THE EFFECTS OF ROAD DUST ON AGRICULTURAL AND HORTICULTURAL PRODUCTION SYSTEMS IN NEW ZEALAND: A SYSTEMS APPROACH

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Road dust emissions cause considerable productive losses to farming systems adjoining unsealed rural roads. Yet these costs are currently excluded from economic appraisals, required by the National Roads Board with each roading improvement project proposal.

This study evaluates the magnitude and types of road dust effects on farming systems, based on an extensive literature review and numerous personal interviews. Findings indicate that the main causes of road dust cost are; photosynthetic yield loss, increased levels of pest, disease and weed incidence, dirty produce and reduced pollination. The magnitude of these costs, however, are highly dependent on environmental, roading, biological and economic factors.

A computer simulation model of road dust emission, distribution and effects on farming systems is developed. This model, which is exploratory in nature, predicts approximately according to a priori expectations. The model is built on a modular basis, so that components of the model can easily be refined as new data becomes available. Also, the model is user friendly, thus allowing simple testing of sensitive variables.

Application of the model shows that high value, intensively grown horticultural crops suffer the greatest costs from road dust, but traditional pastoral type farms, in comparison, incur only relatively minor costs. In addition, the magnitude of costs calculated using the road dust model suggests that road dust costs to farming systems should be included in the economic appraisal of roading improvement projects.

However, further applied research to refine and validate the model would be desireable.

KEYWORDS: dust; road dust; particulate; particles; emissions; air pollution; fugitive dust; dust sampling; particle size distribution

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This study may never have begun were it not for the great inspiration provided in a document prepared by the Manawahe Branch of the New Zealand Federated Farmers. Their observations of the rural road dust problem are worth recording:

"1) The risk to school buses filled with a whole generation of rural residents travelling on dusty roads.

2) The damage to morale endured by those whose houses are sited adjacent to roads and need constant washing to obviate the dust nuisance.

3) The premature ageing and the effect money-wise of corrosion and dust upon residents' vehicles.

4) The greatly increased accident risk attending all those using these roads.

5) The effect upon country women in particular who leave home cleanly dressed and with clean cars who arrive at their destination, brush against a now dirty car and are left with soiled clothing for the rest of the day."

The decision to spend a portion of my life studying road dust was motivated, to a great extent, by the lure of the "filthy luka". The financial assistance provided by the National Roads Board and the Waikato, Whakatane, Rodney and Tauranga County Councils was most thankfully received.

The means for producing a coherent and useful output from the study was largely a consequence of some much appreciated assistance from a wide range of people. Although there are far too many to name individually, the help give by staff at Lincoln University College, the Ministry of Agriculture and Fisheries, the Department of Scientific and Industrial Research, the Ministry of Works and Development, plus a host of farmers, growers and rural servicing personnel, is gratefully acknowledged.

The transformation of the thesis document from a chaotic scrawl into the format presented here, is due to the quick and efficient typing of Jenny Hayes. I would like to thank her for her efforts.

The moral support and encouragement to see the final stage of this project brought quickly to its logical conclusion, was provided jointly by the over-bearing presence of my supervisor, Professor Tony Bywater, and also by my ever-loving, but exasperated, wife, Dee. Their patience and sense of humour were most commendable.

A major constraining factor in the completion of this thesis, partly a result of the moral support, was the arrival of my son, Robbie. Long may he be asthma free!

TABLE OF CONTENTS

LIST OF TABLES

APPENDIX TABLES

LIST OF FIGURES

APPENDIX FIGURES

CHAPTER 1

INTRODUCTION

"Ashes to ashes, dust to dust ..."

1.1 Background to Study

The economic boom, caused by high agricultural export prices during the 1960s and early 1970s, brought with it rural roading policies apparently based largely on ad hoc processes, rather than on formal evaluation techniques.

However, the situation has changed drastically since 1973 due mainly to the effects of the oil price increases and to a severe downturn in agricultural export prices; leading to a greater level of fiscal restraint. Roading funds have been substantially reduced in New Zealand and approximately 62 percent of rural roads, excluding State Highways, were unsealed (N.Z. Yearbook, 1985). Rural roading programmes have been restricted chiefly to maintaining the existing, often inadequate, structure rather than upgrading it.

In response to these economic pressures, the National Roads Board (NRB) introduced a requirement during 1980, that all fund applications for roading improvement works must contain an economic appraisal, from which project priorities are ranked (M.W.D., 1980).

For roads where sealing programmes are planned, the NRB presently acknowledges the inclusion of the following quantifiable benefits from sealing:

(1) Accident reduction resulting from improved visibility and greater surface stability.

(2) Lower vehicle operating costs due to decreased fuel consumption and less wear on parts.

(3) Reduced travelling times facilitated by improved smoothness of roads.

However, there are other benefits of sealing roads which are not presently acknowledged by the NRB. They include:

(4) Increased returns from agriculture and horticulture due to dust removal.

(5) Social improvements from dust removal, e.g. health benefits and reduced cleaning times.

With competition for funds for roading improvements now very intense and a recent large increase in high value horticultural production in rural areas, the fourth benefit (increased returns to agriculture and horticulture) is becoming of greater significance in the economic evaluation of roading improvement works for project priority ranking. The model described in this report has been developed in response to this new level of awareness of the problem.

1.2 Aims of the Study

The primary objective of this study is to provide a generalised computer simulation model which can be used to estimate the benefits to agricultural and horticultural production, of dust removal from unsealed roads.

Road dust can affect, either directly or indirectly, both the yield and marketability of produce. It is the aim of this study to identify all road dust factors influencing economic returns, and to isolate and quantify the most important of these within the model.

A further aim of the study is to ensure that the model is both flexible and useful in a wide variety of situations. Hence, its operation involves a high degree of interactive user input.

1.3 Data Availability

1.3.1 Sources of data

Resource and time constraints required that most information gained for the model constructed and evaluated here was from secondary sources. These included:

(1) Published material concerning the emission, dispersion and effects of non-toxic dusts on production.

(2) Personal communications, on all aspects of inert dusts and their effects, with individuals, research organisations and government departments, both in New Zealand and overseas. This approach yielded much valuable specific information.

(3) Interviews with producers, agricultural field officers and scientists regarding some of the likely effects to various enterprise types. These were conducted in the Tauranga, Rodney and Waikato Counties, and Whakatane District. Specific road and climatic data used in this report relates to Tauranga County.

(4) Regular liaison with staff in various Departments at Lincoln College, the Ministry of Agriculture and Fisheries and various other organisations around Canterbury.

1.3.2 Previous studies

Little previous research has been carried out on the effects of road dust on agricultural and horticultural production, although considerable work has been conducted concerning related topics. These include:

(1) Atmospheric levels of road dust pollution.

It has been generally accepted that dust originating from unpaved roads can aggravate respiratory ailments, create driving hazards and cause considerable discomfort to those living alongside these roads. Studies to establish the nature and extent of the road dust problem have been carried out only recently.

With the imposition of strict air pollution regulations by both federal and state authorities in the United States during the last decade, environmentalists have concluded that road dust emissions are of greater significance to air pollution levels than initially thought. This realisation led to a number of attempts to quantify the amount, concentration and distribution of dust coming off roads, including those by: PEDCO Environmental Specialists (1973), Handy, et al. (1975), Roberts, et al. (1975), Heinsohn, et al. (1977), Dyck and Stuckel (1976), Becker (1978), McCaldin and Heidel (1978), Ward, et al. (1979) and Hoover, et al. (1981).

The findings of these studies have been used as the basis for estimating the road dust emission and distribution equations in the model.

(2) The effects of various inert[1] dusts on plant, animal and insect biological processes.

The Mount St Helens volcanic eruption during May 1980 initiated the most extensive research to date on the effects of particulate matter on a host of biological processes

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1. Inert dusts include volcanic dusts, road dust and field dust, which do not react chemically with animal or plant matter, as opposed to toxic dusts such as coal, cement and sulphurous dusts.

related to agriculture and horticulture. Most were conducted by the Washington and Oregon State Universities and also by various environmental agencies within these states.

The effects of the volcanic ash on insect capacity, animal respiration and digestion, plant growth and fruit production were some of the major areas studied. The findings are of particular significance to this study, as volcanic ash is one of the few forms of particulate matter studied to date which, like road dust, is relatively inert.

(3) Other research.

Other related research areas include studies into the effects of inert field and road dusts on:

a) Insect populations (Fleschner, 1958; Alexandrakis and Neuenschwander, 1979; Bartlett, 1982).

b) Plant respiration, transpiration and photosynthesis processes (Auclair, 1976; Eller, 1977; Tabata and Tanabe, 1980; Ricks and Williams, 1974; Stanhill, et al., 1976; Gourdriaan and van Larr, 1978; Danno, et al., 1980).

c) Animal physiological processes (Kirton, et al., 1976; Barnicoat, et al., 1957; Healy and Ludwig, 1965; Bruere, et al., 1975).

In addition to these published sources additional information was gained by personal correspondence with a number of the authors and other researchers.

The only known attempt to place a value on the costs of road dust to agriculture was by Norton (1969). He based his calculations on a generalised scenario of;

(1) 'good' dairying land;

(2) 200 metre dust drift from the road; and

(3) 5 percent production loss for the affected area.

Although they were intended only as an illustration, Norton's figures have been used by several others since (Harkness, 1976; Inglis and Dunlop, 1979; and Sampson and Stretton, 1981), with no attempts made to extend or validate them. Although Norton's results were useful for highlighting the possible magnitude of the road dust problem, they are too crude to be used in any quantitative analysis.

CHAPTER 2

POSSIBLE EFFECTS OF ROAD DUST

Road dust is believed to have a number of both direct and indirect effects on production systems sited alongside unsealed roads. An extensive list of the possible effects is given below. Some of these relationships appear more important than others and whenever possible, some conclusion is drawn regarding the likelihood of significant effects of road dust.

2.1 The Effect of Dust on Leaf Surfaces with Regard to Plant Photosynthesis, Transpiration and Respiration Rates

Dust cover on leaf surfaces may affect yield in a variety of ways, with the yield reduction depending upon the thickness of cover and to some extent, the type of plant. The effect is likely to be greater on plants with pubescent (hairy) leaves, as these retain a greater amount of dust, even after a moderate rainfall.

2.1.1 Photosynthesis

Photosynthesis provides the fuel for plant growth, and any reduction in its level would be accompanied by an approximately corresponding percentage loss of plant growth and yield.[2]

Cook, et al. (1981), investigating the impact of the Mount St Helens eruption on agricultural production, found that a coating of ash one millimetre thick on a leaf surface

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2. The degree of correspondence between percentage changes of photosynthesis and yield will vary to some extent with respect to such factors as: time of year; stage of plant growth, etc.

reduced photosynthesis by 90 percent and that a lighter coating reduced it by 25-33 percent.

Exactly how plant growth and yield are affected appears to differ, depending on plant type and circumstances. It is predicted by P.E. Storey (pers. comm., 1984) that a probable major effect would be a cumulative retardation of plant growth and maturity time, thus diminishing expected crop yields each year. Cook, et al. (1981) hypothesised that reduced photosynthesis may also be responsible for the early senescence of leaves, thus further retarding plant growth.

In the presence of adequate water and nutrients, a reduced photosynthesis rate could directly affect fruit production in three ways (D. Jackson, pers. comm., 1984):

(1) By reducing the number of buds formed, resulting in lower flower initiation and hence, lower fruit numbers.

(2) By reducing fruit size due to an inadequate supply of carbohydrates. This is important in fruits which are graded for size (e.g. apples and kiwifruit). However, low bud formation may offset this effect.

(3) By lowering the sugar content of fruits. Some fruits (e.g. grapes and kiwifruit) are harvested according to sugar levels and low readings will delay harvesting. This may be a crucial factor in marginal areas where the growing season is shortened by the advent of autumn.

Although it was too complex to isolate and quantify each effect caused by reduced photosynthesis for inclusion in the model, an attempt has been made to predict the overall yield loss from road dust-related photosynthesis reduction (Section 4.5.1).

2.1.2 Stomatal interference

Dust particles of a size range less than 5μm in diameter can interfere with the mechanism of stomatal pores. These small openings are largely responsible for the basic respiration and transpiration functions of plants.

Work by Ricks and Williams (1974) and Eller (1977a and b) indicate that the plugging of stomatal pores by small particles may lower the rate of respiration and also the maximal stomatal diffusion resistance at night. However N. Gallagher, (pers. comm., 1984) held that these effects would be very small and likely to be of little significance to yield.

Further, Stanhill, et al. (1976) found that kaolin dust applied to crop foliage during a drought period in Israel, actually increased crop yield by 7-20 percent over a three year period. The dust had the effect of increasing the reflectivity of plants and reducing their transpiration heat load, thus increasing transpiration resistance. Road dust is not as reflective as kaolin, but it may have a similar effect and it cannot be discounted that during dry summers, road dust could increase yield by;

(1) alleviating drought damage to plants at critical growth stages; and by

(2) reducing the potential water demand of the atmosphere.

However, it is likely that few areas in New Zealand would ever experience the severity or length of droughts experienced in Israel. Thus for this study, all yield effects caused by road-dust induced stomatal interference are assumed to be negligible.

2.2 Increased Incidence of Plant Pests and Disease

Although there is little hard evidence on the subject of dust as a predisposing cause of plant disease and increased pest infestation, opinions and observations of several growers and scientists tend to support a relationship. The effects vary according to plant type and in some cases the type of fruit produced. However, some of the major problems include the following:

2.2.1 Establishment of conditions conducive to disease initiation

Dust accumulation in the nooks and crevices of fruit and plant surfaces aids moisture retention; thus providing, in the right conditions, a medium for the growth of bacteria and fungi.

2.2.2 Pest-beneficial insects[3] population balances

Studies by Alexandrakis, et al. (1979), Fleschner (1958) and Bartlett (1982) show that road dust inhibits the activity of beneficial insects and consequently increases the damage from pests. The reasons for this stem chiefly from the habits and structures of the respective types of insects and the mode of action of dust.

Beneficial insects, primarily the predators and parasites of insect pests, are particularly susceptible to three possibly lethal modes of action of dust on their systems:

(1) Dessication may be facilitated by dust by;

- (a) abrading the epicutular waxes, thereby increasing the permeability of the cuticle;
- (b) exposing the permeable intersegmental membranes; and

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3. For convenience, the term 'insect' is used loosely to include all mites, etc. which are not strictly insects.

(c) increasing the evaporative area of the body.

(2) Starvation may be caused by the formation of a mechanical barrier to the insects' food supply, by impeding their movement or by clogging their digestive systems.

(3) Respiration may be hindered where spiracles are clogged by dust particles.

The reasons for their vulnerability to these effects, compared to the pest insects, stems from a number of factors.

(1) Whereas most pests are relatively immobile, parasites and predators must search over the leaves and fruit of plants if they are to control the pest species satisfactorily. The more efficient the benefit insect is in this respect, the lower will be the host population and the greater will be the surface area of the plant over which the benefit insect must travel. Hence, on dust covered plants, as the amount of travel required over dusty surfaces by beneficial insects begins to increase so too does the death rate of beneficial insects, thus moving the population balance back in favour of the pest community.

(2) Some pests are well protected from dust deposits by wax covers or by hard, thick body walls. Conversely, few beneficial insects have any special protective covers to shield them from dust.

(3) In contrast to pest species, which are in constant contact with a food supply of living plant material which is high in moisture content, beneficial insects do not have a constant supply

of food and water available. Adult parasites generally depend upon the chance supply of natural sugars (honeydew and nectar) as their main source of food and water, while predators supplement this by feeding off their host.

Thus (as in their search for hosts), beneficial insects must travel almost continuously over the surface of the plants in the search for food and water. This constant contact with dust becomes especially critical when the dust has a desiccating effect on the insect, as there is little opportunity for them to replenish vitally needed water.

(4) Most pest species have piercing mouthparts which penetrate the plant cuticle, so that these pests feed on clean, dust free plant sap. On the other hand, the honeydew and nectar which parasites, and to a lesser extent predators, depend on for their food source, are found exposed on plant surfaces. These foods could be so covered by dust deposits that they are unavailable to beneficial insects, or they may be so contaminated with dust particles that digestion is impaired; both can result in death by starvation.

(5) Dust adhering to the beneficial insects delicate sensory organs, used to locate and recognise food and host insects, may dull the insects' senses, agitate them and cause them to depart the area, or may slow down their rate of travel, so that their searching capacity is reduced. Each can ultimately lead to starvation.

These factors tend to support the findings of Alexandrakis, et al. (1979) that the beneficial population increased, and the pest population decreased, further away from an unsealed road-dust source. Of course, these effects are most important when predators play an important role in the pest control strategy adopted by orchardists and growers.

2.2.3 Spray effectiveness

Closely aligned with the problems already mentioned, is the detrimental effect which dust has on the efficiency of many agricultural sprays.

A basic aim when spraying plants is to gain a maximum retention of spray droplets on the leaf surfaces. Dust may affect this retention ability and also may reduce plant uptake of chemicals where applicable. Although producers usually spray after rain when leaf surfaces are clean, lengthy dry spells during summer may necessitate spraying at sub optimal times, in terms of spraying efficiency.

(1) Herbicides.

All except those which are soil applied must be absorbed by the leaf; thus a dust cover will impede this movement. Also, some herbicides (e.g. Roundup) are known to be deactivated on contact with the soil surface, due largely to the effect of soil micro-organisms. Although it has not been conclusively proven that road dust will produce this effect, producer observations and work by J.S. Dunn (pers. comm., 1984) at the Sarjab Agricultural Research Station, Pakistan, support the view that spray effectiveness is severely reduced when road dust is present.

Dunn found that when Paraquat was applied to broad-leafed weeds, at both single and double strength following dust storms, the spray had little effect and further, that wetting agents did not improve the effectiveness.

Production loss could be as high as 100 percent for the affected area where no weed control is achieved in low growing crops (e.g. cereals and berryfruit) (R.J. Field, pers. comm., 1984). This effect is due to either increased weed competition or to reduced harvesting efficiency. However, a more realistic loss may be in the vicinity of 20 percent (R.J. Field, pers. comm., 1984).

(2) Pesticides and Fungicides.

Only the systemic and eradicant action sprays may be affected, with their uptake by plants possibly being impeded by a dust layer. Resultant increases in pest or disease incidence can hinder plant growth, affect fruit set, or damage fruit appearance.

2.3 Reduced Light Intensity on Fruit

Highly coloured fruits (e.g. red apples, nectarines and peaches) require high light and low temperature to achieve full colour. Road dust present on fruit surfaces may reduce the light intensity reaching fruit so that expected colour levels are not achieved.

The Apple and Pear Marketing Board's grading schedule requires that coloured varieties of apples contain a minimum colour percentage for each grade. Standards for nectarines and peaches are not specified, but under-coloured fruit would probably be down-graded, at least from export designation to local market.

2.4 Pollination

Well pollinated flowers are a basic requirement for the development of large and well formed fruit. Although there have been no scientific investigations conducted into the effects of road dust on pollination, many growers and several Ministry of Agriculture and Fisheries Advisors, have strong suspicions that road dust on the flowers of small seeded fruit plants (e.g. kiwifruit, strawberries, blueberries and raspberries) can cause substantial losses in affected areas.

Of particular significance is the kiwifruit which, even without a dust coating, has a fairly unattractive flower to insects. It is suspected that a dust coating on flowers may dissuade bees from pollinating them effectively, leading to either;

(1) total flower abortion; or
(2) the development of 'scrub' (i.e. small and/or mis-shapen) fruit, not suitable for export.

2.5 Rejection and Down-Grading of Horticultural Produce Due to Road-Dust Contamination

According to the horticultural marketing trade, little produce is rejected or downgraded because of dust contamination. However, many growers, either trying to establish or to protect a good name, grade out any contaminated produce so that it does not reach the market.

Dust contamination affects different produce in different ways and to varying degrees. Pubescent fruits (e.g. peaches), berryfruit and leafy vegetables are perhaps the worst affected, as dust particles cannot be removed effectively.

Kiwifruit for export undergoes a dehairing process which rids it of most dust, but sometimes enough dust can remain on the fruit to cause downgrading. This effect can be accentuated when the fruit has been wet. A combination of the dust and moisture can produce a stain on the fruit. Likewise, export apples are subjected to a waterdumping and polishing process. However, where dust has accumulated in the stem cavity at the end, this method may not be sufficient to pass the fruit for export.

Dust causes citrus fruit to lose their lustre, a problem which mechanical graders do not entirely remove. This impairment of the fruits' attractiveness tends to lower its market price.

Asparagus can be affected when grit gets into the spears and cannot be removed. In addition, a major problem can occur when packing sheds are situated in the vicinity of metal roads. Asparagus is packed wet, with the insides of packing boxes kept moist. Hence a dusty atmosphere within a packing shed can involve a significant penalty to the grower.

As mentioned above, small, deformed or diseased fruit can necessitate quite large amounts of down-grading or even dumping. Because much of the grading is conducted informally, only rough estimates can be made of how much produce is actually down-graded or dumped due to dust.

Government regulations state that all produce for export, and it's packaging, must be clean and free of disease and dirt. This regulation is becoming more strictly applied and within the last two years, a few major cases of produce downgrading due to road dust have come to light, including:

(1) A Bay of Plenty kiwifruit orchardist who successfully sued the Tauranga County Council for 520 trays of export kiwifruit rejected by the MAF; and

(2) A Waikato berryfruit grower who was awarded $40,000 damages by the Waikato County Council for loss of revenue due to road dust contamination on berries.

In addition, marketing authorities require that most produce meet set standards regarding, for example, size, shape and colour.

Several producers mentioned that significant quantities of produce grown alongside unsealed roads are often not submitted for export, due to either the direct or indirect effects of road dust. A further amount are graded out by marketing authorities. Depending upon the extent of the problem, there are a number of alternative ways of dealing with sub-export standard produce. These are given below.

2.5.1 Place in local auction market

For many fruit types (e.g. kiwifruit, avocados and strawberries), withholding fruit from export consignments on its own represents a substantial cost to growers. In addition, all contaminated produce submitted to the local market would only receive about 66 percent of the price gained by premium produce submitted to the local market (K.J. Russell, pers. comm., 1981).

Further, if a grower were submitting a percentage of sub-standard fruit, this may have the effect of lowering the price of even his best quality produce, as buyers often make decisions on the basis of grower reputation.

2.5.2 Gate sales

Several growers agreed that gate sale prices of poorer quality produce, in general, are about 30-40 percent below prices received for good quality produce in the market. Selling by this method has the advantage of protecting the growers' name in the marketplace. However, it is often not a serious alternative for growers on metal roads. Many such raods do not get enough through traffic to make gate-selling economic.

2.5.3 Sell as process grade

Selling as a process grade involves a much reduced price but has the advantages of being quick, convenient and often a least cost method of clearing substandard fruit. There are several drawbacks however. Firstly, it is usually only a feasible alternative for growers situated in the vicinity of processing plants, and secondly, processors often require that contracts be signed before the produce is harvested. Hence, any shortfalls must be met with high quality produce.

2.5.4 Dumping

One method, used most frequently by market gardeners and berryfruit growers, is simply to dump or abandon dust damaged produce.

During the preliminary field visits, several berryfruit growers mentioned having to abandon the harvest of berries, while two market gardeners cited cases where they had ploughed in, or fed to pigs, leafy vegetables grown in the nearest few rows bordering unsealed roads, because of dust contamination. They felt that it was often cheaper, easier and more beneficial in the longer term to dispose of inferior produce in these ways, than to sell it off at minimal rates. This helped to ensure that good prices were gained by top quality produce and also protected the grower's name.

2.6 Road Dust as a Fertiliser

Although road dust is considered to be a relatively inert material, in some instances it may contain quantities of nutrients which can be taken up by plants through their leaf surfaces.

Dust from glacial and recent soils contain many primary minerals (e.g. phosphate and potash) which are relatively unweathered and available to plants, and are likely to provide some benefit to plant growth. The predominant gravels used on most New Zealand roads, however, are greywacke, volcanic and well weathered materials which are fairly low in primary minerals. But there are two other ways in which the nutrient supply to plants may be affected by road dust.

Organic matter on roads can be pulverised and included with the dust from roading materials (K.F. O'Connor, pers. comm., 1984). This has a significant effect on the growth of roadside plants growing on poor substrata (e.g. hard hill country sheep farms) but probably has little effect on plants growing on rich soils (e.g. horticultural properties).

Further, in areas where local materials are limestone derived, continual deposition of road dust can lead to increasing soil pH levels which can accentuate any trace element deficiencies, although there may be some benefit in areas with acid soils. This is also true for roads which are lime stabilised (J.S. Dunn, pers. comm., 1984).

Overall, it is unlikely that these fertiliser effects have a great effect on plant growth and yield on the more intensive farming areas of New Zealand and hence, they have been assumed to be negligible for the purposes of this study.

2.7 Ovine Pneumonia

Pneumonia is one of the most common diseases of sheep in New Zealand and may affect most young sheep during their first two years of life. The disease is usually subclinical or accompanied only by coughing, but serious outbreaks occasionally occur.

Davis (1974) found that pneumonia accounted for 9 percent of deaths in adult sheep during a survey in the Hawkes Bay, and Pyke (1974) found a slightly higher incidence in the King Country. Sheep deaths in New Zealand average around 5 percent of the flock per annum (New Zealand Meat and Wool Board's Economic Service, 1985). Thus, assuming that Davis's and Pyke's results are reasonably representative of all New Zealand districts, it could be that pneumonia accounts for about 0.5 percent of all adult sheep deaths.

Kirton, et al. (1976) reported from a five year experiment with 3243 lambs at Ruakura Animal Research Centre, that moderate to severe pneumonia, on average, reduced carcass weight by 0.45 kg per lamb, but that only

6.5 percent of lambs were affected to this extent (total prevalence of pneumonia in the flock averaged about 60 percent).

Also, occasionally lesions cause damage to the visceral pleura. Secondary pleurisy follows with fibrous adhesions between the viscera and parietal pleura. This results in the down-grading of carcasses at meatworks. Over the 1984/85 killing season for all New Zealand meatworks, on average 0.12 percent of sheep and 0.01 percent of lamb carcasses were condemned due to pleurisy.

The pathogenesis of pneumonia has not been finally elucidated. However, the consensus of opinion among scientists is that it is the result of an interaction betwen a primary virus and other infection, bacterial secondary invaders, and environmental factors (Kirton, et al., 1976). Further, G.B. Davis (pers. comm., 1984) deduced that dust could be one of these factors.

Although there is no hard information on the effects of dust on ovine pneumonia, many scientists, including G.B. Davis (pers. comm., 1984) and B.W. Manktelow (pers. comm., 1984) strongly suspect that dust particles up to 3 μm in diameter, reaching the respiratory tract in appreciable numbers, may overload the normal clearance mechanisms, thus preventing the removal of harmful bacteria.

Approximately 30-50 percent (by weight) of all dust coming off Tauranga County's unsealed roads is 3 μm or less in diameter (Ministry of Works and Development (Tauranga), pers. comm., 1984). Thus, assuming road dust deposition levels are from 90,000-600,000 gm/km per dry day[4] , a range

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4. Estimated road dust deposition levels ranging from 90,000-600,000 gm/km/day are calculated using an equation developed by McCaldin and Heidel (1978) and using assumptions of daily traffic volumes ranging from 75-500 vehicles per day (Section 4.5.1).

from about 27,000-300,000 g/km of road, of fully respirable road dust is drifting onto pastures adjoining unsealed roads every dry day of the year.

This is an appreciable amount and it seems reasonable that where sheep are frequently grazing paddocks bordering unsealed roads, road dust could be a factor in the development of ovine pneumonia.

2.8 Excessive Teeth Wear

There has been some speculation that road dust may also play some minor role in the wear of grazing animals' teeth leading to premature culling. However, dental research workers tend to agree that this effect is of no real significance, and that the major cause is soil ingestion. Experiments by Ludwig, et al. (1966) confirm this opinion, showing that 70 percent of teeth wear occurs between July and October, when there is a reduced dust problem.

2.9 Lowered Weight Gains in Animals

Physiologically it would appear that road dust ingested with normal pasture feed has little or no direct effect on either animal weight gain nor on the level of milk production. Preston (1980) investigating the after-effects of the Mount St Helens eruption found that:

(1) Day old chicks suffered a 6 percent growth reduction for each 10 percent of ash and a 4 percent reduction for each 10 percent of sand included in total dry matter percent intake.

(2) Dairy calves with a 10 percent ash content of dry matter exhibited completely normal growth patterns.

(3) Dairy cows which were subjected to an increase of ash content from 0 percent to 6.3 percent of dry matter over 5 weeks, maintained constant levels of milk production.

The findings with dairy cattle are potentially relevant to the New Zealand pastoral sector but the levels of contamination mentioned here (Preston, 1980) would be far in excess of any likely amount due to road dust. Hence it is most unlikely that road dust has any physiological effect on animal growth and development.

However, where stock are grazing pastures adjoining metal roads, dust may have an indirect effect on retarded growth rate. Observations indicate a reluctance by animals to graze the pasture along roadsides. Road dust may be a cause, especially as similar observations of reduced forage intake have been noted on silt covered pasture, due to border dyke irrigation (D.G. Elvidge, pers. comm., 1984). However, evidence is far from conclusive and other factors such as traffic noise may be of primary importance.

If in fact dust causes depressed appetites, Elvidge estimates that the very maximum allowance for retarded growth rate would be around 20 percent for each day the animal is kept on the contaminated pasture. This figure roughly represents the difference between reasonable and good feeding patterns.

2.10 Pinkeye (Contagious Ophthalmia)

Pinkeye can cause ulceration and blindness of animals' eyes and can also lead to pregnancy toxaemia in ewes and the mismothering of lambs.

There has been no experimental work undertaken to show that road dust is a predisposing cause of pinkeye in either sheep or catle, but Cooper (pers. comm., 1984) believes that it seems perfectly reasonable that subclinical infections may be rendered overt by dust irritation. His belief is reinforced by many farmers living along unsealed roads who state that the instances of eye infections in animals grazed along roadside paddocks are higher than those in paddocks away from the road.

2.11 Wool Yield

Road dust may lower the yield of wool from sheep grazed alongside unsealed roads, but this has little effect on the economic returns, since the yield of all clippings are tested and farmers paid out on the clean weight. Thus, any loss of yield is compensated for by an overall greater greasy wool weight (J. Simpson, pers. comm., 1984).

2.12 Conclusions

The most significant physical effects of road dust on agricultural and horticultural production appear to be:

(1) Reduced photosynthesis leading to loss of plant yield.

(2) Increased pest and disease incidence causing yield losses and reduced quality of horticultural produce.

(3) Dust contamination reducing fruit and vegetable attractiveness.

(4) Dust hindering the pollination of small seeded fruits causing abortion and deformed fruit.

(5) The possibility of animal health problems such as ovine pneumonia and pinkeye.

Any attempt to isolate and assess the effects of road dust on production cannot ignore the economic consequences of the effects. Consequently, road-dust is likely to have a far greater impact on horticulture than agriculture for the following reasons:

(1) Horticultural land usually returns a far higher gross revenue per hectare.

(2) Horticulture generates a much higher traffic volume, and hence much more dust, per kilometre of unsealed road.

(3) The nature of horticultural produce and grading systems make horticultural crops far more vulnerable to the effects of road dust.

(4) Horticultural enterprises are smaller scale and generally sited near to roads.

Hence, this study places most emphasis on the effects of road dust on horticultural production.

CHAPTER 3

SOURCES OF DUST AND SOME THEORETICAL ASPECTS OF INFLUENCES ON THE MAGNITUDE OF ROAD DUST EFFECTS

For the purposes of this study, dust is defined as all particles which are less than 75 µm in diameter. This figure is consistent with that used by Heinsohn, et al. (1977) and also McCaldin and Heidel (1978) who define these particles as representing the fraction of the road surface which easily becomes airborne due to passing vehicles.

In attempting to assess the effect of road dust on production, it is not only necessary to identify all possible sources of nuisance caused by dust, but also to make certain assumptions regarding any physical factors which may influence the rate of road dust emission, distribution and deposition.

3.1 Sources of Dust

Dust can be carried onto agricultural land from almost any site containing free particulate matter. However, there are three principle types of particulate matter affecting agriculture and horticulture.

3.1.1 Road dust

Road dust is taken to be any dust which originates from an unsealed road source, including the unsealed verges of sealed roads. However, only totally unsealed roads are dealt with in this report.

3.1.2 Ambient dust

Ambient dust includes all dust present in the atmosphere excluding that from metal roads, with the majority originating from exposed ground subject to wind erosion, such as cultivated paddocks and riverbeds. The amount present at any one time may vary according to soil type, amount of ground cover in the region, climatic conditions and time of year. There is generally assumed to be a relative base level of ambient dust present for any region, but with micro-environmental extremes present (e.g. dust deposited on an orchard from an adjoining cultivated paddock).

Measures of ambient dust levels in New Zealand are unavailable, so for the purposes of the model, the effects of ambient dust levels on production systems, are assumed to be nil. By adopting this assumption, the effects of road dust deposition on production systems can be expected to occur "on top" of the ambient base level of dust.

Obviously, this assumption must be regarded as being of a very tentative nature, valid only until reasonable data on ambient dust levels can be obtained; since the impact of ambient dust levels on production effects of road dust will be very dependent on the nature of the relationship between dust deposition levels and production effects. Depending upon this relationship, it is conceivable that certain levels of ambient dust could accentuate the production costs caused by road dust while at other levels, it could completely supplant them.

Hence, given the current uncertainty surrounding the levels and effects of ambient dust in relation to road dust, the above assumption appears to provide the best method of dealing with the problem since:

(1) Most production estimates and decisions are made using intrinsic assumptions of "normal" ambient dust levels.

(2) Dust is easily observable on plants close to unsealed roads, but becomes less and less observable away from unsealed roadways.

The inclusion of ambient dust effects into road dust calculations would require the isolation of ambient levels by measuring dust deposition levels transversely at distances away from the roadway. When the measurements stabilised to a constant level, then this could be assumed to be the normal ambient level. This density level could then be added on to the road dust readings and estimations of dust effect calculated from this.

3.1.3 Rain splash

Although not strictly a form of dust, dirt particles splashed up by the impact of falling rain can contaminate ground crops (e.g. lettuces) and sometimes cover pasture plants. However, where this occurs, it can easily be differentiated from other forms of dust cover because:

(1) Particles are on low surfaces only.

(2) The particles are larger than wind blown dust.

(3) A blotchy type cover effect occurs where concentrated splashes have fallen.

Thus, although all the above-mentioned forms of dust may be of significance to agricultural and horticultural production, this study concentrates only on the effects of road dust because:

(1) Road dust is the only form for which dust control can reasonably be carried out.

(2) Road dust occurs in sufficiently large and consistent quantities to be both relatively important to production and reasonably predictable in distribution and deposition.

(3) Road dust is emitted from a fixed point public good over a long period of time. There is a need therefore, to value the cost of the dust in order

to evaluate the economics of dust control measures.

3.2 Factors Influencing the Road Dust Problem

3.2.1 Rainfall

Rain has the double effect of both settling the dust from dry roads and also of cleaning plant surfaces covered in dust, although the extent to which this occurs depends largely on the frequency and intensity of the rain.

3.2.2 Dew

Dew is often a cause of road dust suppression, especially during the evening till early morning and in the winter time. Although dew may inhibit road dust emissions, it is unlikely that it would be of sufficient quantity to affect the dust which is already present on plant surfaces.

3.2.3 Irrigation

Trickle irrigation has no effect on the amount of road dust present on plants, but spray irrigation may have a significant effect. Basically, these are the same as for rain, i.e.

(1) Washing dust off leaves.

(2) Washing dust into nooks and crevices.

(3) Dirt splash.

There can however, be complications. Dust deposited immediately after irrigation tends to adhere more readily to plant surfaces and becomes more difficult to remove because the road is still dry, while plant surfaces are wet. This may accentuate the dust problem in some circumstances, but due to the uncertainty surrounding the use of irrigation, its effect is omitted from calculations in this study.

