozone forming in the Lower Mainland of B.C. is restricted laterally by the surrounding mountain ranges and vertically by stagnant high pressure systems. Land/sea breezes aid in transporting ozone and its precursors from Vancouver up the Fraser Valley towards important crop growing regions. The highest levels of ozone occur during spring and summer coinciding with the most active agricultural season for many crops.

Seasonal ozone dose, measured as hours-ppm$>0.10$ppm, was found to be high at rural monitoring stations during the late 1970's and early 1980's, especially at Abbotsford, but much lower in
more recent years. As there is no reason to believe that precursor emissions have fallen during this period, the lower ozone levels may be attributed to climatic variations. This seasonal variability of ozone concentrations means year-specific damage estimation must be interpreted with extreme caution. Studies conducting year-specific economic assessments need to clarify exactly how representative their results are of a typical growing season.

Table 20 illustrates the range of total damages predicted by the scenario analysis of Chapter IV, assuming all regions are affected by the same seasonal dose as Abbotsford. The damages shown are around one million dollars annually for four out of eight years. The last column shows the estimated total damages as a percentage of B.C. potato farm cash receipts for each year. The damage in 1981 stands out, causing a loss equivalent to 19-22.5 percent of total revenue.

These total damages may overestimate actual damage even if dose were the same across the Lower Mainland. This is because not all potato cultivars are as sensitive as that used in the estimation of damages, and because 20-30 percent of potato production takes place outside the Lower Mainland. In addition, Abbotsford has shown the highest readings in several years, suggesting less damage may occur in other regions of the Lower Mainland.

Despite these qualifications there are reasons to be cautious over discounting these damages as too large. Firstly, ozone may increase plant stress making crops more susceptible to damage from other factors, such as insect attack and biological
pathogens. Secondly, current research has been limited to yield loss, leaving much uncertainty as to the effects of ozone on crop quality. If crop quality is affected then, in addition to the supply shift analysed here, the demand function will be shifted. Thirdly the information on air quality at rural sites has been extremely limited until recent years, and even when stations are operational, data may be missing for a large part of the growing season, as apparent in Table 20. Even with the latest additions to the Lower Mainland Air Quality Monitoring Network, no information exists as to the levels of pollutants beyond Chilliwack.

Table 20. Total Damages to Potatoes Based Upon Ozone Doses at Abbotsford Monitoring Station

<table>
<thead>
<tr>
<th>Year</th>
<th>Seasonal Ozone Dose (hrs-ppm&gt;0.10ppm)</th>
<th>Valid Days* (No.)</th>
<th>R (%)</th>
<th>Total Damages to Potato Producers (000's of $)</th>
<th>Proportion of Total Potato Revenue B.C. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1978</td>
<td>16.00</td>
<td>115</td>
<td>16.5</td>
<td>2,396 - 2,853</td>
<td>18.92 - 22.52</td>
</tr>
<tr>
<td>1979</td>
<td>6.52</td>
<td>47</td>
<td>6.7</td>
<td>976 - 1,163</td>
<td>7.52 - 8.96</td>
</tr>
<tr>
<td>1980</td>
<td>0.22</td>
<td>77</td>
<td>0.2</td>
<td>33 - 39</td>
<td>0.26 - 0.30</td>
</tr>
<tr>
<td>1981</td>
<td>0.40</td>
<td>110</td>
<td>0.4</td>
<td>60 - 71</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

*Maximum number of valid days 124, seasonal dose calculated from 15th May to 15th August.
R is the percentage reduction in potato tuber weight calculated from the dose response function presented in Chapter 2.
Reducing ozone levels measured as hours-ppm>0.10ppm to a dose of zero is equivalent to a one hour annual standard of 0.10 ppm. Meeting this standard would have saved potato producers the losses in Table 20. However, the desirability of obtaining this standard from the economic point of view is not at all clear. Rather than focusing upon total damages, economic efficiency requires the comparison of marginal pollution damages with marginal control costs. Thus the marginal damages were presented for each sensitivity scenario in Chapter IV. The marginal damages ranged from 149,768 to 178,322 dollars per hour-ppm>0.10ppm. The marginal damage function derived from a linear total damage function is constant, and thus all the estimates here are constant.

These marginal damage estimates are of little practical use because no information currently exists on the marginal costs of controlling ozone. Lave\(^1\) has argued that not only are the costs of different control options difficult to estimate, but also that the state of current knowledge makes calculating the resulting decrease in ozone virtually impossible. Yet he concludes that in order to develop a sensible policy for ozone control, the marginal cost of an efficient abatement programme needs to be calculated and compared with the marginal benefits. Estimating control costs is an obvious area for future research.

Interpretation of the marginal damages for potatoes is further restricted because other crops are susceptible to damage and ozone may affect human health, visibility and materials. Vegetables in the Lower Mainland susceptible to ozone damage include lettuce, sweet corn, onions, green beans, peas and
cabbages. In addition, research is required to determine the sensitivity of important economic crops such as blueberries, cranberries, raspberries, and mushrooms. Small fruits are of particular concern because (a) blueberries, cranberries and raspberries accounted for approximately 26 million dollars (28 percent) of farm cash receipts in the Lower Mainland in 1984, (b) Abbotsford accounts for nearly half the provincial cash receipts from small fruits, (c) small fruit bushes such as cranberries require several years to reach maturity, preventing cross-crop substitution, and (d) Lower Mainland production has been steadily increasing.

Regional economic assessment of ozone effects upon agriculture requires the combination of information on air quality, plant response and economic systems. This interdisciplinary approach has been employed to present evidence of damages to potato farmers in the Lower Mainland. Ozone pollution appears to be a potentially serious problem for the agricultural sector in the Lower Mainland and one which requires a comprehensive assessment of both damages and control costs.

Footnotes

BIBLIOGRAPHY


Adams, R.M.; Ledeboer, M.V.; and McCarl, B.A. The Economic Effects of Air Pollution on Agriculture: An Interpretive Review of the Literature Special Report 702 Oregon, Corvallis: Agricultural Experiment Station, Oregon State University, 1984.


Adamowicz, W. "Production Technology in Canadian Agriculture" Canadian Journal of Agricultural Economics 34 (March, 1986) 87-104.


British Columbia, Legislative Assembly, Select Standing Committee on Agriculture. Inventory of Agricultural Land Reserve in British Columbia 1978.


British Columbia, Ministry of Agriculture and Food. Production of Vegetable Crops Together with an Estimate of Farm Value various annual issues.

British Columbia, Ministry of Agriculture and Food. Production of Berry Crops Together with an Estimate of Farm Value various annual issues.


California, Department of Food and Agriculture. Air Pollution Manual, 1986.


Canada, Food Prices Review Board. Table Potatoes, 1975.

Canada, Statistics Canada. Cansim.

Canada, Statistics Canada. Farm Wages in Canada Catalogue 21-002 various.


Canada, Statistics Canada. Farm Inputs Price Index Western Canada Catalogue 62-004 various annual.

Canada, Statistics Canada. Farm Cash Receipts Catalogue 21-001 various annual.

Canada, Statistics Canada. Fruit and Vegetable Production Catalogue 22-003 various annual.


Canada, Statistics Canada. Canadian Statistical Review 11-003E.


Dixon, B.L.; Garcia, P.; Mjelde, J.W.; and Adams, R.M.
"Estimation of the Cost of Ozone on Illinois Cash Grain
Farms: An Application of Duality" Urbana: Agricultural
Economics Staff Paper No.84 E-276, University of

Dixon, B.L.; Garcia, P.; and Mjelde, J.W. "Primal versus Dual
Methods for Measuring the Impacts of Ozone on Cash Grain
Farms" American Journal of Agricultural Economics 67:2
(May, 1985) 402-406.

Dupuit, J. "On the Measurement of the Utility of Public Works"
Annales des Ponts et Chausees, 2nd Series Vol.8 (1844)
reprinted in Munby, D. (ed.) Transport: Selected

Eidman, V.R., and Benson, F.J. "Economic Assessment of Crop Loss:
Discussion" in Lee, S.D. (ed.) Evaluation of the
Scientific Basis for Ozone/Oxidant Standards Pittsburg:
Air Pollution Control Association, 1985.

Flinn, J.C.; Kalirijan, K.P.; and Castillio, L.L. "Supply
Responsiveness of Rice Farmers in Laguna, Phillipines"
Australiann Journal of Agricultural Economics 26:1

Freeman, A.M. The Benefits of Environmental Improvement: Theory
and Practice London, England: John Hopkins Press,
1979.

Garcia, P.; Dixon, B.L.; Mjelde, J.W.; and Adams, R.M. "Measuring
the Benefits of Environmental Change Using a Duality
Approach: The Case of Ozone and Illinois Cash Grain
Farms" Journal of Environmental Economics and Management

Guilkey, D.K.; Lovell, K.C.A.; and Sickles, R.C. "A Comparison of
the Performance of Three Flexible Functional Forms"
International Economic Review 24:3 (October, 1983) 591-
616.

Hamilton, S.A.; McCarl, B.A.; and Adams, R.M. "The Effect of
Aggregate Response Assumptions on Environmental Impact
Analysis" Corvallis: Department of Agricultural and

Hamilton, S.A.; McCarl, B.A.; and Adams, R.M. "The Effect of
Aggregate Response Assumptions on Environmental Impact
Analysis" American Journal of Agricultural Economics
67:2 (May, 1985) 407-413.


Henderson A. "Consumer's Surplus and the Compensating Variation" Review of Economic Studies 8 (Feb., 1941) 117-121.


Jacobson, J.S. "Economics of Biological Assessment" Journal of Air Pollution Control Association 32:2 (February, 1982) 145-146.


Smith, M., and Brown, D. Crop Production Benefits from Ozone Reduction: An Economic Analysis. Station Bulletin No.388 Indiana: Purdue University, Agricultural Experimentation Station, 1982.