3.2.4 Time of year

Agricultural and horticultural production and marketing cycles are directly controlled by the time of year. Thus the effects of dust will take on greater economic significance, depending upon the season. Deciduous trees are dormant over the winter months and are not affected by dust during this time. However, during the dustiest months over the summer, plants are generally experiencing rapid growth, crops are ready for harvest and pest and disease incidence is often at its height.

An additional factor is that sunlight intensity is much stronger during the summer than during the winter. This has the double effect of:

(1) Increasing the actual level of photosynthesis.

(2) Reducing the impact of dust cover on photosynthesis rates compared to winter.

3.2.5 Wind and advection

The effect wind has upon dust (plume) dispersion depends largely upon the prevailing wind direction and to a much lesser extent, its intensity.

Work by Handy, et al. (1975), Ward, et al. (1979) and Hoover, et al. (1981) showed that dust levels on either side of a metal road can be almost identical for up to the first 20 metres. However, further away from the road the prevailing downwind side appears to receive approximately twice the amount of dust deposition as the prevailing upwind side, depending upon conditions.

Wind speed as a determinant of road dust plume dispersion and distribution is highly dependent on a number of other factors, especially surface roughness[5] and an

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5. Surface roughness is determined by the height of vegetation, prevalence of buildings, etc., situated alongside a metal road.

advection component. The advective effect is the simple horizontal transport of the dust particles as they settle due to gravity. As the wind speed increases the dust would be spread more thinly over a greater distance (i.e., the total quantity of dust is fixed). However, the effect of surface roughness is to increase the amount of turbulent mixing of the air as wind speed increases. The mixing process causes more dust to be carried into the surface (a crop) than by simple gravitational settling. Any dust carried onto the surface is caught (as in an air filter) and not carried out again.

Advective deposition decreases with windspeed while turbulent deposition (due to roughness) increases with windspeed. The two effects are of similar magnitude and more or less cancel out except over smooth surfaces when the turbulent effect is not as significant (V.J. Bidwell, pers. comm., 1985).

Where smooth surfaces (e.g. pasture land) border metal roads, wind speed has a direct influence on the distance and distribution of dust plume deposition (Becker, 1978). Thus, the stronger the wind, the greater the deposition will be at locations away from the road. This effect could not be explicitly accounted for in this study due to lack of data. Instead, deposition distribution away from the roadway was calculated for an averaged set of parameters (windspeed, surface roughness, source height). This should not be too crucial since most smooth surfaced enterprise types (e.g. pastoral farming) are generally of little importance to this study, due to their extensive nature and comparatively low economic returns.

3.2.6 Surface roughness height

The height of vegetation on land adjacent to metal roads has a significant influence on the rate of road dust deposition. Deposition close to the road is always greater over rough surfaces than smooth surfaces.

Becker (1978) showed that deposition differences due to the different roughness heights may be very large. This can be explained by the fact that surface roughness causes a larger friction velocity which in turn, enhances the deposition velocity resulting in more deposition.

Because of the lack of other data regarding the effects of roughness height on road dust deposition distribution away from the roadway, the averaged findings of Becker are used in this study. Roadside buildings and structures, where present, would have an effect on the road dust deposition distribution, but there are no data available to quantify the effect.

3.2.7 Shelterbelts

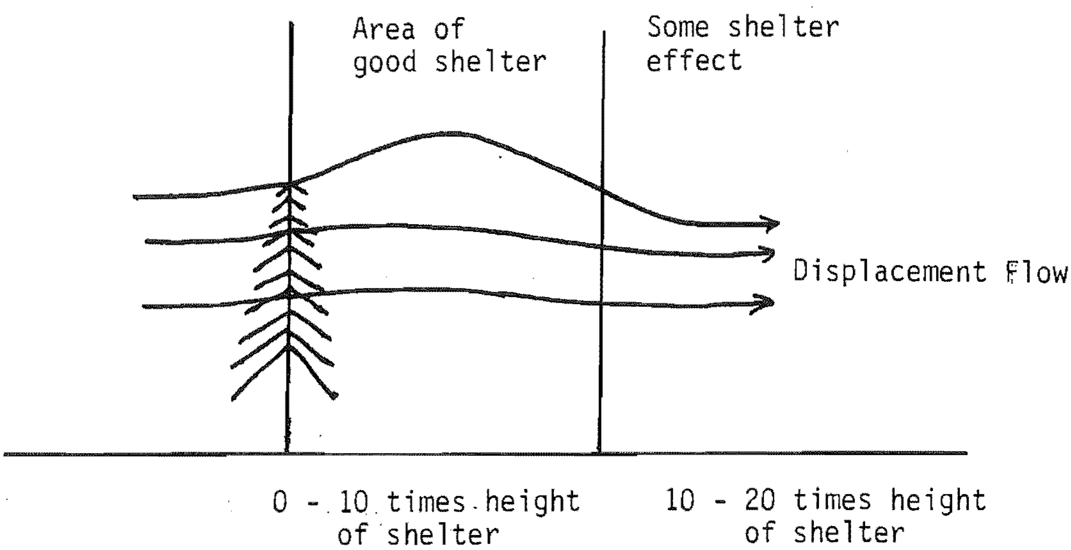
The effect of shelterbelts on road dust deposition is an extension of the concept of surface roughness. That is, they increase the surface friction velocity, but more than most rough surfaces, due to their greater height and continuous line.

Most shelterbelts are designed to be 50 percent permeable to wind (Batt, 1979) so that a smooth airstream is retained rather than pockets of turbulence. It would seem reasonable to assume then, that a shelterbelt may reduce the amount of dust which reaches a paddock by up to 50 percent. However, taking into account the displacement flow (Figure 3.1) which would cause some dust to be transported over the shelters, it is considered that a figure of 40 percent may be more appropriate.

Considering that wind speed has little effect on dust plume deposition except over smooth surfaces (refer to Sections 3.2.5 and 3.2.6 above), it is assumed that the 60 percent of dust which gets past a shelterbelt, is deposited at a proportionally similar rate away from the road source, as dust where there is no shelterbelt present.

FIGURE 3.1

Distance of Effect of a 50 Percent Permeable Shelterbelt on Flat Ground



Although road dust is often a factor in poor plant growth and fruit production in the rows nearest to a road, two other factors related to shelterbelts should be considered:

(1) Where shelterbelts are present, they provide competition to fruit trees for sunlight, water and soil nutrients.

(2) Where there are no shelterbelts, the outside rows of trees may be stunted by wind stress.

Caution is therefore required to ensure that the magnitude of the effects of road dust on plant growth and crop yield are not overstated.

3.2.8 Topography

A metal road which winds through undulating countryside will not have a consistent distribution of dust deposition. The mechanics which apply to surface roughness also have an application here and there will also be areas of turbulence and wind funnelling. However, as topography constantly changes, the positive effects on dust depositions will tend to cancel out the negative ones, thus leaving no overall effect of topography on road dust plume deposition distribution.

3.2.9 Road maintenance

Regular road grading and maintenance play an important role in reducing the level of dust which an unsealed road may emit. The assumption is made that all roads are in reasonable condition, thus allowing an emission factor developed by McCaldin and Heidel (1978) for well maintained roads, to be applied.

3.2.10 Vehicle usage

The types, speeds and number of vehicles using a metal road all affect the volume of dust emission from that road. Vehicles travelling along metal roads cause airborne dust due to two mechanisms (Heinsohn, et al., 1977):

(1) The action of tyres which disturbs the road surface and causes it to adhere to the tyre and then be thrown from it, or to be directly made airborne by the motion of the car induced by the tyre or the vehicle.

(2) The action of aerodynamic wake behind the vehicle and the earth's surface wind that causes the airborne dust to be transported downwind.

Given these factors, it would follow that the amount of emission per vehicle pass would depend largely upon its;

1. shape;
2. weight;
3. number of tyres; and
4. speed,

which would all affect both the aerodynamic wake and the amount of dust projection by tyres.

Since no data are available regarding these factors, no account could be taken of them in this study. Instead a generalised daily emission level for road dust is used, which is the product of an emission factor (g/vehicle kilometre) (McCaldin and Heidel, 1978) and the daily traffic count.

3.2.11 Silt content of road

The percentage of silt content contained in roading materials is a basic component of all dust generation models. The amount of dust generated increases linearly with increases in silt content (McCaldin and Heidel, 1978).

3.3 Conclusions

In the development of a road dust model, all of the factors identified in this chapter need to be considered. Some have been included within the model, some exogenously accounted for, whilst some have to be omitted completely; at this stage at least.

Chapter 4 describes the model building techniques used in this study and sets out the variables and relationships which comprise the road dust model.

CHAPTER 4

ROAD DUST MODEL DEVELOPMENT, STRUCTURE AND EVALUATION

4.1 Introduction

The choice of a methodology and the development of a working model are influenced to some degree by the type and quality of data already available and by the special characteristics of the system being simulated.[6] The chief factors influencing the form of the road dust model include:

(1) Limited data availability (see Section 1.3), to guide model construction; and

(2) A need for generality to enable application to a wide range of enterprise types and environmental conditions.

Where sufficient data were available to establish component relationships, stochastic variables were introduced into the model to represent the uncertainty

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6. For a predictive model, such as the road dust model, the adoption of stochastic routines are useful since they can be used to describe the uncertainty surrounding both unexplained events and events which are truly random (Dent and Blackie, 1979). This is accomplished by establishing a probability distribution for the event and drawing from it in a Monte Carlo fashion, during each replication and/or run of the model. However, where the probability distribution is unknown (as for many components of this model), then it is simpler to use deterministic routines, which are run only once and return a single output figure, based on a set (usually an average) value assigned to each particular variable.

associated with these relationships. For parts of the system where data were lacking, deterministic routines were used, with scope provided for the user to vary the levels of many variables and parameters via interactive input. The model was built on a modular concept to allow ease of modification as new data becomes available.

4.2 Model Evaluation

The process of model evaluation is an important stage within the development of a simulation model, since it largely determines the confidence placed in generated results and the value of the analysis for decision support. Model evaluation comprises two distinct aspects.

4.2.1 Verification

Model verification involves testing the final model in relation to the modeller's concept of the model at the outset. The methods used to evaluate and correct a model include two important sets of techniques known as 'antibugging'[7] and 'debugging' (Dent and Blackie, 1979).

The road dust model has been verified to the author's satisfaction. This was achieved mainly by inserting numerous WRITE statements in the various routines to allow hand checking of the model's operations. The unnecessary WRITE statements were removed when verification was completed. Subsequent testing revealed that model responses conformed with expectations.

4.2.2 Validation

Model validation involves testing the agreement between the behaviour of the model and that of the real

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7. The terms 'antibugging' and 'debugging' are from the jargon of computer programming and refer to the various methods available for both preventing and removing logical flaws in programs.

system (Herman, 1967; Fishman and Kiviat, 1967). As model validation occurs both during model construction and at the completion of model building, the description of model validation is outlined throughout both this chapter and the following chapter.

The methods used for validation are necessarily linked to both the purpose and to the costs and benefits of modelling and hence, depend largely on the subjective judgement of the modeller (Greig, 1978). There are both subjective and objective tests available, with each type being complimentary and of equal importance. Subjective tests were used predominantly for this model due to the lack of adequate data to perform statistical tests against model output.

The most appropriate tests for this model then, were to:

(1) Use experts and research results closely related to the system to guide modelling. The development of the road dust model was based on the results of an extensive literature search of previous dust studies, a large number of interviews with farmers, growers, etc., and also regular liaison with various experts from related disciplines.

(2) Use simple empirical results to assess hypotheses and assumptions wherever possible. These were conducted to measure the effects of dust cover on the intensity of light reaching leaf surfaces. However, the cost of conducting tests prevented any other empirical tests being conducted in this study. Nevertheless, the use of other research results should serve as a good indicator at this stage.

(3) Use subjective tests to assess output from;
    a) individual modules of the model; and
    b) the complete model.

Since little other work has been conducted of the scope of this study, most assessment was conducted against the results of previous related studies and also some manual calculations prepared by the author. Outputs of the model, and of the various modules, displayed good correlation with the calculated results.

(4) Perform sensitivity analysis on the model to assess whether it performs as expected. Sensitivity analyses were conducted on all variables and parameters contained in the model. These are outlined in Chapter 6.

(5) Use common sense and logic in building the model and to assess the validity during model development. This was perhaps the most important aspect involved in the evaluation of the model, especially due to the uniqueness of the study. At all times during model development, the logic of various relationships were assessed in relation to the author's expert knowledge developed in this field (Van Horne (1971); Shannon (1975); Dent and Blackie (1979)).

The process of validation should never be regarded as complete, since there is no such concept as perfect truth. Thus, although the model has been validated as much as possible based on present knowledge, greater confidence in the ability of the model to accurately predict the costs to production from road dust, can only be gained by the constant assessment and refinement of the model, in response to the availability of new system data.

4.3 Suitability of Data and Model Structure

The structure of a model can be influenced strongly by the availability and applicability of data, and for this system, data, or the lack of them, necessitated a split stochastic-deterministic model.

4.3.1 Photosynthetic yield reduction

The only part of the system for which there was sufficient data available for detailed modelling of the processes involved, was photosynthetic yield reduction. However, the data were often only slightly related, disjointed and/or lacking proven validity. Also, there are a large number of exogenous variables influencing the effects of road dust on photosynthesis which could not be quantified.

In order to minimise error, wherever possible, each variable and relationship within the submodel was subjectively validated before inclusion and stochastic variables were introduced into the model to reflect the uncertainty of the data. In addition, values were always assigned to variables and parameters conservatively, in order to avoid a cumulative effect of overestimation.

In this way, a fairly detailed submodel was developed for the effect of road dust on photosynthesis.

4.3.2 Other Effects of Road Dust

Though there were insufficient data available to accurately simulate the mechanics of road dust effects on other aspects of agricultural or horticultural enterprises, from the information collected, it was possible to isolate a number of effects which may be of economic significance.

Each of these effects was incorporated into the model by including them at given percentage levels of effect on production. This provides the flexibility to reflect the attitudes and opinions of the model user, and to provide a basis for the user to undertake some sensitivity testing of the outputs. Scope is provided for the user to input whether they expect a high, low or zero level of influence for each specified effect.

The costs derived from these routines are only illustrative and should be regarded as such until experimental data are available.

4.4 Model Overview

A general structure diagram of the system being studied is shown in Figure 4.1. The system is modelled in two major subsystems; an animal enterprise subsystem and a plant enterprise subsystem.[8] The animal enterprise subsystem consists of only a single deterministic routine. The plant enterprise subsystem comprises of a series of stochastic modules to calculate yield losses due to reduced levels of photosynthesis and a single deterministic routine to handle losses from all other effects of road dust. The two subsystems are invoked on an either/or basis, depending on the type of enterprise being evaluated.

Whilst the animal submodel and the 'other effects' routine in the plant submodel only involve simple estimations of cost, the calculation of photosynthetic yield loss cost is relatively complex.

Conceptually, the modelling of photosynthetic yield loss comprises of a number of major components. The first involves the emission of road dust from an unsealed road, which is represented as a function of the road's average traffic density, average traffic speed and percentage silt content of roading material. The second component, the road dust deposition density distribution, is a function of the distance from the roadway, the side of the road and various other climatic and physical factors. The final component involves the actual estimation of photosynthetic yield loss due to reduced sunlight intensity reaching plant surfaces because of dust cover. This is calculated for each square

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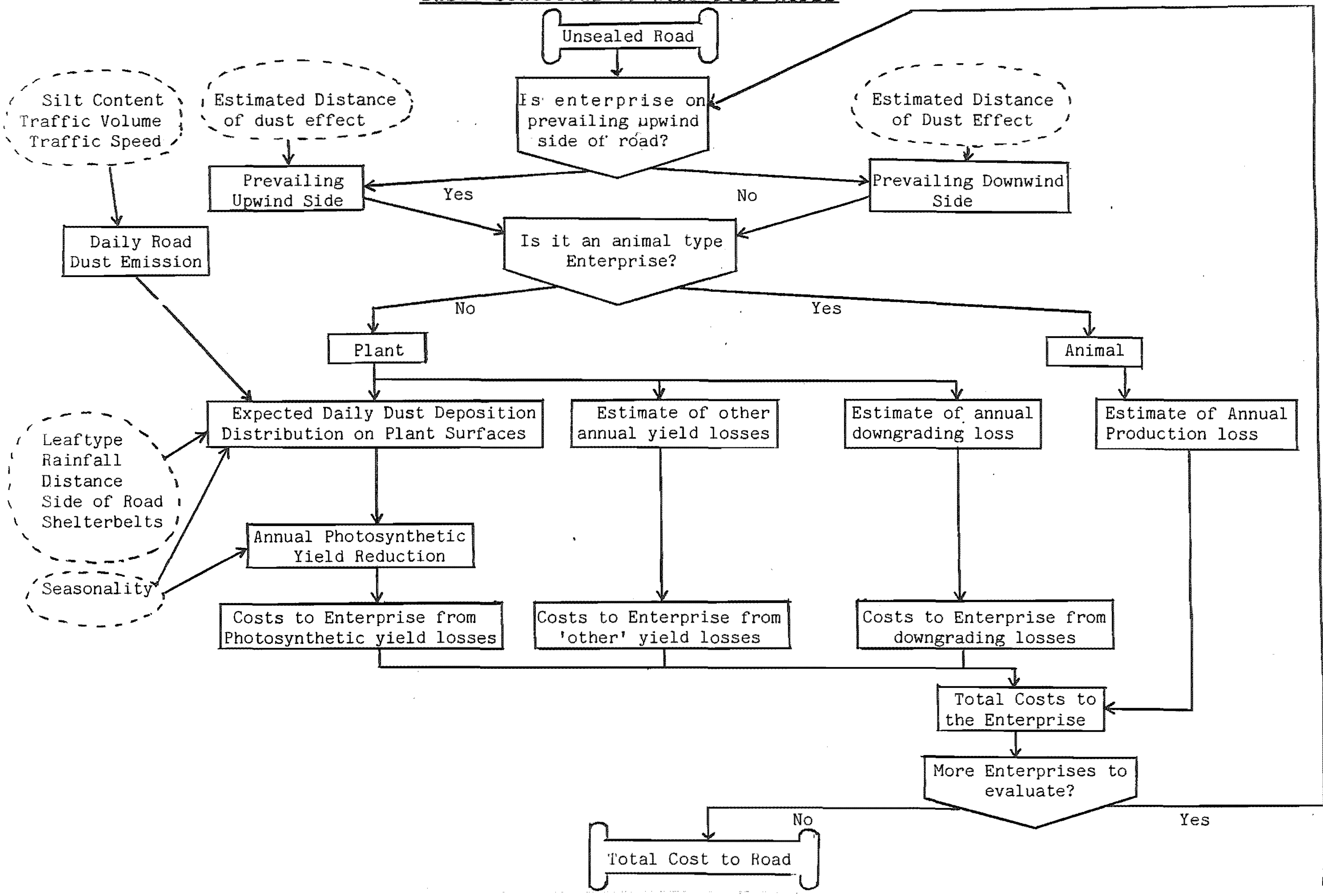
8. The plant enterprise subsystem includes all horticultural and arable enterprise types.

FIGURE 4.1

BASIC STRUCTURE OF ROAD DUST MODEL



metre of productive land away from the roadway and summed to provide an expected total loss to the enterprise being evaluated. The standard deviation of the expected total loss is also estimated.

The deterministic routine for the plant enterprise subsystem provides estimates of other possible road dust induced losses, through either yield reduction or downgrading of produce. Effects accounted for include:

1) Reduced pollination.
2) Increased levels of pest, disease and weed incidence.
3) Dust contamination.

The animal enterprise subsystem generalises the combination of effects which road dust may have on animal production.

The costs due to each relevant effect are totalled for each enterprise, analysed and then summed, to provide a total cost from loss of production due to road dust, for a given stretch of road. In addition, a pooled standard deviation of the total photosynthetic yield loss costs is calculated. Finally, given the expected life for road seal of 15 years, the annual costs from road dust over 15 years are discounted into a net present value equivalent cost, which can readily be compared to the costs of dust suppression (i.e. generally sealing).

4.5 Conclusions

The development of the road dust model was hampered by a lack of suitable data. Yet every effort has been made to ensure that the model simulates the real system as well as possible, given the modelling constraints. Data was evaluated carefully before inclusion in the model and where data were unavailable, assumptions were stated clearly and conservatively. In addition, the model has been constructed on a modular basis so that it can be further refined as new information becomes available.

The following chapter describes in greater detail the data and components used in the development and construction of the model.

CHAPTER 5

MODEL CONSTRUCTION

The road dust model is constructed in two major submodels:

1. Horticultural and Arable Production Submodel.
2. Pastoral Production Submodel.

The submodels each consist of a number of modules, the number and complexity of which depend upon the availability of adequate data. The following provides an explanation of the development and construction of the submodels and modules.

5.1 Modelling the Effects of Road Dust on Horticultural and Arable Production Systems

5.1.1 Photosynthetic yield reduction

5.1.1.1 Daily road dust emission on dry roads. McCaldin and Heidel (1978) showed that the rate of dust emission from metal roads varies as a square of speed rather than directly with speed as had been earlier thought (Cowherd, et al, 1974 and United States Environmental Protection Agency, 1975). Their equation provides a better fit to most experimental data than any others developed to date and hence, is used in the model. It is expressed as:[9]

9. McCaldin and Heidel's (1978) equation has been metricated by the author.

$$Emis = 0.0038 * S * T * X^2$$

where: Emis = daily emission (grams) per metre

S = silt content of road surface expressed as a decimal fraction

T = average daily traffic count

X = traffic speed in kilometres per hour.

The crudeness of the equation is apparent since it takes no account of effects of:

(i) The shape, number of tyres and type of vehicle.

(ii) Physical characteristics of the road surface.

(iii) Meteorological conditions that affect the transport of dust.

(iv) The size, distribution and density of the dust particles.

However, the output of the equation corresponds fairly closely to the findings of both the New Zealand Institute of Engineers (NZIE) Standing Committee on Rural Roads (1937)[10] and to Hoover, et al. (1981).[11]

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10. The NZIE figure is based on the assumptions of:
   (i) Traffic wear on metal roads of 0.475m per kilometre per vehicle per day; and
   (ii) A dry, loose density aggregate weight of 1500 kilograms per cubic metre (MWD, pers. comm., 1984).

11. Hoover, et al. (1981) quantified dust sources and emissions created by traffic on unpaved roads and found that the average dust generation was 631 kilograms per kilometre per vehicle per annum (converted from imperial standard measures by the author).

For example if assumptions of;

(1) average trafic speed of 70 km/hr along unsealed roads; and

(2) six percent silt content of roads;

are chosen for the equation,[12] then the emissions from each of the studies can be compared (Table 5.1).

TABLE 5.1

Comparison of Findings on the Daily Emission of Road Dust

	Average Daily Traffic Count (vehicles per day)		
	75	250	500
	(Kilograms of dust per kilometre of road)		
McCaldin and Heidel (1978)	84	279	559
NZIE (1937)	146	488	976
Hoover, et al. (1981)	129	432	864

The figures shown in Table 5.1 indicate that although the emission figures of McCaldin and Heidel (1978) are significantly lower than those found in the other studies, they are at least, of a similar magnitude. Thus, McCaldin and Heidel's equation provides a reasonably conservative estimate of road dust emission for New Zealand conditions.

An allowance for uncertainty was introduced into the equation by providing user input of high, medium and low values for the silt content, traffic speed and daily traffic

12. The assumptions of 70 km/hr average traffic speed and 6 percent silt content are an average for New Zealand roads.

count variables and then drawing each from a triangular distribution for each run of the model.

5.1.1.2 Deposition distribution. The road dust deposition distribution away from the roadway differs depending upon whether an enterprise is on the prevailing upwind or on the prevailing downwind side of the road. User input of the particular side of the road for each enterprise analysed, switches the program into either a downwind or an upwind subroutine, each of which output the expected deposition densities of road dust on plant surfaces per metre squared, for each metre away from the roadway.

The calculation of downwind deposition distribution is based primarily on the work of Becker (1978) who developed a mathematical model which predicted the total downwind deposition from an infinite instantaneous line source of 1.0 g/m,[13] during neutral conditions,[14] at distances of 4, 8, 16, 32, 64, 128, 256, 512 metres from the road.

Table 5.2 presents the averaged deposition levels estimated at each distance, from sixteen tests conducted by Becker (1978) in which the vegetation, roughness height, atmospheric stability, deposition height, source height and wind speed were all varied. Average deposition figures were used in this study largely because of problems involved in obtaining adequate data on the various influencing factors. This should not be too crucial at this stage, since the

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13. A dust plume resulting from a vehicle traversing a dry unsealed roadway, may be considered as originating from a moving point source, or it may be treated, approximately, as an infinite instantaneous line source. Over large sampling periods, the difference in the two methods is negligible.

14. Becker (1978) defines neutral conditions as those incorporating a "range of conditions typifying a rural environment".

effects of windspeed and roughness height will largely cancel each other out; except over smooth pastures, where the economic effect of dust deposition will be very small.

TABLE 5.2

Estimated Average Deposition Levels at Various Sites Downwind of an Instantaneous Line Source of 1.0 g/m

Distance from Road (m)	Average Deposition (g/m^2)
4	263
8	188
16	118
32	70
64	39
128	22
256	12
512	5

Source: Becker (1978).

The following equation (1) was fitted to the data in Table 5.2 using ordinary least squares regression.[15]

$$Y = 1012.183\ X^{-0.809} \qquad (1)$$

R^2 = 98.51% adjusted for degrees of freedom.

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15. All equation estimations in this study have been conducted using the Time Series Processor (TSP) statistical computer package.

where: Y = Dust Deposition (g/m^2)
X = Distance from Roadway (m).

Becker's downwind estimates were adapted for the prevailing upwind situation using the findings of:

(1) Ward, et al. (1979), who recorded the lead content of pasture species adjacent to a highway; and

(2) Hoover, et al. (1981), who recorded the level and distribution of road dust emissions prior to roading improvement programmes.

Both discovered almost identical differences between prevailing upwind and downwind deposition levels at different distances within relatively close proximity of the roadway.

Their actual findings are graphed in Appendix I and the magnitudes of their differences, as well as an average of the different factors, are presented in Table 5.3.

These averaged differences were extrapolated and applied to the downwind deposition distribution figures to arrive at an estimate of upwind deposition distribution, shown in Table 5.4.

The equation estimated from the data in Table 5.4 is;

$$Y = 891.533\ X^{-1.042} \qquad (2)$$

R^2 = 98.69% adjusted for degrees of freedom.

where: Y = Dust deposition (g/m^2)
X = Distance from roadway (m).

TABLE 5.3

Factor by Which Prevailing Downwind Road Dust Deposition was Greater than that for Upwind Side

Distance from Road (m)	0	5	10	15	20	25	30
			Factor				
Ward's Experiments	1.06	1.74	2.0	1.93	2.0	2.1	2.5
Hoover's Experiments	1.01	1.70	1.5	2.40	Data not Recorded		
Average	1.035	1.72	1.75	2.10	2.0	2.1	2.5

Source: Ward, et al. (1979) and Hoover, et al. (1981).

TABLE 5.4

Estimated Average Deposition Levels at Various Sites Upwind of an Instantaneous Line Source of 1.0 g/m

Distance from Road (m)	Average Deposition (g/m^2)
4	154
8	108
16	57
32	28
64	13
128	6
256	3
512	1

Because the level of road dust decreases expontentially away from the roadway, it was necessary to calculate the dust deposition density (and the resultant effects on photosynthetic yield reduction), for each metre away from the roadway, up to an estimated distance of significant effect for each side of the road.

The equations estimated above ((1) and (2)) relate to the actual deposition levels found by Becker (1978). The expected deposition levels for each metre away from either side of the roadway in this study, are found by calculating the percentage of total deposition which falls at each metre (from Becker's results); and then multiplying these percentages by the level of dust emission. The percentage deposition levels are calculated by transforming the regression equations into integration terms; viz

1) Downwind side

$$Yd = \int_{n-1}^{n} (5299.38\ X^{-0.191})\,\partial X$$

2) Upwind side

$$Yu = \int_{n-1}^{n} \left(\frac{-891.533}{0.042X^{0.042}}\right)\partial X$$

where: Yu & Yd = prevailing upwind and downwind dust deposition (g/mp2)

X = distance from roadway (m)

n = 1 to 500.

These are then used to calculate the percentages of total deposition at each metre away from the roadway on either side of the road. An expression for these procedures are shown below;

1) Downwind side

$$\%Yd_i = \sum_{i=1}^{200} \frac{Yd_i}{YT} * \frac{100}{1}$$

2) Upwind side

$$\%Yu_j = \sum_{j=1}^{60} \frac{Yu_j}{YT} * \frac{100}{1}$$

where: Yu & Yd = prevailing upwind and downwind dust deposition (g/m^2)

YT = total dust deposition on both sides of road up to 500 metres away from the road

i = 1 to 200

j = 1 to 60.

The 'cut-off' distances for calculations on either side of the road were based loosely on the findings of Becker (1978), Ward, et al. (1979) and Hoover, et al. (1981).

A distance of 200 metres was chosen for the prevailing downwind side. Within this distance, it is estimated that approximately 80 percent of the downwind side dust would be deposited. For the prevailing upwind side, a distance of 60 metres was chosen. At these distances, the average expected level of actual deposition is approximately the same for both the prevailing upwind and the prevailing downwind sides of the road.

Once the deposition density levels have been calculated for either side of the road, three further adjustments are required to allow for differences between deposition on leaf surfaces and flat ground. These include percentage reductions for:

(1) Dust not intercepted by plant surfaces. Obviously not all the road dust predicted to fall within a given ground

area will settle on the plant surfaces within that area. Also, because plants have a greater surface area than flat ground per unit area of flat ground (hence the dust is spread more thinly on average), the deposition density of road dust on plant surfaces will be less than that calculated for flat ground. A reduction factor is used to reflect this reduced dust density.

A midpoint of 35 percent was chosen with upper and lower limits of 70 percent and 20 percent respectively, from within which a reduction figure is chosen randomly from a triangular distribution. The incorporation of this feature is aimed at representing some of the uncertainty surrounding the figure.

Initially it was felt that the figure of 35 percent should be higher, but it is likely that the natural layering effect of plant canopies, combined with the angled movement of dust towards the ground, would cause a great deal of the suspended dust to be intercepted by plants. Also, the outer leaves which receive maximum sunlight and are responsible for much of the photosynthesis of plants, also receive the greatest amounts of dust cover. Thus, reduced levels of dust on inner and lower leaves is not so crucial to the overall photosynthesis level.

2) Smooth leaf surfaced plants. In addition to the density reduction for plant dust interception, a further reduction is required for plants with smooth leaves, since they are less likely to retain as much dust as hairy leaved plants. Arbitary figures of 50 percent, 15 percent and 5 percent were chosen for the parameters of a triangular probability distribution.

3) Enterprises with shelterbelts bordering roadsides. As outlined in Section 3.2.7, shelterbelts reduce the quantity of dust reaching productive land, with a likely reduction level of around 40 percent. The reduction figure used in

the model is drawn from a triangular probability distribution with high, medium and low parameters of 70 percent, 40 percent and 20 percent respectively. This introduces some of the uncertainty surrounding the estimated shelterbelt reduction level of 40 percent (Section 3.2.7).

The final output from either the downwind or the upwind subroutines is an array of deposition density levels of road dust on leaf surfaces, for each square metre away from the roadway, up to the respective cut off distances (i.e. 60 or 200 metres).

5.1.1.3 Calculation of yield loss. The density of road dust present on leaf surfaces is the chief determinant of the amount of plant photosynthesis reduction, and varies according to climatic and seasonal factors. Obviously more dust is present in summer than winter due to the absence of dew and also, dust accumulates during long dry periods.

Some seasonal effects are accounted for in the model by dividing the year into two parts:

(1) Summer - from November to April inclusive;
(ii) Winter - from May to October inclusive.

A subroutine (RAIN) is used to isolate the seasonal effects and also to generate a rainfall pattern from which to calculate the accumulated deposition of road dust density. This subroutine reads the daily rainfall records for any selected area from a data file (RAIN.DAT) set out in monthly arrays of historical daily rainfall records (in this case for Tauranga County).

An assumption is made that any road dust which is deposited on leaf surfaces accumulates daily until sufficient rain falls to wash it off, when the cycle begins again.

P. Storey (pers. comm., 1984) suggests that it takes 4mm of rain on any day to remove road dust from plant surfaces, since it takes approximately 6-12mm of rain to remove agricultural sprays, which would be more adhesive to leaf surfaces than road dust. The model uses the assumption that on any day with 4mm of rain or more, there would be no road dust present on leaves and further, that one day in summer and two days in winter after a period of rain, are required for the roads to dry and dust conditions to resume.

The RAIN subroutine records all days, both for summer and winter, when there would be no dust, 1 day's accumulation of dust, 2 days accumulation, etc.; and forms a probability distribution for the number of days of accumulated dust, for both summer and winter, based on the historical records.

The routine also calculates the number of both summer and winter days as a percentage of the total number of annual active growing days for each particular enterprise.

These percentages are stored as a probability distribution from which, for each replication of a model run,[16] the subroutine RAIN is randomly directed into either the winter or summer probability distribution for the number of days accumulated dust density. This number is then multiplied by the appropriate upwind or downwind daily deposition density array to provide the expected road dust density on leaf surfaces, for each metre away from the roadway.

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16. The model has been set up to include 365 replications on each model run. Although this number represents the number of days in a year, and is perhaps useful for illustrating to model users that a model run simulates one year's production for any enterprise evaluated, the number in itself is of no practical significance.

In order to link the dust density on leaf surfaces to photosynthetic yield loss, the reduction of light intensity reaching plant surfaces caused by dust cover, was simulated under artificial sunlight conditions (see Appendix II). The results of these simulations are graphed in Figure 5.1.

Assuming that the percentage reduction in photosynthetic rate, due to reduced light intensity is proportional to the percentage loss of plant yield[17] (W. Scott, pers. comm., 1984), yield losses can be calculated using the asymptotic exponential function of Goudriaan and van Larr (1978) for temperate plants, viz;

$$P = Pmax\ (1 - e(- \frac{S}{Sm})$$

where: P = percentage reduction of photosynthetic rate;

Pmax = the amount of photosynthesis in bright light, $Pmax = 0.7\ mg\ CO_2\ m^{-2}s^{-1}$;

S = the absorbed photosynthetically active radiation (Wm^{-2});

Sm = the level of S to reach half the saturation level (i.e., 0.5 Pmax), $Sm = 50\ Wm^{-2}$;

e = exponential.

The amounts of photosynthesis reduction found for various levels of light reduction are shown in Table 5.5.

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17. The assumption of an exact linear relationship between percentage photosynthesis and yield loss is fairly simplistic in that the amount of correspondence between the two will vary depending upon the stage of plant growth. However, it is reasonable for the overall purposes of this model.