APPENDIX I

CONSUMER WELFARE THEORY

Historical Note

The concept of a consumer being able to obtain an amount of utility in excess of the price paid for a commodity was first expounded by Jules Dupuit, in 1844.\(^1\) Dupuit's consumer surplus was adopted by Alfred Marshall some forty years later. It was Marshall who equated the concept to the area under a demand curve. Marshall was trying to find a cardinal measure of utility, but the conditions under which his definition of consumer surplus could act as such were restrictive and unrealistic. The connection of consumer surplus with cardinal analysis meant it was neglected as ordinal analysis came to the fore.\(^2\)

In the 1940's John Hicks redefined the idea using ordinal analysis.\(^3\) Hicks introduced four new measures of a consumer welfare change. Two of these became accepted as practical tools for applied welfare analysis --- namely, the compensating variation and the equivalent variation. However, despite the improvements these measures offered, direct measurement was not easy. Consumer surplus could be, and was, used as an approximation to the Hicksian measures but as such remained
controversial. Robert Willig removed the reasons for criticising this practice by providing the circumstances under which it could be justified. Willig showed the specific range of conditions within which consumer surplus approximated the compensating and equivalent variations, and the accuracy of that approximation when those conditions were altered. In addition, Willig showed that in most common applications consumer surplus was a close approximation to the Hicksian measures.

**Dupuit Surplus**

Dupuit described consumer surplus as being the difference between the price actually paid when purchasing a commodity and the price the consumer would have been willing to pay. This willingness to pay diminishes as more units of the commodity are consumed. Figure A1.1 shows the price a given consumer is prepared to pay for each successive unit of a commodity. The demand curve $W$ is a marginal willingness to pay curve. For the first unit the consumer would be willing to pay $p_1$, for the second $p_2$, for the third $p_3$, and so on. If we assume the consumer can buy all the units one through to $q_0$ at a constant price $p_0$, there will be a surplus of utility on every unit consumed up to, but not including, the last, $q_0$. (The assumption of a constant price is as would exist in a perfectly competitive market.) Thus, if the commodity is perfectly divisible, the Dupuit surplus from buying $q_0$ at $p_0$ is given by the triangle-like area above the price and below the willingness to pay curve. The net benefits of consuming $q_0$ are given by this area, while the gross benefits are given by that area plus area $p_0,q_0$. 

167
Figure A1.1 Dupuit Consumer Surplus
It should be clear that lowering (raising) the purchase price will increase (decrease) net benefits i.e., the Dupuit surplus. As Dupuit stated:

Hence the saying which we shall often repeat because it is often forgotten: the only real utility is that which people are willing to pay for. We see that in general the relative or definitive utility of a product is expressed by the difference between the sacrifice which the purchaser would be willing to make in order to get it and the purchase price he has to pay in exchange. It follows that anything which raises the purchase price diminishes the utility to the same extent, and anything which depresses the price increases the utility in the same manner.

However, it is important to note how the change in price is caused. The producer can reap a similar surplus to the consumer (see Appendix II) by charging more for a commodity than it cost to produce. A price change which does not correspond to a reduction in production costs cannot increase the overall welfare of society. Such a price change merely reduces the producers welfare and increases the consumers. As Dupuit remarked:

For an increase or decrease of utility to take place, there must be, provided there is no change in quality, a decrease or increase in the cost of production. When there is merely a change in the market price the consumer gains what the producer loses, or vice versa.

In fact the changes due to a reduction in production costs are likely to cause some transfer payments as well, depending upon the relative characteristics of supply and demand.

In a relatively short paper Dupuit managed to make many insightful remarks and had intended to follow these up, but never published more on the subject. When Marshall took up these ideas he was searching for a cardinal measure of utility. The Dupuit surplus was not a measure of actual utility changes, or the real net benefits of a commodity, but only a money measure.
Consumer Surplus

Marshall was concerned with finding the conditions under which a money measure of consumer welfare would equal the 'true' utility surplus. It was Marshall who developed the association of consumer surplus with the curvilinear triangle under the ordinary demand curve. In Figure A1.2 an individual's Marshallian demand curve, D, is shown. The area abc is the net benefit to the consumer of purchasing quantity od of the good. The area bcdo is the gross, or total, benefit of purchasing od of the good. The difference between the two is the total cost of quantity od to the individual --- given by area oacd. In the remainder of this paper consumer surplus will be taken to mean this triangular area (abc). It should be noted that the equivalence of the triangle to the true surplus is not a definition; it is a theorem, true under certain restrictive assumptions, but only if these assumptions are granted. A detailed analysis of these assumptions can be found in the literature and only the main points are summarised here.9

The use of a money measure of a utility change means it may not always be possible to guarantee uniqueness. A money measure can vary depending upon the order in which certain changes are assumed to occur. In particular, this problem arises where the utility change of interest involves a change in the price of more than one commodity, or an income and price change occur simultaneously. In these situations the order in which the changes are analysed can determine the size of the resulting money measure of welfare. When the path of adjustment affects the outcome in this manner there is path dependence.
Figure A1.2 Marshallian Consumer Surplus
Certain conditions when met can ensure that the money measure is unique i.e., path independent. For a simultaneous price-income change the consumer surplus is unique if and only if the income effect (or income elasticity) is zero. That is, the quantity consumed remains the same when income changes. For a price-price change the consumer surplus measure is unique if and only if all income elasticities of demand, for the goods whose prices change, are equal. (If the prices of all goods are changed then the income elasticity of demand must equal unity.) This means the consumer must adjust consumption of all goods whose price change, proportionally e.g., a ten percent increase in income causes a five percent increase in the quantity of butter and petroleum consumed (if these are the only goods consumed, the ten percent increase in income must cause a ten percent increase in the consumption of both goods).

These conditions restrict the scope of the analysis which can be performed while maintaining unique results. This would not pose a problem if the constraints were found in consumers' preference mappings in reality. Unfortunately, it seems unlikely that the conditions will hold in the majority of cases. It is improbable that the consumption of goods will not change as income changes. Although, there may be some goods for which the income elasticity is zero, e.g., salt, this is rarely true of most goods. Perhaps even more unlikely is the requirement that an income change cause consumption of all goods whose prices change to alter in proportion. "Such preference structures are contradicted by the bulk of empirical evidence." 10
Even when path independence is not a problem, changes in money measures of consumer surplus may not correspond to changes in utility, and the true surplus. The problem here is that the marginal utility of money (M.U.M.) may vary with respect to all prices that change as well as with respect to income, if it changes. Uniqueness of consumer surplus is not sufficient to guarantee any meaningful interpretation of the change in consumer surplus as a money measure of utility changes. In order to be a meaningful money measure, the M.U.M. must be constant, which guarantees uniqueness (but not vice versa).

Marshall assumed the M.U.M. was constant for two reasons: firstly, to permit the use of money as an acceptable cardinal index of utility; secondly, so that for movements along the ordinary demand curve, (a) the area under the demand curve would measure the total utility; and (b) the consumer surplus triangle would approximate the true surplus. In order to maintain an exactly constant M.U.M., with respect to price changes, the price elasticity of demand needs to be unity, and the marginal utilities of other goods should be unaffected (in fact Marshall went further and, as required by cardinal analysis, assumed independent marginal utilities).

In an indepth review of consumer welfare theory, Richard Just et al. concluded that the condition of constancy for the M.U.M. is "... at least as restrictive as the implications of path independence." They go on to state that:
... the economic implications of these conditions on the consumer indifference map are so restrictive as to prevent use of the "money measure of utility change" approach in an a priori sense for essentially all practical purposes. That is, one would have little basis for estimating money measures of utility change without first carrying out considerable empirical analysis to determine for example, whether or not all income elasticities of demand are consistent with the implications of path independence. Even then, constancy of marginal utility of income may not hold.\textsuperscript{12}

This is a strong attack upon the practicality of using the consumer surplus measure of utility. If this applied problem is combined with the underlying utilitarian background of cardinal analysis, the consumers surplus measure as proposed by Marshall becomes totally unacceptable. However, cardinal analysis was replaced by ordinal analysis and it was in this context that John Hicks redefined consumer surplus. When Hicks argued for the rehabilitation of consumers' surplus he stated:

If the marginal utility of money is constant, it implies that the consumer's demand schedules are unaffected by changes in his real income; all it need imply for this purpose is that the demand schedule for this commodity is unaffected (or substantially unaffected) by changes in real income which arise as a result of changes from one to another of various hypothetical situations which we may want to consider.

Hicks goes on to point out that the requirements for constant M.U.M. need not be unrealistic, and are equivalent to requiring that there be a small or negligible income effect.

Whenever the commodity in question is one on which the consumer is likely to be spending a small proportion only of his total income, the assumption of "constant marginal utility of money" can usually be granted; and it can still be granted, even if this condition is not fulfilled, provided the particular change under discussion does not involve a large net change in real incomes.\textsuperscript{14}

Thus, the practicability of the consumer surplus measure will vary depending on the complexity of the analysis, e.g., it might be argued that for the case of a price change in one good, which
is a small part of total expenditure, no problems arise. The more commodities whose prices change, the less likely is a money measure of the change in consumer surplus to match the change in the true surplus. Ordinal analysis, by concentrating on relative changes, allows money measures of consumer welfare to be developed which do not require the unrealistic preference assumptions of Marshall. Consumer surplus as a welfare measure in its own right implies unrealistic a priori assumptions and, if defined as a cardinal measure, departs from accepted indifference mappings.