Figure 5.1
The Effect of Dust Deposition Density Levels on the Light Intensity Reaching Leaf Surfaces

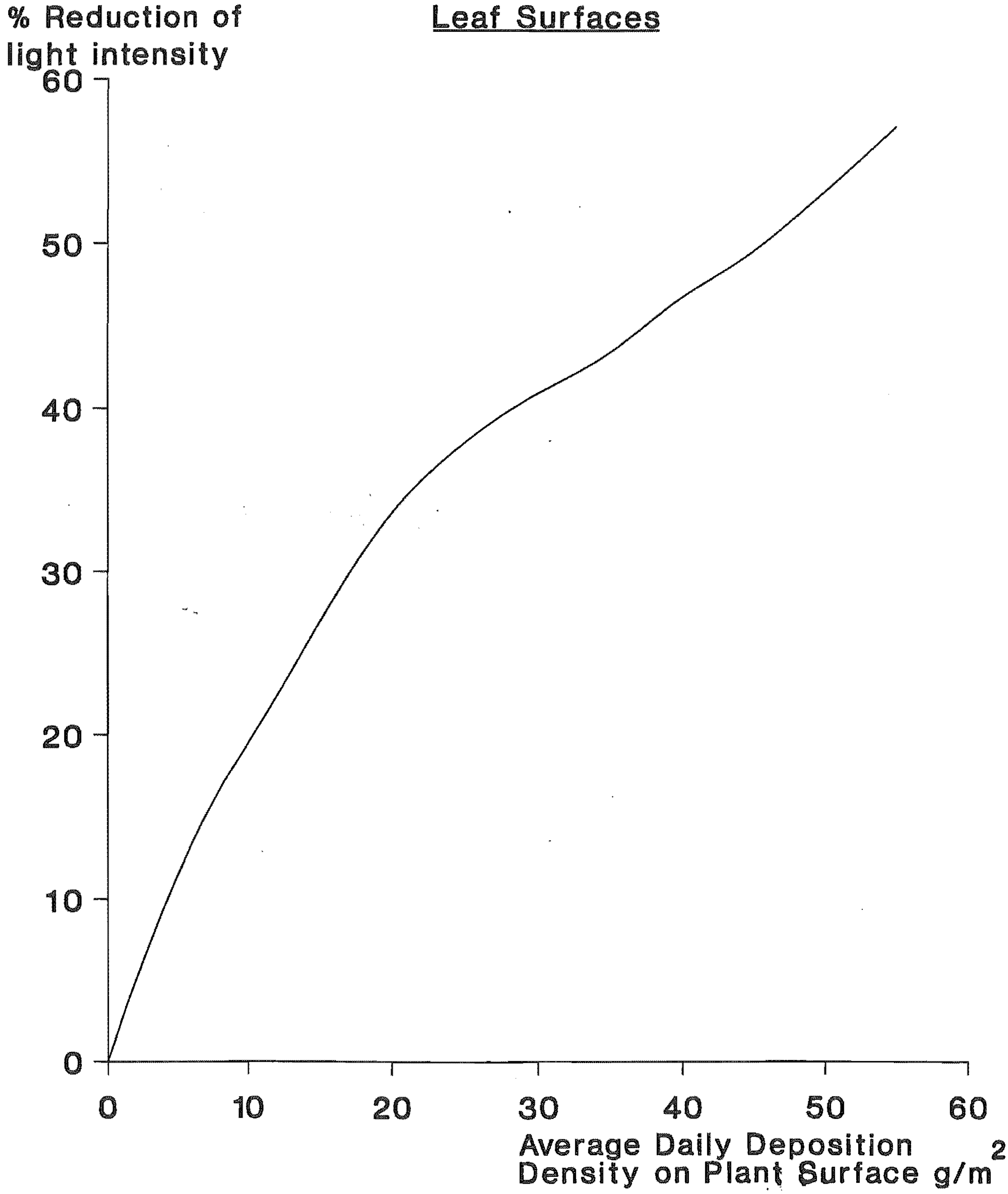

TABLE 5.5

Photosynthesis as a Function of Reduced Light Intensity

% Reduction of Light Due to Dust	Photosynthesis Rate (mg^{-2} s^{-1})	% Reduction of Photosynthesis
a) Average Summer Sun (225 Wm^{-2})		
0	0.69	0.0
10	0.69	0.0
20	0.68	1.5
30	0.67	2.9
40	0.65	5.8
50	0.64	7.3
b) Average Winter Sun (40Wm^{-2})		
0	0.39	0.0
10	0.36	7.7
20	0.33	15.4
30	0.30	23.1
40	0.27	30.8
50	0.23	41.1

Source: Gourdriaan and van Larr (1978).

The differentiation of summer and winter light intensity levels highlights the greater percentage effect which road dust has on photosynthesis rates during the winter period. Actual levels of photosynthesis activity over the winter period are much lower than summer levels (i.e., 0.39/0.69 = 56 percent) and this fact has been accounted for in the estimation of the photosynthetic yield loss function for winter. In addition, the effect of dew would suppress dust emission for at least part of any dry day in winter. This effect was incorporated within the model by including a reduction factor for the average daily traffic count during the winter period, of an estimated 50 percent.[18]

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18. This estimate is based on the assumption that around 50 percent of rural traffic travels during the evening or early morning.

Thus, considering these moderating influences on the winter levels of photosynthetic yield reduction, the differences in overall photosynthetic effect between summer and winter are largely negated.

Equations estimated using regression analysis on the relationship between both summer and winter road dust cover on leaf surfaces, and percentage photosynthesis reduction, are given below and illustrated in Figure 5.2.

(1) Summer

$Y = 0.226 X^{0.878}$
$R^2 = 0.994\%$ adjusted for degrees of freedom.
Standard deviation = 3.28

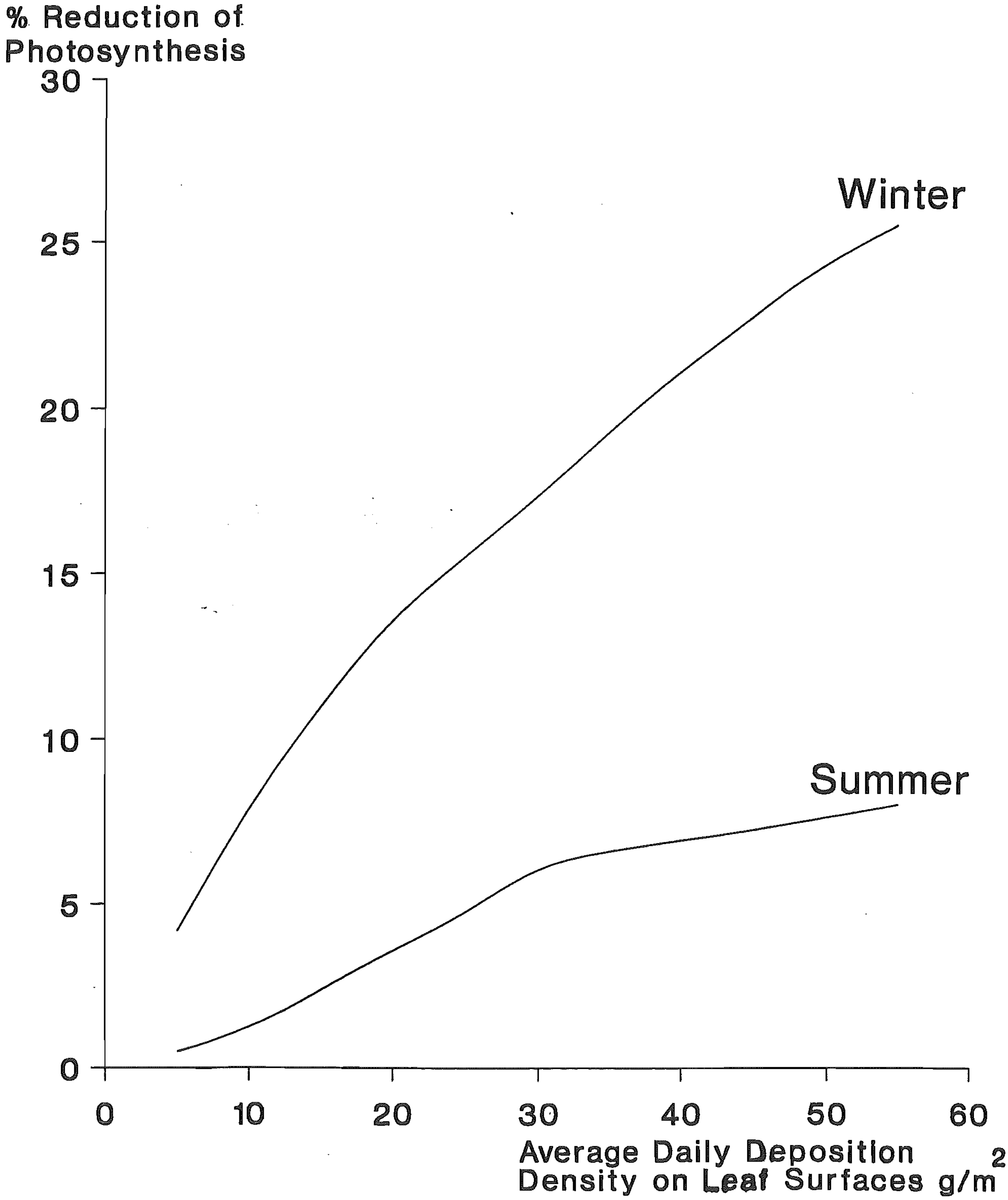
(2) Winter

$Y = 1.421 X^{0.733}$
$R^2 = 0.991\%$ adjusted for degrees of freedom.
Standard deviation = 0.549

where: Y = Percentage photosynthetic yield reduction; and
X = Density of road dust cover on leaf surface (g/m^2).

Depending upon the season randomly selected for each daily replication of the model, these equations are multiplied by the enterprise type's expected yield (t/m^2) and used to calculate the photosynthetic yield loss (t/m^2) for each square metre away from the roadway. The total yield loss to the enterprise is calculated by summing these losses and then multiplying by the length of the enterprise road frontage.

Figure 5.2
Photosynthetic Response to Road Dust Cover on Leaf Surfaces



The costs from photosynthetic yield loss are found by subtracting the costs which vary with yield,[19] from the weighted average price per tonne[20] and then multiplying the difference by the total yield loss for the enterprise. All costs are calculated using national resource costs and prices in 1985 dollars (see Appendix III).

5.1.2 Accounting for other road dust effects

Apart from photosynthetic yield losses, it is not yet possible to make an encompassing estimate of the amount of yield reduction or produce downgrading, caused by road dust contamination. Considerable field research and experimentation would be required to estimate the average losses from other road dust effects.

Estimates of possible road dust effects on production, provided by scientists and producers and cited in Chapter 2 (e.g. 20 percent loss of yield due to poor weed control, R. Field, pers. comm. (1984)) provide a starting point, but it is likely that the magnitude of these estimates may only be relevant to plants very close to the roadside. Thus, no attempt has been made to link these estimates to the dust deposition distribution functions used in the photosynthetic yield loss calculations.

Instead, arbitrary figures of 1.0 percent and 0.5 percent have been chosen as high and low estimates of the average amount of yield reduction or downgrading due to a number of road dust effects.

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19. Costs which vary with yield include costs of harvesting, packaging and freight.

20. Weighted average price is the average price received for all grades of produce, with respect to the proportion of each grade sold.

The costs are calculated for each effect (listed below), depending upon the inclusion and level of the effect as determined by the user.

The effects included are:

(1) Extra pest and disease incidence;
  (a) Yield losses; and/or
  (b) Downgrading.
(2) Reduced pollination;
  (a) Yield losses; and/or
  (b) Downgrading.
(3) Downgrading due to dust contamination on produce.
(4) Yield losses due to increased weed incidence.

5.2 Modelling the Effects of Road Dust on Pastoral Production Systems

Costs to pastoral farming from road dust are even more difficult to assess than those accruing to horticultural and arable crops, mainly because animals are never grazed continuously along the area adjoining a metal road and thus, any effects are not as clearly defined as for plant systems.

It is simple enough to calculate the theoretical loss of pasture production due to reduced photosynthesis and a specific reduction of pasture production per hectare can be related theoretically to animal production losses. However, there are a number of complicating factors which include:

(1) Pasture growth is not uniform throughout the year and does not correspond exactly to animal feed requirements. Thus, at certain times there are excesses of feed, during which time any retarded pasture growth due to road dust is insignificant to animal production. Also, during some dry periods

pasture growth is minimal due to lack of water, rather than to any effects of dust.

(2) The impact which any retarded pasture growth has upon animal production depends very much upon the quality of the herbage, the composition of the sward and also the stage of grass growth. Hence, the degree of influence may vary markedly from paddock to paddock.

(3) Animal production figures vary widely and it is difficult to attribute any reductions of production directly to road dust effects. In addition, because the animals are rotated about paddocks, any loss of production is likely to be extremely difficult to gauge on individual animals. Small losses may be expected to occur across a total flock or herd.

It would appear that any animal production losses due to road dust depend very much upon management, especially how the farmer utilises his available feed and organises his stock rotations.

Acknowledging the difficulties involved in assessing the losses to pastoral farming systems from road dust, two major simplifying assumptions are made. These are:

(1) That animals are distributed at a static uniform stocking rate over the entire farm. Although not realistic in the physical sense, this assumption seems reasonable in that it assumes an averaged annual loss for a set number of animals grazed on the dust affected area. The total losses should correspond to the losses which could be expected over a year from heavy stocking rates for relatively short and periodic intervals.

(2) Because of the difficulties involved in directly measuring any animal production losses due to road

dust, this variable is included at a user determined level of 1.0 or 0.5 percent of gross income.

5.3 Description of the Computer Model

5.3.1 Model structure

The model is constructed in a modular form and accesses a series of subroutines. Information required for the operation of the model is obtained from three sources:

(1) Variables and components of the model which are assumed to be common to each run, are incorporated directly within the main routine and the various sub-routines;

(2) Essential historical climatic data unique to any particular region are stored in a data file (RAIN.DAT) (see Appendix VII);

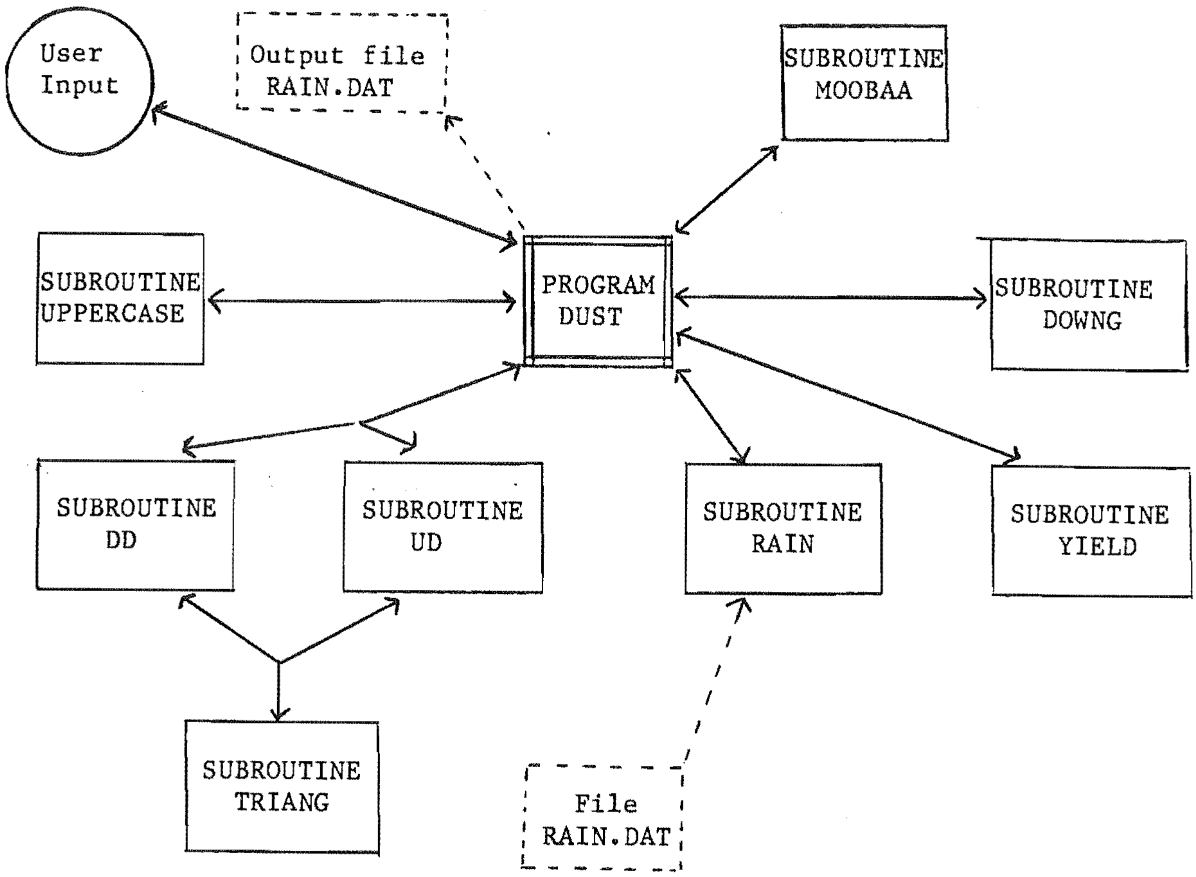
(3) Data unique to each enterprise and/or road segment being analysed are input using a direct user interactive process. This format seemed the most appropriate given the wide diversity of circumstances under which the model will be used.

A diagram of the subroutines shown in Figure 5.3 gives an outline of how the model is constructed. All sub-routines used in the model are listed in Appendix V.

Photosynthetic yield reduction due to road dust deposition on horticultural and arable production systems adjoining unsealed roads, is simulated by the subroutines DD, UD, RAIN and YIELD. None of these subroutines are directly linked. All information is passed from the main program to the subroutines and back again for further use.

FIGURE 5.3

Structure of the Computer Model



Subroutine DD estimates the quantity of road dust emitted per metre of unsealed road for any dry day. It then estimates the deposition density distribution of dust onto plant surfaces for each metre away from the roadway on the prevailing downwind side of the road. This is calculated for each dry day and includes allowances for the factors which may influence the level of dust deposition (e.g. leaf type, shelterbelts, etc.). Subroutine UD provides similar estimates for the prevailing upwind side of the road. Because of the assumption that an enterprise can only be sited on either the prevailing downwind or the prevailing upwind side of the road, only one of these subroutines is called for each run of the model; the choice of which depends upon user input.

A number of variables contained within the DD and UD subroutines are stochastically determined from a probability distribution. Hence, subroutine TRIANG, which is a routine to sample from a triangular distribution, is called a number of times by these subroutines in order to reflect the uncertainty surrounding such variables.

Subroutine RAIN reads data from historical rainfall records stored in a file called RAIN.DAT and then passes seasonal and climatic probability distributions, relevant to the growing season of the enterprise being analysed, back to the main program (DUST).

The output from the UN, DD and RAIN subroutines are used in a function contained in subroutine YIELD to estimate percentage yield losses due to photosynthesis reduction. Subroutine YIELD returns figures for both the actual and the average percentage yield loss to the main program.

Subroutine DOWNG is a deterministic routine which calculates a cost from 'all other' effects to horticultural and arable enterprise types. The total cost found in this subroutine is added to the costs from photosynthetic yield, in the main program.

Subroutine MOOBAA is also a deterministic routine which is used to calculate costs to animal enterprise types.

It is important to note that the use of the horticultural/arable enterprise subroutines (i.e. DD, UD, RAIN, YIELD, DOWNG and TRIANG) and the animal enterprise subroutine (i.e MOOBAA) are mutually exclusive for each run of the model.

Subroutine UPPERCASE is included to ensure that user responses are interpreted correctly by the computer when responses are input in lower case.

The main program, DUST, is used for all computer input and final output. It also collates, analyses and combines the information provided by the various subroutines. Final output (transferred to an output file RES.DAT) includes an outline of the major road dust effects and costs, for each enterprise analysed and also, a summary of the dust costs for the complete stretch of road. This includes both the annual cost and a net present value cost.

5.3.2 Flexibility of the model

The model has been built to be interactive and has a number of characteristics termed 'user friendly'. The reason for this design was to facilitate flexibility to aid any sensitivity analyses which may be required. Aspects that can easily be changed include most physical parameters associated with both the road and the enterprises being analysed, and all the economic parameters. Values that can be altered by the user are listed in Table 5.6. The parameters that can be varied are numerous and necessary for the varied requirements of the model.

The main program, DUST, which is listed in Appendix V,[21] allows the menus and the questions to be set out neatly on the screen, giving this program 'user friendly' characteristics. The neatness and layout of results in the output file RES.DAT also allows for ease of interpretation. As can be seen from the output example in Appendix IX, most of the physical and economic parameters are incorporated in the output, for each enterprise analysed alongside an unsealed road. This allows each run to be relatively self-explanatory. Presenting the physical and economic

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21. In addition to the program listing given in Appendix V, a list of all variable names and definitions used in the model is provided in Appendix VI.

parameters in the output printout allows the user to undertake some validation, which encourages confidence in the model.

The model has been constructed to be accessible to users other than the developer. The model output file is self-explanatory and allows for ease of interpretation. Flexibility built into the model aids sensitivity analysis and allows the model to be relevant in the future when economic parameters have altered and when more precise information is available regarding the effects of road dust on production systems.

TABLE 5.6

List of Variables Which can be Altered Via User Input

Category	Variables
Road Parameters	- road name
General	- length of road segment being analysed (metres)
	- vehicle speed (km/hr)
	- traffic count variables (vehicles per day)
	- silt content of roading material (decimal fraction)
Enterprise Parameters	
General	- enterprise type (e.g. kiwifruit)
	- enterprise discipline (i.e. animal/ plant)
	- distance from road centre to start of productive land (metres)
	- side of road (i.e. prevailing upwind/ downwind)
	- road frontage (metres)
Horticultural/Arable	- extra pest and disease incidence (yes/no)
	- yield effect (yes/no)
	- high estimate (yes/no)
	- downgrading effect (yes/no)
	- high estimate (yes/no)
	- reduced pollination (yes/no)
	- yield effect (yes/no)
	- high estimate (yes/no)
	- downgrading effect (yes/no)
	- high estimate (yes/no)
	- downgrading due to dust on produce (yes/no)
	- high estimate (yes/no)
	- increased yield affected by weed incidence (yes/no)
	- high estimate (yes/no)
	- yield (t/ha)
	- weighted average price ($/t)
	- premium grade price ($/t)
	- lowest grade price ($/t)
	- weighted average costs that vary with yield ($/t)
	- premium grade costs that vary with yield ($/t)
	- lowest grade costs that vary with yield ($/t)
	- type of leaf surface (smooth/hairy)
	- shelterbelt along roadside (yes/no)
	- first month of growing season (e.g. Jan., Sept., etc.)
Pastoral	- gross income ($/ha)
	- estimate of yield reduction (hi/lo)

CHAPTER 6

SENSITIVITY ANALYSIS

6.1 Introduction

The nature of the simulation model is such that the major assumptions related to any projection, are input as data or are explicitly included within the model. It is important to test the sensitivity of model responses to variations in these data because either they cannot be estimated with complete accuracy or they have been incorporated as hypothetical representations only.

Although sensitivity analyses of simulation models are often conducted using deterministic versions in order to estimate any sources of external variance, it was decided that for this model, the final version of the model, which is partly stochastic, would be used. The basic reason underlying this decision was that it was impractical to 'disengage' the main drive from the appropriate probability distributions for rainfall and seasonality.

6.2 Variable and Parameter Testing

Sensitivity analyses were carried out on all the main variables and parameters[22] used in both the stochastic and the deterministic sections of the model. Because costs in the model structure are based on three submodels (i.e. photosynthetic yield reduction, other horticultural and arable losses, and pastoral enterprise losses), the

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22. In this report, variables are defined as values which are user inputted whilst parameters are defined as values contained within the model.

sensitivity analyses were conducted separately for each submodel. This procedure has the advantage that variations due to sensitivity ranging can be expressed in terms of the cost output for each particular submodel.

Although the real monetary values used in the analyses for each submodel differ, the methods of analysis and presentation are the same, viz:

(1) The use of performance function graphs to illustrate the actual output differences resulting from varying each variable and parameter; and
(2) The use of multipliers to show the dollar change of output per unit change of variable parameter. These take the form:

$$M = \frac{\Delta Y}{\Delta X}$$

where: Y = output measured in dollars
X = variable or paramater, in appropriate units
M = change of output per unit change of variable or parameter.

The variables and parameters tested and the relevant sensitivity analyses results for each submodel are presented below.

6.2.1 Photosynthetic yield submodel

This section of the model, which is fully stochastic, contains a large number of variables and parameters. In order to analyse the changes in output from changes of each variable and parameter, a single standard enterprise example (kiwifruit) was used, from which deviations could be measured. The standard input variables and parameters used for this enterprise are shown in Table 6.1.

TABLE 6.1

Standard Variables and Parameters for Photosynthetic Yield Sensitivity Analysis

Variable/Parameter	Value(s)		
USER INPUTTED VARIABLES	Low	Medium	High[23]
Length of Road (m)		1000	
Speed variables (km/hr)	50	70	90
Daily traffic count	230	250	270
Silt content of road		.06	
Animal enterprise		No	
Distance from road to start of production (m)		10	
Prevailing upwind side		No	
Road frontage (m)		100	
Pest and disease problems		No	
Pollination problems		No	
Dust downgrading problems		No	
Weed problems		No	
Yield (t/ha)		21	
Weighted average price ($/t)		1496	
Premium grade price ($/t)		1750	
Low grade price ($/t)		350	
Weighted variable costs ($/t)		916	
Premium grade variable costs ($/t)		1059	
Low grade variable costs ($/t)		315	
Smooth leaf surface		No	
Shelterbelts present		Yes	
Start of growing season		Sept.	
End of growing season		May	
PROGRAM PARAMETERS			
Distance from road of road dust effect (m)		200	
Reduction of road dust density on plants per unit area of ground surface	0.20	0.35	0.70
Reduction of road dust density for smooth leaf surfaces	0.05	0.15	0.50
Reduction of road dust density for shelterbelts	0.20	0.40	0.70

23. Low, Medium and High values are assigned for variables and parameters which are drawn from a triangular distribution.

The output from this standard run of the submodel was used for comparing the outputs of model runs when variable and parameter values were changed. The cost obtained from the standard run was $71.30.

Where variables and parameters have been included as a triangular distribution (e.g. speed), all values (i.e. high, medium and low) were altered consistently for each sensitivity run.

6.2.1.1 Speed variables. The rate of dust emission from unsealed roads varies as a square of speed (McCaldin and Heidel (1978)) and thus, photosynthetic yield costs increase at an exponential rate as vehicle speeds are increased. This is illustrated in Figure 6.1, which shows the effects on costs of changing the mean vehicle speed by increments of 20 km/hr. Table 6.2 sets out the actual cost changes and the multiplier effects from changing the speed variables. Obviously photosynthetic yield loss costs are very sensitive to the speeds travelled by vehicles along unsealed roads and especially on roads which are travelled at higher speeds. The major cause of this is probably the greater aeordynamic wake caused by faster moving vehicles.

6.2.1.2 Average daily traffic count. Shifts in the levels of average daily traffic count appear to have a linear effect on cost, as illustrated in Figure 6.2, although this curve could be expected to flatten out slightly in line with the photosynthetic yield loss curve (Figure 5.2).

Yield costs are reasonably sensitive to the traffic volume variable and the example provides a multiplier cost of $0.23 per extra vehicle using the unsealed road.

Figure 6.1
Sensitivity of Photosynthetic Yield Loss Changes in Speed Variables

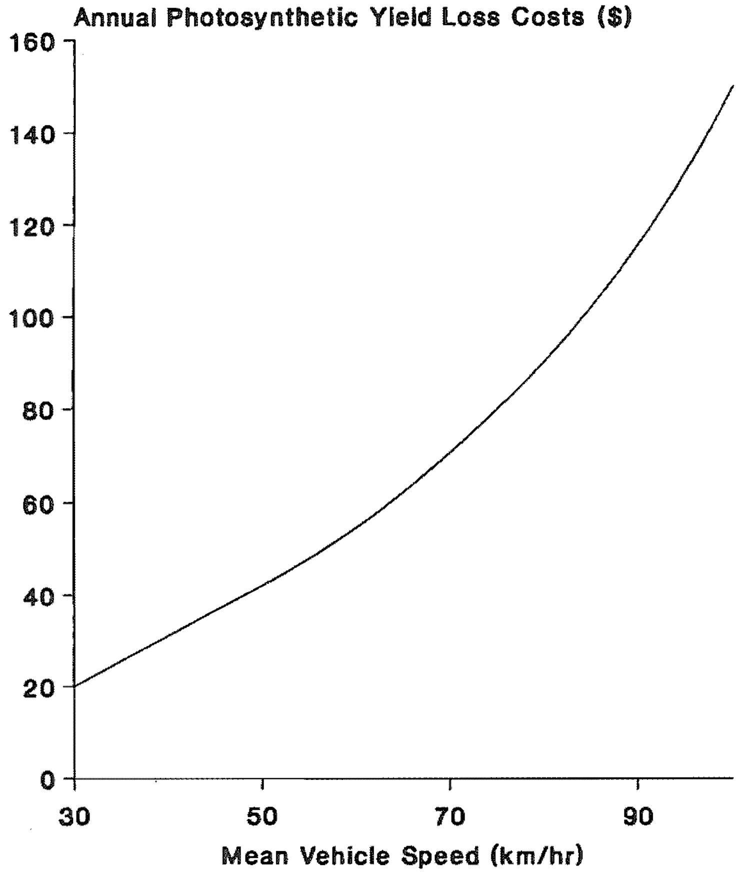


Figure 6.2
Sensitivity of Photosynthetic Yield Loss to Changes in the average Daily Traffic Count

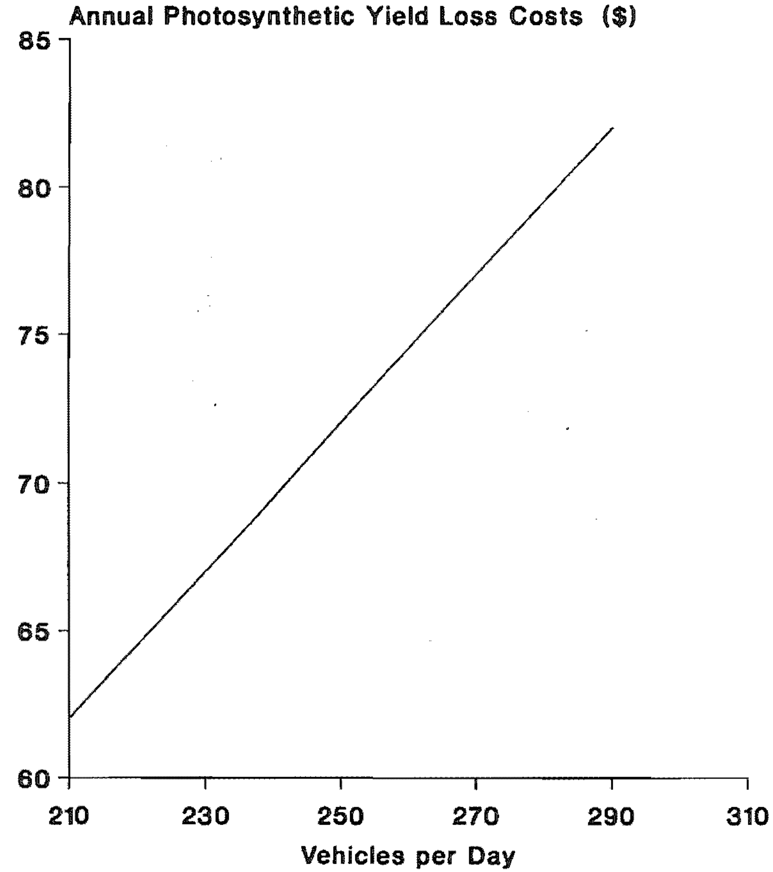


TABLE 6.2

Results of Sensitivity Analysis on Speed Variables

Standard Variables	90	70	50 (km/hr)	
Output	$71.30			
Sensitivity Values of Variables (km/hr)			Actual Change of Output Resulting from Adjusting ($)	Multiplier Effect Adjusting Variable ($/km/hr)
50	30	10	-51.44	1.29
70	50	30	-28.80	1.44
110	90	70	+34.23	1.71
130	110	90	+73.41	1.84

6.2.1.3 Silt content of roading material. Costs are quite sensitive to changes in the levels of silt contained in roading material, with a virtual linear multiplier effect on cost of around $9.50 per percentage silt content (see Figure 6.3). This implies that roads constructed with materials which pulverise easily, or have a high silt content, will be of greater significance in terms of road dust problems.

6.2.1.4 Distance from road centre to start of productive land. Photosynthetic yield costs decrease exponentially the further away from the road the beginning of the productive enterprise is (Figure 6.4). The multipliers for this variable (Table 6.3) indicate that photosynthetic yield loss costs, especially near to the road, are quite sensitive to changes in the distance used and hence, it is important that the accurate distance of each enterprise from the roadside is measured and input separately.

Figure 6.3
<u>Sensitivity of Photosynthetic Yield Loss Costs to Changes in Silt Content of Road Material</u>

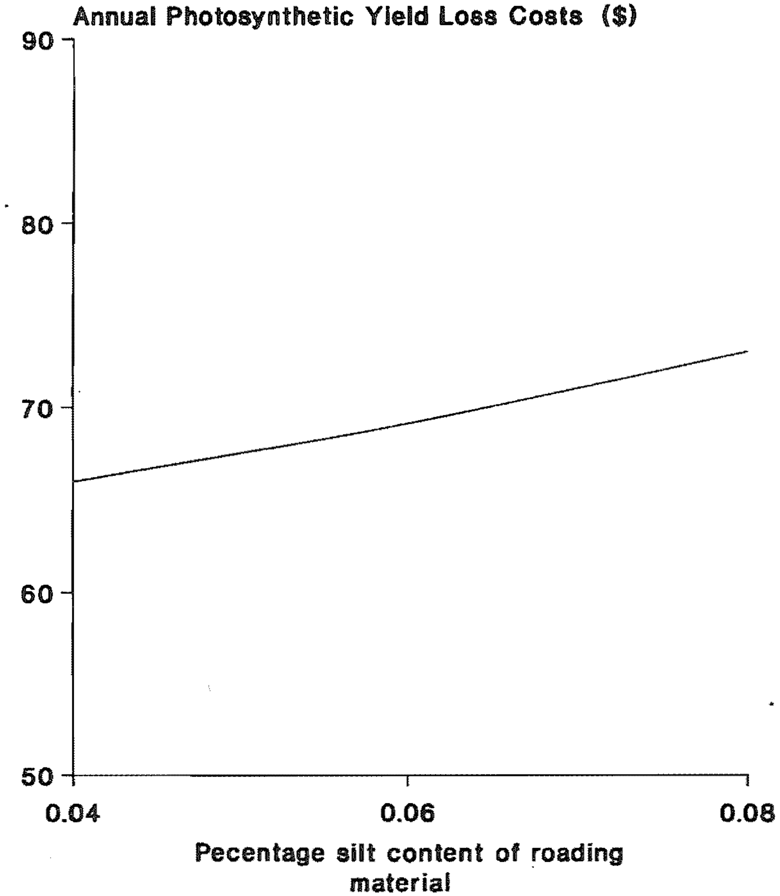


Figure 6.4
<u>Sensitivity of Photosynthetic Yield Loss Costs to Changes in the Distance from Road Centre to Start of Productive Land</u>

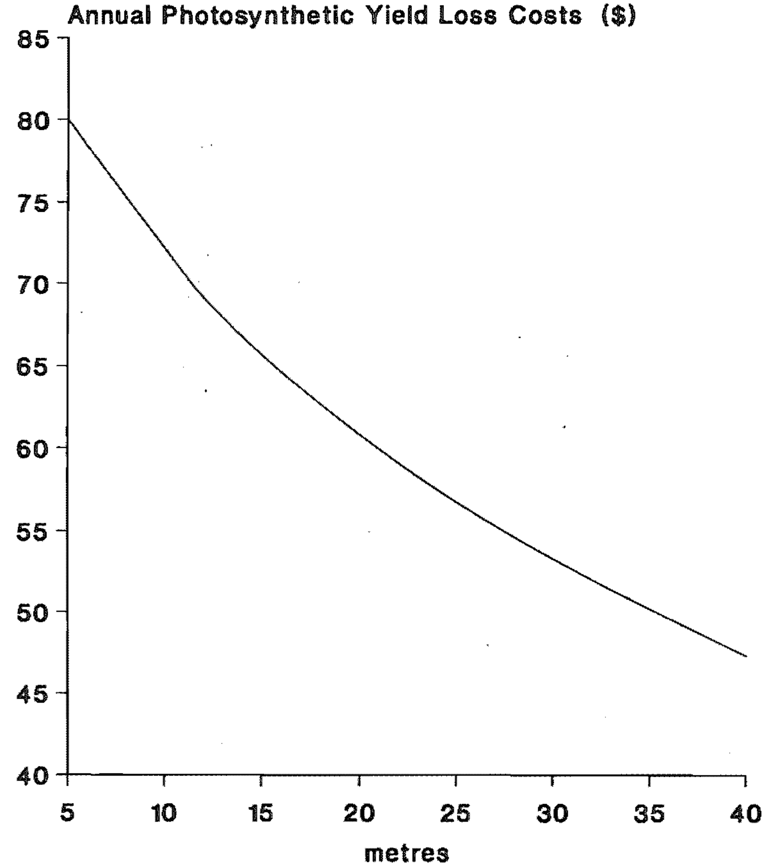


TABLE 6.3

Results of Sensitivity Analysis on Distance from Road Centre to Start of Productive Land

Standard Variable 10 (m)

Output $71.30

Sensitivity Values of Variable (m)	Actual Change of Output Resulting from Adjusting Variable ($)	Multiplier Effect of Adjusting Variable ($/m from road centre)
5	+ 8.93	1.79
20	-10.80	1.08
30	-18.29	0.91
40	-24.25	0.81

6.2.1.5 Price variables. Changes to the prices received for produce, have a linear cost multiplier of $0.12 per $1.00 change in produce price per tonne (Figure 6.5). For high value horticultural crops, often with wildly fluctuating price levels, this seemingly low multiplier figure can be deceiving. As Figure 6.5 illustrates, quite feasible price changes can produce fairly large changes to the yield cost output. This serves to illustrate the importance of selecting price values for model input carefully.