Compensation Measures of Consumer Welfare

Hicks refined four measures of consumer welfare change resulting from a price change. These are compensating variation, compensating surplus, equivalent variation and equivalent surplus. The compensating surplus and equivalent surplus measures require that the quantity consumed be held constant, which constrains the consumer's freedom of choice, and are inapplicable to most policy situations. These two measures were designated as Marshallian by Henderson who originally specified the four measures. Mishan has contended that only equivalent variation and compensating variation are tenable in all familiar circumstances. However this contention may only hold under perfectly competitive equilibrium situations, and there are circumstances where compensating and equivalent surplus may be the more appropriate measures. Attention here is focused on the more commonly used measures which allow the consumer freedom to chose the quantities purchased after a change in the
economic environment —-compensating and equivalent variation.

In order to illustrate the meaning of these two measures it is assumed that only one commodity undergoes a price change. The results of this analysis can be generalised to the many goods case and more than one price change. In Figure A1.3 two goods X1 and X2 are shown along with the indifference mapping of an individual. Good X2, which can be regarded as a composite good, has a price of unity and acts as a numeraire. Good X1 has an initial price of p0. Now, assume air pollution reductions cause the cost of producing X1 to fall and the price changes from p0 to p1. If income is held constant at m0 the consumption of X2 falls from X2' to X2", and the quantity of X1 consumed increases from X1' to X1". This is the change according to a Marshallian demand curve.

The welfare gained by the consumer from this change can be defined by the variation in income. The compensating variation of the price fall is the sum of money that when taken away from the consumer leaves him or her just as well off with the price change as if it had not occurred. In Figure A1.3 this is given by the income m0-m1. That is, the vertical distance between the new budget line and a parallel line which is tangential to the original indifference curve. Thus, removing a sum of money m0-m1 after the price change will return the consumer to the original utility level U0.

The equivalent variation of a price fall is the sum of money that when given to the consumer leaves him or her just as well off without the price change as if it had occurred. In Figure
Figure A1.3
Compensating and Equivalent Variations
A1.3 this is given by income m2-m0, or the vertical distance between the original budget line \((m_0, \frac{m_0}{p_0})\) and a parallel line tangential to the new indifference curve. This sum of money may differ from the compensating variation, because income is being increased here whereas the compensating variation reduces income.

In order to show the relationship between these two measures it is helpful to derive the Hicksian Compensated Demand Curve (H.C.D.C.). This is done by expressing the changes, just described, in the price/quantity plane for \(X_1\). The top part of Figure A1.4 shows a similar change to before. There are two price levels of \(X_1\) shown, \(p_0\) and \(p_1\), and there are two utility levels, \(U_0\) and \(U_1\).

Before deriving the H.C.D.C. it is helpful to derive the ordinary or Marshallian demand curve. The Marshallian demand curve is given as:

\[
X_i = x_i(P, M)
\]

That is, the quantity of \(X_1\) demanded is a function of its price \(P\) and money income \(M\). This is the solution to the utility maximization problem:

Maximize \(U = U(X)\)

subject to \(\sum p_i x_i = M\)

where \(X\) is the vector of quantities \((X = x_1, \ldots, x_i, \ldots, x_n)\).

The Marshallian demand curve holds income constant and gives the quantity of a good demanded at different prices, while allowing utility to vary. In Figure A1.4 income is held constant at \(m_0\) while the price of \(X_1\) falls from \(p_0\) to \(p_1\). Maximizing utility subject to the budget constraint at the original price requires
Figure A1.4 Relationship Between Ordinary and Compensated Demand Curves
the consumption of \( q_1 \) of \( X_1 \), and at the new price \( q_2 \) of \( X_1 \). Thus two points on the price/quantity plane can be specified --- \( p_0, q_1 \) and \( p_1, q_2 \). These two points lie on a Marshallian demand curve which can be mapped by repeatedly changing the price. This curve is shown as \( D(m_0) \) in the bottom part of Figure A1.4.

An alternative method of approaching the utility maximization problem involves using the expenditure function. This is the dual to the above problem:

\[
\begin{align*}
\text{minimize} & \quad E = \sum p_i x_i \\
\text{subject to} & \quad U(X) = U_{\text{max}}
\end{align*}
\]

That is, minimize the expenditure on \( x_i \) subject to a utility constraint. The solution to this problem is

\[ x_i' = x_i'(P, U) \]

which is the H.C.D.C. In the bottom part of Figure A1.4 two such curves are derived.

The price of \( X_1 \) falls from \( p_0 \) to \( p_1 \) as before. However, as it does so, assume income is removed from the individual so as to leave him or her on the original indifference curve \( U_0 \). The result is to increase the quantity consumed from \( q_1 \) to \( q_3 \), not \( q_2 \) as before. This gives the two points \( p_0, q_1 \) and \( p_1, q_3 \) which lie on the H.C.D.C. \( H(U_0) \). The H.C.D.C. only takes account of the substitution effect, because the income effect is excluded by the reductions of income. As \( X_1 \) is a normal good so the income effect is positive and the H.C.D.C. is less elastic than the Marshallian demand curve.

The demand curve \( H(U_0) \) is relevant to the compensating variation which was defined above, and held \( U_0 \) constant. The
equivalent variation for the price fall holds U1 constant. The equivalent variation is the amount of income which if given to the individual would leave him or her just as well off without the price fall as with it. That is, the amount of income which shifts the original budget constraint to the right until it is tangential to the indifference curve which the individual would reach if the price had fallen. In the top part of Figure A1.4 after a fall in price to p1, the individual would have consumed q2. If instead, the price does not change, but income is increased until U1 is reached, the quantity of X1 demanded will be q4. The two points which are plotted in the bottom part of the figure are p1,q2 and p0,q4, and lie on the H.C.D.C. H(U1).

The compensating variation associated with the price fall is m0-m1, in the top of the figure, and the area to the left of H(0) and between the two price lines p0 and p1 in part (b). The equivalent variation for the same price change is m2-m0, in the top of the figure, and the area to the left of H(U1) and between the two price lines, in the bottom of the figure. In general, the area to the left of the H.C.D.C. cutting through the original position defines the compensating variation, whereas the area to the left of the H.C.D.C. cutting through the final position defines the equivalent variation.\(^{21}\)

The two measures will be the same if the income elasticity of demand for good X1 is zero. For a normal good the equivalent variation exceeds the compensating variation for a price decrease, and vice versa for a price increase. The higher the income elasticity of demand for X1, the larger is the difference between the compensating and equivalent variation, and between
each of these and the Marshallian consumers' surplus.

Given that these two measures are theoretically well established, there is a problem as to which should be used in a particular situation. Myrick Freeman attempted to answer this question using four criteria --- practicability, the implied property rights, the uniqueness of the measures and their consistency. He found both measures failed the first criterion. At the same time he notes that consumer surplus is relatively easy to calculate.

The second criterion does not favour either measure in preference to the other. Compensating variation takes the initial level of utility as the reference point. This presumes the individual has no right or claim to make purchases at the new set of prices. In contrast, equivalent variation presumes the individual has a right to the new set of prices and must be compensated if the new price set is not attained. The choice between the two measures therefore depends upon a value judgement as to which system of property rights is more equitable.

The third criterion is more decisive and "(F)or reasons that lie in the mathematics of the measurement technique, the answers are different for the two measures being considered." This criterion judges whether the measure is independent of the order of the price changes when multiple changes occur, i.e., it is concerned with path dependence. For example, reducing ozone pollution may reduce the price of a sensitive crop by increasing output. This price change may then cause the price of substitute commodities to alter. Freeman states:
The CV (compensating variation) is independent of the order of evaluation. The EV (equivalent variation) will be independent of the order of the evaluation only in the special case of a homothetic utility function, that is, where the income elasticities of the goods are unitary. Unless this condition is met there is no unique EV in the case of multiple price changes.

The implausibility of unitary income elasticities has already been discussed. Thus, compensating variation is the more appropriate measure in this instance.

The final criterion involves the situation where more than one policy option is available. The compensating variation may not provide a ranking of alternative policies that is consistent with individual preferences. The equivalent variation does not suffer from this deficiency, and is therefore favoured under these circumstances.

Thus, the choice between the two measures will depend upon the characteristics of the welfare change being analysed. For example, a price change which affects the prices of other goods but is the only policy option would favour the use of the compensating variation. However, while both measures are consistent with a theoretical definition of welfare, neither is readily observable from market data. The Marshallian consumer surplus is observable and lies between the two variation measures. This suggests the possibility of using consumer surplus as an approximation to the more theoretically justified variation measures.

The bottom half of Figure A1.4 is redrawn in Figure A1.5. The compensating variation associated with a price fall is exactly equal to area x. The equivalent variation associated with a price fall is given by area x+z+w. The consumer surplus is given by
Figure A1.5 Willig Approximation
area $x+z$. Thus, for a commodity with a positive income effect, the change in consumer surplus, due to a price fall from $p_0$ to $p_1$, is bounded from below by the compensating variation and from above by the equivalent variation; and differs from the compensating variation by area $z$ and from the equivalent variation by area $w$.\textsuperscript{25}

It was Robert Willig who calculated the accuracy with which consumer surplus could approximate the variation measures.\textsuperscript{26} Willig showed that under certain specific conditions, area $z$ and area $w$ could be calculated as percentage confidence limits to the consumer surplus estimate. In this way it could be shown that the areas $z$ and $w$ would be insignificant for most empirical studies. As Willig stated:

... observed consumer's surplus can be rigorously utilized to estimate unobservable compensating and equivalent variations --- the correct theoretical measures of welfare impact changes in prices and income on an individual.

This can be achieved by deriving,

... precise upper and lower bounds on the percentage errors of approximating the compensating and equivalent variations with consumer's surplus. These bounds can be explicitly calculated from observed demand data, and it is clear that in most applications the error of approximation will be very small. In fact, the error will often be overshadowed by errors involved in estimating the demand curve.\textsuperscript{27}
Footnotes


5. Dupuit, "Utility of Public Works".

6. Hicks, Demand Theory, p. 86.


8. Ibid, p. 41.


11. Ibid.

12. Ibid, p. 82.


14. Ibid.

15. Idem, Demand Theory.


Such as when government restricts quantities; or where goods are not perfectly divisible e.g., a given family may, under reasonable circumstances, consume only one or two automobiles, not 1.5. This essentially limits consumption quantities and may make the surplus, rather than the compensation, measures more appropriate.


See, Just et al., *Applied Welfare Economics*, p.87, for a willingness to pay interpretation.

The compensating variation equals the negative of the equivalent variation, and vice versa. That is, the compensating variation for a price fall equals the equivalent variation for a price rise, and vice versa.

Freeman, *Benefits of Environmental Improvement*, pp.43-47.

Ibid, p.45.

Ibid, pp.45-46.


Willig, "Consumer's Surplus Without Apology".

Ibid, p.31.
Unlike consumers' welfare theory there has been relatively little controversy surrounding producers' welfare measures. Producers' welfare can be measured directly and is observable; that is, there need be no problems choosing the best method of approximating an unobservable concept such as utility. Despite this, there are several methods of measuring producers' welfare. These can be placed into two categories—input market measures and output market measures. The output market is where a firm sells its production. Two measures will be discussed in this context; namely, producer surplus and quasi-rent. The input market is where factors of production (i.e., land, labour, and capital) are purchased by the firm. No measures are discussed in this context (as they do not form part of the empirical study) but some of the theoretical advantages of this approach are mentioned.

Producer surplus is the traditional approach to the measurement of producers' welfare, and was developed by Marshall. It is defined as the area above the short run supply curve and below the price line. It is assumed that the firm is operating in
a perfectly competitive market. The supply curve for all variable inputs is perfectly elastic; that is, the firm is able to purchase all the variable inputs it needs at a fixed price. It is also assumed that the costs of fixed factors are sunk, during the short run. For example, a farmer pays rent for land at the beginning of the season and cannot recoup that sum of money.

The producer surplus of a perfectly competitive firm is shown in Figure A2.1. The firm will supply nothing below the price $p_1$ because it cannot cover variable costs. As long as the price stays above the average variable cost (AVC) curve the firm can make payments on fixed costs. Above the average total cost (ATC) curve profits are made, as all costs are covered. The short run supply curve is SS and equals the marginal cost (MC) curve. Marshall's producer surplus is given by area $p_0,SS,p_1$. The surplus accrues to the firm via the ownership of fixed factors. Only these factors can receive payments above their marginal costs, because of their limited supply in the short run. In the long run these factors become variable and the surplus to the firm disappears.\(^2\) This short run economic rent is a quasi-rent to the firm, and producer surplus is one method of measuring it.

In the short run, the area above a competitive firm's supply curve and below the price line provides a measure of the excess of gross receipts over prime costs i.e., quasi-rent. Prime costs are the extra costs a firm incurs in order to produce a commodity, and which it could have avoided if it had not produced the commodity. Another measure of quasi-rent is total revenue (gross receipts) minus total variable costs (prime costs).\(^3\)
Figure A2.1  Producer Surplus

Figure A2.2  Quasi-rent
Figure A2.2 shows a similar situation to Figure A2.1. Total revenue is the quantity produced $q_0$ times the price $p_0$, and total variable cost is the quantity $q_0$ times the average variable cost $TVCO$. Thus, quasi-rent is given by area $x$.

Despite other possible measures of quasi-rent the producer surplus approach is "...the most common approach in empirical and graphical theoretic work...". The concept can also be applied at the industry level. The industry supply curve is the sum of the firms' marginal cost curves, and the area above this aggregate curve and below the price line is the aggregate surplus accruing to the owners of the firms. However, care is required when applying the producer surplus measure.

For example, relaxing the price elasticity of supply of variable inputs leads to the producer surplus measure being unrelated to actual welfare. Producer surplus will overstate actual welfare changes when the price of a necessary factor input increases as industry use of the factor expands. In Figure A2.3 the industry is in equilibrium at price $p_0$ and quantity $q_0$, and the producer surplus would be $p_0,B,A$ (if supply equalled $MC_0$). If the price were to rise to $p_1$, the firms, expecting marginal cost to remain at $MC_0$, would supply $q_1$. Working on the presumption that marginal cost (i.e., $MC_0$) equals the supply curve the producer surplus would be measured as $p_1,E,A$. However, as the factor demand increases, so does its price and the marginal cost curve shifts to $MC_1$. The area of producers' welfare is $p_1,D,C$ and $q_2$ is supplied, not $q_1$, at price $p_1$. The supply curve is $SS$ and does not equal the marginal cost curve. The area above the supply curve and below the price line bears no relationship to the
Figure A2.3 Producer Surplus and Non-elastic Factor Supply
economic rent accruing to producers.

Certain other conditions must also be met; namely, that the income, or welfare, effect be zero and that nonpecuniary advantages be unimportant to producers. A zero income effect is required to maintain economic rent as an objective measure which can be captured by producer surplus without recourse to individual preferences. As long as the firms are explicit profit maximizers they are unaffected by welfare effects. Thus, there is no divergence between money measures and welfare changes as there is with consumer theory (where compensating or equivalent variations being different money measures of the same utility change diverge when income effects are not zero). Similarly, nonpecuniary goals must not conflict with profit maximizing behaviour or producer surplus will not capture the full extent of economic rent.

The conditions for producer surplus to act as a good measure of welfare have been summarised by Mishan. He concluded that the supply curve must be:

... constructed for a period during which the output of the good in question can be increased only by adding to fixed-factors amounts of other factors that are imperfect substitutes for it but are perfectly elastic in supply with respect to their money prices. In such cases the rent of the fixed factor is exactly equal to the area above the supply curve under the conditions mentioned --- zero welfare effect and complete indifference to nonpecuniary advantages. The further we move from these conditions, especially the latter condition, the greater the divergence between the true rent (either compensating or equivalent variation) and the area in question.

Mishan contended that the term producer surplus is misleading. The producer referred to is in fact the owner of the firm, while it is only via ownership of fixed factors that any
surplus accrues to the firm. It is more accurate to use the term producer in reference to the input factor of concern, and therefore to the "owner" to whom the economic rent is directly attributable. Currie et al. agree with Mishan and feel, "(I)t is more satisfactory to think in terms of economic rent ---rent to a short-run fixity of some factor of production, rent to land, rent to entrepreneurial ability, rent to market power and so on." 

Mishan has argued in favour of input market measures. This approach is analogous to the consumer welfare measures of Hicks, and involves individual preferences. It avoids the problem just outlined by working directly with the factors of production which create the welfare. Mishan found "... that consumer's surplus and economic rent are both measures of the change in the individual's welfare when the set of prices facing him are changed or the constraints imposed upon him are altered. Any distinction between them is one of convenience only: consumer's surpluses have reference to demand prices, economic rent to supply prices." 

This leaves the applied welfare economist with a choice as to whether economic rent is to be measured in the input market or the output market. This choice may often be made by the availability of data. Thus, it can be more practical to measure economic rent by the area above the supply curve and below the price line. Divergences between the theoretical assumptions and actual market conditions can cause serious errors in measuring gains and losses using producer surplus. Thus, the proximity of actual conditions to the theoretical must be assessed and
corrections and qualifications made where necessary. If this is done, and divergences are not serious, the producer surplus can be justified as a measure of economic rent.

Footnotes


3. Yet another measure is given in, Just et al., Applied Welfare Economics, pp.55-56.


5. This example is taken from Currie et al., "Concept of Economic Surplus", p.755 footnote 4.


APPENDIX III

A MULTIPLE-OUTPUT MULTIPLE-INPUT MODEL
OF THE AGRICULTURAL SECTOR
IN BRITISH COLUMBIA

Introduction

In this appendix a dual model with two outputs and three inputs is presented for the agricultural sector in B.C. This aggregate model of crop production was originally intended for use in an aggregate analysis of the response of producers and consumers to alterations in ambient ozone levels. However, the best model estimated from available data showed serious parameter errors. This model, the data base and parameter estimates are presented. Chapter 5 applies an alternative methodology to potato production and analyses the damages from variations in ambient ozone dose.

As shown in Chapter 3, duality theory has been employed by the most recent econometric studies of agricultural production. Duality approaches to microeconomic theory have been reviewed by Diewert.\textsuperscript{1} The dual approach involves specification and estimation of cost or profit functions which, unlike production functions, already embody the optimizing behaviour of producers. A cost
function, for example, relates the minimum costs of producing a given output to input prices and the output level. The nature of the cost function is determined by production characteristics, which can be retrieved from the parameters of the function. Advantages of the dual approach include the ease of deriving the marginal cost functions for outputs and of measuring elasticities of factor demand and substitution.  

First the theoretical cost function model is described and the assumptions necessary for a well defined function are presented. The behavioural implications of the model are then discussed in the context of agriculture. Next the empirical model is introduced and a functional form is specified, and the database is outlined. The empirical model is then applied to the agricultural sector in B.C. Parameter estimates are used to derive ray and product-specific scale economies, and factor elasticities of substitution and demand. Finally, the inaccuracy of the parameter estimates is outlined.
The Theoretical Model

Cost Function

A fundamental paradigm in economics is that producers competitively minimize costs subject to technological constraints. Competition in this context means that factor prices are fixed, during a given time period, irrespective of an individual producers' demand. Thus, the cost function gives the minimum value of producing a given quantity of output at fixed factor prices.\(^3\)

Assume that one output \(y\) is produced using \(N\) inputs; and that the nonnegative vector of inputs \(x=(x_1,\ldots,x_n)\) produces a nonnegative, maximal amount of \(y\) in a given period. Furthermore, the cost of purchasing one unit of input \(i\) is \(p_i>0\), \(i=1,\ldots,N\), and that the positive vector of input prices facing the producer is \(p=(p_1,\ldots,p_n)\). The cost minimization problem is,

\[
\min C = \sum_{i=1}^{n} x_i^\prime P_i \quad (i=1,2,\ldots,n)
\]

subject to \(Y = f(x_1,x_2,\ldots,x_n)\),

and a solution to this problem can be written as,

\[
C = f(y,p_1,\ldots,p_n),
\]

which is the cost function.