6.2.1.6 Estimated distance of road dust effect from roadway. Because the levels of dust deposition density away from an unsealed roadway decrease at an exponential rate, so too do the related costs from road dust. This would continue until a saturation point is reached where no more road dust is present. Figure 6.6 partly illustrates this trend, but it is more apparent when the multipliers shown in Table 6.5 are compared to those in Table 6.4 (the effect of

Figure 6.5
Sensitivity of Photosynthetic Yield Loss
Costs to Changes in the Price Levels

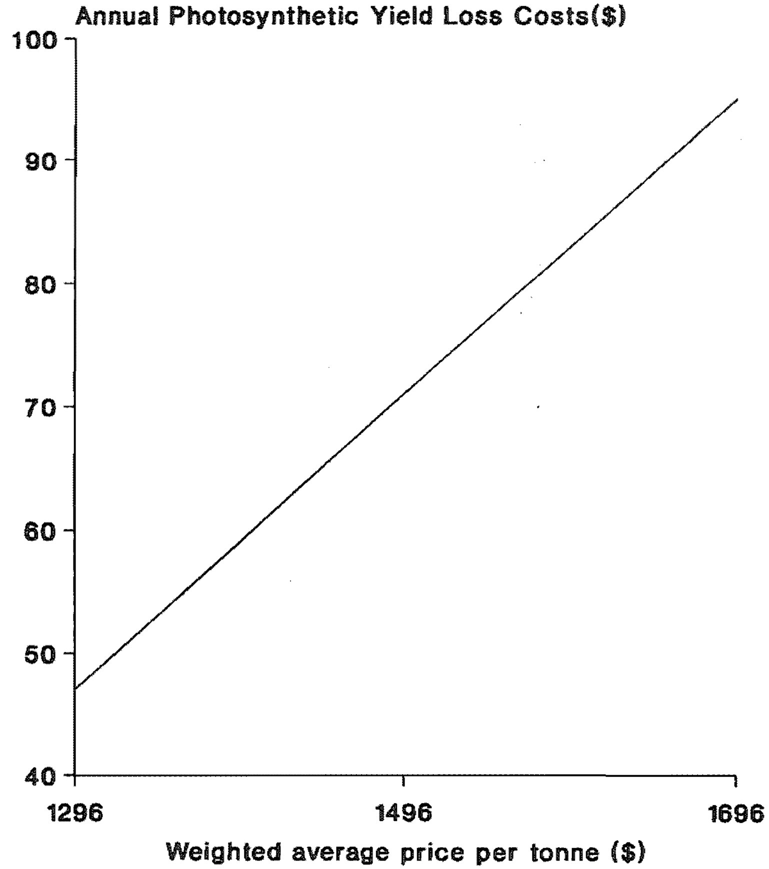


Figure 6.6
Sensitivity of Photosynthetic Yield Loss Costs to Changes in the Esimated Distance of Road Dust Effect Away from Roadway

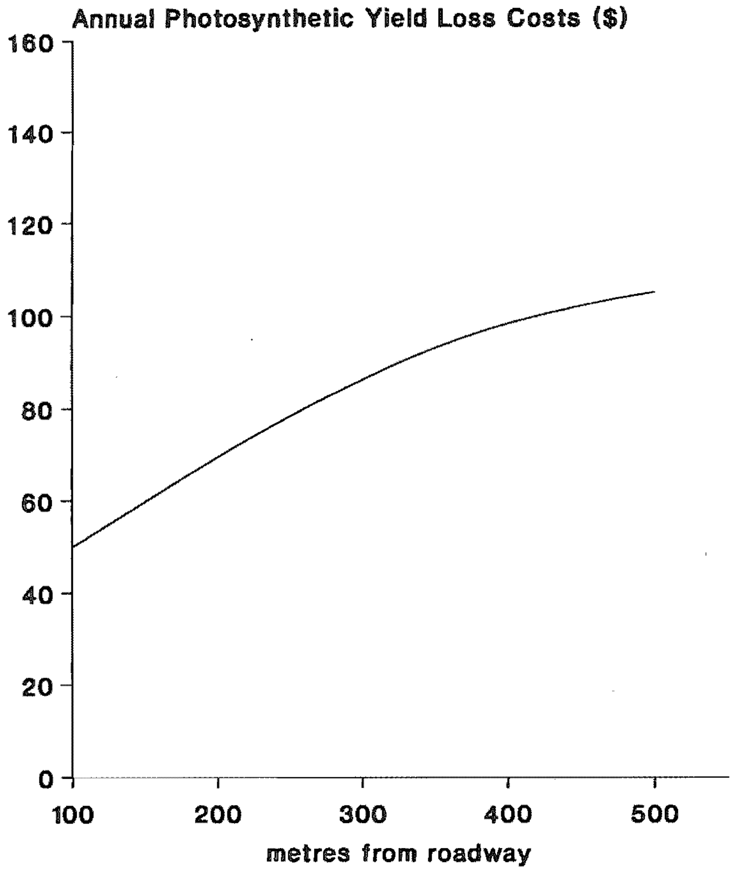
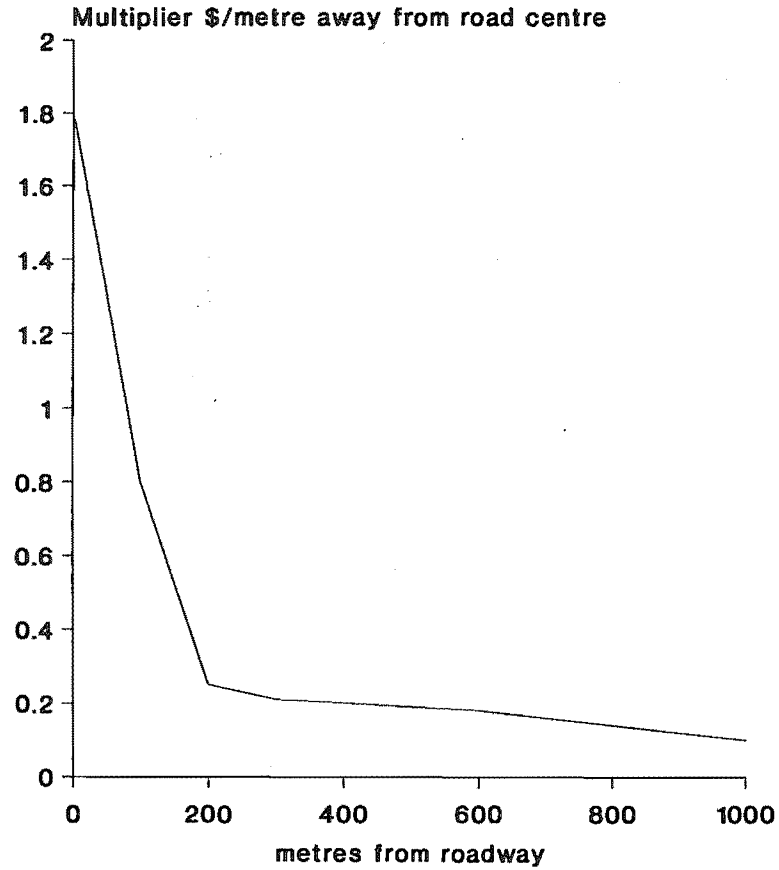


Figure 6.7
Multiplier Effect on Photosynthesis Yield Costs Between Different Distances



altering the distance from road centre to start of productive land). A graphic illustration of these comparisons is shown in Figure 6.7.

TABLE 6.4

Results of Sensitivity Analysis on Estimated Distance of Road Dust Effect from Roadway

Standard Variable	200 m	
Output	$71.30	
Sensitivity Value of Variable (m)	Actual Change of Output Resulting from Adjusting Variable ($)	Multiplier Effect of Adjusting Variable ($/m from centre)
100	-29.34	0.19
300	+16.61	0.17
500	+41.32	0.14
1000	+83.10	0.10

Although the multiplier effect is greatly reduced away from the roadway, costs are still quite sensitive to changes in the estimated distance of road dust effect beyond 200 metres. Consequently, even though the standard figures used in the model (200 and 60 metres respectively) are based on the best information available, they should still be regarded with some caution.

6.2.1.7 Estimate of reduction of road dust density on plants per unit area of ground surface. The multiplier effects from possible differences in this parameter are shown in Table 6.5 and the sensitivity of cost to dust density reduction on plants, per unit area of flat ground, is illustrated in Figure 6.8. These indicate that the level

Figure 6.8
Sensitivity of Photosynthetic Yield Loss
Costs to Changes in the Esimate of Road
Density Reduction on Plants, per Unit Area of Ground Area

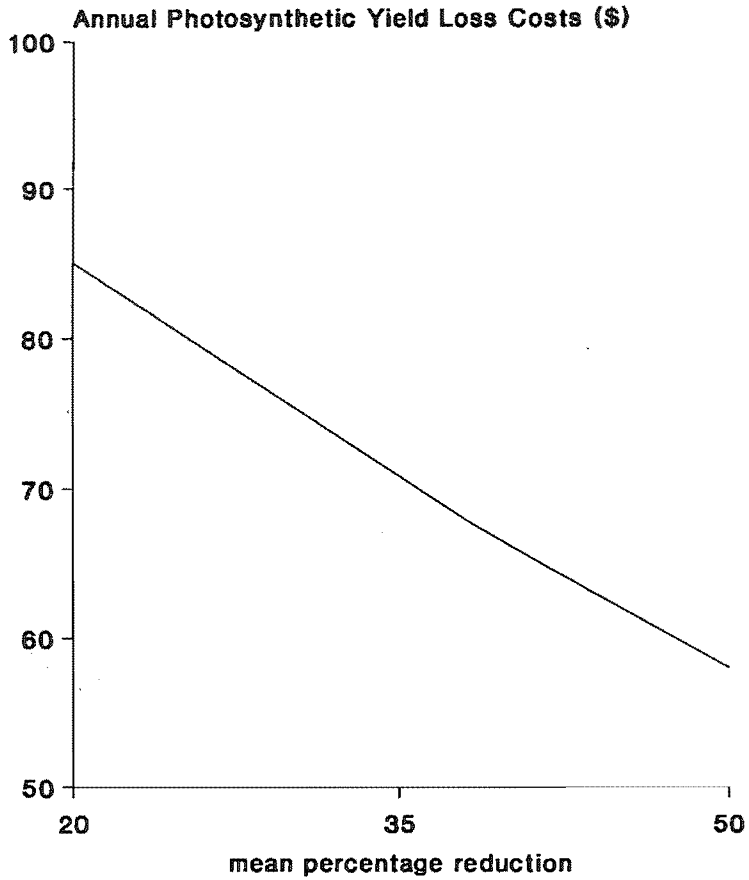
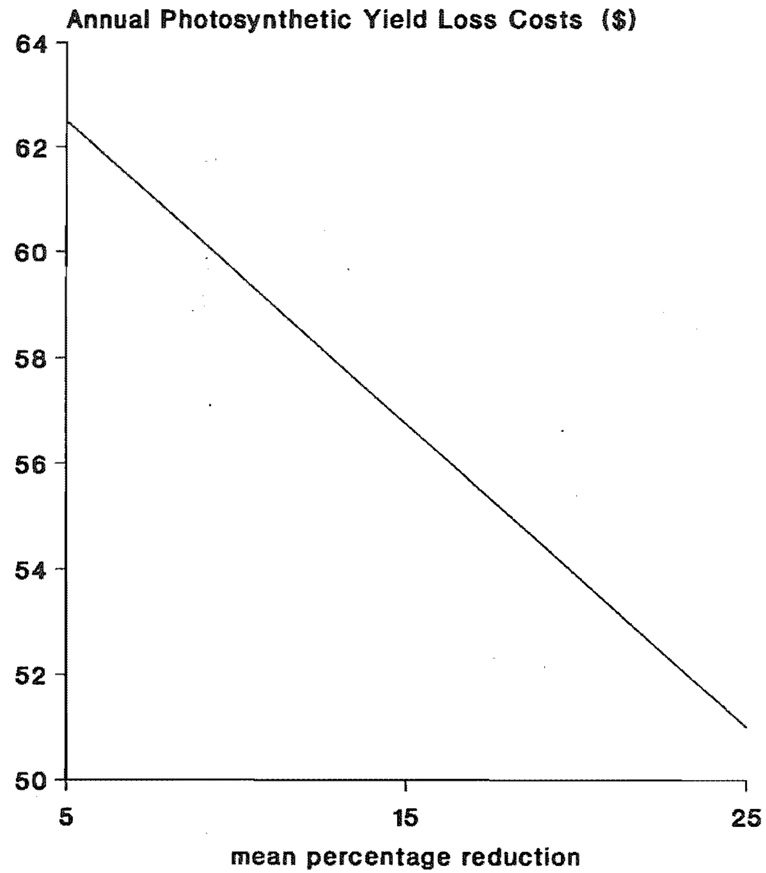


Figure 6.9
Sensitivity of Photosynthetic Yield Loss
Cost to Changes in the Estimate of Road
Dust Density Reduction for Smooth Leafed Plants



of dust retained on plant surfaces is an important determinant of road dust cost.

TABLE 6.5

Results of Sensitivity Analysis on Estimate of Reduction of Road Dust Density on Plants, per Unit Area of Ground Surface

Standard
Variable 20 35 70 (%)

Output $71.30

Sensitivity Values of Variable (%)			Actual Change of Output Resulting from Adjusting Variable ($)	Multiplier Effect of Adjusting Variable ($/percentage reduction)
5	20	55	+14.27	0.95
35	50	85	-15.06	1.00

6.2.1.8 Estimate of reduction of road dust density for smooth leafed plants. The above described (Section 6.2.1) standard run for the sensitivity ranging was conducted using a kiwifruit enterprise example. Since kiwifruit have hairy leaf surfaces, a separate run of the model was necessary to evaluate the sensitivity of the smooth leaf reduction parameter. This involved the hypothetical inclusion of smooth leaves for kiwifruit[24] and resulted in a photosynthetic yield loss cost of $57.15.

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24. Although running the submodel with a smooth leafed parameter for kiwifruit creates an artificial situation, it was felt justified on two counts. Firstly, it maintains consistency in comparing sensitivity results and secondly, it could equally apply to other plant types which do have smooth leaves.

The effects on cost from altering the variables by 10 percent are graphed on Figure 6.9. The multiplier effect is around $0.55 for a one percent change in the parameters.

6.2.1.9 Estimate of road dust density reduction due to shelterbelts. The mean parameter value used in the model for dust reduction, due to the effect of shelterbelts, was 60 percent. Photosynthetic yield loss costs are fairly sensitive to changes in this parameter (see Figure 6.10) with a multiplier effect of approximately $1.00 per percentage change in road dust density reduction. This implies that the design and efficiency of shelterbelts could have a considerable influence on the level of road dust costs.

Where no shelterbelt is present (or it is assumed to have zero effect on dust density on enterprises - see Figure 6.10) then a total cost of $112.53 is incurred from photosynthetic yield loss.

6.2.1.10 Winter dew parameters. Winter dew parameters are set to account for the vehicles which travel during the winter when dew is present and dust is suppressed. For kiwifruit, less than half the growing season (4 months) occurs during the winter period (defined in Section 5.1.1.3). Consequently, the cost sensitivity to changes in the winter dew parameter is not great (Figure 6.11), with a multiplier effect of about $0.47 per percentage change of traffic count reduction. Therefore, as long as the value of this parameter is at least an approximation of the true value, then any differences are likely to have little effect on the final photosynthetic yield cost for each enterprise analysed.

6.2.2 Other horticultural and arable losses submodel

All costs to horticultural and arable enterprise types, other than those from photosynthetic yield loss, are handled in a deterministic routine. The model user can

Figure 6.10
Sensitivity of Photosynthetic Yield Loss Cost to Changes in the Estimate of Road Dust Density Reduction due to shelterbelts

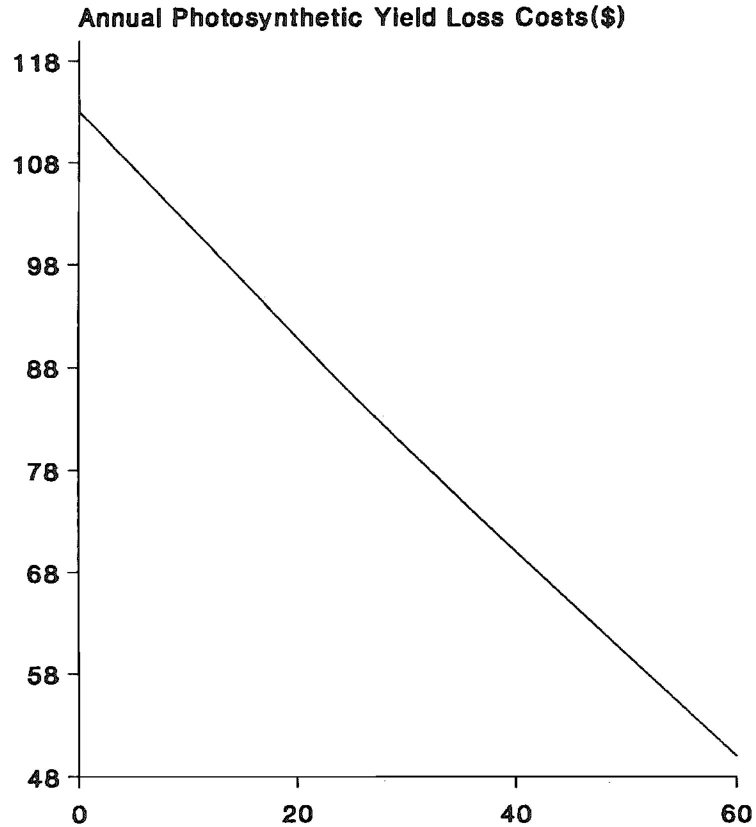
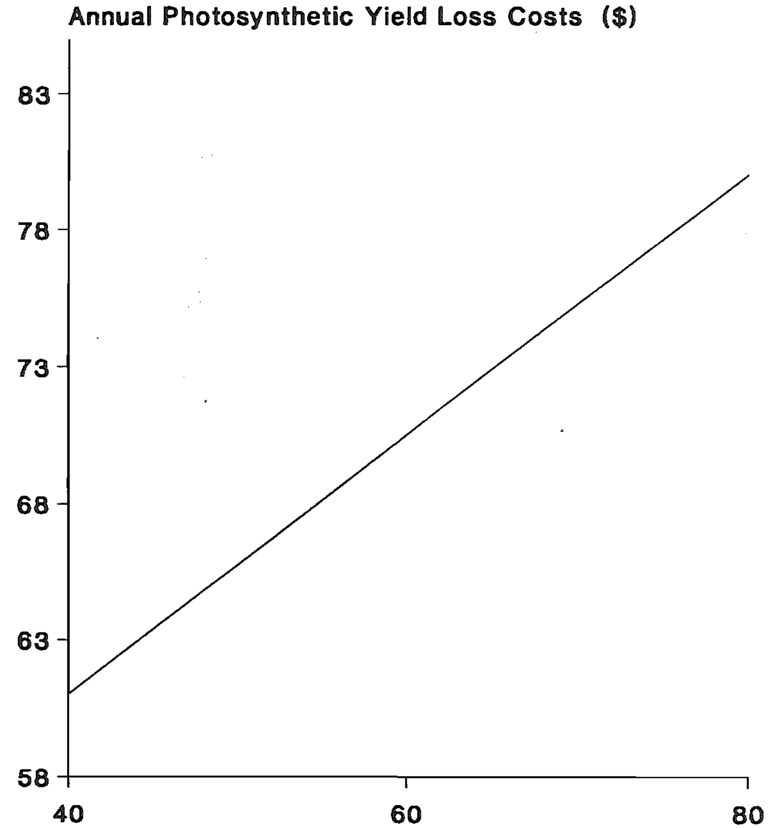


Figure 6.11
Sensitivity of Photosynthetic Yield Loss Cost to Changes in the Winter Dew Parameters



choose either a zero, low (0.5 percent) or high (1.0 percent) estimate of effect for each effect. Because each estimate is stated as a single figure, any variations in the values of variables and parameters have a linear effect on the costs incurred from each effect.

The variables and parameters which may influence cost levels in this submodel include;

(1) product price;
(2) variable cost;
(3) distance from road to start of enterprise; and
(4) distance of road dust effect away from roadway.

Given both the linearity and the similarity of the type (between the first two and the second two) of variables, only the sensitivity of cost to changes in product price and the distance of road dust effect are analysed here. These relate to both yield and downgrading losses, which are accounted for in this submodel.

6.2.2.1 Produce price. Figure 6.12 presents the sensitivity of yield loss costs to the weighted average price changes, whilst Figure 6.13 illustrates the sensitivity of downgrading costs to changes in the premium grade produce price. The multiplier effects for both the yield and the downgrading costs are approximately $0.40 per dollar price change for the high estimates, with the low estimate multipliers being half this value.

Considering the large price variability of many forms of produce, plus the additive consequence of a number of these effects occurring, the sensitivity of cost to these variables is rather large.

6.2.2.2 Distance of road dust effect from road. The sensitivity of yield loss costs and downgrading costs to changes in the parameter for distance of road dust effect,

Figure 6.12
Sensitivity of 'Other' Yield Costs to Produce Price Changes

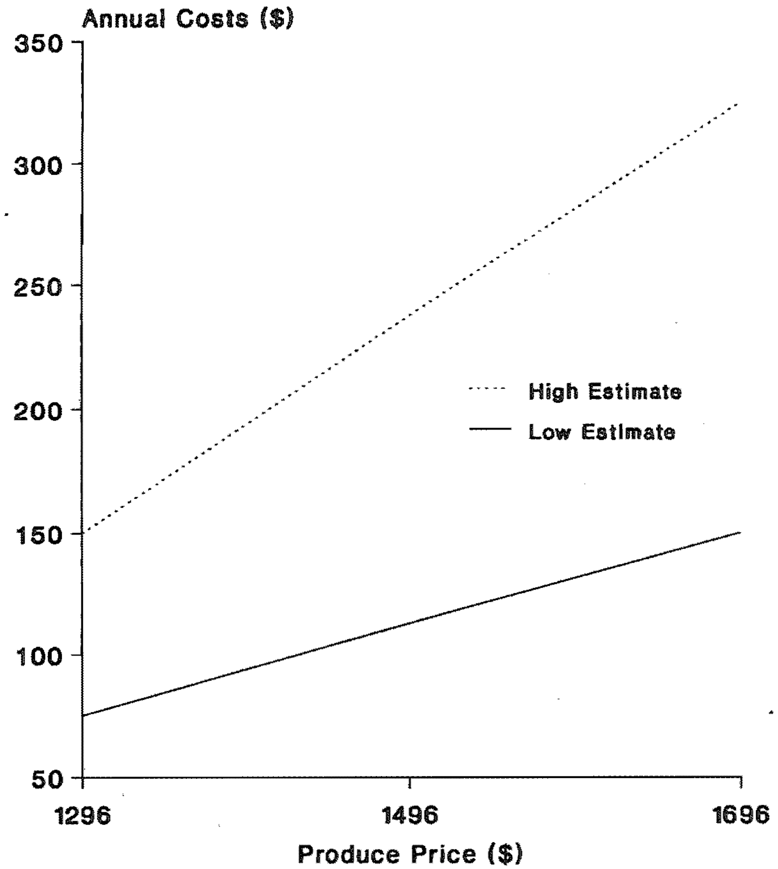
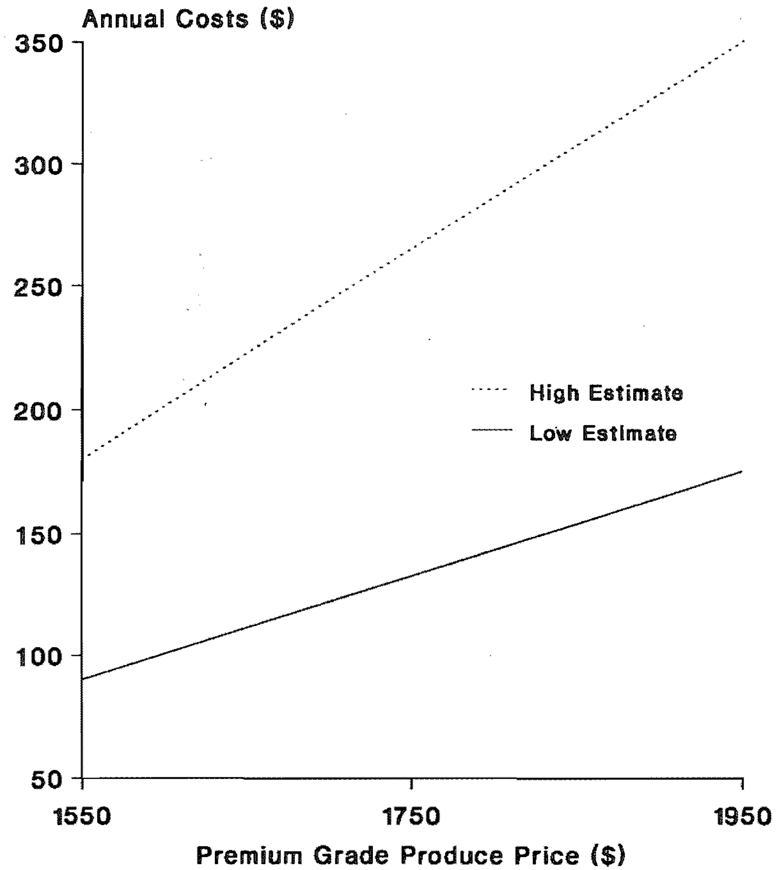


Figure 6.13
Sensitivity of Downgrading Costs in Produce Price Changes



are shown in Figures 6.14 and 6.15 respectively. The multiplier cost effects for the high estimates are approximately $1.22 per metre for yield, and $1.38 per metre for downgrading. The multipliers for the low estimates are half this amount.

This shows that, as with photosynthetic yield costs, the costs in this submodel are very sensitive to the distance parameter for road dust effect.

6.2.3 Animal enterprise submodel

A standard run was conducted for the simple deterministic routine of the animal enterprise (dairying) type submodel. The variables used in this run are shown in Table 6.6. The costs to the enterprise for the standard runs of the high and low estimates of dust effect (two percent and one percent) were $49.10 and $24.55 respectively.

Cost sensitivities were conducted on only two of the variables as the last three (Table 6.6) are similar, in that they all are related to the area of the enterprise affected by road dust. The variables analysed and their results are set out below.

TABLE 6.6

Unique Standard Variables to Animal Enterprise Sensitivity Analysis

Variable	Value
Gross dairying income $4/ha)	2,370
Distance from road centre to start of productive land (m)	5
Distance of road dust effect from road centre (m)	200
Length of road frontage (m)	100

Figure 6.14
Sensitivity of 'Other' Yield Costs in Distance of Road Dust Effect Parameter

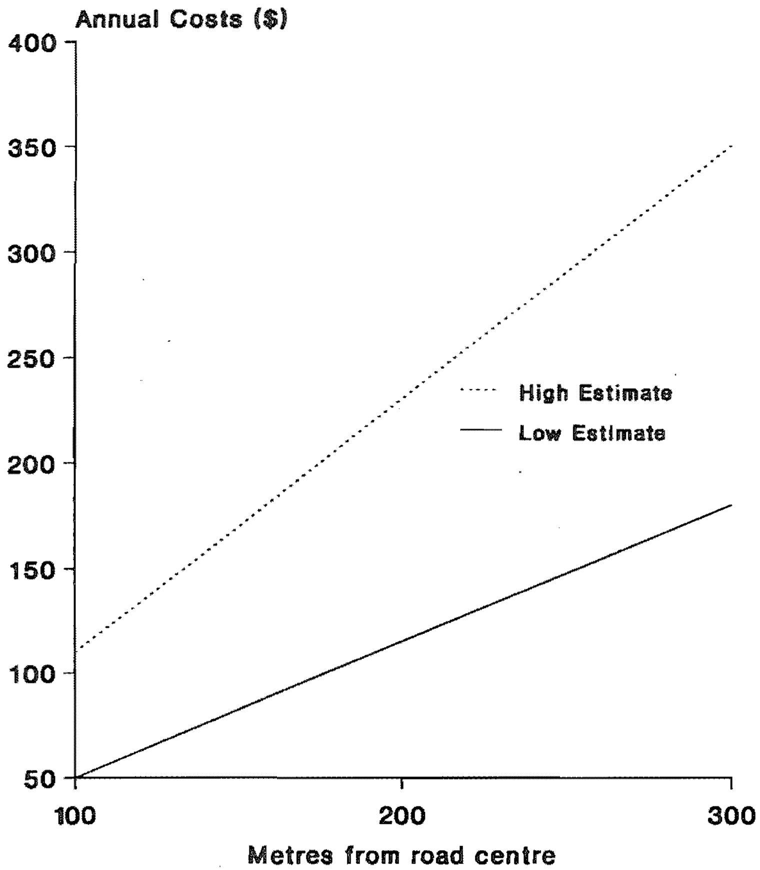
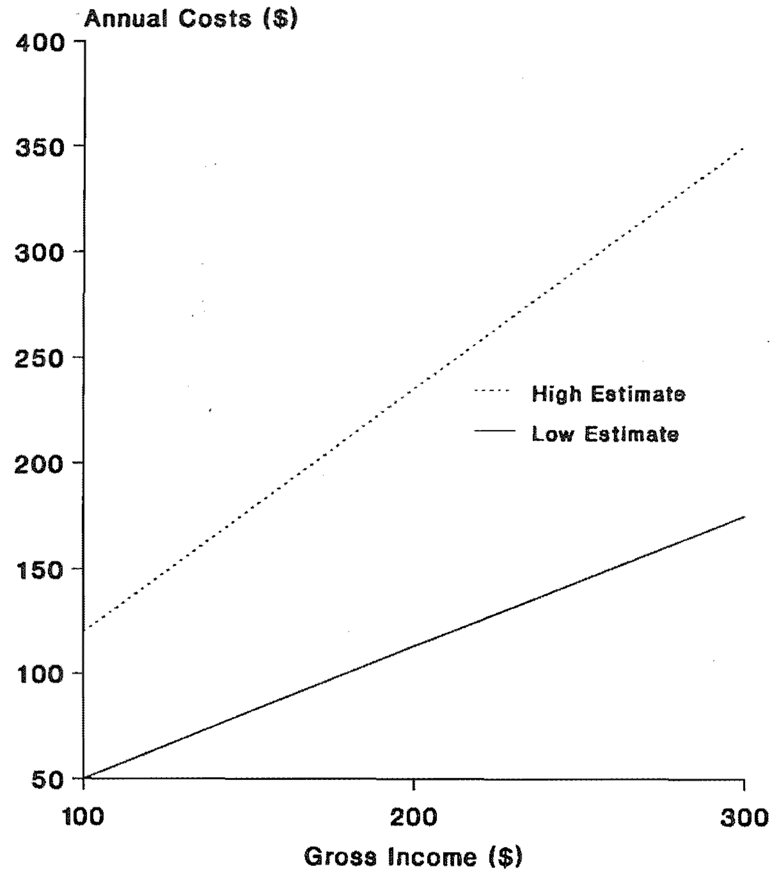


Figure 6.15
Sensitivity of Downgrading Costs to Changes in Distance of Road Dust Effect Parametres



6.2.3.1 Gross income. Figure 6.16 illustrates that the sensitivity of cost to changes in the level of gross income for dairying is not significant, especially given the low costs incurred by dairy enterprises. This lack of effect would be even more apparent for sheep and beef enterprise types, which have lower per hectare gross margins.

The multiplier effect on cost is $0.06 and $0.03 per $1.00 change of gross dairying income for the high and low estimates respectively.

6.2.3.2 Distance of road dust effect from road. Costs are more sensitive to changes in the distance of dust effect parameter (see Figure 6.17) than to the gross income variables, with cost multipliers of $0.48 and $0.24 per metre changed, for the high and low estimates respectively.

It is clear from the results that the animal enterprise sensitivities will have little significance to roading economics, since the overall cost level is very low.

6.3 Conclusions

The model contains a large number of variables and parameters, many of which are based on subjective assessment. Given the uncertainty surrounding many of the values included in the model, it is important to gain an indication of the sensitivity of road dust costs to variations in the levels of these variables and parameters. A summary of the sensitivity of all factors considered is presented in Table 6.7. The most significantly cost sensitive variables and parameters which warrant further examination are:

(1) Average speed travelled on unsealed roads.
(2) Silt content of roading material.

Figure 6.16
Sensitivity of Dairying Costs to Gross Income Changes

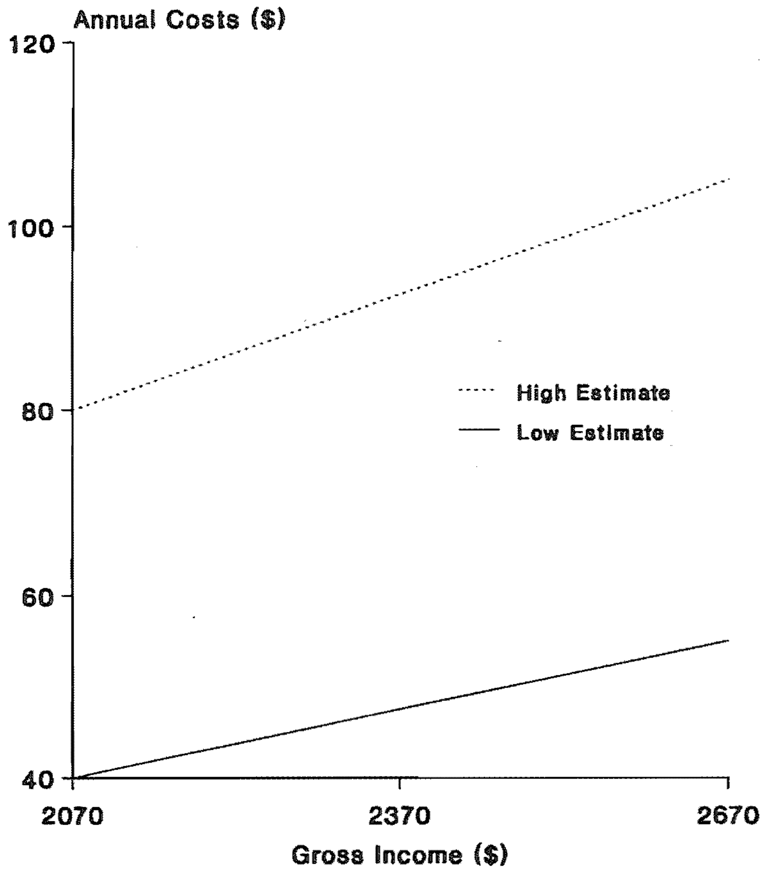
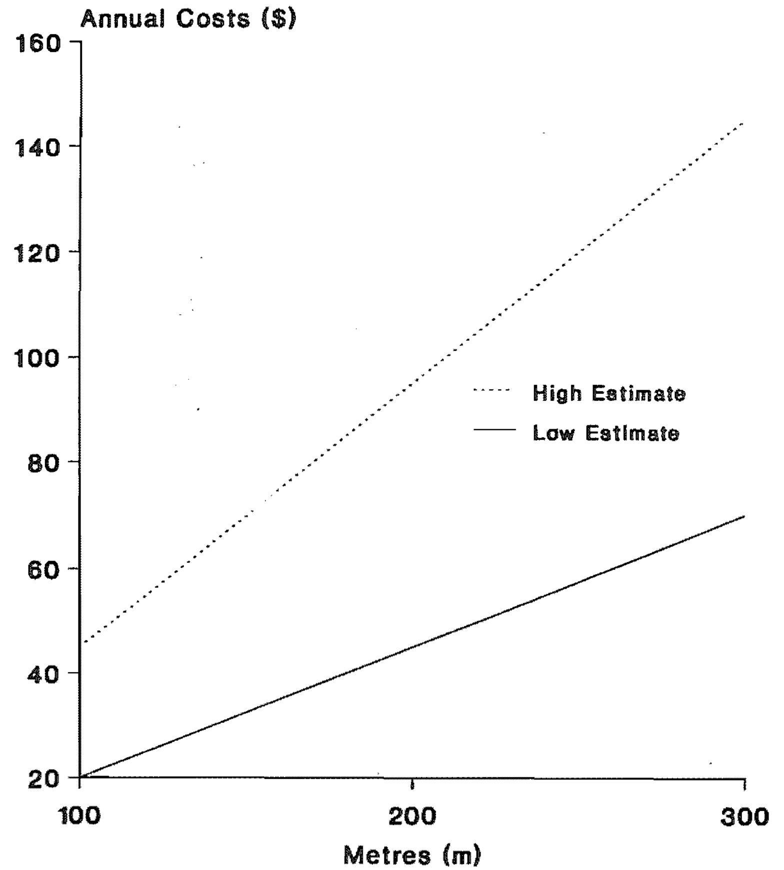


Figure 6.17
Sensitivity of Dairying Costs to Changes in the Distance of the Road Dust Parameter



(3) Distance of road dust effect from road centre.

(4) The road dust reduction factors for; road dust density on plant surfaces per unit of ground area, smooth leafed plants, and for shelterbelts.

In addition, the components of the 'other horticultural and arable losses submodel' require further close scrutiny.

To some extent, sensitivity is accounted for within the model by the inclusion of a figure for the standard deviation of mean photosynthetic yield loss cost, for each enterprise analysed and the total length of road evaluated. The inclusion of these values is useful as a guideline to show the magnitude of variability surrounding the estimates of road dust cost and the assumptions upon which they are based.

TABLE 6.7

Summary of Sensitivity of Variables and Parameters

Factor	Unit Change	Average Output Change Per Unit Change ($)
PHOTOSYNTHETIC YIELD SUBMODEL		
Traffic speed	kilometre/hour	1.58
Daily traffic count	vehicles/day	0.23
Silt content of roading material	percent silt	9.50
Distance from road centre to start of productive land	metre	1.15
Produce price	dollar	0.12
Distance of road dust effect	metre	0.15
Reduction of road dust density on plants per unit area of ground surface	percent	0.98
Road dust density reduction for smooth leafed plants	percent	0.55
Road dust density reduction due to shelterbelts	percent	1.00
Winter dew reduction of effective traffic count	percent	0.47
OTHER HORTICULTURAL AND ARABLE LOSSES SUBMODEL		
Produce price - high estimate	dollar	0.40
- low estimate	dollar	0.20
Distance of road dust effect		
- Yield - high estimate	metre	1.22
- low estimate	metre	0.61
- Downgrading - high estimate	metre	1.38
- low estimate	metre	0.69
ANIMAL ENTERPRISE SUBMODEL		
Gross income - high estimate	dollar	0.06
- low estimate	dollar	0.03
Distance of road dust effect		
- high estimate	metre	0.48
- low estimate	metre	0.24

CHAPTER 7

APPLICATION OF THE MODEL

The objective of building this model was to provide a relatively simple method of estimating the costs from road dust to horticultural and agricultural production systems adjoining unsealed roads. These costs can then be incorporated into an overall cost-benefit model for the priority ranking of future roading projects. Although at this stage any such inclusion would have to be regarded with caution (since the cost estimates derived are based on a number of assumptions and generalisations), it does at least provide a tentative quantitative estimate of a previously ignored benefit of sealing. Hence, given that the model can be easily modified as more reliable data comes to hand, the use of the model can be regarded as a further step towards assessing the true benefits of proposed roading projects.

7.1 Input-Output of the Model

An analysis of road dust costs to production systems along any specified stretch of road, requires user input of data specific to both the road segment and to each enterprise sited adjacent to the road segment. In response, the model produces an output file which contains data and costs relevant to each enterprise analysed and for the total road segment.

7.1.1 Data input

Data pertaining to both the road segment in question and to each enterprise sited alongside that road segment are input on an interactive basis between the model-user and the computer, in screen mode. Once the model has been set to run, it automatically prompts the user to key in responses regarding both physical and economic aspects of the road segment and its adjoining enterprises. For details of data input requirements refer to Appendix VIII.

Information required regarding the road itself includes the following physical data:

1) Length of the road segment.
2) Average traffic count variables.
3) Silt content of roading material.

This information can be obtained from individual councils and local Ministry of Works and Development offices.

Information required for each enterprise includes:

(1) Physical specifications pertinent to each particular enterprise, e.g. length of road frontage of enterprise, whether it is protected by a shelterbelt, etc.

(2) General physical production data, e.g. yield per hectare and whether different types of dust effect occur for the type of production.

(3) Economic data specific to the enterprise type and (preferably) to the particular locality, although average national data may be used.

The information required for '2' and '3' above may be obtained from grower organisations, the Ministry of Agriculture and Fisheries Economics Division and produce merchants. The economic and production statistics used for a case study run of the model (see Appendix IX) are contained in Appendices III and IV. This data covers a wide range of enterprises and the non-time dependent items (i.e. non-economic data), can form the basis of analysis for future applications of the model.

7.1.2 Output of data

Model output is stored in an output file (RES.DAT) which contains the following information:

(1) A summary of the input data for the road and for each enterprise being analysed.

(2) The percentage photosynthetic yield loss for each enterprise.

(3) The mean cost resulting from photosynthetic yield loss for each enterprise.

(4) The total mean road dust cost incurred by each enterprise.

(5) The standard deviation of total cost for each enterprise.

(6) The mean total cost for the whole road segment.

(7) The standard deviation of the total cost for the road segment.

(8) The present value of the total road segment cost (at the Treasury discount rate of 10 percent over the expected life of a sealed road (15 years)).

This method of output has the distinct advantage that a summary of the road and enterprise data being evaluated is presented in a clear and explicit manner. In addition, the results of the analyses are presented in a precise and readily usable format, for use in wider cost-benefit studies, to rank the overall priorities of future roading projects.

An outline of how to operate and interpret the model is provided in Appendix VIII and a case study example of a model run is shown in Appendix IX.

7.2 A Case Study Example of Model Operation

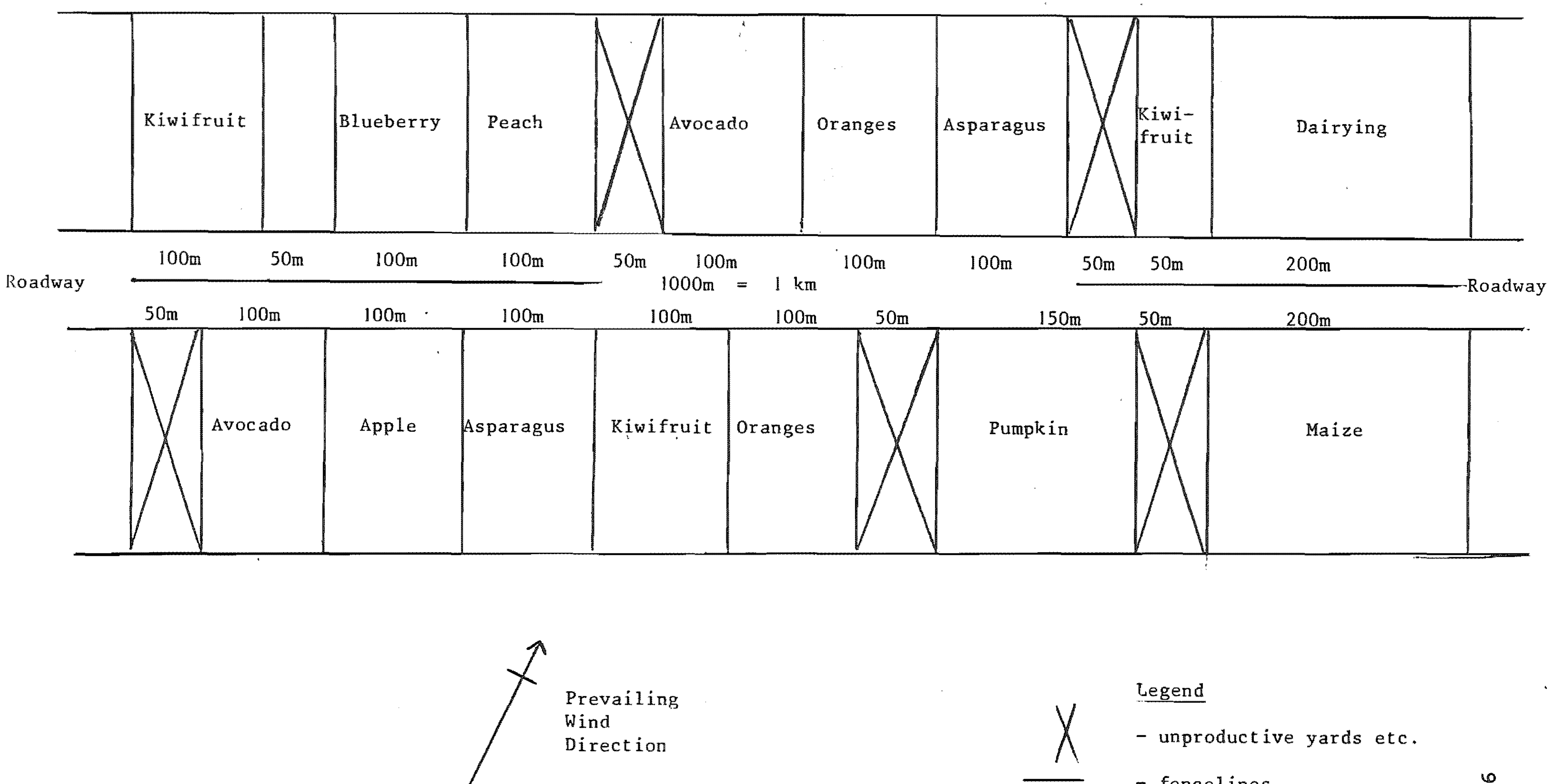
In order to illustrate the road dust model operation and output, a case study of a hypothetical one kilometre stretch of unsealed rural road has been selected. The enterprise layout plan of the land adjoining this section of roadway is shown in Figure 7.1. All of the production data used in this analysis are based on the generalised data contained in Appendices III and IV, while the road use data relates to that of an average road in a predominantly horticultural locality.

The resultant output from conducting a model analysis of the effects of road dust, on the production systems adjacent to this hypothetical stretch of road, are presented in Appendix IX. The final output for this stretch of road shows that the total annual road dust costs for all 15 enterprises sited along the roadside is $7,684, with a standard deviation of $136. The net present value cost of the road dust effects is $58,448, which relates to an approximate average road sealing cost of between $90,000-$150,000 per kilometre.

Most unsealed roads in New Zealand would show a lower net present value road dust cost per kilometre than the case study cost, since the majority of roads serving such an intensive area of production would already be sealed. Still, the magnitude of these present value costs does tend to suggest that the effects of road dust emissions on agricultural and horticultural production systems, should be considered when assessing the economic viability of sealing rural roads; especially in areas of intensive horticultural production.

FIGURE 7.1

Hypothetical Roadside Layout Plan



CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The purpose of this study was to conduct an analysis of the effects of road dust emissions on agricultural and horticultural production systems adjoining unsealed roads. In addition, the study established a relatively easy and flexible means of assessing the costs of road dust for any given road.

Since little or no previous research has been conducted directly concerning this subject, the study was exploratory in nature. The development of model components and relationships were adapted largely from the findings of other partly related dust studies, informed observations and opinions. Before the model can be fully incorporated into an overall cost-benefit model for the priority ranking of future roading projects, further research will be required to validate and update parameters in the present model.

The model as presented has a valuable role to play, both for providing information concerning the effects of road dust on rural production systems and for guiding the priorities for further research into the subject. In addition, since the model has been built with a modular structure, it can be readily updated as improved data come to hand and can be included as part of a comprehensive roading model.

The major conclusions which can be drawn from this study are:

(1) The major probable causes of road dust cost are; photosynthetic yield loss, increased levels of pest, disease and weed incidence, dirty produce and poor pollination on small seeded fruits.

(2) The main determinants of the extent of road dust effect are environmental factors (e.g. rainfall, shelter, wind, etc.), biological factors (e.g. type of leaf and fruit surfaces, type and method of pollination, etc.), and the grading criteria and standards required for the produce.

(3) High value, intensively grown horticultural crops suffer the greatest costs from road dust whereas traditional pastoral type farms incur only minor costs.

(4) The magnitude of costs calculated by the road dust model using conservative figures suggests that road dust costs to rural production systems should be considered when road upgrading priorities are being assessed. In addition, some further research is required to enable the road dust model to be incorporated into a proposed overall cost-benefit roading model.

8.2 Recommendations for Further Research

The results of this study show that the road dust model possesses considerable potential for use in the economic appraisal of roading projects. However, until more accurate information is available regarding road dust emission, distribution and production effects, model use should be restricted to providing general guidelines for roading improvement works only. Since the present availability of data on the subject is sparce and because the type and extent of road dust effects are dependent on many other factors, there is considerable scope for further research.

However, any decisions regarding future research programmes will need to be closely linked to the costs and benefits of conducting such research. These costs are the costs of actually conducting the research, whilst the benefits are the returns which may be gained as a result of better decision making about roading projects.

Since the effects of road dust are closely inter-related with a large number of other factors affecting production and are also dependent on many uncontrollable variables, it is likely that any research programme designed to validate the individual components and relationships contained within the model, would involve a very substantial cost. In addition, it may be almost impossible to establish these components and relationships with any great degree of precision and confidence. In contrast, there are probably relatively few areas of intensive horticultural production which are still serviced by unsealed roads. Further, the benefits of gaining an extremely accurate model of road dust costs to production are probably reasonably minor since other quantitative and qualitative factors are involved in the decisions regarding the allocation of funds for roading projects.

Hence, since there are a number of factors which should be considered in the ranking of roading project priorities (not all quantifiable), the main purpose of this model (initially at least) should be to provide an idea of the order of magnitude of road dust costs for any particular road. These can be taken into consideration during the assessment of proposed roading projects. If this stance is taken then the first priority for any future research, should be to test the ability of the overall model to predict the total costs to production systems due to road dust. If the results of this work show that the benefits are significant then further research into aspects concerning individual components of the model should be conducted.

An additional point to note is that, although it may be economically inefficient to conduct further research into the subject in this country, in other larger countries it may not be. In fact there is a considerable amount of research already being carried out on matters related to this topic in the United States and a number of other countries. Consequently, a low cost approach to partially validating and refining this model, is to consistently search the current literature on the subject and to apply it to this study where relevant.

However, the aim of the NRB is to include a road dust submodel within an overall roading cost-benefit model (P.B. Clouston, pers. comm., 1985). Therefore, it is likely that further concrete evidence of the ability of this model to predict road dust costs to a reasonable level of accuracy will be required, before the model could be adopted by the NRB. If this is the case, then further research into road dust effects should be conducted in two stages. These are outlined below.

8.2.1 Field measurements of crop economic yields away from unsealed roads

This would entail the physical measurement of crop yields and also the measurement of the quantity of produce downgraded because of road dust, at incremental distances away from the road. Such an approach would give an indication of the ability of the model to predict the effects of road dust on productivity.

8.2.2 Scientific investigation of model components

There may be a number of components and relationships within the model which will require further validation and refinement. The priorities for these should be highlighted in the first stage of any further research (above). However, during the model building phase, it became apparent that the following factors warrant further analysis.

8.2.2.1 Measurement of road dust emission and deposition distribution. The function estimated for road dust deposition away from the roadway in the model was based on extrapolations of data from a number of disjointed studies, conducted in the main, overseas. It may therefore, be desirable to conduct some empirical studies into the following aspects of these activities:

(1) The effects of road surface moisture levels on the emission of road dust.
(2) The dust emitting characteristics of different vehicle types.
(3) The dustiness and "stickability" of different types of roading material.
(4) The response of dust deposition distribution to surface roughness, shelterbelts, wind speed, atmospheric stability, and different types of crops and canopy systems.

8.2.2.2 The effect of dust cover on plant leaf functions. A relationship was developed in the model which described the effects of dust cover on plant photoshythesis rates. This relationship included a number of assumptions and generalisations. In addition, other possible effects of dust on plant leaf functions could not be adequately addressed.

8.2.2.3 The effect of dust deposition on flower pollination. It is widely held by both growers and horticultural advisors, that dust deposition can have a detrimental effect on pollination, especially of small seeded fruits. If this is correct then the costs of low and improper fruit set, which result from poor pollination, could be significant. To date there has been virtually no research conducted in this field and hence, these claims cannot be substantiated.

8.2.2.4 Insect levels in crops. Overseas studies (e.g. Alexandrakia and Neuenschwander, 1979) have shown that in general, dust cover on plant surfaces is detrimental to the pest-benefit insect population balances. With the current trend towards integrated pest management control techniques in New Zealand orchards, this effect is likely to increase in importance. Yet, there has been virtually no work done in New Zealand to establish the effects of dust cover on the insect and crop types specific to this country and certainly no attempt to relate increased insect pest levels to economic returns.

8.2.2.5 The impact of dust cover on spray effectiveness. Dust present on leaf surfaces is known to have a detrimental effect on the functioning of many agricultural and horticultural sprays. Little is known about the degree of sensitivity of specific sprays to various levels of dust cover.

8.2.2.6 The effects of dust contamination on the marketability of produce. Quantities rejected and prices received for produce contaminated with road dust were estimated on the basis of subjective 'guestimates' by a number of growers and produce merchants. Surveying of enterprises and markets could establish far more objective estimates of expected losses.

8.2.2.7 Measurement of ambient dust levels and effects. It was not possible to include directly the effects of ambient dust levels in this model. It is possible that these could have a great bearing on the magnitude of road dust effect on production systems and in some cases, completely overshadow the importance of road dust. At present there is very little information regarding ambient dust levels in New Zealand, although Paynter (1977) found that wind blown soil erosion from cultivated paddocks can be extremely high.

8.2.3 Overview of research recommendations

It was stated above that any decisions regarding future research into the effects of road dust on farming systems must be closely linked to the costs and benefits of undertaking that research. Given that there is only limited intensive horticultural production alongside unsealed roads in New Zealand, it is unlikely that further expensive studies specifically into the effects of road dust, could be economically justified.

Literature based studies should be the first priority for further research to refine and validate the road dust model. If primary research[25] is undertaken then two points need to be considered:

(1) A first stage research study, involving field measurements of crop economic yields away from unsealed roads, should be conducted as a necessary pre-requisite for second stage research, involving scientific investigation of model components. This would be beneficial both as an additional test of the validity and potential value of the road dust model and also as an aid for identifying and prioritising potential research projects.

(2) Unsealed roads are not the only source of inert dust nuisance on farming systems in New Zealand. Other sources include mining operations, coal fired power stations, exposed paddocks and riverbeds. From an environmental stance, there may be significant

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25. Primary research is used here to describe that research which uses primary data sources (e.g. actual physical experimentation) as compared to secondary data sources (e.g. literature-based studies).

economic benefits to be gained from studies into the effects of inert dusts in general, on farming systems. The results of such studies could then be applied to the road dust model or used in studies such as the environmental impact of mining operations.

This leads to the conclusion; that before any decisions are made regarding any future research into the effects of road dust on farming systems, it is important that all of the costs and benefits of conducting that research are clearly identified.

REFERENCES

AGRICULTURAL RESEARCH COUNCIL. (1967) The Effects of Air Pollution on Soil and Plants. London.

AKRE, R.D. (1980) Effects of Volcanic Ash on Insects. Proceedings of Washington State University's Conference on the Aftermath of Mt St Helens. 14-16.

ALEXANDRAKIS, V. and NEUENSCHWANDER, P.B. (1979) The Influence of Road Dust on Pests and Parasites of Olives. Annales de Zoologie-Ecologie Animale, 11(2): 171-184.

BARNICOAT, C.R. (1957) Wear in Sheep's Teeth. New Zealand Journal of Science and Technology, April: 583-585.

BARNICOAT, C.R. (1963) Attrition of the Hypospondent Tooth: Mechanisms of Hard Tissue Destruction. Journal of the American Association for the Advancement of Science, 75: 155-170.

BARRET, L.B. and WADDEL, T.E. (1973) The Cost of Air Pollution Damages: A Status Report. United States Environmental Protection Agency, Publication No. AP85.

BARTLETT, P.R. (1982) One of Growers Worst Enemies is Dust: It Kills Beneficials. Avocado Grower, 6(9): 20-43.

BATT, P.J. (1979) Shelter Requirements and Establishment for Horticultural Crops. New Zealand Ministry of Agriculture and Fisheries, Aglink Publication No. HPP120.

BECKER, D.L. (1978) Quantifying the Environmental Impact of Particulate Deposition from Dry Unpaved Roadways. Unpublished Thesis, Master of Science, Iowa State University, USA.

BECKER, D.L. and TAKLE, E.S. (1979) Particulate Deposition from Dry Unpaved Roadways. Atmospheric Environment, 13: 661-668.

BIDWELL, V.J. (1985) (Personal Communication).

BLACKTIN, S.C. (1934) Dust. Chapman and Hall Ltd, London.

BLACKWOOD, T.R. and DREHMEL, D.C. (1981) New Concepts for Control of Fugitive Particle Emissions from Unpaved Roads. Environmental International, 6: 333-336.

BRADWAY, R.M.; RECORD, F.A. and BELANGER, W.D. (1978) Monitoring and Modelling of Resuspended Roadway Dust Near Urban Arterials. Transportation Research Record 670: 25-32.

BRUERE, A.N. (1979) A Syndrome of Dental Abnormalities of Sheep. New Zealand Veterinary Journal, 27: 152-167.

BUSTAD, L.K. (1980) Biomedical Effects of Mt St Helens Ash (Bases for our Evaluations of its Consequences). Proceedings of Washington State University's Conference on the Aftermath of Mt St Helens. 4-6.

CIONCO, R.M. (1965) A Mathematical Model for Air Flow in a Vegetative Canopy. Journal of Applied Meterology, 4: 517-522.

CLARK, M.B. and BURTT, E.S.; editors. (1986) Farm Budget Manual. Lincoln University College, New Zealand.

CLINCH, P. (1979) Honeybees and Kiwifruit Pollination. Proceedings of New Zealand Kiwifruit Growers Federation Seminar. 21-26.

COLWILL, D.M.; editor. (1979) The Impact of Road Traffic on Plants. British Transport and Road Research Laboratory: Supplementary Report 513.

COMMONWEALTH BUREAU OF ANIMAL HEALTH. (1982) The Effects on Animal Health of Contamination of Pastures by Dusts. London.

COOK, R.J.; BARRON, J.C.; PAPENDICK, R.I. and WILLIAMS, G.W. (1981) Impact on Agriculture of Mt St Helens Eruptions. Science, 211 (January): 16-21.

COOPER, B.S. (1984) (Personal Communication).

COWHERD, J.L.; CHATTEN, S.R. and CONNOLLY, J.L. (1974) Development of Emission Factors for Fugitive Dust Sources. United States Environmental Protection Agency, Publication No. 450/3-74-037.

CRUMP, D.R.; BARLOW, P.J. and van REST, D.J. (1980) Seasonal Changes in the Lead Content of Pasture Grass Growing Near a Motorway. Agriculture and Environment (Netherlands), 5: 213-225.

DANNO, A.; MIYAZATO, M. and ISHIGURO, E. (1980) Effect of Volcanic Ashes from Mt Sakurakima on Spectoral Reflectance of Plants. Kagoshima University, Faculty of Agriculture, Bulletin 30: 217-224.

DAVIES, C.N.; editor. (1967) Aerosol Science. Academic Press, New York.

DAVIS, G.B. (1974) A Sheep Mortality Survey in Hawkes Bay. New Zealand Veterinary Journal, 22: 39-42.

DAVIS, G.B. (1984) (Personal Communication).

DAVISON, R.M. (1977) Some Factors Affecting Flowering and Cropping in Kiwifruit. Proceedings of New Zealand Kiwifruit Growers Federation Seminar.

DENT, J.B. and BLACKIE, M.J. (1979) Systems Simulation in Agriculture. Applied Science Publishers Ltd, London.

DUNN, J.S. (1984) (Personal Communication).

DYCK, R.J. and STUKEL, J.J. (1976) Fugitive Road Dust Emissions from Trucks on Unpaved Roads. Environmental Science and Technology 10(10): 1046-1048.

ECONOMIC COMMISSION FOR EUROPE. (1979) Fine Particulate Pollution: A Report to the United Nations. New York.

ELLER, B.J. (1977) Road Dust Induced Increase of Leaf Temperature. Environmental Pollution, 13: 99-107.

ELVIDGE, D.G. (1984) (Personal Communication).

ENGIBOUS, J.C. and PAPENDICK, R.I. (1980) Impact of Mt St Helens Volcanic Ash on Northwest Agriculture. Proceedings of Annual Meeting of American Society of Agronomy. 33-41.

ESMAN, A.N. (1973) A Direct Measurement Method of Dustfall. Journal of Air Pollution Control Association, 23(1): 34-36.

EVANS, J.S. and COOPER, D.W. (1981) The Contributions of Open Sources to Ambient TSP Levels. Journal of the Air Pollution Control Association, 31(5): 549-556.

EVANS, J.W.; COOPER, D.W. and HARRINGTON, J.J. (1983) Strategies for the Optimal Control of Dust Emissions from Unpaved Roads. Journal of the Air Pollution Control Association, 33(4): 312-317.

FEDON, J.S. (1981) Effects of Mt St Helens Ash on the Response of Rat Trachea to Smooth Muscle Agonist. Environmental Research, 26: 497-499.

FERRO, D.N.; editor. (1976) New Zealand Insect Pests. Lincoln University College, New Zealand.

FIELD, R.J. (1984) (Personal Communication).

FISHER, R.B. (1983) Background to Factors Included in the Economic Analysis of Roading Projects. Unpublished Report. New Zealand National Roads Board, Wellington.

FISHMAN, G.S. and KIVAK, P.J. (1967) The Analysis of Simulation-Generated Time Series. Management Science, 13(7): 525-557.

FLESCHNER, C.A. (1958) The Effects of Dust Pollution on Avocado Production. California Avocado Society Yearbook: 22-27.

FORBES, R.N.; editor. (1986) Product Price Assumptions 1984. New Zealand Ministry of Agriculture and Fisheries: Economics Division, Technical Paper 2/86.

FRANK, J. and LOOMIS, W.E. (1950) Photosynthesis in Plants. Iowa State University, Iowa.

FREEMAN, A.M. (1982) Air and Water Pollution Control: A Benefit-Cost Assessment. J. Wiley and Sons, New York.

FYE, R.E. (1982) The Impact of Volcanic Ash on Pear Psylla and Associated Predators. Unpublished Report, Yakima Agricultural Research Laboratory, Japan.

GALLAGHER, N. (1984) (Personal Communication).

GOUDRIAAN, J. and van LARR, H.H. (1978) Calculation of Daily Totals of the Gross CO_2 Assimilation of Leaf Canopies. Netherlands Journal of Agricultural Science, 26: 373-382.

GREBB, B.W. and BLACK, A.L. (1961) Effects of Windbreak Plantings on Adjacent Crops. Journal of Soil and Water Conservation, 16: 223-227.

GREEN, F.H.Y. (1983) Health Implications of the Mt St Helens Eruptions: Laboratory Investigations in Inhaled Particles. Unwin Brothers Ltd, England.

HANDY, R.L.; HOOVER, J.M.; BERGESON, K.L. and FOX, D.E. (1975) Unpaved Roads as Sources of Dust. Transportation Research News, 60(75): 6-9.

HARKNESS, N.R. (1976) To Seal or Not to Seal? Internal Report. New Zealand Ministry of Works, New Zealand.

HARRIS, B.B. (1978) Wherever the Wind Blows Fugitive Dust. Pollution Engineering, 10(9): 59-60.

HEALY, W.B. and LUDWIG, T.G. (1965) Wear of Sheep's Teeth: The Role of Injested Soil. New Zealand Journal of Agricultural Research, 8(4): 737-752.

HEINE, D.G. (1980) Rural Roading Improvements - Are They Worth the Hay? New Zealand National Roads Board, Road Research Unit Newsletter 68: 16-18.

HEINSOHN, R.Y.; BIRNIE, C. and CUSCINO, T.A. (1975) Fugitive Dust from Vehicles Using Unpaved Roads. Proceedings from the United States National Conference on Energy and the Environment: 393-404.

HERMAN, C. (1967) Validation Problems in Games and Simulation. Behavioural Science 12: 216-230.

HOOVER, J.M.; PITT, J.M.; LUSTIG, M.T. and FOX, D.E. (1981) Mission Orientated Dust Control and Surface Improvement Processes for Unpaved Roads. Iowa State University, Engineering Research Institute, Iowa.

HOWELL, S. (1984) Kiwifruit: Crop Costing. Unpublished Report. Lincoln College College, New Zealand.

INGLIS, J. and DUNLOP, R.J. (1979) Living with Unsealed Roads. Proceedings of New Zealand Roading Symposium: 74-87.

JACKSON, D.I. (1984) (Personal Communication).

JOHANSEN, C. (1980) Mount Saint Helens Blows the Season for Many Washington Beekeepers. American Bee Journal, July: 500-504.

JOHNSTONE, J.G.; WINSCHE, W.E. and SMITH, L.W. (1949) The Dispersion and Deposition of Aerosols. Chemical Reviews, 44(2): 353-371.

KING, W.R. (1980) Siting Ambient Air Particulate Samplers Near Dirt Roads. Journal of the Air Pollution Control Association, 30(3): 275-277.

KIRTON, A.H.; O'HARA, P.J.; SHORTRIDGE, E.H. and CORDES, D.O. (1976) Seasonal Incidence of Enzootic Pneumonia and Its Effect on the Growth of Lambs. New Zealand Veterinary Journal, 24: 59-63.

LEMON, E.; STEWART, D.W. and SHOWCROFT, R.G. (1972) The Suns Work in a Cornfield. Science, 174: 371-378.

MANKTELOW, B.W. (1970) The Problem of Pneumonia in Sheep. Massey University, Sheepfarming Annual: 115-123.

MCCALDIN, R.O. and HEIDEL, K.J. (1978) Particulate Emissions From Vehicles Travelling Over Unpaved Roads. Abstracts of Papers from: Air Pollution Control Association, 71st Annual Meeting and Exhibition.

MONTIETH, J.L. (1975) Vegetation and the Atmosphere; Volume 1 : Principles. Academic Press, London.

MOYLE, G.L.; editor. (1982) An Economic Survey of Factory Supply Dairy Farms in New Zealand, 1983-84. New Zealand Dairy Board, Wellington.

NEW ZEALAND APPLE AND PEAR MARKETING BOARD. (1985) Local Market Grade Standards for Apples and Pears. Wellington.

NEW ZEALAND DEPARTMENT OF STATISTICS. (1985) Agricultural Statistics 1983-84. Wellington.

NEW ZEALAND DEPARTMENT OF STATISTICS. (1985) Monthly Abstract of Statistics. Wellington.

NEW ZEALAND DEPARTMENT OF STATISTICS. (1985) New Zealand Yearbook. Wellington.

NEW ZEALAND DAIRY BOARD. (1985) Annual Report. Wellington.

NEW ZEALAND GOVERNMENT. (1975) The New Zealand Grown Fruit and Vegetables Regulations. Government Printer, Wellington.

NEW ZEALAND INSTITUTE OF ENGINEERS. (1937) Report of the Standing Committee on Rural Roads. Wellington.

NEW ZEALAND KIWIFRUIT MARKETING AUTHORITY. (1985) Kiwifruit Export Grade Standards: Guidelines. Auckland.

NEW ZEALAND MEAT AND WOOL BOARDS' ECONOMIC SERVICE. (1985) Sheep and Beef Farm Survey, 1982-83. Wellington.

NEW ZEALAND MEAT PRODUCERS BOARD. (1985) Annual Report. Wellington.

NEW ZEALAND MINISTRY OF AGRICULTURE AND FISHERIES. Aglink Series Publications: FPP: 68, 161, 164, 213, 234, 302, 326, 490, 781. HPP: 13, 32, 55, 94, 97, 99, 120, 158, 169, 197, 229, 230, 233, 236, 238, 246, 301. NZA: 29. Wellington.

NEW ZEALAND MINISTRY OF AGRICULTURE AND FISHERIES. (1985) Cropping and Livestock Gross Margins. Auckland.

NEW ZEALAND MINISTRY OF AGRICULTURE AND FISHERIES, MEAT DIVISION. (1985) Unpublished report. Statistics for Pleurisy in Stock at New Zealand Freezing Works; Incidence and Carcases Condemned. Wellington.

NEW ZEALAND MINISTRY OF AGRICULTURE AND FISHERIES. (1985) Strawberry Gross Margin. Auckland.

NEW ZEALAND MINISTRY OF WORKS AND DEVELOPMENT. (1980) Economic Appraisal of Roading Improvement Projects. Internal Report. Circular Memorandum, Roading Division No. 98. Wellington.

NEW ZEALAND MINISTRY OF WORKS AND DEVELOPMENT. (1984) (Personal Communication). Tauranga.

NEW ZEALAND MINISTRY OF WORKS AND DEVELOPMENT. (1984) (Personal Communication). Wellington.

NORTON, F.W. (1960) Submission Presented to the National Symposium on the Economics of Roading and Transport. Wellington.

O'CONNOR, K.F. (1984) (Personal Communication).

PAINTER, D.J. (1976) What Cost Wind Blown Soil? New Zealand Farmer. December: 47-48.

PAINTER, D.J. (1977) Wind Erosion Control on Arable Land. Internal Publication. New Zealand Soil Conservation and Rivers Control Council. Wellington.

PARERA, F.P. and AHMEO, A.K. (1979) Respirable Particles: impact of Airborne Fine Particles on Health and the Environment. Ballinger Publishing Co., Cambridge.

PRESTON, R.L. (1980) Results of Research on Volcanic Ash in Farm Livestock. Proceedings of Washington State University's Conference on the Aftermath of Mt St Helens. 7-8.

PYKE, B.N. (1974) Sheep Mortality in the King Country. New Zealand Veterinary Journal, 24: 59-65.

REEVES, R.J. (1984) Sweet Oranges: Crop Costing. Unpublished Report. Lincoln University College, New Zealand.

RICKS, G.R. and WILLIAMS, R.J.H. (1974) Effects of Atmospheric Pollution on Deciduous Woodland Part 2: Effects of Particulate Matter Upon Stomatal Diffusion Resistance in Leaves of Quercus Pataea (Mattuschka) Leibl. Environmental Pollution 6: 87-109.

ROBERTS, B.R. (1980) How Air Pollution Affects Plants. American Nurseryman, July: 12: 44.

ROBERTS, J.W. (1973) Benefits to the Community from Reducing Dust in the Air in Seattle's Duwamish Valley. Proceedings from the Annual Meeting of the Pacific North West International Section of the Air Pollution Control Association. Paper No. 73-AO-33.

ROBERTS, J.W.; WATTERS, H.A.; MANGOLD, C.A. and ROSSANO, A.T. (1975) Costs and Benefits of Road Dust Control in Seattle's Industrial Valley. Journal of the Air Pollution Control Association, 29(9): 948-952.

ROBINSON, E. and ROBBINS, R.C. (1971) Emissions, Concentrations and Rate of Particulate Atmospheric Pollutants. American Petroleum Institute Report No. 4076.

RUSSELL, K.J. (1984) (Personal Communication).