The cost function \(C\) has the following properties:\(^4\)

1. Nonnegative; i.e., \(C(y,p)>0\).
2. Linearly homogeneous in input prices for each fixed output level; i.e. \(C(y,hp)=hC(y,p)\) for \(y>=0\) and \(h>=0\).
3. Nondecreasing in input prices for a fixed output; i.e., \(C(y,p_1)>=C(y,p_2)\) for \(y>=0\), \(p_1>=p_2>=0\).
4. Concave in prices for a fixed output.
5. Nondecreasing in output for fixed prices; i.e. \( C(y',p) \geq C(y'',p) \) for \( y' \geq y'' \geq 0 \).

6. Continuous from below in output for fixed prices.

Given a minimum cost function \( C(y,p) \) which satisfies these properties and is differentiable with respect to input prices then:

\[
\frac{\partial C(y,p)}{\partial p_i} = x_i(y,p) \quad i(1, \ldots, N).
\]

where \( x_i(y,p) \) is a cost minimizing bundle of input \( i \) needed to produce output \( y > 0 \) given positive factor prices \( p >> 0 \). That is, the cost minimizing demand for the \( i \)th input is equal to the partial differential of the cost function with respect to the \( i \)th input price. This result is commonly called Shephard's lemma.

Behavioural Assumptions

Implicit in the theoretical cost function are several behavioural assumptions. Producers are assumed to take prices as given and optimize with respect to the quantity variables they control. Defence of these assumptions can be made in general for agricultural production at the firm and regional levels, but may be violated by the circumstances concerning particular products.

At the farm level, output prices are unlikely to be influenced by the individual farmer because agricultural products are homogeneous and supplied by a relatively large number of farms. Where fewer, larger, farms exist or regional output is concerned, price may still be assumed to be exogeneous to production because of interregional competition. Thus, in the case of crop production in B.C., the United States (especially, Washington and California) provides considerable competition for
the producers of many products. 7

In the demand for factors of production the agricultural sector also seems likely to be a price taker. Labour in most industrial countries is largely employed in the manufacturing and service industries. If labour is mobile, farm wages may be set by these much larger sectors. 8 Alternatively, the price of some factors may be cost determined, e.g., petrol determining the price of fertilizer. 9 Evidence also exists to suggest that the price of machinery is exogeneous to the agricultural sector and is largely determined by fuel costs, and cost conditions in the machinery producing and repairing industries. 10 Land is a possible exception to the exogeneous factor price assumption with agriculture being a land intensive activity. However, even in this case, proximity to a major urban area may be the most important determinant of price. Thus, in general, the assumption that factor prices are exogeneous to agriculture appears acceptable.
Econometric Model

The Multiple-Output Multiple-Input Translog Cost Function

In order to generate a system of input demand (and output supply) equations a functional form for the cost function has to be postulated, and then partially differentiated with respect to each input (and each output quantity). The m-output n-input translog cost function incorporating Hicks Neutral Technical Change (HNTC) is defined as follows:

\[
\ln C = \ln k + \sum_{i=1}^{m} a_i \ln q_i + \frac{1}{2} \sum_{i=1}^{m} \sum_{j=1}^{m} d_{ij} \ln q_i \ln q_j \\
+ \sum_{r=1}^{n} b_r \ln W_r + \frac{1}{2} \sum_{r=1}^{n} \sum_{s=1}^{n} f_{rs} \ln W_r \ln W_s \\
+ \sum_{i=1}^{m} \sum_{r=1}^{n} g_{ir} \ln q_i \ln W_r + hT \tag{1}
\]

where \( C \) is cost; \( q_i \) is the output of product \( i \); \( W_r \) is the price of input \( r \); \( T \) is an annual index of time; and \( a_i, d_{ij}, b_r, f_{rs} \) and \( g_{ir} \) are parameters determined by the technology of the industry.\(^{10}\)

Differentiating both sides with respect to the logarithm of the \( r \)th input price gives the input cost share, or factor demand, equation:

\[
s_r = b_r + \sum_{s=1}^{n} f_{rs} \ln W_s + \sum_{i=1}^{n} g_{ir} \ln q_i \tag{2}
\]

where, \( r=(1,\ldots,n) \), \( s_r=W_r/C \) and \( x_r \) is the quantity of the \( r \)th input. The input share equations are derived from the translog cost function and Shephard's lemma.\(^{11}\)

In an \( m \)-output \( n \)-input model with matrices \((d_{ij})\) and \((f_{rs})\)
symmetrical the number of parameters to be estimated is \((m+n)(3+m+n)/2\), which is twenty parameters in this model of B.C. agriculture, not including the intercept and HNTC. In practice the data available are often not sufficient to allow estimation of the full cost function, even with the restrictions imposed by homogeneity in input prices. Estimating the full dual system (i.e., cost and share equations together) is a more efficient econometric approach and can compensate for informational inadequacy in the estimation of the cost function alone.\(^{13}\)

Hall\(^{14}\) has suggested that for the case of perfect competition, another \(m\) behavioural equations can be obtained by noting that marginal cost is equal to price. In the case of the translog function there would be \(m\) equations of the form:

\[
R_i = \frac{\partial \ln C}{\partial \ln q_i} = \left(\frac{\partial C}{\partial q_i}\right) \frac{C}{q_i} = \frac{p_i q_i}{C},
\]

where \(R_i\) is the share of the \(i\)th output in total revenue.\(^{15}\) These revenue share equations can be more fully specified as:

\[
R_i = a_i + \sum_{i=1}^{m} d_{ij} \ln q_j + \sum_{r=1}^{n} g_{ir} \ln W_r
\]

The parameters of the cost function, excluding the intercept, could be estimated indirectly from a system of input and revenue share equations alone. The estimation of cost, revenue and share equations together further increases the efficiency of parameter estimates. This approach has been applied in a cost function study of U.S. agriculture (1939-77) by Ray.\(^{16}\) Employing the revenue share equations for B.C. data gave improved parameter estimates (evidenced by the t-statistic) and this approach was used in the final model. Following Ray, instead of using price
indices to obtain \( p_i q_i / C \), the numerator is directly measured as market sales revenue plus government payments.

Additional econometric considerations are, (a) that the cost share equations add to one and, (b) that the parameters which occur in more than one equation are unique across equations. Symmetry restrictions, implied by the twice differentiable nature of the cost function, are assumed, i.e., \( d_{ij} = d_{ji} \) and \( f_{rs} = f_{sr} \). From property two for cost functions given above, the economic constraint of linear homogeneity in input prices arises, e.g., the total cost doubles when all factor prices double. This basic requirement implies,

\[
\sum_{r=1}^{n} a_r = 1, \quad \sum_{r=1}^{n} f_{sr} = 0, \quad \text{and} \quad \sum_{i=1}^{n} g_{ir} = 0 \quad \text{for} \quad r=(1,\ldots,n).
\]

Under the condition that the sum of the cost shares is unity, the symmetry and homogeneity constraints imply exactly the same constraints on the parameters.\(^{17}\)

### Variable Definitions and Data Description

Time series data were collected for the period 1961 to 1984 for two outputs and three inputs. All time series data were converted to index numbers with base year 1981 before estimation. Output \( q_1 \) is livestock output and \( q_2 \) is crop output. These outputs are measured by the total cash receipts from each in B.C.\(^{18}\) The prices and cost shares of the three inputs capital \( K \), labour \( L \) and miscellaneous \( M \), are required in order to estimate equations 1 and 2.

The cost of labour was taken as the total wage bill paid to
farm labour in B.C.\textsuperscript{19} The price of labour ($W_1$) was calculated, from monthly farm wages for B.C., as an annual wage rate without board.\textsuperscript{20}

The cost of farm capital was calculated as the capital stock multiplied by the chartered bank prime business loan rate, deflated.\textsuperscript{21} Capital stock was taken as the current value of livestock, land and buildings, and implements and machinery, which was then deflated by a capital price index (1981=100).\textsuperscript{22} The interest rate used above was taken as the price of capital ($W_2$).

Miscellaneous, or aggregate intermediate, inputs were calculated as the summation of farm operating expenses for B.C. This categorization includes expenditures on fertilizer and seed, feeds, other animal and crop expenses, fuel and electricity, debt and miscellaneous expenses.\textsuperscript{23} The miscellaneous input price was measured by the price index of all commodities purchased for farm production ($W_3$).\textsuperscript{24}

The dependent variables are as follows:

- $SH_{LABR} = (\text{total wages to farm labour})/(\text{farm operating expenses})$
- $SH_{CAPT} = (\text{capital cost})/(\text{farm operating expenses})$
- $SH_{MISC} = (\text{miscellaneous expenses})/(\text{farm operating expenses})$
- $SH_{REV1} = (\text{livestock marketing revenue})/(\text{farm operating expenses})$
- $SH_{REV2} = (\text{crop marketing revenue + government payments})/(\text{farm operating expenses})$, and
- $COST = \text{an index of farm operating expenses, i.e., the sum of input costs}$. 

204
Empirical Results
Cost Function for B.C. Agriculture

Various models were estimated in order to obtain the best parameter estimates using the t-test statistic. The full unrestricted model with 22 parameters was initially estimated. This model gave insignificant values for all \( g_{ir} \) terms, with the approximate probability of being greater than the t-statistic varying from 0.58 to 0.99. On this basis a test for separability was performed. Separability in the translog requires that:

\[
\frac{\partial}{\partial \ln W_i} \left( [a_i + \sum_{i=1}^{m} d_{ij} \ln q_j + \sum_{r=1}^{n} g_{ir} \ln W_r] \right) = 0 \tag{4}
\]

That is, the relative marginal costs of outputs are independent of the input prices. Separability holds if: \( g_{ir} = 0 \) \( (i=1, \ldots, n), (r=1, \ldots, n) \). The computed F-value (with 6 and 8 degrees of freedom) was 0.5801, which is insignificant. The probability greater than F was 0.7384. Consequently separability was accepted and the term

\[
\sum_{i=1}^{m} \sum_{r=1}^{n} g_{ir} \ln q_i \ln W_r,
\]

was excluded from the final model.