SAMPSON, P.A. (1980) Setting Priorities for Roading Projects. Internal Report. Taupo County Council, New Zealand.

SAMPSON, P.A. and STRETTON, M.I. (1981) Economic Appraisal of Seal Extension. Internal Report. Taupo County Council, New Zealand.

SAN PIETRO, A.; editor (1967) Harvesting the Sun: Photosynthesis in Plant Life. Academic Press, New York.

SCOTT, P.J. (1980) Sheep and Cattle Nutrition. New Zealand Ministry of Agriculture and Fisheries, Wellington.

SCOTT, W.R. (1984) (Personal Communication).

SHANNON, R.E. (1975) Systems Simulation: The Art and the Science. Englewood Cliffs: Prentice-Hill Inc., New York.

SHARPLIN, B.D. and ELLIOT, M.B. (1980) County of Rodney Roading Needs Survey: Part One. Internal Report. Rodney County Council, New Zealand.

SIEVERS, H.E. (1978) Modified Line Source Models for Predicting 24 Hour and Annual Particulate Concentrations Resulting from Re-entrainment of Roadway Dust. Abstracts of Papers from: Air Pollution Control Association, 71st Annual Meeting and Exhibition.

SIMPSON, J. (1984) (Personal Communication).

STANHILL, G.; MORESHET, S. and FUCHS, M. (1976) Effect of Increasing Foliage and Soil Reflectivity on the Yield and Water Use Efficiency of Grain Sorghum. Agronomy Journal, 68 (April): 329-332.

STERN, A.C.; editor. (1968) Air Pollution (2nd Edition): Volume 1, Air Pollution and Its Effects. Academic Press, New York.

STOREY, P.E. (1984) (Personal Communication).

TABATA, S. and TANABE, M. (1980) Studies on the Physiological Effect of Soil Dust Adhesion to Plant Surfaces. Journal of Shinshu University, Faculty of Agriculture, 14(1): 13-21.

TESKEY, B.J.E. and SHOEMAKER, J.S. (1972) Tree Fruit Production (2nd Edition). Avi Publishing Co., Connecticut.

UNITED STATES DEPARTMENT OF ENVIRONMENT. (1963) Dust Laying on Unsurfaced Earth and Gravel Roads. Washington.

UNITED STATES DEPARTMENT OF HEALTH AND HUMAN SERVICES. (1980) Volcano Health Report. Washington.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, OFFICE OF AIR PROGRAMS. (1975) Compilation of Air Pollutant Emission Factors. Publication No. AP-42.

VAN HORN, R.L. (1971) Validation of Simulation Results. Management Science 14: 247-258.

VELTMAN, A. (1984) Apples: Crop Costings. Unpublished Report. Lincoln University College, New Zealand.

WARD, N.I.; REEVES, R.D. and BROOKES, R.R. (1975) Lead in Soil and Vegetation Along a New Zealand State Highway with Low Traffic Volume. Environmental Pollution, 9: 243-251.

WARD, N.I.; ROBERTS, E. and BROOKES, R.R. (1979) Seasonal Variation in the Lead Content of Soils and Pasture Species Adjacent to a New Zealand Highway Carrying Medium Density Traffic. New Zealand Journal of Experimental Agriculture, 7: 347-351.

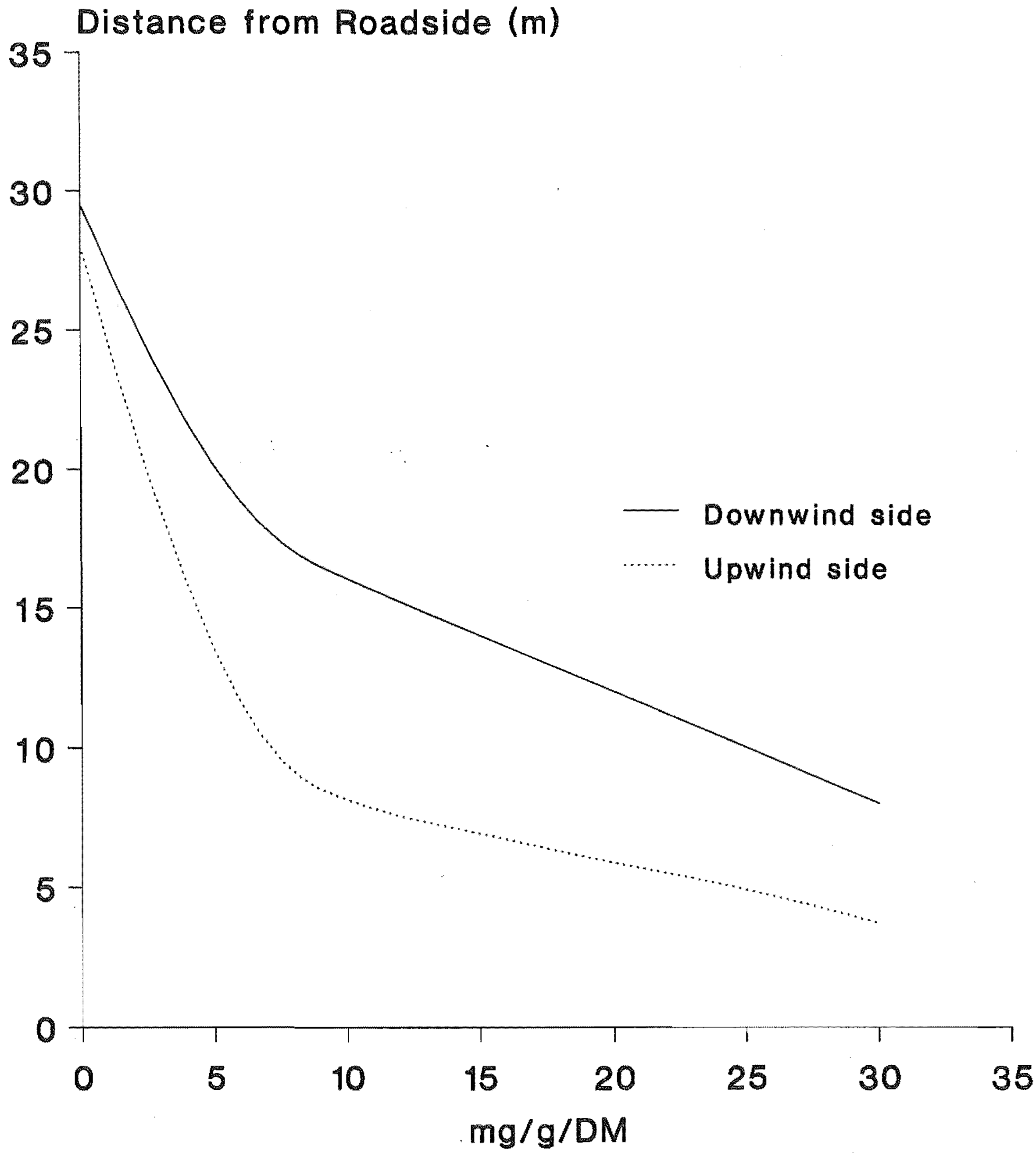
WHEELER, G.L. and ROLFE, G.L. (1979) The Relationship between Daily Traffic Volume and the Distribution of Lead in Roadside Soil and Vegetation. Environmental Pollution, 18: 265-274.

APPENDICES

APPENDIX I

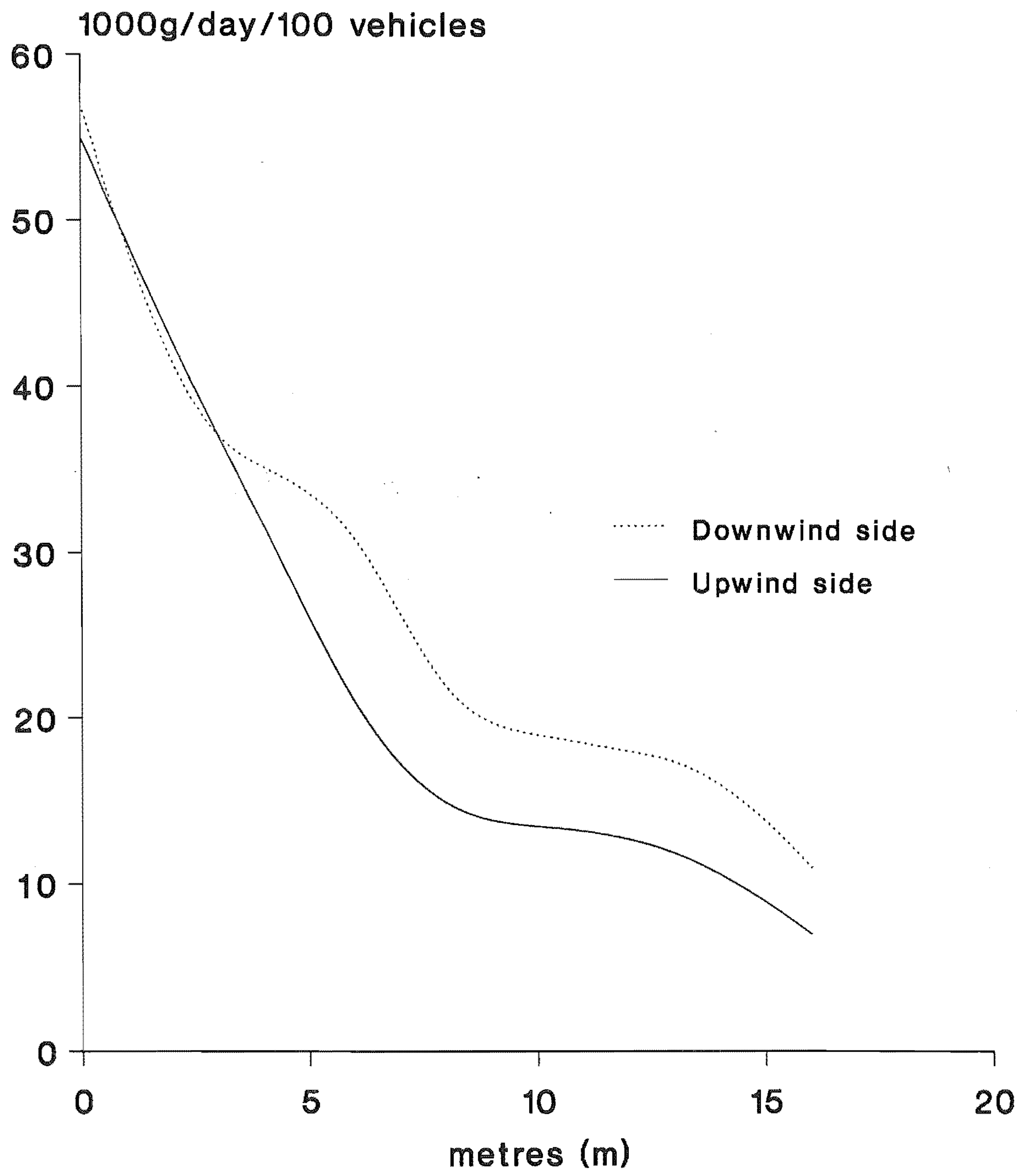
FINDINGS OF WARD ET AL. (1979) AND HOOVER ET AL. (1981) ON PREVAILING UPWIND AND DOWNWIND DEPOSITION DIFFERENCES

Figure I.1
Average Lead Concentration on leaves of Lolium perenne Bordering a Rural Road



(Ward et al., 1979)

Figure I.2
Average Dustfall Away From Metal Roads



(Hoover et al., 1981)

APPENDIX II

THE EFFECTS OF DUST COVER ON LIGHT INTENSITY

Introduction

Information is available regarding the reduction of photosynthesis due to reduced light intensity reaching plant surfaces (Goudriaan and van Larr (1978)). In order to link this information to the road dust study, it was necessary to measure the effect of dust cover in reducing the light intensity reaching plant leaf surfaces.

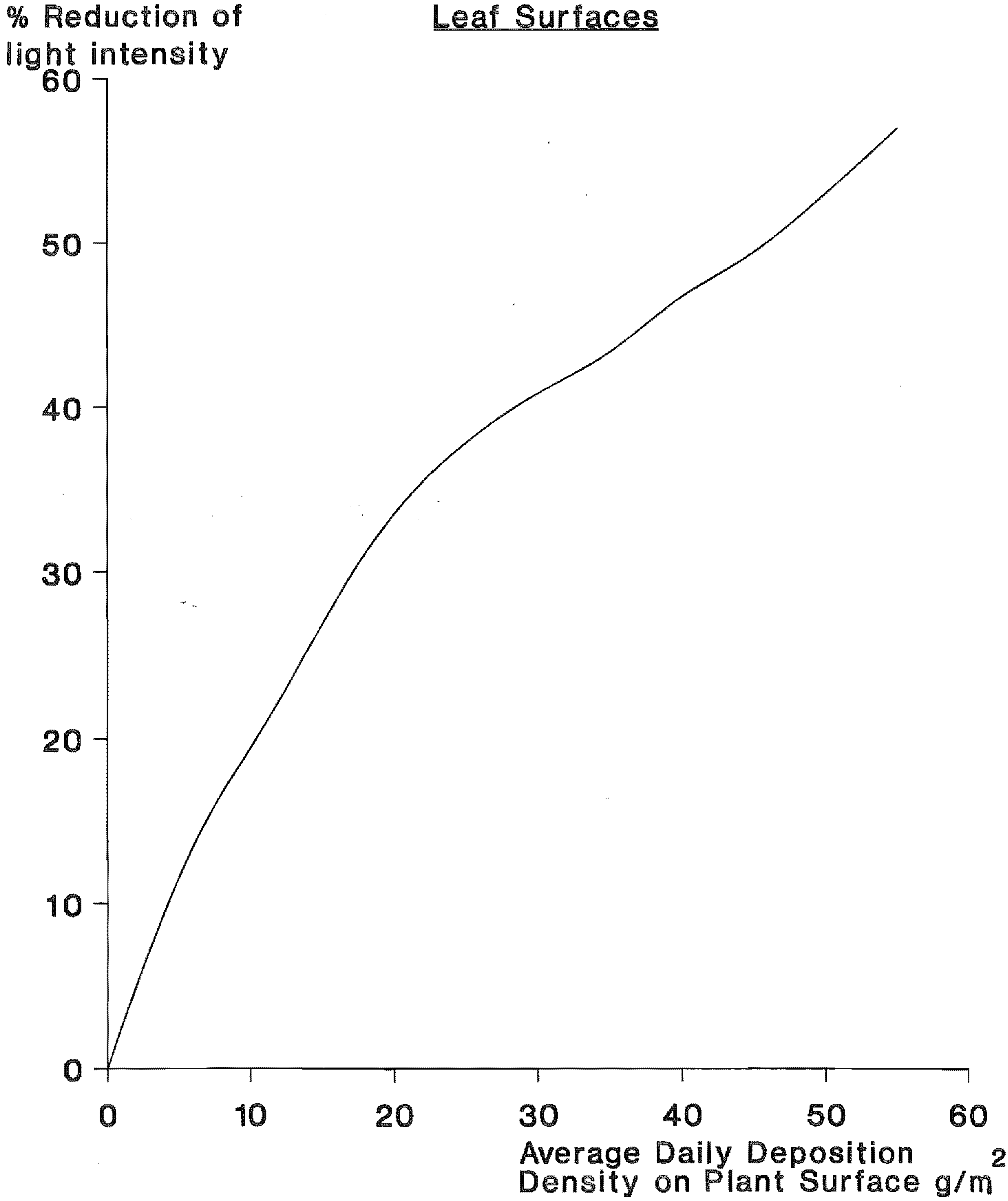
Materials and Methods

Roading material, sieved through a 75μm mesh screen, oven dried and weighed into quantities corresponding to predicted leaf surface levels, was spread evenly over a piece of clean glass of 25 square centimetres. Each treatment of dust coated glass was placed under a set of artificial bright lights and the reduction of light intensity caused by the dust cover, was measured using a LICOR LI185 photometer with a quantum sensor, placed in a black box under the glass sheet.

Results

The results of the light reduction tests are graphed on Figure II.1. This shows that the response of light intensity reduction to increasing levels of dust cover takes the form of a hyperbolic saturation curve. Initially, small increases in the level of dust cover have a great effect on the amount of light intensity reduction, but this response gradually decreases as the light intensity is further

Figure II.1
The Effect of Dust Deposition Density Levels on the Light Intensity Reaching Leaf Surfaces



reduced. Obviously saturation would be reached when the dust cover reaches a level which prevents all light reaching leaf surfaces.

Conclusions

The results of this experiment provide the data for estimating a mathematical relationship between the level of road dust on plant surfaces and the reduction of plant photosynthesis rates. Because the experiment was conducted under a closely controlled artificial environment, the results require further validation under field conditions, since other factors are also likely to affect the amount of light reduction (e.g. intensity of sunlight, type of dust, etc.).

APPENDIX III

SOME GENERALISED ESTIMATES OF NATIONAL RESOURCE COSTS, PRICES AND RETURNS ($1985)

TABLE III.1

Estimates of Average National Resource Costs and Prices that Vary with Yield, for Various Crop Types (1984/85 Season)
($/tonne)

Crop Type	PT[a]	PM[b]	PL[c]	AVP[d]	VCT[e]	VCM[f]	VCL[g]	AVC[h]
Apple[i]	460	290	100	319	68	68	68	68
Kiwifruit	1750	870	350	1496	1059	425	315	916
Peaches	1100	600	300	453	624	225	104	171
Blueberry	5000	4434	2000	4709	2289	1457	1249	2029
Avocado	4230	2834	-	3951	564	564	-	564
Asparagus	3855	1800	1677	2996	1353	1041	312	685
Orange	-	485	140[j]	451	-	76	-	76
Boysenberry	6836	4466	1285	2095	494	494	104	186
Grapes (for wine)	-	350	-	350	-	74	-	74
Strawberries	6270	2214	1150	3935	1145	1282	208	946
Maize	-	233	-	233	-	52	-	52
Pumpkin	-	337	-	337	-	78	-	78
Cabbage	-	308	-	309	-	150	-	150
Wheat	-	272	-	272	-	21	-	21

Sources: Ministry of Agriculture and Fisheries, Various Fruit and Produce Merchants and grower organisations.

Notes for Table III.1.

a PT = Price of top grade (usually export).
b PM = Price of medium grade (usually local fresh).
c PL = Price of low grade (usually processing).
d AVP = Average weighted price for all grades.
e VCT = Costs that vary with yield for top grade.
f VCM = Costs that vary with yield for medium grade.
g VCL = Costs that vary with yield for low grade.
h AVC = Weighted average costs for all grades.
i Applicable only to apples sold to the Apple and Pear Marketing Board.
j Applicable only to Gisborne district for Watties Canning.

TABLE III.2

Estimates of Average Gross Revenue (Per Hectare) for Various Animal Enterprise Types

Enterprise Type	Approximate Stock Units per Hectare	Gross Revenue ($/hectare)
Dairying-factory supply (NI)	20	2370
Prime lamb sheep flock (NI)	13.3	576
Sheep breeding flock (NI hill country)	11.1	383
Prime lamb-breeding flock (SI)	7	245
Prime beef herd (SI)	10	958
Deer (SI)	10	1553

Source: Lincoln College Farm Budget Manual, MAF Product Price Assumptions 1985, MAF estimates and gross margins.

TABLE III.3

Gross Margin for Factory Supply Dairy Farming
(Typical North Island)

Assumptions: 100 cows milked
5% losses of cows
10% losses of bobbies
95% calving

Stock Reconciliation (June)

		SU
105	Cows @ 6.5 SU	683
25	RI Yr @ 2.0 SU	50
2	Bulls @ 3.0 SU	6
---		---
132		739

Calves: 100

Sales:	Cull cows	20
	Bobbies	65
Losses:		15

		100

Gross Income per 100 milking cows:

Income

Milkfat; 150 kg/cow, 100 cows - @ $5.16/kg	$77,400
Bobbies; 65 @ $28	1,820
Cull cows; 20 @ $419 (220.5 kg @ $1.90/kg)	8,380

	$87,600
	======

Expenses

Animal health @ $15.6/cow milked	$ 1,560
Electricity @ $8.30	830
Shed expenses @ $5.20	520
AI & Herd testing @ $10.40	1,040
Feed costs @ $15.60	1,560

	$ 5,510
	=====

Gross Margin	$82,090.00

Gross Margin per Stock Unit	$ 111.08
	=========

TABLE III.4

Gross Margin for Prime Lamb, Sheep Flock
(Typical NI)

Assumptions: Romney ewe X meat breed sire
105% lambing
5% culling
Sell 6 yr ewes as works ewes
Buying 2 tooth ewes

		SU
Stock:	1000 ewes	1000
	20 rams	14
		1014

Gross Revenue per 1000 Ewes	
4900 kg wool @ $4.03	$19,747
1050 lambs @ $25.50	26,775
200 cull ewes @ $12.30	2,460
Gross Income per 1000 ewes	$48,982
Direct Costs per 1000 Ewes	
250 2t ewes @ $38.30	$ 9,575
5 rams @ $139.00 each	695
Animal Health $1.04/ewe	1,040
Shearing and crutching $1.77/SSU	1,795
Freight $1.04/ewe	1,040
Total Direct Costs per 1000 ewes	$14,145
Gross Margin per 1000 Ewes	$38,837
Gross Margin per SU	$ 34.36

TABLE III.5

Gross Margin for Sheep Breeding Flock
(NI Hill Country)

Assumptions: Romney ewes X romney rams
95% lambing
selling 53% fat, remainder store
rearing replacements

Stock:		SU
	1000 ewes	1000
	300 ewe hoggets	300
	20 rams	14
		1314

Gross Revenue (per 1000 ewes)		
6570 kg wool	@ $4.03/kg	$26,477
500 fat lambs	@ $25.50	12,750
150 store lambs	@ $20.80	3,120
50 cull ewes	@ $12.30	615
195 CFA ewes	@ $12.30	2,399
Gross Income per 1000 Ewes		$45,361
Direct Costs (per 100 ewes)		
Ram purchase 5 @ $139		695
Animal health @ 0.95c/SU		1,248
Shearing ($2.17/SSU)		2,851
Freight (0.62/SSU)		815
Direct Cost per 1000 Ewes		$ 5,609
Gross Margin per 1000 ewes		$39,752
Gross Margin per SU		$ 30.25

TABLE III.6

Gross Margin for Sheep Breeding Flock
(South Island)

Assumptions: Corriedale flock selling 5 year old ewes and breeding own replacement
93% lambing
5% ewe culling
20% 2th culling
80% wethers sold as prime

Gross Revenue (per 1000 Ewes)	
364 prime lambs @ %25.50	$ 9,282.00
180 store lambs @ $20.80	3,744.00
75 2th ewes @ $38.30	2,873.00
189 5yr ewes @ $23.20	4,385.00
50 cull ewes @ $12.30	615.00
5658 kg wool @ $4.03 kg	22,802.00
Gross Revenue	$43,701.00
Direct Costs (per 1000 Ewes)	
Shearing - 1380 @ $76.37/100	$ 1,053.90
Woolshed expenses	449.00
Tup Crutching - 990 ewes @ $25.46/100	252.10
Main Crutching - 990 ewes @ $34.62/100	342.70
Animal health	1,804.00
Ram purchase 5 @ $183.30	916.50
Freight	1,487.00
Selling Charges	443.00
Total Direct Costs	$ 6,748.20
Gross Margin per 1000 ewes	$36,853.00
Gross Margin per SU	$ 29.61

TABLE III.7

Gross Margin for Prime Beef Herd
(Typical SI)

Assumptions: Weaner beef steers purchased in the autumn, selling at 18-20 months of age
2% losses
100 rising 1 year old steers - 470 SU

Gross Income per 100 Steers Purchased	
98 steers @ 230 kg cw @ $2.00	$43,080
Direct Costs per 100 Steers Purchased	
100 weaner steers @ $300	$30,000
Animal health	489
Hay 400 bales @ $3.12	1,248
Freight	926

	$32,663
	======
Gross Margin per 100 Steers Purchased	
Gross margin per 100 steers	$12,417.00
Gross margin per SU steers	$ 26.40

TABLE III.8

Gross Margin for Deer
(Typical SI)

This example gross margin is for a policy of running velveting stags and buying replacements. Cull animals are processed as venison.

No. on Hand (1 July)	**Stock Units**
100 mixed aged stags	150
15 yearling stags	15
---	---
115	165

Purchase	**Deaths**
15 Weaner Stags	5
	Sales
	2 cull stags
	8 CFA stags
--	--
15	15

Gross Revenue (per 100 stags)

Cull stags - 2 @ $544.40 (90 kg dressed @ $5.8 kg plus by products @ $22.40)	$ 1,044.80
CFA stags - 8 @ $305.50	2,444.00
Velvet - 100 stags, 2 kg/head @ $110/kg	22,000.00
- 15 yearlings, 0.4 kg/head @ $22/kg	132.00
Gross Revenue	$25,620.80

Direct Costs (per 100 stags)

Animal health - at $5.70/head	$ 655.50
Freight - culled stags plus purchased replacements @ $8.35/head	208.80
Supplementary feed - hay, 2 bales per head @ $5.09/bale	1,170.70
- concentrates, 100 kg nuts to adult stags and 50 kg to all young stock @ $473.20/tonne	5,086.90
Velvet harvesting - vet, etc. @ $25.46/stag	2,927.90
Stock purchase - 15 weaner stags @ $356.40 each	5,346.00
Total Direct Costs	$15,395.80

Gross Margin per 100 stags	$10,225.00
Gross Margin per stag (- 100)	$ 102.25
Gross Margin per stock unit (- 165)	$ 62.00

APPENDIX IV

SOME GENERALISED ESTIMATES OF NATIONAL PRODUCTION AND MARKETING FIGURES FOR USE IN GUIDING USER INPUT DURING MODEL ANALYSIS OPERATIONS

TABLE IV.1

Estimates of Average Expected Yields for Various Crop Types

(A) LONG TERM CROPS

	Year					(Tonnes per hectare)											
Crop Type	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Apple	-	-	-	3.2	15.1	36.1	56.1	58.1	65.0	71.7	93.2	113.7	134.1	150.2	162.2	168.0	168.0
Kiwifruit	-	-	-	-	6.0	8.5	12.5	17.0	20.0	21.1	21.1						
Peach (and Nectarine)	-	-	-	11.3	18.8	22.6	22.6	22.6	22.6	22.6	22.6						
Blueberry	-	-	-	0.8	2.6	4.4	5.1	5.4	7.0	7.0	7.0						
Avocado	-	-	-	-	0.6	6.4	1.6	14.6	2.1	19.5	2.1	29.8	20.4	29.8	29.8	16.3	29.8
Asparagus	-	-	3.0	4.5	6.0	7.0	4.5	-	-	3.0	4.5	6.0	7.0	4.5	-	-	3.0
Orange	-	-	-	4.5	6.0	7.0	4.5	-	-	3.0	4.5	6.0	7.0	4.5	-	-	3.0
Boysenberry	-	-	10.0	15.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0						
Grapes (for Wine)	-	-	-	2.0	8.0	12.0	16.0	18.0	18.0	18.0	18.0						

(B) ANNUAL CROPS

Crop Size	Yield (tonnes per hectare)
Strawberries	24
Maize	8
Pumpkin	16
Wheat	4
Cabbage	20

TABLE IV.2

Types of Leaf Surfaces and Growing

Season's Assumptions for Various Crop Types

TYPE OF CROP	TYPE OF LEAF SURFACE	GROWING SEASON START	FINISH
Apple	Hairy	September	May
Kiwifruit	Hairy	September	May
Peach (& Nectarine)	Smooth	September	May
Blueberry	Hairy	September	May
Avocado	Smooth	January	December
Asparagus	Smooth	November	March
Orange	Smooth	January	December
Boysenberry	Hairy	October	May
Grapes	Smooth	September	May
Strawberry	Hairy	June	April
Maize	Hairy	October	May
Pumpkin	Hairy	October	January
Wheat	Hairy	June	February
Cabbage	Smooth	Approximately 3 months growing at any time of the year.	

TABLE IV.3

Suggested Tentative Levels of "Other Effects" For Various Crop Types

Crop Type	Increased Pest & Disease Incidence		Decreased Pollination		Down-grading Due to Dust Contamination	Increased Weed Incidence
	Yield Effect	Down-grading Effect	Yield Effect	Down-grading Effect		
Apple	Low	High	Nil	Nil	Low	Nil-Low
Kiwifruit	Low	Low	Low	High	High	Nil-Low
Peach	Low	Low	Nil	Nil	High	Nil-Low
Blueberry	Low	Low	High	Low	High	Low
Avocado	Low	Low	Nil	Nil	Low	Nil-Low
Asparagus	Nil	Nil	Nil	Nil	Low	Low
Orange	Low	Low	Nil	Nil	Low	Nil-Low
Boysenberry	Low	Low	High	Low	High	Low
Grapes (for wine)	Low	Nil	Nil	Nil	Nil	Nil-Low
Strawberry	Low	Low	Low	High	High	Nil
Maize	Low	Nil	Nil	Nil	Nil	Low
Pumpkin	Nil	Nil	Nil	Nil	Nil	Low
Wheat	Low	Nil	Nil	Nil	Nil	Low
Cabbage	Low	Nil	Nil	Nil	High	Low

TABLE IV.4

Approximate Percentages of Crops Sold as Different Grades
(1984/85 Year)

	Grade[a]		
Crop Type	Top	Medium	Low
Apples	54	15	32
Kiwifruit	80	5	15
Peaches	3	43	54
Avocadoes	80	20	-
Oranages	-	90	10
Blueberries	70	25	5
Boysenberries	6	15	79
Strawberries	49	26	25
Wine Grapes	-	100	-
Asparagus	60	10	-
Pumpkin	-	100	-
Cabbage	-	100	-
Maize	-	100	-
Wheat	-	100	-

a Grades used here are very generalised and relate approximately to:
Top - usually export
Medium - usually local fresh
Low - usually processing.

Sources: MAF Horticultural Statistics 1985.
Department of Statistics.
Ministry of Agriculture and Fisheries.

APPENDIX V

PROGRAM LISTING OF THE MODEL

A program listing of the model used to simulate the effects of road dust on agricultural and horticultural production systems adjoining unsealed roads. This program is written in FORTRAN 77 programming language.

PROGRAM:	DUST.FOR
SUBROUTINES:	RAIN.FOR
	DD.FOR
	UD.FOR
	YIELD.FOR
	TRIANG.FOR
	DOWING.FOR
	MOOBAA.FOR
	UPPERCASE.FOR

```
C
C                              TABLE V.1
C
C                    Program Listing of DUST.FOR
C                    ---------------------------
C
C*******************************************************************
C       PROGRAM TO SIMULATE THE EMISSION AND DISTRIBUTION OF ROAD   *
C       DUST FROM UNSEALED ROADS ONTO ADJOINING FARMLAND AND ALSO,  *
C       TO SIMULATE THE RESULTANT LOSSES,BOTH IN PHYSICAL AND       *
C       ECONOMIC TERMS,TO PRODUCTION FROM ROAD DUST RELATED EFFECTS.*
C*******************************************************************
C
        PROGRAM DUST
C
        REAL PRICEPU,VARCPU,COSTE,SCOSTE
        REAL ACOSTE,SACOSTE,STDCOST
        REAL SI,KM
        REAL HIS,AVS,LOS,DT
        REAL PROBS(0:40),PROBW(0:40)
        REAL UDENS(500),DDENS(500)
        REAL HIT,AVT,LOT,HITT,AVTT,LOTT
        REAL TIM(12)
        INTEGER PROD,ROADL
        LOGICAL AFLAG
        CHARACTER SWITCH * 3,FLAG * 3,SWITCH1 * 3,FLICK * 3
        CHARACTER ROADN * 30,ENTERP * 30
        CHARACTER LOOHI * 3,YON * 3
        CHARACTER CHAR1 * 3,CHAR2 * 3,CHAR3 * 4
        CHARACTER GROW * 3,ENTT * 3,HILO * 2
        CHARACTER SUMWIN * 3,SEAS1 * 3,SEAS2 * 3
        DIMENSION SUMWIN(12)
        DIMENSION LOOHI(6),YON(8)
C
        DATA SUMWIN /'JAN','FEB','MAR','APR','MAY',
     1              'JUN','JUL','AUG','SEP','OCT',
     2              'NOV','DEC'/
        DATA TIM /31.,28.25,31.,30.,31.,30.,31.,31.,
     1             30.,31.,30.,31./
C
C***********************************
C       OPEN INPUT AND OUTPUT FILES    *
C***********************************
C
        OPEN(UNIT=5,FILE='RAIN.DAT',STATUS='OLD')
        OPEN(UNIT=18,FILE='RES.DAT',STATUS='NEW')
        OPEN(UNIT=21,FILE='TEST.DAT',STATUS='NEW')
C
C*********************************************************************
C       INITIALISE TOTALS                                            *
C         SUMCOS=SUM OVER THE ENTERPRISES OF THE AVERAGE COSTS       *
C         TOTSS=STD DEVIATION OF TOTAL COSTS OVER ALL ENTERPRISES    *
C         TOTSSSC=SUM OF VARIANCE OF TOTAL COSTS OVER ALL ENTERPRISES*
C*********************************************************************
C
        SUMCOS=0.
        TOTSS=0.
        TOTSSSC=0.
C
C*******************
C       INPUT VALUES  *
C*******************
C
        TYPE *,'TYPE THE ROAD NAME'
        ACCEPT '(A30)',ROADN
        CALL UPPERCASE (ROADN,30)
        TYPE *,'WHAT IS THE TOTAL LENGTH OF ROAD (METRES)'
        ACCEPT *,ROADL
C
C****************************************************************
C       HIGH,AVERAGE AND LOW VALUES ARE INPUTTED FOR BOTH TRAFFIC*
```

```
C       DRAWN FROM A TRIANGULAR DISTRIBUTION.                        *
C*********************************************************************
C
        TYPE *,'INPUT SPEED VARIABLES HIS,AVS,LOS (KM/HR)'
        ACCEPT *,HIS,AVS,LOS
        TYPE *,'INPUT DAILY TRAFFIC COUNT VARIABLES HIT,AVT,LOT ',
     1        '(NB-HIT,AVT & LOT ARE THE HIGH,MEDIUM AND LOW ',
     2        'ESTIMATES OF AVERAGE DAILY TRAFFIC COUNT FOR THE ROAD.'
        ACCEPT *,HIT,AVT,LOT
        HITT=HIT
        AVTT=AVT
        LOTT=LOT
        TYPE *,'INPUT SILT CONTENT OF ROAD (AS DECIMAL FRACTION)'
        ACCEPT *,SI
C
C**********************************************************
C       PREPARE TO OUTPUT IN A CONCISE REPORT FORMAT        *
C**********************************************************
C
       WRITE(18,100)
 100   FORMAT('1',///1X,10X,'ROAD DUST COST EVALUATION')
       WRITE(18,110)
 110   FORMAT('+',1X,9X,'____ ____ ____ __________')
       WRITE(18,120)ROADN
 120   FORMAT(//1X,5X,'ROAD NAME',23(' '),':',1X,A30)
       WRITE(18,130)ROADL
 130   FORMAT(/1X,5X,'LENGTH OF ROAD SEGMENT (METRES) :',
     1       1X,I6)
       WRITE(18,140)SI
 140   FORMAT(/1X,5X,'SILT CONTENT OF ROAD              :',
     1        1X,F4.3)
       WRITE(18,150)HIT,AVT,LOT
 150   FORMAT(/1X,5X,'TRAFFIC COUNT VARIABLES(AVE/DAY):',
     1                 2X,'HIGH   AVERAGE   LOW',/2X,31X,
     2                 8X,F4.0,4X,F4.0,4X,F4.0)
       WRITE(18,160)HIS,AVS,LOS
 160   FORMAT(/1X,5X,'SPEED VARIABLES(KM/HR)',10(' '),':',
     1                 2X'HIGH   AVERAGE   LOW',/2X,31X,
     2                  8X,F4.0,4X,F4.0,4X,F4.0)
C
C***********************************
C       SET THE RANDOM NUMBER SEED   *
C***********************************
C
        IX=345657
C
C*********************************************************************
C       SET UP FOR EITHER DOWNWIND OR UPWIND                          *
C       THESE PARAMETERS ARE CHANGED MANUALLY WITHIN THE PROGRAM      *
C       IIDIST IS USED FOR THE UPWARD PREVAILING WIND                 *
C       IDIST IS USED FOR THE DOWNWIND PREVAILING WIND                *
C       NUM IS THE NUMBER OF LOOPS THROUGH THE INNER SIMULATION       *
C*********************************************************************
C
        NUM=365
        NUMM=NUM
        IDIST=200
        IIDIST=60
C
C*********************************************************************
C       NOW CALL THE RAIN ROUTINE WHICH RETURNS A PROBABILITY         *
C       DISTRIBUTION FOR EACH OF WINTER AND SUMMER CONTAINING         *
C       THE PROBABILITY OF THE DAYS OF ACCUMULATED DUST DEPOSITION.   *
C        THESE ARE CALCULATED FROM MET. OFFICE DATA AND INCLUDE       *
C       ALLOWANCES FOR;                                               *
C         1)NO DUST ON DAYS WITH 4MM OF RAIN OR MORE AND;             *
C         2)2 DAYS FOR ROAD DRYING AFTER RAIN IN WINTER(APRIL TO      *
C             OCTOBER) OR;                                            *
C         3)1 DAY FOR ROAD DRYING IN SUMMER(NOVEMBER TO MARCH)        *
C                                                                     *
C       PROBS AND PROBW ARE THE PROBABILITY DISTRIBUTIONS FOR         *
```

```
C***********************************************************************
C
        CALL RAIN(PROBS,PROBW)                                      140
C
C***********************************************************************
C       THE MAIN SIMULATION DRIVE BEGINS HERE                          *
C                                                                      *
C       INPUT ALL THE ENTERPRISE PARAMETERS AS PROMPTED                *
C                                                                      *
C     INITIALISE DECISION VARIABLES AS NECESSARY                       *
C***********************************************************************
C
      NKOUNT=0
 170  DO I=1,8
       YON(I)='NO'
C
C***********************************************************************
C       YON1 IS A MATRIX CONTAINING USER RESPONSES TO THE PRESENCE     *
C       OF ROAD DUST EFFECTS                                           *
C***********************************************************************
C
      ENDDO
      DO I=1,6
       LOOHI(I)='NO'   !USER RESPONSE FOR HIGH OR LOW EFFECT**********
      ENDDO
      NKOUNT=NKOUNT+1  !DO NEXT REPLICATION*************************
C
C*******************************************************************
C     THE FOLLOWING SECTION ASKS DETAILS ABOUT EACH ENTERPRISE     *
C     EVALUATED                                                    *
C                                                                  *
C     IF THE ENTERPRISE INVOLVES ANIMAL PRODUCTION CALCULATE       *
C     A STANDARD COST DEPENDANT UPON AREA OF LAND  UP TO IDIST     *
C*******************************************************************
C
      TYPE *,'INPUT THE ENTERPRISE TYPE (EG. KIWIFRUIT,DAIRYING,ETC.)'
      ACCEPT '(A30)',ENTERP
      CALL UPPERCASE (ENTERP,30)
C
C***************************************************************
C     DECIDING WHETHER A PLANT OR AN ANIMAL ENTERPRISE TYPE   *
C***************************************************************
C
      TYPE *,'DOES THE ENTERPRISE INVOLVE ANIMAL PRODUCTION ?'
      TYPE *,'                 (YES/NO)'
      ACCEPT '(A3)',ENTT
      CALL UPPERCASE (ENTT,3)
C
C*******************************************************************
C     THIS SECTION IS COMMON TO ALL ENTERPRISE TYPES               *
C*******************************************************************
C
      TYPE *,'INPUT THE DISTANCE (METRES)  FROM THE ROAD ',
     1       'CENTRE TO START OF PRODUCTIVE LAND.',
     2       'THE DISTANCE MUST BE GREATER THAN 0'
       ACCEPT *,PROD
       TYPE *,'IS THE ENTERPRISE ON THE PREVAILING UPWIND ',
     1       'SIDE OF THE ROAD (YES/NO)',
     2       'IF NO THEN IT MUST BE ON THE PREVAILING ',
     3       'DOWNWIND SIDE OF THE ROAD',SWITCH
       ACCEPT '(A3)',SWITCH
       CALL UPPERCASE (SWITCH,3)
       TYPE *,'INPUT THE LENGTH OF ROAD FRONTAGE FOR THIS ',
     1       'ENTERPRISE (METRES)'
       ACCEPT *,RFRONT
       IF(ENTT.EQ.'YES')GO TO 240
C
C*********************************************************************
C     THIS SECTION DEALS ONLY WITH PLANT TYPE ENTERPRISES            *
C*********************************************************************
C
```

```
      TYPE *,'ARE THERE LOSSES ASSOCIATED WITH EXTRA PEST',
     1      ' AND DISEASE INCIDENCE ? (YES/NO)'
      ACCEPT '(A3)',YON(1)
      CALL UPPERCASE (YON(1),3)
      IF(YON(1).EQ.'NO')GO TO 190
      TYPE *,'ARE THEY YIELD LOSSES (YES/NO)'
      ACCEPT '(A3)',YON(2)
      CALL UPPERCASE (YON(2),3)
      IF(YON(2).EQ.'NO')GO TO 180
      TYPE *,'DO WISH A HIGH ESTIMATE (YES) ',
     1       'OR LOW ESTIMATE (NO)'
      ACCEPT '(A3)',LOOHI(1)
      CALL UPPERCASE (LOOHI(1),3)
 180  TYPE *,'IS THERE DOWNGRADING ? (YES/NO)'
      ACCEPT '(A3)',YON(3)
      CALL UPPERCASE (YON(3),3)
      IF(YON(3).EQ.'NO')GO TO 190
      TYPE *,'DO WISH A HIGH ESTIMATE (YES) ',
     1       'OR LOW ESTIMATE (NO)'
      ACCEPT '(A3)',LOOHI(2)
      CALL UPPERCASE (LOOHI(2),3)
C
 190  TYPE *,'ARE THERE COSTS FROM REDUCED POLLINATION ?',
     1                 '(YES/NO)'
      ACCEPT '(A3)',YON(4)
      CALL UPPERCASE (YON(4),3)
      IF(YON(4).EQ.'NO')GO TO 210
C
      TYPE *,'ARE THEY YIELD LOSSES (YES/NO)'
      ACCEPT '(A3)',YON(5)
      CALL UPPERCASE (YON(5),3)
      IF(YON(5).EQ.'NO')GO TO 200
      TYPE *,'DO WISH A HIGH ESTIMATE (YES) ',
     1       'OR LOW ESTIMATE (NO)'
      ACCEPT '(A3)',LOOHI(3)
      CALL UPPERCASE (LOOHI(3),3)
 200  TYPE *,'IS THERE DOWNGRADING ? (YES/NO)'
      ACCEPT '(A3)',YON(6)
      CALL UPPERCASE (YON(6),3)
      IF(YON(6).EQ.'NO')GO TO 210
      TYPE *,'DO WISH A HIGH ESTIMATE (YES) ',
     1       'OR LOW ESTIMATE (NO)'
      ACCEPT '(A3)',LOOHI(4)
      CALL UPPERCASE (LOOHI(4),3)
 210  TYPE *,'IS THERE DOWNGRADING DUE TO DUST ON FRUIT ?',
     1             '(YES/NO)'
      ACCEPT '(A3)',YON(7)
      CALL UPPERCASE (YON(7),3)
      IF(YON(7).EQ.'NO')GO TO 220
      TYPE *,'DO WISH A HIGH ESTIMATE (YES) ',
     1       'OR LOW ESTIMATE (NO)'
      ACCEPT '(A3)',LOOHI(5)
      CALL UPPERCASE (LOOHI(5),3)
 220  TYPE *,'IS YIELD AFFECTED BY WEED INCIDENCE ?',
     1             ' (YES/NO)'
      ACCEPT '(A3)',YON(8)
      CALL UPPERCASE (YON(8),3)
      IF(YON(8).EQ.'NO')GO TO 230
      TYPE *,'DO WISH A HIGH ESTIMATE (YES) ',
     1       'OR LOW ESTIMATE (NO)'
      ACCEPT '(A3)',LOOHI(6)
      CALL UPPERCASE (LOOHI(6),3)
 230  CONTINUE
C
C*************************************************************
C      INITIALISE DEFAULT VARIABLES FOR LOGICAL VARIABLES    *
C*************************************************************
C
       SWITCH1='NO'
       FLICK='NO'
C
C*************************************************************
```

```
C       INPUT PRODUCTION AND PRICE VARIABLES                         *
C*******************************************************************
C
        TYPE *,'INPUT THE YIELD (TONNES) PER HECTARE ',
     1          'FOR THIS ENTERPRISE'
        ACCEPT *,YPHEC
        TYPE *,'INPUT THE WEIGHTED AVERAGE PRICE ',
     1          'PER TONNE FOR PRODUCE FROM THIS THIS ENTERPRISE',
     1          '                                          ',
     2          '(N.B.  WEIGHTED AVERAGE PRICE IS THE OVERALL AVERAGE ',
     3          'PRICE WITH RESPECT TO THE PRICE AND PROPORTION OF ',
     4          'EACH GRADE OF PRODUCE SOLD.)'
        ACCEPT *,PRICEPU
        TYPE *,'INPUT PRICE PER TONNE FOR PREMIUM GRADE'
     1      ,' (I.E. GENERALLY EXPORT GRADE)'
        ACCEPT *,EXP
        TYPE *,'INPUT PRICE PER TONNE FOR LOW GRADE ',
     1           '(I.E. GENERALLY PROCESS GRADE)'
        ACCEPT *,PROSP
        TYPE *,'INPUT THE COSTS WHICH VARY WITH YIELD (PER TONNE) ',
     1          '(E.G. FREIGHT,PACKAGING,ETC)'
        ACCEPT *,VARCPU
        TYPE *,'INPUT COSTS WHICH VARY WITH YIELD FOR ',
     1          'PREMIUM GRADE'
        ACCEPT *,CTOP
        TYPE *,'INPUT COSTS WHICH VARY WITH YIELD FOR ',
     1          'LOW GRADE'
        ACCEPT *,CLOW
C
C*****************************************
C       DUST REDUCTION PARAMETERS         *
C*****************************************
C
        TYPE *,'ARE THE PLANT LEAVES SMOOTH? (CF. HAIRY) - (YES/NO)'
        ACCEPT '(A3)',SWITCH1
        CALL UPPERCASE (SWITCH1,3)
        TYPE *,'IS THE LAND PROTECTED FROM ROAD DUST',
     1           'BY A SHELTERBELT ? (YES/NO)'
        ACCEPT '(A3)',FLICK
        CALL UPPERCASE (FLICK,3)
C
C*******************************************************************
C       SET UP ANNUAL GROWING SEASON                                 *
C                                                                    *
C       NEED TO TAKE ACCOUNT OF DIFFERENT LENGTH AND DIFFERENT TIMES *
C       OF YEAR OF VARIOUS ENTERPRISE GROWING SEASON (IE. EVERGREEN  *
C       VERSUS DECIDUOUS.)                                           *
C*******************************************************************
C
        SUMM=O.   !NO OF SUMMER DAYS IN GROWING SEASON***************
        WIN=O.    !NO OF WINTER DAYS IN GROWING SEASON***************
C
        TYPE *,'THE MONTHS FOR GROWING SEASON ARE ABBREVIATED AS:'
        TYPE *,'JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC'
        TYPE *,'IF THE GROWING SEASON IS THE COMPLETE YEAR INPUT'
        TYPE *,'JAN AS THE START AND DEC AS THE END'
        TYPE *,'OTHERWISE INPUT START AND END NORMALLY'
        TYPE *,'FOR EXAMPLE MAR  AUG'
        TYPE *,'            OR OCT  MAR'
        TYPE *,'INPUT START OF GROWING SEASON'
        ACCEPT '(A3)',SEAS1
        CALL UPPERCASE (SEAS1,3)
        TYPE *,'INPUT END OF GROWING SEASON'
        ACCEPT '(A3)',SEAS2
        CALL UPPERCASE (SEAS2,3)
        DO I=1,12
            IF(SEAS1.EQ.SUMWIN(I))THEN
             IS=I
            ENDIF
            IF(SEAS2.EQ.SUMWIN(I))THEN
             IF=I
            ENDIF
```

```
      ENDDO
C
C***********************************************************
C      IF 'IS' > 3 AND < 11 THEN THE SEASON STARTS IN WINTER *
C      OTHERWISE IT STARTS IN SUMMER AND SIMILARLY FOR ENDING*
C                                                          *
C      IF SEAS2 < SEAS1 SEASON STARTS IN ONE YEAR AND      *
C      RUNS TO THE NEXT                                    *
C***********************************************************
C
C****************************************
C      FOR SEASON ALL IN ONE YEAR EG MAR-NOV  *
C****************************************
C
      IF(IF.GT.IS)THEN
        DO I=IS,IF
           IF(I.LE.3)THEN
             SUMM=SUMM+TIM(I)
           ELSEIF(I.GT.3..AND.I.LE.10)THEN
             WIN=WIN+TIM(I)
           ELSE
             SUMM=SUMM+TIM(I)
           ENDIF
        ENDDO
      ELSE
C
C**************************************************************
C      FOR SEASON FROM ONE YEAR TO NEXT EG NOV-MAR            *
C      (NB IF AN EVERGREEN CROP AND IT GROWS FROM EG JAN-JAN  *
C          THEN IS TREATED AS ONLY ONE YEAR)                  *
C**************************************************************
C
        DO I=1,IF
           IF(I.LE.3)THEN
             SUMM=SUMM+TIM(I)
           ELSEIF(I.GT.3..AND.I.LE.10)THEN
             WIN=WIN+TIM(I)
           ELSE
             SUMM=SUMM+TIM(I)
           ENDIF
         ENDDO
         DO I=IS,12
           IF(I.LE.3)THEN
             SUMM=SUMM+TIM(I)
           ELSEIF(I.GT.3..AND.I.LE.10)THEN
             WIN=WIN+TIM(I)
           ELSE
             SUMM=SUMM+TIM(I)
           ENDIF
         ENDDO
      ENDIF
C
C*******************************************************************
C      THIS SECTION DEALS ONLY WITH ANIMAL ENTERPRISES             *
C*******************************************************************
C
      COSTM=0.     !INITIALISE COSTS TO ANIMAL ENTERPRISE***********
      IF(ENTT.EQ.'NO')GO TO 250
  240 CONTINUE
      TYPE *,'INPUT GROSS INCOME PER HECTARE ($)'
      ACCEPT *,GROSSY
      TYPE *,'DO WISH A HIGH OR LOW ESTIMATE OF YIELD'
      TYPE *,'REDUCTION (HI/LO)'
      ACCEPT '(A2)',HILO
      CALL UPPERCASE (HILO,2)
      IF(HILO.EQ.'HI')RED=.02
      IF(HILO.EQ.'LO')RED=.01
C
C***********************************************************
C      CALL THE SUBROUTINE THAT ESTIMATES THE COST OF DUST   *
C      ON LIVESTOCK PRODUCTION                              *
C***********************************************************
```

```
C
      COSTM=0.
      CALL MOOBAA(RFRONT,PROD,GROSSY,SWITCH,COSTM,RED,
     1            IDIST,IIDIST)
 250  CONTINUE
C
C*************************************************************
C     IF SIMULATING FOR LIVESTOCK ENTERPRISES THERE IS NO    *
C     ELEMENT OF STOCHASTICITY                               *
C*************************************************************
C
      IF(ENTT.EQ.'YES')THEN
       NUM=1
      ELSE
       NUM=NUMM
      ENDIF
C
C*********************************************************
C     INITIALISE ROLLING TOTALS -FOR PLANT ENTERPRISES  *
C*********************************************************
C
      PHOTO1=0.  !PERCENTAGE PHOTOSYNTHETIC YIELD LOSSES*******
      PHOTO=0.   !TOTAL PHOTOSYNTHETICYIELD LOSSES************
      COSTL=0.   !DOWNGRADING COSTS***************************
      COSTE=0.   !TOTAL OF PHOTOSYNTHETIC YIELD COSTS*****************
      TOTSYN=0.  !ROLLING TOTAL OF PHOTOSYN. COST FOR EACH ENTERPRISE*
      STOTSYN=0. !SUM OF SQUARES OF OBSERVATIONS OF PHOTOSYNTHETIC
C                 YIELD LOSS
      SCOSTE=0.  !SUM OF SQUARED PHOTOSYN YIELD COSTS**********
C
      DO 280 JK=1,NUM
C
C****************************************************************
C     STORE TRAFFIC DENSITIES SO THAT THEY ARE NOT REDUCED EVERY*
C     REPLICATION DUE TO WINTER                                 *
C****************************************************************
C
      LOT=LOTT
      AVT=AVTT
      HIT=HITT
C
C***************************************************************
C
C      THE AMOUNT OF LOSS VARIES BETWEEN WINTER AND SUMMER AND    *
C     SO SUBROUTINE YIELD IS CALLED WITH THE ARGUMENT LIST USED   *
C     FOR EACH DAY SIMULATED,DEPENDING ON WHETHER A WINTER OR A   *
C     SUMMER DAY WAS SELECTED FROM THE APPROPRIATE PROBABILITIES  *
C     VIS;-WINTER DAYS PER YEAR IS 214                            *
C         -SUMMER DAYS PER YEAR IS 152 OR 151 (I.E.151.25)        *
C****************************************************************
C
      UURAN=RAN(IX)                        !SELECT SEASON*************
      IF(ENTT.NE.'YES')THEN
        IF(UURAN.LE.(SUMM/(SUMM+WIN)))THEN  !SUMMER*******************
          AFLAG=.TRUE.
        ELSE                                !WINTER*******************
          AFLAG=.FALSE.
        ENDIF
C
C*****************************************************************
C     IF WINTER CUT BACK THE TRAFFIC COUNT BY 40% TO TAKE ACCOUNT OF*
C     THE EFFECT OF DEW.                                           *
C*****************************************************************
       IF(AFLAG.EQ..FALSE.)THEN
         LOT=.6*LOT
         AVT=.6*AVT
         HIT=.6*HIT
       ENDIF
      ENDIF
C
       IF(ENTT.EQ.'YES')GO TO 270  !IE ANIMAL PRODUCTION*********
       IF(SWITCH.EQ.'YES')THEN
```

```
C
C*************************************************************
C      CALL A SUBROUTINE TO CALCULATE THE DENSITY OF ROAD DUST  *
C      WHICH MAY BE DEPOSITED ON PLANT SURFACES AT EACH METRE   *
C      AWAY FROM THE ROAD,ON ANY 'DUSTY' DAY.                   *
C           -UD IS FOR THE PREVAILING UPWIND SIDE AND;          *
C           -DD IS FOR THE PREVAILING DOWNWIND SIDE             *
C*************************************************************
C
         CALL UD(IX,UDENS,LOS,AVS,HIS,LOT,AVT,HIT,SI,PROD,IIDIST,
     1          SWITCH1,FLICK)
       ELSE
         CALL DD(IX,DDENS,LOS,AVS,HIS,LOT,AVT,HIT,SI,PROD,IDIST,
     1          SWITCH1,FLICK)
       ENDIF
C
C***************************************************************
C     NOW SIMULATE DAILY PHOTOSYNTHETIC YIELD LOSSES FOR THE      *
C     ENTERPRISE AND AVERAGE THEM TO GET AN EXPECTED ANNUAL LOSS. *
C      THIS IS DONE BY TYING IN THE PROBABILITIES OF THE NUMBER OF*
C     DAYS ACCUMULATED DUST DEPOSITION ON PLANT SURFACES AND THE  *
C     APPROPRIATE DENSITY SUBROUTINE,WITH A SUBROUTINE WHICH      *
C     CALCULATES THE PHOTOSYNTHETIC YIELD LOSS WITH RESPECT TO    *
C     DUST COVER.                                                 *
C                                                                 *
C           *********************************************         *
C                                                                 *
C     CALCULATE DAILY PHOTOSYNTHETIC YIELD LOSS                   *
C***************************************************************
C
      IF(AFLAG.EQ..TRUE..AND.SWITCH.EQ.'YES')THEN
        CALL YIELD(IX,AFLAG,PROBS,UDENS,PROD,IIDIST,PHOTO,PHOTO1,
     1          YPHEC,RFRONT)
      ELSEIF(AFLAG.EQ..TRUE..AND.SWITCH.EQ.'NO')THEN
        CALL YIELD(IX,AFLAG,PROBS,DDENS,PROD,IDIST,PHOTO,PHOTO1,
     1          YPHEC,RFRONT)
      ELSEIF(AFLAG.EQ..FALSE..AND.SWITCH.EQ.'YES')THEN
        CALL YIELD(IX,AFLAG,PROBW,UDENS,PROD,IIDIST,PHOTO,PHOTO1,
     1          YPHEC,RFRONT)
      ELSE
        CALL YIELD(IX,AFLAG,PROBW,DDENS,PROD,IDIST,PHOTO,PHOTO1,
     1          YPHEC,RFRONT)
      ENDIF
C
C*******************************************************************
C     NOW CALL THE ROUTINE (DOWNG) WHICH ACCOUNTS FOR LOSSES OTHER     *
C     THAN PHOTOSYNTHETIC YIELD LOSSES.WHETHER THE ENTERPRISE BEING    *
C     EVALUATED IS UPWIND OR DOWNWIND IS IMPORTANT SINCE THIS          *
C     DETERMINES THE AREA OF LAND ADJOINING THE ROAD WHICH IS TO BE    *
C     EVALUATED.                                                       *
C                                                                      *
C     DOWNG IS A DETERMINISTIC ROUTINE AND SO FOR EFFICEINCY IT IS     *
C     ONLY CALLED ONCE.                                                *
C*******************************************************************
C
      IF(JK.EQ.1)THEN
        CALL DOWNG(SWITCH,IDIST,IIDIST,PROD,PRICEPU,
     1          VARCPU,COSTL,PERLOSS,PERLOSS1,
     2          YON,LOOHI,EXP,PROSP,YPHEC,RFRONT,
     3          CTOP,CLOW)
      ENDIF
 270  CONTINUE

C
C****************************************************************
C     NOW STORE THE SUM OF THE PHOTSYNTHETIC LOSSES FOR             *
C     EACH ENTERPRISE IN TOTSYN                                     *
C     THE SUM OF THE SQUARED OBSERVATIONS OF PHOTOSYNTHETIC         *
C     LOSSES IS STORED IN STOTSYN                                   *
C     THESE ARE THEN USED TO CALCULATE THE AVERAGE AND STANDARD     *
C     DEVIATION OF PHOTOSYSNTHETIC LOSS                             *
C****************************************************************
```

```
C
      TOTSYN=TOTSYN+PHOTO
      STOTSYN=STOTSYN+(PHOTO**2)
C
C****************************************
C     CALCULATE THE COST PER ENTERPRISE.     *
C     COSTE IS ADDED TO EACH CYCLE AND STORES*
C     THE TOTAL OF YIELD COSTS. COSTL STORES *
C     THE ONCE THROUGH DOWN GRADING COSTS.   *
C     SINCE THERE IS NO STOCHASTICITY IN     *
C     THE DOWNGRADING ROUTINE IT IS THE ONCE *
C     THROUGH COST MULTIPLIED BY THE NUMBER  *
C     OF CYCLES.                             *
C****************************************
C
      COSTE=(PRICEPU-VARCPU)*PHOTO+COSTE
      SCOSTE=((PRICEPU-VARCPU)*PHOTO+COSTL)**2+SCOSTE
C
 280  CONTINUE
C
C************************************************
C     THIS PART IS TO BE OUTSIDE THE ENTERPRISE LOOP   *
C                                                      *
C     CALCULATION OF STD DEVIATION OF PHOTOSYNTHETIC   *
C     LOSS FOLLOWS                                     *
C************************************************
C
      TMEANC=COSTE+COSTL*NUM !TOTAL COST FOR EACH
C                               REPLICATION********
      IF(NUM.EQ.1)GO TO 285
      AVEPS=TOTSYN/(NUM*1.0) !TOTAL MEAN PHOTOSYN. LOSS*******
      SAVEPS=-NUM*AVEPS**2
      STDPS=SQRT((1./(NUM-1.))*(STOTSYN+SAVEPS))
 285  CONTINUE
C
      ACOSTE=TMEANC/(NUM*1.0)  !AVERAGE COST PER ENTERPRISE****
      IF(NUM.EQ.1)GO TO 286
C
C************************************************
C     CALCULATION OF SD OF COST PER ENTERPRISE        *
C************************************************
C
      SACOSTE=-NUM*ACOSTE**2
      STDCOST=SQRT((1./(NUM-1.))*(SCOSTE+SACOSTE))
 286  CONTINUE
C
C*************************************************************************
C                                                                        *
C       END OF MAIN SIMULATION LOOP                                      *
C       *************************                                        *
C       THE TOTAL COST AND IT'S STANDARD DEVIATION FOR                   *
C       ALL THE ENTERPRISES BEING EVALUATED IS OF MAJOR IMPORTANCE.      *
C       THE MEAN TOTAL COST IS MERELY THE SUM OF THE ENTERPRISE MEAN COSTS.  *
C       THE SAMPLE POPULATION CAN BE ASSUMED TO BE NORMAL DUE TO THE     *
C       SAMPLE SIZE. IN ADDITION THE SIMULATION FOR EACH ENTERPRISE      *
C       IS BEING DRIVEN WITH THE SAME SIZE SAMPLE POPULATION.            *
C       THE POOLED STANDARD DEVIATION IS THEN :                          *
C                                                                        *
C             SUM OVER i OF(SUM OF SQUARES FROM ENTERPRISE i)            *
C         -----------------------------------------------------          *
C          DEGREES OF FREEDOM FROM ONE SAMPLE * NUMBER OF SAMPLES        *
C                                                                        *
C       KKKOUNT KEEPS TRACK OF THE NUMBER OF ENTERPRISES BEING           *
C       EVALUATED                                                        *
C*************************************************************************
C
       KKKOUNT=KKKOUNT+1
C
C**********************************************
C      OUTPUT THE RELEVANT VARIABLES FOR EACH ANALYSIS*
C**********************************************
C
```

```
      IF((KKKOUNT/2.0).NE.INT(KKKOUNT/2.0))THEN
        WRITE(18,290)
 290    FORMAT('1'//1X,10X,'ENTERPRISE ANALYSIS')
        WRITE(18,300)
 300    FORMAT('+',1X,9X,'__________ _________')
      ELSE
        WRITE(18,310)
 310    FORMAT(///1X,10X,'ENTERPRISE ANALYSIS')
        WRITE(18,300)
      ENDIF
      WRITE(18,320)NKOUNT,ENTERP
 320  FORMAT(//1X,'NO.',I2//1X,5X,'ENTERPRISE TYPE '35(' '),':'
     1       ,A30)
C
C*****************************************************************
C     PRINT THE SIDE OF THE ROAD PREVAILING DOWNWIND OR OTHERWISE*
C*****************************************************************
C
      IF(SWITCH.EQ.'YES')THEN
        WRITE(18,330)
 330    FORMAT(/1X,5X,'SIDE OF ROAD    ',35(' '),':    UPWIND')
      ELSE
        WRITE(18,340)
 340    FORMAT(/1X,5X,'SIDE OF ROAD    ',35(' '),':    DOWNWIND')
      ENDIF
      WRITE(18,350)RFRONT
 350  FORMAT(/1X,5X,'ROAD FRONTAGE (M)',34(' '),':', F6.0)
C
C****************************************************************
C                                                               *
C     IF THE ENTERPRISE IS LIVESTOCK PRODUCTION THEN ALTER      *
C     THE OUTPUT ACCORDINGLY                                    *
C****************************************************************
C
      IF(ENTT.EQ.'YES')THEN
        IF(HILO.EQ.'HI')THEN
          WRITE(18,360)RED
 360      FORMAT(//1X,5X,'COSTS ESTIMATED AT THE HIGHER LEVEL',
     1          ' OF                :',F6.3)
        ELSE
          WRITE(18,370)RED
 370      FORMAT(//1X,5X,'COSTS ESTIMATED AT THE LOWER LEVEL',
     1          ' OF                 :',F6.3)
        ENDIF
        WRITE(18,380)COSTM
 380    FORMAT(//1X,5X,'TOTAL ENTERPRISE COST IS($) ',23(' '),':',F8.2)
      ENDIF
      IF(ENTT.EQ.'YES')GO TO 580
C
C****************************************************************
C     DECIDE WHETHER PROTECTED BY SHELTERBELTS                  *
C****************************************************************
C

      IF(FLICK.EQ.'YES')THEN
        WRITE(18,390)
 390    FORMAT(/1X,5X,'PROTECTED BY SHELTER BELTS',
     1              18(' '),'       :   YES')
      ELSE
        WRITE(18,400)
 400    FORMAT(/1X,5X,'PROTECTED BY SHELTER BELTS',
     1              18(' '),'       :    NO')
      ENDIF
      WRITE(18,410)YPHEC
 410  FORMAT(/1X,5X,'YIELD PER HECTARE(T) ',30(' '),':',F8.0)
      WRITE(18,420)PRICEPU
 420  FORMAT(/1X,5X,'WEIGHTED AVERAGE PRICE($/T)',24(' '),':',F8.0)
      WRITE(18,430)EXP
 430  FORMAT(/1X,5X,'PREMIUM GRADE PRICE($/T)   ',24(' '),':',F8.0)
      WRITE(18,440)PROSP
 440  FORMAT(/1X,5X,'LOW GRADE PRICE($/T)       ',24(' '),':',F8.0)
      WRITE(18,450)VARCPU
```

```
 450   FORMAT(//1X,5X,'WEIGHTED AVERAGE COSTS THAT VARY ',
     1         'WITH YIELD ($/T)  :',F8.1)
       WRITE(18,451)CTOP
 451   FORMAT(/1X,5X,'COSTS THAT VARY WITH YIELD ',
     1         'FOR PREMIUM GRADE ($/T) :',F8.1)
       WRITE(18,452)CLOW
 452   FORMAT(/1X,5X,'COSTS THAT VARY WITH YIELD ',
     1         'FOR LOW GRADE ($/T)     :',F8.1)
C
C*********************************************
C      SET UP FOR OUTPUTTING ENTERPRISE COST DATA  *
C*********************************************
C
       WRITE(18,460)
 460   FORMAT(1X///1X,5X,5X,'COSTS OF DUST EFFECT :')
       WRITE(18,470)
 470   FORMAT('+',1X,4X,5X,'_____ __ ____ ______')
       WRITE(18,480)
 480   FORMAT(/1X,5X,21X,1X,6X,'MEAN % LOSS',5X,'MEAN TOTAL COST')
C
C*****************************************
C      OUPUT THE PHOTOSYSNTHETIC YIELD LOSSES  *
C*****************************************
C
       WRITE(18,490)(PHOTO1/(NUM*1.0)),(COSTE/(NUM*1.0))
 490   FORMAT(/1X,5X,'PHOTOSYNTHETIC YIELD LOSSES',1X,F8.2,5X,7X,F8.2)
       WRITE(18,500)
 500   FORMAT(///1X,5X,'OTHER ESTIMATES OF COST',5X,'ESTIMATED ',
     1        'LEVEL OF % LOSS'/1X,5X,23X,5X,3X,'(HI/LO/NIL)')
C
C****************************************************
C      SET UP TO OUTPUT THE VARIBLES AFFECTING YIELD WHICH*
C      WERE ORIGINALLY INPUTTED MANUALLY                  *
C****************************************************
C
       CHAR1='NIL'
       CHAR2='LOW'
       CHAR3='HIGH'
 510     FORMAT(/1X,5X,'PESTS AND DISEASE',/1X,5X,10X,
     1          '- YIELD ?                  ',A4)
 520     FORMAT(/1X,5X,10X,
     1          '- DOWNGRADING ?            ',A4)
       IF(YON(2).EQ.'YES')THEN
          IF(LOOHI(1).EQ.'YES')THEN
            WRITE(18,510)CHAR3
          ELSE
            WRITE(18,510)CHAR2
          ENDIF
       ELSE
          WRITE(18,510)CHAR1
       ENDIF
       IF(YON(3).EQ.'YES')THEN
          IF(LOOHI(2).EQ.'YES')THEN
            WRITE(18,520)CHAR3
          ELSE
            WRITE(18,520)CHAR2
          ENDIF
       ELSE
          WRITE(18,520)CHAR1
       ENDIF
C
 530     FORMAT(/1X,5X,'REDUCED POLLINATION',/1X,5X,10X,
     1          '- YIELD ?                  ',A4)
 540     FORMAT(/1X,5X,10X,
     1          '- DOWNGRADING ?            ',A4)
        IF(YON(5).EQ.'YES')THEN
          IF(LOOHI(3).EQ.'YES')THEN
            WRITE(18,530)CHAR3
          ELSE
            WRITE(18,530)CHAR2
          ENDIF
        ELSE
```

```
          WRITE(18,530)CHAR1
         ENDIF
         IF(YON(6).EQ.'YES')THEN
           IF(LOOHI(4).EQ.'YES')THEN
             WRITE(18,540)CHAR3
           ELSE
             WRITE(18,540)CHAR2
           ENDIF
         ELSE
           WRITE(18,540)CHAR1
         ENDIF
C
        IF(YON(7).EQ.'NO')THEN
          WRITE(18,550)CHAR1
 550      FORMAT(/1X,5X,'DOWNGRADING FROM DUSTY FRUIT ?',
     1            '     ',A4)
        ELSE
          IF(LOOHI(5).EQ.'YES')THEN
            WRITE(18,550)CHAR3
          ELSE
            WRITE(18,550)CHAR2
          ENDIF
        ENDIF
C
        IF(YON(8).EQ.'NO')THEN
          WRITE(18,560)CHAR1
 560      FORMAT(/1X,5X,'EXTRA WEED YIELD EFFECT ?',
     1            '                ',A4)
        ELSE
          IF(LOOHI(6).EQ.'YES')THEN
            WRITE(18,560)CHAR3
          ELSE
            WRITE(18,560)CHAR2
          ENDIF
        ENDIF
        WRITE(18,570)ACOSTE,STDCOST
 570    FORMAT(///1X,5X,'ENTERPRISE TOTAL MEAN COST',26(' '),':',F8.2/
     1              1X,5X,'STANDARD DEVIATION OF COST',26(' '),':',F8.2)
 580    CONTINUE
C
C***************************************************************
C       RATHER THAN KEEPING A RUNNING TOTAL OF THE SUM OF SQUARES,*
C       BECAUSE OF THE SAME SAMPLE SIZES ,IT IS ONLY NECESSARY TO *
C       KEEP TOTALLING THE VARIANCES BETWEEN ENTERPRISES          *
C***************************************************************
C
        TOTSSSC=TOTSSSC+STDCOST**2
C
C****************************************************
C       KEEPING A RUNNING TOTAL OF THE TOTAL MEAN COSTS*
C****************************************************
C
        SUMCOS=SUMCOS+ACOSTE
        TYPE *,'ARE THERE MORE ENTERPRISE EVALUATIONS REQUIRED',
     1        '(YES/NO)'
        ACCEPT '(A3)',FLAG
        CALL UPPERCASE (FLAG,3)
        IF(FLAG.EQ.'YES')GO TO 170
C
C***********************************************************
C       CALCULATE THE POOLED VARIANCE OF TOTAL COSTS        *
C       KKKOUNT =THE DENOMINATOR                            *
C       TOTSSSC=NUMERATOR                                   *
C***********************************************************
C
        TOTSS=SQRT(TOTSSSC/KKKOUNT) !POOLED VARIANCE********
C
C*********************************************************
C       CALCULATE THE PRESENT VALUE OF ROAD DUST ASSUMING A *
C       HORIZON OF 15 YEARS AND AN DISCOUNT RATE OF 10%     *
C*********************************************************
C
```

```
      PVV=(SUMCOS*((1.1**15)-1))/(.1*(1.1**15))
C
C*************************************************************
C     NOW OUTPUT THE MEAN TOTAL COST, ITS STANDARD DEVIATION  *
C     AND THE PRESENT VALUE COST                             *
C*************************************************************
C
      WRITE(18,585)
  585 FORMAT('1',//10X,'SUMMARY OF DUST COSTS')
      WRITE(18,586)
  586 FORMAT('+',1X,8X,'_______ __ ____ _____')
      WRITE(18,590)KKKOUNT,SUMCOS,TOTSS,PVV
  590 FORMAT(///1X,14X,'NUMBER OF ENTERPRISES IS  : ',I6,
     1       //1X,14X,'THE MEAN TOTAL COST IS    : ',F10.3,
     2       //1X,14X,'THE STD. OF TOTAL COST IS :',F10.3,
     3       //1X,14X,'THE PRESENT VALUE OF COST :',F10.3)
      CLOSE(UNIT=5)
      CLOSE(UNIT=18)
      CLOSE(UNIT=21)
      STOP
      END
```

```
C
C                           TABLE V.2
C
C              Program Listing of Subroutine RAIN.FOR
C              ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
C
C*************************************************************
C     THIS SUBROUTINE READS RAINFALL RECORDS FROM A FILE CALLED *
C     RAIN.DAT AND THEN CALCULATES THE PROBABILITY OF THE       *
C     NUMBER OF ACCUMULATED DAYS DUST DEPOSITION PRESENT ON     *
C     PLANT SURFACES FOR ANY GIVEN DAY.                         *
C*************************************************************
C
      SUBROUTINE RAIN(PROBS,PROBW)
C
C****************************************************************
C     PROBS AND PROBW ARE THE PROBABILITY DISTRIBUTIONS FOR        *
C     SUMMER AND WINTER                                            *
C****************************************************************
C
      INTEGER JAN(10,31),FEB(10,31),MARCH(10,31),APRIL(10,31)
      INTEGER MAY(10,31),JUNE(10,31),JULY(10,31),AUGUST(10,31)
      INTEGER SEPT(10,31),OCT(10,31),NOV(10,31),DEC(10,31)
      INTEGER YEARI(10),SUMMER(10,152),WINTER(10,214)
      INTEGER DUSTS(10,0:40),DUSTW(10,0:40)
      REAL ADUSTS(0:40),ADUSTW(0:40)
      REAL PROBS(0:40),PROBW(0:40)
      LOGICAL ZBOL,ZO,Z1
      DATA DUSTS/410*0/,DUSTW/410*0/
      DATA ADUSTS/41*0./,ADUSTW/41*0./
C
C*******************************
C     INITIALISE PROBS AND PROBW   *
C*******************************
C
      DO IK=0,40
       PROBS(IK)=0.
       PROBW(IK)=0.
      ENDDO
C
C******************************************
C     READ DATA FOR EACH YEAR INTO MONTH ARRAYS*
C******************************************
C
      DO I=1,10
       READ(5,90)YEARI(I)
       DO J=1,31
        READ(5,100)JAN(I,J),FEB(I,J),MARCH(I,J),APRIL(I,J),
     1             MAY(I,J),JUNE(I,J),JULY(I,J),AUGUST(I,J),
     2             SEPT(I,J),OCT(I,J),NOV(I,J),DEC(I,J)
       ENDDO
      ENDDO
   90 FORMAT(16X,I4)
  100 FORMAT(I4,11(2X,I4))
C
C*************************************************************
C     NOW REWIND THE FILE TO ENABLE REREADING OF THE DATA INTO  *
C     ARRAYS CLASSIFYING SUMMER AND WINTER. THE READS COULD HAVE*
C     BEEN DONE AT THE SAME TIME, HOWEVER PROBLEMS INVOLVING    *
C     LEAP YEARS WOULD HAVE BEEN INTRODUCED. I TOOK THE FORMER  *
C     APPROACH ON THE GROUNDS OF SIMPLICITY AND READABILITY     *
C*************************************************************
C
      REWIND 5
C
C*************************************************************
C     ZBOL IS A LOGICAL USED HERE TO SIGNAL WHETHER THE YEAR IS*
C     A LEAP YEAR OR NOT.                                      *
C*************************************************************
C
```

```
       ZBOL=.TRUE.
        READ(5,90)YEARI(I)
        IF(YEARI(I)/4..EQ.INT(YEARI(I)/4.0))THEN
         ZBOL=.FALSE.
        ENDIF
         IF(ZBOL)THEN
          DO  J=1,28
           READ(5,100)SUMMER(I,J),SUMMER(I,J+31),
     1                SUMMER(I,J+59),
     1                WINTER(I,J),
     2                WINTER(I,J+30),WINTER(I,J+61),
     3                WINTER(I,J+91),WINTER(I,J+122),
     4                WINTER(I,J+153),WINTER(I,J+183),
     5                SUMMER(I,J+90),
     2                SUMMER(I,J+120)
          ENDDO
         DO  J=29,30
           READ(5,1001)SUMMER(I,J),SUMMER(I,J+59),
     1                WINTER(I,J),
     2                WINTER(I,J+30),WINTER(I,J+61),
     3                WINTER(I,J+91),WINTER(I,J+122),
     4                WINTER(I,J+153),WINTER(I,J+183),
     1                SUMMER(I,J+90),SUMMER(I,J+120)
         ENDDO
 1001     FORMAT(I4,2X,4X,10(2X,I4))
         READ(5,1002)SUMMER(I,31),SUMMER(I,90),
     1              WINTER(I,61),WINTER(I,122),WINTER(I,152),
     2              WINTER(I,214),SUMMER(I,151)
 1002     FORMAT(I4,2X,4X,2X,I4,2X,4X,2X,I4,2X,4X,2X,I4,
     1           2X,I4,2X,4X,2X,I4,2X,4X,2X,I4)
        ELSE
          DO  J=1,29
           READ(5,100)SUMMER(I,J),SUMMER(I,J+31),
     1                SUMMER(I,J+60),
     1                WINTER(I,J),
     2                WINTER(I,J+30),WINTER(I,J+61),
     3                WINTER(I,J+91),WINTER(I,J+122),
     4                WINTER(I,J+153),WINTER(I,J+183),
     1                SUMMER(I,J+91),
     2                SUMMER(I,J+121)
          ENDDO
         READ(5,1001)SUMMER(I,J),SUMMER(I,J+60),
     1                WINTER(I,J),
     2                WINTER(I,J+30),WINTER(I,J+61),
     3                WINTER(I,J+91),WINTER(I,J+122),
     4                WINTER(I,J+153),WINTER(I,J+183),
     1                SUMMER(I,J+91),SUMMER(I,J+121)
         READ(5,1002)SUMMER(I,31),SUMMER(I,90),
     1              WINTER(I,61),WINTER(I,122),WINTER(I,152),
     2              WINTER(I,214),SUMMER(I,151)
        ENDIF
      ENDDO
C
C***************************************************************
C      CHECK FOR DUSTY DAYS FOR BOTH SUMMER AND WINTER         *
C      DUSTY DAY IN SUMMER IS WHEN THE FIRST DAY WITH LESS     *
C                          THAN 4MM FOLLOWING ADAY WITH LESS   *
C                          THAN 4MM.                           *
C      DUSTY DAY IN WINTER IS THE FIRST DAY WITH LESS THAN     *
C                          4MM FOLLOWING TWO CONSECUTIVE       *
C                          DAYS WITH LESS THAN 4MM             *
C***************************************************************
      DO I=1,10
       K11=151
C
C****************************
C      CHECK FOR LEAP YEARS *
C****************************
       IF(YEARI(I)/4..EQ.INT(YEARI(I)/4.))THEN
        K11=152
       ENDIF
```

```
C*********************************************************************
C       ZO AND Z1 ARE LOGICALS AND ARE USED SHOW SIMPLY WHETHER        *
C       THE LAST 1 OR 2 DAYS HAVE BEEN DRY.                            *
C       N.B. THEY ARE SET OUTSIDE BOTH THE YEAR AND THE SUMMER/WINTER *
C            LOOP. THIS IS IN ORDER TO CAPTURE THE EFFECT OF GOING     *
C            FROM SUMMER/WINTER TO WINTER/SUMMER AND FROM YEAR TO YEAR*
C*********************************************************************
C
       ZO=.FALSE.
       Z1=.FALSE.
        DO J=1,K11
C
C***********************
C        FIRST FOR SUMMER *
C***********************
C
         IF(SUMMER(I,J).GE.40)THEN
          DUSTS(I,O)=DUSTS(I,O)+1
          ZO=.TRUE.
          KOUNT1=1
          Z1=.FALSE.
         ELSE
          IF(ZO)THEN
           DUSTS(I,O)=DUSTS(I,O)+1
           ZO=.FALSE.
          ELSE
           IF(Z1)THEN
            KOUNT1=KOUNT1+1
            DUSTS(I,KOUNT1)=DUSTS(I,KOUNT1)+1
            Z1=.TRUE.
           ELSE
            DUSTS(I,1)=DUSTS(I,1)+1
            Z1=.TRUE.
           ENDIF
          ENDIF
         ENDIF
      ENDDO
C
C******************************************************************
C      SECONDLY FOR WINTER (NOTE LOGICALS HOLD VALUES FROM SUMMER  *
C                          IN ORDER TO CAPTURE EFFECT OF OF MOVING*
C                          BETWEEN SEASONS)                        *
C******************************************************************
C
        DO J=1,214
         IF(WINTER(I,J).GE.40)THEN
          KOUNT=O
          DUSTW(I,O)=DUSTW(I,O)+1
          ZO=.TRUE.
          KOUNT1=1
          Z1=.FALSE.
         ELSE
          IF(ZO)THEN
           DUSTW(I,O)=DUSTW(I,O)+1
           KOUNT=KOUNT+1
           IF(KOUNT.EQ.2)THEN
            ZO=.FALSE.
           ENDIF
          ELSE
           IF(Z1)THEN
            KOUNT1=KOUNT1+1
            DUSTW(I,KOUNT1)=DUSTW(I,KOUNT1)+1
            Z1=.TRUE.
           ELSE
            DUSTW(I,1)=DUSTW(I,1)+1
            Z1=.TRUE.
           ENDIF
          ENDIF
         ENDIF
       ENDDO
       ENDDO
```

```
C*************************************************************
C      NOW FIND THE AVERAGE FREQUENCIES FOR THE TEN YEARS  *
C*************************************************************
C
      TEMP2=0.0
      TEMP3=0.0
      DO J=0,40
       TEMP=0.0
       TEMP1=0.0
       DO I=1,10
        TEMP=DUSTS(I,J)+TEMP
        TEMP1=DUSTW(I,J)+TEMP1
       ENDDO
       ADUSTS(J)=TEMP/10.0
       ADUSTW(J)=TEMP1/10.0
       TEMP2=TEMP2+ADUSTS(J)
       TEMP3=TEMP3+ADUSTW(J)
      ENDDO
C
C**************************************************************************
C      NOW ADUSTS AND ADUSTW CONTAIN THE AVERAGE FREQUENCIES OF DUSTY*
C      DAYS FOR SUMMER AND WINTER.TEMP2 AND TEMP3 CONTAIN THE TOTAL  *
C      AVERAGE FREQUENCIES FOR EACH.THIS INFORMATION IS THEN USED TO *
C      CALCULATE THE PROBABILITIES OF DUSTY DAYS GIVEN SUMMER OR     *
C      WINTER                                                         *
C**************************************************************************
C
      DO I=0,40
       PROBS(I)=ADUSTS(I)/TEMP2
       PROBW(I)=ADUSTW(I)/TEMP3
      ENDDO
      RETURN
      END
```

```
C
C                        TABLE V.3
C
C             Program Listing of Subroutine DD.FOR
C             ------------------------------------
C
C*************************************************************
C       SUBROUTINE TO CALCULATE ROAD DUST DEPOSITION DENSITY ON *
C       PLANT SURFACES FOR EACH METRE AWAY FROM AN UNSEALED ROAD*
C       ON THE PREVAILING DOWNWIND SIDE.                        *
C*************************************************************
C
      SUBROUTINE DD (IX,DENS,LOS,AVS,HIS,LOT,AVT,
     1                   HIT,SI,PROD,DIST,SWITCH,FLICK)
c
      CHARACTER FLICK * 3,SWITCH * 3
      REAL DPA(200),DENS(200),LAI,IDIST
      REAL LOS,AVS,HIS,LOT,AVT,HIT,DT,KM,SI
      INTEGER PROD,DIST
C*********************************************
C       ENSURE THAT DENS AND DPA MATRICES ARE ZEROED *
C       BETWEEN RUNS                                 *
C*********************************************
C
      DO IK=1,200
       DPA(IK)=0.
       DENS(IK)=0.
      ENDDO
C
C**************************************************************
C       CALL TRIANGULAR DISTRIBUTION TO CALCULATE THE               *
C       ESTIMATES FOR ROAD SPEED (KM) AND DAILY TRAFFIC KOUNTS (DT)*
C**************************************************************
C
      CALL TRIANG(IX,LOS,AVS,HIS,KM)
      CALL TRIANG(IX,LOT,AVT,HIT,DT)
      CALL TRIANG (IX,0.20,0.35,0.70,LAI)    !Variables speculative
      CALL TRIANG (IX,0.20,0.40,0.70,SHELT)  !Variables speculative
      CALL TRIANG (IX,0.05,0.15,0.50, REDN)  !Variables speculative
C
      EMIS=0.0038*(KM**2)*SI*DT
C
C***************************************************************
C         A PROD OF 0 IS UNREASONABLE .HOWEVER TO ENSURE THAT       *
C         A PROD OF 0,IF INPUTTED DOES NOT HINDER PROGRAM OPERATION *
C***************************************************************
C
      IF(PROD.EQ.0)PROD=1
C
C**************************************************************
C       FIND THE TOTAL QUANTITY OF DUST DEPOSITED UP TO 550 METRES *
C**************************************************************
C
      QUAN=5299.38*((550**.191)-(0.1**.191))
      QLOW=5299.38*((PROD-1)**.191)
      TQUAN=QUAN+((-891.533/.042)*(1./(550**.042)-1./(.1**.042)))
C
      TSUM=0.
      DO IDIST=PROD,DIST
C
C*************************************
C       DEPOSITION DENSITY ON THE GROUND  *
C*************************************
C
         IF(IDIST.EQ.1)THEN
          DPA(IDIST)=EMIS*(5299.38*(IDIST**.191)-QLOW)/TQUAN
          TSUM=TSUM+DPA(IDIST)
         ELSE
          DPA(IDIST)=(EMIS*(5299.38*(IDIST**.191)-QLOW)/TQUAN)-TSUM
          TSUM=TSUM+DPA(IDIST)
                    ENDIF
```

```
C
C*********************************************************************
C       CONVERT TO DENSITY FOR ON PLANT SURFACES;OBVIOUSLY NOT ALL DUST*
C       LANDS ON,OR IS INTERCEPTED BY PLANTS.                         *
C         -ALLOW FOR UNCERTAINTY OF QUANTITY OF DUST INTERCEPTED BY   *
C       PLANTS(LAI=PERCENTAGE REDUCTION OF DUST DENSITY ON PLANT      *
C       SURFACES COMPARED TO GROUND DENSITY).                         *
C*********************************************************************
C
          DENS(IDIST)=DPA(IDIST)*(1-LAI)
        ENDDO
C
C***************************************************
C       ALLOW FOR EFFECT OF SMOOTH LEAF SURFACES    *
C***************************************************
C
       IF (SWITCH.EQ.'YES') THEN
         DO IDIST=PROD,DIST
             DENS(IDIST)=DENS(IDIST)*(1-REDN)
         ENDDO
       END IF
C
C*******************************************************************
C       ALLOW FOR THE SCREENING EFFECTS OF SHELTERBELTS IF PRESENT    *
C*******************************************************************
C
        IF (FLICK.EQ.'YES') THEN
         DO IDIST=PROD,DIST
            DENS(IDIST)=DENS(IDIST)*(1-SHELT)
          ENDDO
        END IF
C
C******************************************************
C       ENSURE THAT DUST DEPOSITED IS NOT LESS THAN ZERO *
C******************************************************
C
        SUM=0.
        DO IK=PROD,DIST
           IF(DENS(IK).LT.O.)THEN
              DENS(IK)=O.
           ENDIF
           SUM=SUM+DENS(IK)
        ENDDO
        AVE=SUM/(DIST-PROD)
        RETURN
        END
```

```
C
C                               TABLE V.4
C
C                Program Listing of Subroutine UD.FOR
C                ------------------------------------
C
C*******************************************************************
C       SUBROUTINE TO CALCULATE ROAD DUST DEPOSITION DENSITY ON *
C       PLANT SURFACES FOR EACH METRE AWAY FROM AN UNSEALED ROAD*
C       ON THE PREVAILING UPWIND SIDE.                          *
C*******************************************************************
C
        SUBROUTINE UD (IX,DENS,LOS,AVS,HIS,LOT,AVT,
     1                 HIT,SI,PROD,DIST,SWITCH,FLICK)
C
        CHARACTER FLICK * 3,SWITCH * 3
        REAL DPA(60),DENS(60),LAI,IDIST
        REAL LOS,AVS,HIS,LOT,AVT,HIT,DT,KM,SI
        INTEGER PROD,DIST
C***********************************************************
C       ENSURE THAT DENS AND DPA MATRICES ARE ZEROED *
C       BETWEEN RUNS                                 *
C***********************************************************
C
        DO IK=1,60
         DPA(IK)=0.
         DENS(IK)=0.
        ENDDO
C
C*********************************************************************
C       CALL TRIANGULAR DISTRIBUTION TO CALCULATE THE              *
C       ESTIMATES FOR ROAD SPEED (KM) AND DAILY TRAFFIC KOUNTS (DT)*
C*********************************************************************
C
        CALL TRIANG(IX,LOS,AVS,HIS,KM)
        CALL TRIANG(IX,LOT,AVT,HIT,DT)
        CALL TRIANG (IX,0.20,0.35,0.70,LAI)    !Variables speculative
        CALL TRIANG (IX,0.05,0.15,0.5,REDN) !Variables speculative
        CALL TRIANG (IX,0.20,0.40,0.70,SHELT) !Variables speculative
C
        EMIS=0.0038*(KM**2)*SI*DT
C
C**********************************************************************
C          A PROD OF O IS UNREASONABLE .HOWEVER TO ENSURE THAT        *
C          A PROD OF O,IF INPUTTED DOES NOT HINDER PROGRAM OPERATION *
C**********************************************************************
C

        IF(PROD.EQ.0)PROD=1
C
        QUAN=(-891.533/.042)*(1./(550**.042)-1./(0.1**.042))
        QLOW=(-891.533/.042)*(1./((PROD-1)**.042))
        TQUAN=QUAN+(5299.38*((550**.191)-(.1**.191)))
        TSUM=0.
        DO IDIST=PROD,DIST
C
C*******************************************
C       DEPOSITION DENSITY ON THE GROUND  *
C*******************************************
C
          IF(IDIST.EQ.1)THEN
           DPA(IDIST)=EMIS*((-891.533/.042)*(1./(IDIST**.042))-QLOW)
     1                /TQUAN
           TSUM=TSUM+DPA(IDIST)
          ELSE
           DPA(IDIST)=(EMIS*((-891.533/.042)*(1./(IDIST**.042))-QLOW)
     1                /TQUAN)-TSUM
           TSUM=TSUM+DPA(IDIST)
          ENDIF
C
C*************************************************************************
```

```
C       CONVERT TO DENSITY FOR ON PLANT SURFACES;OBVIOUSLY NOT ALL DUST*
C       LANDS ON,OR IS INTERCEPTED BY PLANTS.                           *
C         -ALLOW FOR UNCERTAINTY OF QUANTITY OF DUST INTERCEPTED BY     *
C       PLANTS(LAI=PERCENTAGE REDUCTION OF DUST DENSITY ON PLANT        *
C       SURFACES COMPARED TO GROUND DENSITY).                           *
C************************************************************************
C

          DENS(IDIST)=DPA(IDIST)*(1-LAI)
        ENDDO
C
C***********************************************
C       ALLOW FOR EFFECT OF SMOOTH LEAF SURFACES    *
C***********************************************
C
       IF (SWITCH.EQ.'YES') THEN
         DO IDIST=PROD,DIST
             DENS(IDIST)=DENS(IDIST)*(1-REDN)
         ENDDO
       END IF
C
C************************************************************************
C       ALLOW FOR THE SCREENING EFFECTS OF SHELTERBELTS IF PRESENT     *
C************************************************************************
C
        IF (FLICK.EQ.'YES') THEN
         DO IDIST=PROD,DIST
            DENS(IDIST)=DENS(IDIST)*(1-SHELT)
          ENDDO
        END IF
C
C***************************************************
C       ENSURE THAT DUST DEPOSITED IS NOT LESS THAN ZERO *
C***************************************************
C
        SUM=0.
        DO IK=PROD,DIST
           IF(DENS(IK).LT.0.)THEN
              DENS(IK)=0.
           ENDIF
           SUM=SUM+DENS(IK)
        ENDDO
        AVE=SUM/(DIST-PROD)
        RETURN
        END
```

```
C                             TABLE V.5
C
C               Program Listing of Subroutine YIELD.FOR
C               ------------------------------------------
C
C*************************************************************************
C     SUBROUTINE TO CALCULATE THE PERCENTAGE YIELD LOSSES TO HORTICULTURAL*
C     CROPS FROM ROAD DUST INDUCED PHOTOSYNTHESIS REDUCTION.              *
C*************************************************************************
C
      SUBROUTINE YIELD (IX,AFLAG,PROBD,DENS,PROD,IDIST,
     1                  PHOTO,PHOTO2,YPHEC,RFRONT)
C
C*****************************************************************
C     PROBD=PROBABILITY DISTRIBUTION FOR EITHER WINTER OR SUMMER *
C           DEPENDING ON WHICH DISTRIBUTION IS FED IN FROM THE   *
C           MAIN ROUTINE                                         *
C*****************************************************************
C
      REAL PROBD(0:40),DENS(500),ACCUMD(500)
      REAL PHOTO,URN,PHOTO1
      INTEGER IX,DDAY,IDIST,PROD
      LOGICAL AFLAG
C
C*****************************************************
C     ZERO THE ACCUMULATED DUST DEPOSITION ARRAY  *
C*****************************************************
C
      DO IK=1,500  !EACH ARRAY POSITION=1 METRE************
       ACCUMD(IK)=0.
      ENDDO
      URN=RAN(IX)
C
      TEMP=0.
      DO IK=0,40
        TEMP=TEMP+PROBD(IK)
        IF(URN.LE.TEMP)THEN
           DDAY=IK      !NO OF DAYS ACCUMULATED DUST***********
           GO TO 100
         ENDIF
      ENDDO
C
C**********************************************************************
C     NOW USE THE NUMBER OF DAYS OF ACCUMULATED DUST TO CALCULATE THE *
C     PHOTO SYSNTHETIC LOSS                                           *
C**********************************************************************
C
 100  DO IK=PROD,IDIST
       ACCUMD(IK)=DENS(IK)*DDAY
      ENDDO
C
C*************************************************************************
C     SUM INTO PHOTO THE TOTAL PHOTOSYSNTHETIC LOSS AND MULTIPLY         *
C     BY THE ROAD FRONTAGE FOR EACH ENTERPRISE TO GET TOTAL YIELD        *
C     LOSS PER ENTERPRISE.                                               *
C     IN ORDER TO CONVERT  TO PERCENTAGE MULTIPLY BY .01                 *
C                                                                        *
C     ON EXIT FROM THE ROUTINE PHOTO WILL CONTAIN TOTAL YIELD LOSS       *
C     PER ENTERPRISE.                                                    *
C                                                                        *
C     PHOTO1 WILL CONTAIN TOTAL % YIELD LOSS                             *
C*************************************************************************
C
      PHOTO1=0.
      PHOTO=0.
      DO IK=PROD,IDIST
        IF(ACCUMD(IK).LE.1E-11)GO TO 200
C
C**********************************************************************
C      NB THE TOLERANCE OF 1E-11 IS MACHINE DEPENDENT!!!!!!!!         *
C**********************************************************************
```

```
C
       IF(AFLAG.EQ..TRUE.)THEN
         PHOTO=PHOTO+((0.225*ACCUMD(IK)**0.878)*(YPHEC/10000.))*.01
         PHOTO1=PHOTO1+(0.225*ACCUMD(IK)**0.878)
           ELSE
         PHOTO=PHOTO+((1.421*ACCUMD(IK)**.733)*(YPHEC/10000.))*.01
         PHOTO1=PHOTO1+(1.421*ACCUMD(IK)**.733)
       ENDIF
      ENDDO
 200  PHOTO=PHOTO*RFRONT
      PHOTO2=PHOTO1/(IDIST*PROD)+PHOTO2
 210  RETURN
      END
```

```
C
C                          TABLE V.6
C
C             Program Listing of Subroutine TRIANG.FOR
C             ----------------------------------------
C
C*****************************************************************
C       SUBROUTINE TO CALCULATE THE TRIANGULAR DISTRIBUTION     *
C*****************************************************************
C
        SUBROUTINE TRIANG (IX,LO,AV,HI,OUT)
        REAL LO
        URN=RAN(IX)
        IF(URN.GT.(AV-LO)/(HI-LO))THEN
          OUT=HI-SQRT((1.-URN)*(HI-LO)*(HI-AV))
        ELSE
          OUT=LO+SQRT(URN*(HI-LO)*(AV-LO))
        END IF
        RETURN
        END
```

```
C
C                              TABLE V.7
C
C                Program Listing of Subroutine DOWNG.FOR
C                ***************************************
C
C*******************************************************************
C     SUBROUTINE TO TAKE ACCOUNT OF THE YIELD DUE TO              *
C     DOWNGRADES AND THE MARKETABILITY EFFECT                     *
C*******************************************************************
C
      SUBROUTINE DOWNG(SWITCHY,IDIST,IIDIST,PROD,PRICEPU,VARC,
     1                 COSTL,PERLOSS,PERLOSS1,YON1,LOOHI,
     1                 PTOP,PLOW,YPHEC,RFRONT,CTOP,CLOW)
C
C*******************************************************************
C     UH IS SET FOR EITHER LOW OR HIGH ESTIMATE FROM MAIN ROUTINE  *
C*******************************************************************
C
      REAL UH
      INTEGER PROD,DIST,IDIST,IIDIST
      CHARACTER YON1 * 3,LOOHI * 3,SWITCHY *3
      DIMENSION YON1(8),LOOHI(6)
C
C****************************************************************
C     USE SWITCHY TO DECIDE THE DISTANCE FROM THE ROAD BEING    *
C     EVALUATED IE EITHER THE UPWIND OR DOWNWIND SIDE           *
C****************************************************************
C
      IF(SWITCHY.EQ.'YES')THEN
       DIST=IIDIST
      ELSE
       DIST=IDIST
      ENDIF
C
      COSTL=0.  !COSTS FROM DOWNGRADING****************
C
C******************************************
C     SET UH AS =0., AND PERLOSS AS 0.    *
C******************************************
C
      UH=0.
      PERLOSS=0.
      PERLOSS1=0.
C
      JJ=1
      DO IK1=2,8
       IF(IK1.EQ.4)THEN
        JJ=2
        GO TO 400
       ENDIF
       AREA1=(RFRONT*(DIST-PROD))/10000.
        IF(YON1(IK1).EQ.'NO')GO TO 400
            IF(LOOHI(IK1-JJ).EQ.'YES')THEN
              UH=.01*AREA1
            ELSE
              UH=.005*AREA1
            ENDIF
C
C***************************************************
C     NOW NEED TO STORE % YIELD LOSSES IN PERLOSS  *
C     AND OTHER % LOSSES IN PERLOSS1               *
C***************************************************
C
      IF(IK1.EQ.2.OR.IK1.EQ.5.OR.IK1.EQ.8)THEN
        PERLOSS=PERLOSS+UH
        COSTL=UH*YPHEC*(PRICEPU-VARC)+COSTL
      ELSEIF(IK1.EQ.3.OR.IK1.EQ.6.OR.IK1.EQ.7)THEN
        PERLOSS1=PERLOSS1+UH
        COSTL=UH*YPHEC*((PTOP-PLOW)-(CTOP-CLOW))+COSTL
      ENDIF
```

```
C
C                            TABLE V.8
C
C             Program Listing of Subroutine MOOBAA.FOR
C             ----------------------------------------
C
C*****************************************************************
C      SUBROUTINE TO ESTIMATE ARBITARY COSTS TO ANIMAL          *
C      ENTERPRISES FROM ROAD DUST                               *
C*****************************************************************
C
      SUBROUTINE MOOBAA(RFRONT1,PROD1,GROSSY1,
     1                 SWITCH2,COSTM1,RED1,IDIST1,IIDIST1)
C
C****************************************************************
C      DECLARE THE VARIABLES                                    *
C        COSTM=COSTS TO ANIMAL ENTERPRISE                       *
C        GROSSY1=GROSS INCOME PER HECTARE                       *
C        AREA=AREA OF LAND AFFECTED BY ROAD DUST                *
C****************************************************************
C
      REAL COSTM1,GROSSY1,AREA
      INTEGER PROD1
      CHARACTER SWITCH2 * 3
C
      IF(SWITCH2.EQ.'YES')THEN  !UPWIND SIDE***************
        AREA=(RFRONT1*(IIDIST1-PROD1))/10000
        COSTM1=(AREA*GROSSY1)*RED1
      ELSE                      !DOWNWIND SIDE*************
        AREA=(RFRONT1*(IDIST1-PROD1))/10000
        COSTM1=(AREA*GROSSY1)*RED1
      ENDIF
      RETURN
      END
```

```
C
C                        TABLE V.9
C
C         Program Listing of Subroutine UPPERCASE.FOR
C         -------------------------------------------
C
      SUBROUTINE UPPERCASE(STRING,STRINGL)
C
C*****************************************************************
C     CONVERTS 'STRING' OF LENGTH STRINGL TO UPPERCASE VERSION *
C*****************************************************************
C
      CHARACTER*(*) STRING
      INTEGER STRINGL
      DO I=1,STRINGL
          N=ICHAR(STRING(I:I))
          IF (N.GE.97.AND.N.LE.122)N=N-32
          STRING(I:I)=CHAR(N)
      ENDDO
      RETURN
      END
```