The time trend variable \( T \) was set to one in 1961 and increased annually by one. Time trend parameters were estimated for all three inputs and tested for significance. The F-value was 1.5772 (with 3 and 10 degrees of freedom) and insignificant with a probability greater than F of 0.2191. This result supports the use of HNTC, and provides evidence that technical change in B.C.
agriculture has not been biased in favor of specific inputs.

The parameters of the final cost function model, assuming separability, are shown in Table A3.1, together with their standard errors and T-test statistic. The revenue and input share equations are reported in Appendix IV. The parameters of the cost function have little economic meaning of their own, but are related to the elasticities of input substitution and factor demand. In order to evaluate the model, these elasticities and the ray and product-specific economies of scale were calculated. As is shown below, the scale economies appear realistic but the input elasticities show that there are serious problems with the estimated model.

Scale Economies

The estimated parameters reported in Table A3.1 were used to calculate scale economies at each data point. Scale economies may be expressed as the relative change in output when costs change but input prices are held constant. Christensen and Greene define scale economies (SCE) for the single output industry as:

\[ \text{SCE} = 1 - \frac{\partial \ln C}{\partial \ln Y}, \]  

where \( C \) is costs and \( Y \) output. This results in positive numbers for increasing scale economies and negative numbers for diseconomies of scale.

The concept of scale economies can be applied to the multiproduct industry by the use of two related measures: ray economies of scale and product-specific economies of scale. Ray economies of scale are an extension of the concept of single-product scale economies and indicate the behaviour of costs as a
Table A3.1 Parameter Estimates for Translog Cost Function of Agriculture in B.C.

| Variable  | Parameter Estimate | Standard Error | T Ratio | Approx Prob>|T| |
|-----------|-------------------|----------------|---------|-------------|
| Intercept | -0.242278         | 0.073033       | -3.3174 | 0.0106      |
| T (trend) | 0.073323          | 0.024647       | 2.9749  | 0.0177      |
| a1        | 0.767015          | 0.033016       | 23.2315 | 0.0001      |
| a2        | 0.441412          | 0.016373       | 26.9598 | 0.0001      |
| d11       | 0.408438          | 0.113015       | 3.6140  | 0.0068      |
| d12       | -0.630085         | 0.057840       | -10.8935| 0.0001      |
| d22       | 0.522477          | 0.030082       | 17.3685 | 0.0001      |
| b1        | 0.140495          | 0.004405       | 31.8967 | 0.0001      |
| b2        | 0.279689          | 0.009316       | 30.0226 | 0.0001      |
| b3        | 0.579816          | 0.008321       | 69.6799 | 0.0001      |
| f11       | 0.079989          | 0.039132       | 2.0441  | 0.0752      |
| f12       | 0.159833          | 0.063569       | 2.5143  | 0.0361      |
| f13       | -0.239822         | 0.072909       | -3.2893 | 0.0110      |
| f22       | 1.105387          | 0.141610       | 7.8058  | 0.0001      |
| f23       | -1.265221         | 0.144578       | -8.7512 | 0.0001      |
| f33       | 1.505042          | 0.188401       | 7.9885  | 0.0001      |
given bundle of outputs change proportionately. In the case of the m-output n-input translog cost function, this can be defined as:

\[
SCE = 1 - \sum_{i=1}^{m} \frac{\partial \ln C}{\partial \ln q_i}
\]  \hspace{1cm} (6)

That is 1 minus the cost elasticity along an output ray.

Instead of holding the composition of output fixed while the scale varies, one output can be varied while other outputs are held constant. This gives the product-specific economies of scale which can be defined for ith output in the translog cost function as:

\[
SCE_i = 1 - (a_i + \sum_{i=1}^{m} d_{ij} \ln q_j + \sum_{r=1}^{n} g_{ir} \ln w_r)
\]  \hspace{1cm} (7)

Since the cost function for B.C. agriculture is separable the product-specific scale economies can be restated as:

\[
SCE_i = 1 - (a_i + \sum_{i=1}^{m} d_{ij} \ln q_j)
\]  \hspace{1cm} (8)

On the basis of these equations the ray and product-specific economies of scale for the B.C. agricultural model were calculated. The results are shown in Table A3.2. Clearly increasing economies of scale exist across all data points for both livestock and crop outputs, while the ray scale economies show decreasing returns. This implies output specialisation is preferable to joint production. Table A3.2 also shows that the economies of scale in livestock production have increased, while those for crop production have remained relatively stable. The overall diseconomies have been increasing.
Table A3.2. Product-Specific and Ray Economies of Scale for Agriculture in B.C.

<table>
<thead>
<tr>
<th>Year</th>
<th>Livestock SCE1</th>
<th>Crop SCE2</th>
<th>Overall SCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>61</td>
<td>0.090404</td>
<td>0.594598</td>
<td>-0.31500</td>
</tr>
<tr>
<td>62</td>
<td>0.099650</td>
<td>0.599705</td>
<td>-0.30064</td>
</tr>
<tr>
<td>63</td>
<td>0.133001</td>
<td>0.562056</td>
<td>-0.30494</td>
</tr>
<tr>
<td>64</td>
<td>0.159918</td>
<td>0.537319</td>
<td>-0.30276</td>
</tr>
<tr>
<td>65</td>
<td>0.109351</td>
<td>0.593465</td>
<td>-0.29718</td>
</tr>
<tr>
<td>66</td>
<td>0.136882</td>
<td>0.582209</td>
<td>-0.28091</td>
</tr>
<tr>
<td>67</td>
<td>0.166325</td>
<td>0.554500</td>
<td>-0.27917</td>
</tr>
<tr>
<td>68</td>
<td>0.156695</td>
<td>0.567652</td>
<td>-0.27565</td>
</tr>
<tr>
<td>69</td>
<td>0.092905</td>
<td>0.618734</td>
<td>-0.28836</td>
</tr>
<tr>
<td>70</td>
<td>0.150526</td>
<td>0.565068</td>
<td>-0.28441</td>
</tr>
<tr>
<td>71</td>
<td>0.129103</td>
<td>0.584596</td>
<td>-0.28630</td>
</tr>
<tr>
<td>72</td>
<td>0.114174</td>
<td>0.611454</td>
<td>-0.27437</td>
</tr>
<tr>
<td>73</td>
<td>0.178829</td>
<td>0.586647</td>
<td>-0.23452</td>
</tr>
<tr>
<td>74</td>
<td>0.170520</td>
<td>0.597946</td>
<td>-0.23153</td>
</tr>
<tr>
<td>75</td>
<td>0.128471</td>
<td>0.628296</td>
<td>-0.24323</td>
</tr>
<tr>
<td>76</td>
<td>0.136650</td>
<td>0.624377</td>
<td>-0.23897</td>
</tr>
<tr>
<td>77</td>
<td>0.188641</td>
<td>0.572336</td>
<td>-0.23902</td>
</tr>
<tr>
<td>78</td>
<td>0.217129</td>
<td>0.554040</td>
<td>-0.22883</td>
</tr>
<tr>
<td>79</td>
<td>0.215936</td>
<td>0.563121</td>
<td>-0.22094</td>
</tr>
<tr>
<td>80</td>
<td>0.214650</td>
<td>0.569608</td>
<td>-0.21574</td>
</tr>
<tr>
<td>81</td>
<td>0.232985</td>
<td>0.558588</td>
<td>-0.20843</td>
</tr>
<tr>
<td>82</td>
<td>0.191288</td>
<td>0.593887</td>
<td>-0.21482</td>
</tr>
<tr>
<td>83</td>
<td>0.191676</td>
<td>0.577869</td>
<td>-0.23045</td>
</tr>
<tr>
<td>84</td>
<td>0.190069</td>
<td>0.588134</td>
<td>-0.22180</td>
</tr>
<tr>
<td>Mean</td>
<td>0.158157</td>
<td>0.582758</td>
<td>-0.25908</td>
</tr>
</tbody>
</table>
These findings are supported by Ray, who developed a cost function model for U.S. agriculture for the period 1939 to 1977. He reported scale economies for selected years, and those close to the period used here are presented in Table A3.3. These estimates show the same product-specific increasing returns and overall decreasing returns as found for B.C. In addition the trends of all three scale economies are similar to those reported here. Although the absolute value of scale economies is different for each product between the U.S. and B.C., the overall economies are quite close. For example, the ray scale economies for B.C. in 1969 and 1977 were -0.28836 and -0.23902 respectively compared with -0.27065 and is -0.19875 in Ray's study.

Table A3.3. Product-Specific and Overall Scale Economies Reported by Ray

<table>
<thead>
<tr>
<th>Year</th>
<th>Livestock</th>
<th>Crop</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>1959</td>
<td>0.246591</td>
<td>0.343703</td>
<td>-0.409642</td>
</tr>
<tr>
<td>1969</td>
<td>0.342322</td>
<td>0.386992</td>
<td>-0.270648</td>
</tr>
<tr>
<td>1977</td>
<td>0.413283</td>
<td>0.388005</td>
<td>-0.1987532</td>
</tr>
</tbody>
</table>


Elasticities of Substitution

The partial elasticities of substitution for the translog cost function were calculated using the formulae:

\[ e_{ij} = 1 + \left( \frac{a_{ij}}{s_i \cdot s_j} \right) \quad (9) \]

\[ i = K, L, M, \text{ for } i \text{ not equal to } j; \]
\[ e_{ij} = \frac{a_{ii} + s_i(s_i - 1)}{s_i S_i} \]

where \( e_{ij} \) is the elasticity of substitution between inputs, and \( s_i \) is the share of the \( i \)th input.\(^{32}\) The partial elasticities of substitution are related to the price elasticity of demand for factors of production:\(^{33}\)

\[ E_{ij} = s_j e_{ij}. \]

These formulae are the same for single and multiple output industries. The elasticities of substitution calculated for the B.C. model are shown in Table A3.4 and are compared with the results reported by others in Table A3.5. While comparison of results is complicated by the use of different time periods, factor classifications, and areas of study, the underlying technology is not expected to vary and results are expected to conform to theoretical expectations (e.g., own price elasticity should be negative). The main differences between the B.C. model and other studies are the regional nature of the model, and that the capital category, like that of Ray (1982), includes land instead of treating it as a separate input.

The estimated substitution of labour and miscellaneous inputs is the only elasticity of substitution close to previous estimates. This estimate is almost twice that reported by Ray for a more disaggregate classification of miscellaneous. Both of Ray's other categories, aggregated as miscellaneous here, and the results of other studies show positive elasticities (i.e., labour and miscellaneous inputs are complements). Labour and capital are found to be complements as in other work but the size of the elasticity this time is more than twice the closest estimate.
### Table A3.4. Translog Cost Function Estimation of Partial Elasticities of Substitution

<table>
<thead>
<tr>
<th>YEAR</th>
<th>esLK</th>
<th>esLM</th>
<th>esKM</th>
<th>esLL</th>
<th>esKK</th>
<th>esMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>61</td>
<td>3.76690</td>
<td>-2.4195</td>
<td>-6.0804</td>
<td>-2.1132</td>
<td>5.9038</td>
<td>5.79018</td>
</tr>
<tr>
<td>63</td>
<td>4.23800</td>
<td>-2.2684</td>
<td>-6.1694</td>
<td>-2.0829</td>
<td>7.4088</td>
<td>4.78473</td>
</tr>
<tr>
<td>64</td>
<td>3.98490</td>
<td>-2.3226</td>
<td>-6.1196</td>
<td>-2.1030</td>
<td>6.6304</td>
<td>5.23977</td>
</tr>
<tr>
<td>65</td>
<td>4.09586</td>
<td>-2.2616</td>
<td>-6.1697</td>
<td>-2.0997</td>
<td>7.0803</td>
<td>4.99361</td>
</tr>
<tr>
<td>68</td>
<td>3.86366</td>
<td>-2.2616</td>
<td>-6.1832</td>
<td>-2.1182</td>
<td>6.5328</td>
<td>5.41016</td>
</tr>
<tr>
<td>69</td>
<td>3.94302</td>
<td>-2.2197</td>
<td>-6.2124</td>
<td>-2.1165</td>
<td>6.8461</td>
<td>5.21674</td>
</tr>
<tr>
<td>70</td>
<td>3.82663</td>
<td>-2.2578</td>
<td>-6.1918</td>
<td>-2.1204</td>
<td>6.4597</td>
<td>5.48172</td>
</tr>
<tr>
<td>71</td>
<td>3.85692</td>
<td>-2.2371</td>
<td>-6.2052</td>
<td>-2.1201</td>
<td>6.5898</td>
<td>5.39866</td>
</tr>
<tr>
<td>72</td>
<td>4.00134</td>
<td>-2.1661</td>
<td>-6.2610</td>
<td>-2.1172</td>
<td>7.1660</td>
<td>5.06382</td>
</tr>
<tr>
<td>73</td>
<td>4.92464</td>
<td>-1.9486</td>
<td>-6.7360</td>
<td>-2.0773</td>
<td>11.0036</td>
<td>3.85802</td>
</tr>
<tr>
<td>74</td>
<td>5.19334</td>
<td>-1.8919</td>
<td>-6.9461</td>
<td>-2.0681</td>
<td>12.4079</td>
<td>3.64547</td>
</tr>
<tr>
<td>75</td>
<td>4.82004</td>
<td>-1.9207</td>
<td>-6.7393</td>
<td>-2.0919</td>
<td>10.8046</td>
<td>3.92573</td>
</tr>
<tr>
<td>76</td>
<td>4.52311</td>
<td>-1.9383</td>
<td>-6.6131</td>
<td>-2.1093</td>
<td>9.6761</td>
<td>4.20491</td>
</tr>
<tr>
<td>77</td>
<td>4.03716</td>
<td>-2.0273</td>
<td>-6.4106</td>
<td>-2.1237</td>
<td>7.7769</td>
<td>4.88342</td>
</tr>
<tr>
<td>78</td>
<td>4.56459</td>
<td>-1.9213</td>
<td>-6.6504</td>
<td>-2.1091</td>
<td>9.9101</td>
<td>4.15331</td>
</tr>
<tr>
<td>79</td>
<td>5.43060</td>
<td>-1.8410</td>
<td>-7.1578</td>
<td>-2.0627</td>
<td>13.7933</td>
<td>3.48710</td>
</tr>
<tr>
<td>80</td>
<td>5.06631</td>
<td>-1.9028</td>
<td>-6.8698</td>
<td>-2.0761</td>
<td>11.8360</td>
<td>3.73356</td>
</tr>
<tr>
<td>81</td>
<td>5.06752</td>
<td>-1.9440</td>
<td>-6.8019</td>
<td>-2.0653</td>
<td>11.5553</td>
<td>3.75212</td>
</tr>
<tr>
<td>83</td>
<td>4.12803</td>
<td>-2.1166</td>
<td>-6.3159</td>
<td>-2.1138</td>
<td>7.6748</td>
<td>4.81921</td>
</tr>
<tr>
<td>84</td>
<td>4.10364</td>
<td>-2.1171</td>
<td>-6.3137</td>
<td>-2.1152</td>
<td>7.6074</td>
<td>4.85640</td>
</tr>
<tr>
<td>Mean</td>
<td>4.34243</td>
<td>-2.1148</td>
<td>-6.4246</td>
<td>-2.1002</td>
<td>8.5492</td>
<td>4.66522</td>
</tr>
</tbody>
</table>
Table A3.5. Sample Mean Elasticities of Substitution in Agricultural Cost Function Studies

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Binswanger 1974</td>
<td>2.22</td>
<td>0.851</td>
<td>0.204</td>
<td>1.844</td>
<td>-0.31</td>
<td></td>
</tr>
<tr>
<td>Lopez 1980</td>
<td>0.875</td>
<td>1.779</td>
<td>0.113</td>
<td>1.555</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>Ray 1982</td>
<td>-1.147*</td>
<td>0.748</td>
<td></td>
<td>1.661*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adamowicz 1986</td>
<td>1.392</td>
<td>0.553</td>
<td>-0.138</td>
<td>0.089</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>Spash 1987</td>
<td>-2.117</td>
<td>4.10364</td>
<td></td>
<td>-6.4246</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Ray reports feed, seed and livestock costs as a separate input giving substitution elasticities with labour of 1.527 and with capital of 0.486. Table 15 gives further details of all the models.
Finally, miscellaneous and capital inputs are found to be complements which is clearly not supported. One explanation might be the presence of strong complementarity between land and miscellaneous, which overshadows the substitutability with capital. However, such complementarity is only reported by Adamowicz whose estimate was not significant.\textsuperscript{34}

The own elasticity of substitution has little economic meaning and is normally used to calculate the price elasticity via equation 9. However, if the demand for inputs is to be negatively sloped, as is expected, the own substitution elasticity must be negative. As can be seen in Table A3.4, this is not the case for capital or miscellaneous inputs. The own price elasticities calculated from our share and parameter estimates are reported in Table A3.6 and compared with other studies in Table A3.7. The mean price elasticity for labour is of the correct sign, and inelastic as expected. The estimate for labour is comparable to that found by Adamowicz for Canadian agriculture. However the outstanding problem is with the capital and miscellaneous demand elasticities which, as expected from the substitution estimates, are positive.

The size of the error in the parameter estimates can be calculated from the predicted mean shares for given elasticities using the equations:

\[ f_{ij} = (e_{ij}^{-1}) (s_i \cdot s_j), \]

and

\[ f_{ii} = E_{ii} \cdot s_i + s_i (1+s_i). \]

These equations are calculated from 9, 10 and 11. Table A3.8
<table>
<thead>
<tr>
<th>YEAR</th>
<th>Labour</th>
<th>Capital</th>
<th>Misc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>61</td>
<td>-0.31820</td>
<td>2.26494</td>
<td>2.69698</td>
</tr>
<tr>
<td>62</td>
<td>-0.30217</td>
<td>2.49508</td>
<td>2.49133</td>
</tr>
<tr>
<td>63</td>
<td>-0.29840</td>
<td>2.55273</td>
<td>2.45066</td>
</tr>
<tr>
<td>64</td>
<td>-0.31013</td>
<td>2.40746</td>
<td>2.56451</td>
</tr>
<tr>
<td>65</td>
<td>-0.30796</td>
<td>2.49228</td>
<td>2.50344</td>
</tr>
<tr>
<td>66</td>
<td>-0.30719</td>
<td>2.57758</td>
<td>2.45143</td>
</tr>
<tr>
<td>67</td>
<td>-0.31951</td>
<td>2.43240</td>
<td>2.56599</td>
</tr>
<tr>
<td>68</td>
<td>-0.32333</td>
<td>2.38872</td>
<td>2.60611</td>
</tr>
<tr>
<td>69</td>
<td>-0.32140</td>
<td>2.44844</td>
<td>2.55885</td>
</tr>
<tr>
<td>70</td>
<td>-0.32617</td>
<td>2.37462</td>
<td>2.62342</td>
</tr>
<tr>
<td>71</td>
<td>-0.32572</td>
<td>2.39967</td>
<td>2.60332</td>
</tr>
<tr>
<td>72</td>
<td>-0.32213</td>
<td>2.50818</td>
<td>2.52098</td>
</tr>
<tr>
<td>73</td>
<td>-0.29562</td>
<td>3.14888</td>
<td>2.20493</td>
</tr>
<tr>
<td>74</td>
<td>-0.29139</td>
<td>3.35663</td>
<td>2.14565</td>
</tr>
<tr>
<td>75</td>
<td>-0.30326</td>
<td>3.11848</td>
<td>2.22357</td>
</tr>
<tr>
<td>76</td>
<td>-0.31485</td>
<td>2.94089</td>
<td>2.29925</td>
</tr>
<tr>
<td>77</td>
<td>-0.33185</td>
<td>2.61906</td>
<td>2.47571</td>
</tr>
<tr>
<td>78</td>
<td>-0.31466</td>
<td>2.97845</td>
<td>2.28540</td>
</tr>
<tr>
<td>79</td>
<td>-0.28903</td>
<td>3.55106</td>
<td>2.10072</td>
</tr>
<tr>
<td>80</td>
<td>-0.29507</td>
<td>3.27342</td>
<td>2.17036</td>
</tr>
<tr>
<td>81</td>
<td>-0.29017</td>
<td>3.23189</td>
<td>2.17554</td>
</tr>
<tr>
<td>82</td>
<td>-0.30623</td>
<td>2.84899</td>
<td>2.32134</td>
</tr>
<tr>
<td>83</td>
<td>-0.31873</td>
<td>2.60080</td>
<td>2.45944</td>
</tr>
<tr>
<td>84</td>
<td>-0.32012</td>
<td>2.58869</td>
<td>2.46887</td>
</tr>
</tbody>
</table>

Mean  -0.31055  2.73330  2.41532
Table A3.7. Own Price Elasticities in Agricultural Cost Function Studies

<table>
<thead>
<tr>
<th>Author/ Date</th>
<th>Own Price Elasticity Estimates</th>
<th>Labour</th>
<th>Capital</th>
<th>Misc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binswanger 1974</td>
<td></td>
<td>-0.911</td>
<td>-1.089</td>
<td>-1.042</td>
</tr>
<tr>
<td>Lopez 1980</td>
<td></td>
<td>-0.517</td>
<td>-0.347</td>
<td>-0.410</td>
</tr>
<tr>
<td>Ray* 1982</td>
<td></td>
<td>-0.864</td>
<td>-0.524</td>
<td>-0.293</td>
</tr>
<tr>
<td>Adamowicz 1986</td>
<td></td>
<td>-0.344</td>
<td>-0.168</td>
<td>-0.239</td>
</tr>
<tr>
<td>Spash 1987</td>
<td></td>
<td>-0.31055</td>
<td>2.7333</td>
<td>2.41532</td>
</tr>
</tbody>
</table>

*1977 value not mean.
Table 15 gives further details of all the models.
shows the calculated range within which the parameters of the B.C. model would have to be in order to be comparable with previous research. The first column of the range is calculated from the elasticities of previous studies, reported in Tables A3.5 and A3.7, closest to those estimated for the B.C. model. The second column is calculated from the elasticities furthest away from those found for the B.C. model. This analysis shows all the input parameters of the B.C. model to be outside the expected range.

Table A3.8 Expected and Estimated Input Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range Within Which Parameter Expected</th>
<th>Actual Value B.C. Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{12}$</td>
<td>0.038561 to -0.022127</td>
<td>0.159833</td>
</tr>
<tr>
<td>$f_{13}$</td>
<td>-0.167466 to -0.095160</td>
<td>-0.239822</td>
</tr>
<tr>
<td>$f_{32}$</td>
<td>-0.156328 to 0.144830</td>
<td>-1.265221</td>
</tr>
<tr>
<td>$f_{11}$</td>
<td>0.075900 to -0.009150</td>
<td>0.079989</td>
</tr>
<tr>
<td>$f_{22}$</td>
<td>0.106590 to -0.079457</td>
<td>1.105387</td>
</tr>
<tr>
<td>$f_{33}$</td>
<td>0.125320 to -0.292240</td>
<td>1.505042</td>
</tr>
</tbody>
</table>

Key: 1=Labour, 2=Capital, 3=Miscellaneous.

These parameter errors imply that the estimated model fails to reflect the underlying technology. The errors in all $(f_{ij})$ terms can be expected to affect the accuracy with which other model parameters are estimated. Thus, the findings of separability and HNTC are brought into suspicion, and positive conclusion are no longer possible.
Marginal Cost

Marginal cost can be estimated for each product of the joint cost function by differentiating the fitted function with respect to that product. The marginal cost of the ith product is given by:

\[ \frac{\partial C}{\partial q_i} = (a_i + \sum_{i=1}^{m} d_{ij} \ln q_j + \sum_{r=1}^{n} g_{ir} \ln W_r).C^*/q_i \]  \hspace{1cm} (12)

where \( C^* \) is the fitted total cost function. The term in brackets is equivalent to \( 1 - SCE_i \). Assuming price equals marginal cost, 12 gives the supply curve:

\[ P_s = (1 - SCE_i) \cdot C^*/Y \]  \hspace{1cm} (13)

This supply function is obviously dependent upon the accuracy of the parameters estimated in \( C^* \), which as shown above are in error for the B.C. model. In addition, incorrect parameters in one part of the model can be expected to have affected the estimation of other parameters, and \( SCE_i \).
Conclusion

A 2-output 3-input translog cost function model of the agricultural sector in B.C. was estimated from data for the period 1961-1984. The parameters of the model were used to calculate input elasticities of substitution and scale economies. While the estimated scale economies appeared acceptable, serious parameter errors were discovered when the substitution elasticities were calculated. Errors in those parameters analysed can be expected to affect other parameters of the model and the marginal cost for crops. Thus an alternative approach to modelling ozone damage is utilized in the text.
Footnotes


6 See Diewert *Duality Approaches to Microeconomic Theory* sec 11 for a review of duality and non-competitive approaches to microeconomic theory.


9 Binswanger "A Cost Function Approach to the Measurement of Elasticities".


11 Ibid.


13 Ray "Translog Cost Function of U.S. Agriculture".

15 Brown et al., "Modelling the Structure of Cost and Production for Multiproduct Firms".

16 Ray "Translog Cost Function of U.S. Agriculture".


18 Canada, Statistics Canada. Farm Cash Receipts Catalogue 21-001 various annual, and Cansim.


20 Canada, Statistics Canada. Farm Wages in Canada Catalogue 21-002 various.


24 Canada, Statistics Canada. Farm Inputs Price Index Western Canada Catalogue 62-004 various annual, and Cansim.

25 Brown et al., "Modelling the Structure of Cost and Production for Multiproduct Firms".


29 Brown et al., "Modelling the Structure of Cost and Production for Multiproduct Firms".

30 Ray "Translog Cost Function of U.S. Agriculture".
Ray's estimates of SCE were defined as $1/(\partial \ln C / \partial \ln q_i)$, while those reported for the B.C. model are $1-(\partial \ln C / \partial \ln q_i)$. Thus, Ray's estimates were converted by inversion and subtraction from one.


Ibid.

Adamowicz, W. "Production Technology in Canadian Agriculture" Canadian Journal of Agricultural Economics 34 (March, 1986) 87-104.
APPENDIX IV

COST FUNCTION INPUT AND REVENUE
SHARE EQUATION ESTIMATES

MODEL: SHARE OF LABOUR  
DEP VAR: SHLABR

| VARIABLE | PARAMETER ESTIMATE | STANDARD ERROR | T RATIO | APPROX PROB>|T| |
|----------|-------------------|----------------|---------|--------------|
| Intercept | 0.140495          | 0.002785764    | 50.4331 | 0.0001       |
| b1        | 0.039994           | 0.012375       | 3.2320  | 0.0042       |
| b2        | 0.079917           | 0.020102       | 3.9755  | 0.0007       |
| b3        | -0.119911          | 0.023056       | 5.2009  | 0.0001       |

MODEL: SHARE OF CAPITAL  
DEP VAR: SHCAPT

| VARIABLE | PARAMETER ESTIMATE | STANDARD ERROR | T RATIO | APPROX PROB>|T| |
|----------|-------------------|----------------|---------|--------------|
| Intercept | 0.279689          | 0.005891932    | 47.4699 | 0.0001       |
| b1        | 0.079917           | 0.020102       | 3.9755  | 0.0007       |
| b2        | 0.552694           | 0.044781       | 12.3421 | 0.0001       |
| b3        | -0.632610          | 0.045719       | -13.8368| 0.0001       |

MODEL: LIVESTOCK REVENUE SHARE  
DEP VAR: SHREVA

| VARIABLE | PARAMETER ESTIMATE | STANDARD ERROR | T RATIO | APPROX PROB>|T| |
|----------|-------------------|----------------|---------|--------------|
| Intercept | 0.767015          | 0.020378       | 37.6393 | 0.0001       |
| a1        | 0.204219           | 0.034877       | 5.8554  | 0.0001       |
| a2        | -0.315042          | 0.017850       | -17.6495| 0.0001       |
| VARIABLE | PARAMETER ESTIMATE | STANDARD ERROR | T RATIO | APPROX PROB>|T| |
|----------|--------------------|----------------|---------|----------|
| Intercept| 0.441412           | 0.010106       | 43.6799 | 0.0001   |
| a2       | 0.261238           | 0.009283485    | 28.1401 | 0.0001   |
| a1       | -0.315042          | 0.017850       | -17.6495| 0.0001   |
Permission has been granted to the National Library of Canada to microfilm this thesis and to lend or sell copies of the film.

The author (copyright owner) has reserved other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without his/her written permission.

ISBN 0-315-41906-7