APPENDIX VI

LIST OF VARIABLE NAMES AND DEFINITIONS USED IN THE MODEL

ACOSTE	Average costs to enterprise $4/ha).
ADUSTS ADUSTW	Arrays which store the average frequencies of dusty days for summer and winter respectively.
AFLAG	Logical assignment variable to switch routine into either summer or winter.
AREA	Total area of enterprise affected by road dust (ha).
AVE	Average level of dust deposition density for the affected area of productive land (g/m^2).
AVEPS	Average cost of photosynthesis for each enterprise ($/ha).
AVS	Average speed travelled by vehicles on road (kg/hr).
AVT	Estimate of average daily traffic count of road.
AVTT	Used to store the AVT variables as a constant.
CHAR1 CHAR2 CHAR3	Storage characters used to output the level of dust effect for 'other effects'.
CLOW	Costs that vary with yield for low grade produce ($/ha).
COSTE	Total of photosynthetic yield costs ($/ha).
COSTL	Total downgrading costs ($/ha).
COSTM COSTM1	Total costs to animal enterprises ($/ha).
CTOP	Costs that vary with yield for top grade produce ($/t).
DDAY	Number of days of accumulated dust on plant surface.
DENS	Array used in both the UD and DD subroutines to store the density of road dust deposited on plants for each metre away from the roadway (g/m^2). Feeds into DDENS and UDENS of main routine.

DDENS	An array used to store the density of road dust deposited on plants for each metre away from the roadway on the downwind side of the road (g/m^2).
DIST	Predicted distance away from the roadway of road dust effect (m).
DPA	An array used to store the total predicted level of road dust which could be deposited on bare flat land for each metre away from a roadway (g/m^2).
DT	Predicted average daily traffic count for the road.
DUSTS DUSTW	Records the frequencies of various levels of accumulated dust deposition for summer and winter respectively.
EMIS	Daily emission level of road dust (g/m).
ENTERP	Name of enterprise type.
ENTT	Logical assignment variable to switch routine into either plant or animal enterprise evaluation.
EXP	Price received for premium grade ($/t).
FLAG	Logical assignment variable to allow for further enterprise evaluations or stop.
FLICK	Logical assignment variable to detect whether an enterprise is protected by a shelterbelt or not.
GROSSY GROSSY1	Gross income received for animal enterprises ($/ha).
HILO	Logical assignment variable to detect whether a high or low level of effect is expected.
HIS	High estimate of speed of vehicles travelling on the road (km/hr).
HIT	High estimate of average daily traffic count for road.
HITT	Used to store HIT variables as a constant.
IDIST IDIST1	Distance away from roadway for which calculations are conducted on the downwind side of the road.
IIDIST IIDIST1	Distance away from the roadway for which calculations are conducted for the upwind side of the road.
KM	Predicted average vehicle speed travelled on the road (km/hr).

K11	Set equal to the number of summer days for the year to check for leap years.
LA1	Estimated percentage reduction of dust density allowed for plant surfaces compared to bare ground density.
LOOHI	Logical assignment array variables to detect whether a high or low level of effect is expected for 'other' effects.
LOS	Low estimate of speed of vehicles travelling on the road.
LOTT	Used to store LOT variables as a constant.
NUM	Number of replications of the model simulation.
NUMM	Used to bypass replicating in the deterministic part of the model.
PERLOSS	Percentage yield loss from road dust due to 'other' effects.
PHOTO	Percentage photosynthetic yield losses.
PHOTO1	Percentage photosynthetic yield losses.
PHOTO2	Average percentage level of photosynthetic yield reduction for the affected productive arewa.
PLOW	Price received for low grade produce ($/t).
PRICEPU	Weighted average price received for produce ($/t).
PROBD	Probability distribution of dry days for either winter or summer depending on which.
PROBS PROBW	Array variables which contain probability distributions for the expected number of days accumulated dust deposition for the respective summer and winter growing periods.
PROD PROD1	Distance from roadway to start of productive land (m).
PROSP	Price received for low grade produce ($/t).
PTOP	Price received for top grade produce ($/t).
PVV	Total present value cost of road dust for the road.

QLOW[1] Quantity of road dust deposited on area between the roadway and the start of productive land on the side of the road being evaluated (g).

QUAN Total quantity of road dust deposited away from the roadway (up to 550 metres away) on the side of the road being evaluated (g).

RED
RED1 Logical assignment variable to detect whether a high or low level of effect is required.

REDN Percentage reduction of dust density on plant surfaces allowed because of smooth leaf surface types.

RFRONT
RFRONT1 Length of road frontage of enterprise (m).

ROADL Length of road segment being evaluated (m).

ROADN Name of road being evaluated.

SACOSTE Temporary variable (-NUM*ACCOSTE**2) used in the calculation of the enterprise standard deviation of cost.

SCOSTE Sum of squared photosynthetic yield loss costs ($/ha).

SEASI Signifies month that new seasons growth begins for the enterprise.

SEAS2 Signifies last month of growth for the season for the enterprise.

SHELT Percentage reduction of dust density allowed on plant surfaces due to the effect of shelterbelt protection.

SI Silt content of the road as a decimal fraction.

STDCOST Standard deviation of cost for the enterprise ($/ha).

STOTSYN Sum of squares of observations of photosynthetic yield loss ($/ha).

SUM Total level of dust deposited on plant surfaces on the estimated area of productive land (g/m of roadway).

---

1. Note that both QLOW and QUAN are figures derived from Beckers (1978) findings. They are used here only to calculate the percentage deposit of road dust away from the roadway.

SUMCOS	Sum of average costs over all enterprises ($/ha).
SUMM	Number of 'summer' days in the growing season.
SUMMER	Array containing the rainfall figures for each day from November to March inclusive for a period of 10 years.
SUMWIN	Data array used to store the months of the year for calculation of length and seasonality of enterprise growing season.
SWITCH SWITCHY SWITCH2	Logical assignment variable to detect whether the enterprise is on the prevailing upwind or downwind side of the road.
TEMP	Records the accumulated number of days of dust deposition (in YIELD subroutine only).
TEMP	Contains the relative frequencies of dusty days for summer for a recorded period of 10 years (in RAIN subroutine only).
TEMP1	Contains the relative frequencies of dusty days for winter for a recorded period of 10 years.
TEMP2	Contains the total average frequencies of dusty days for summer for the 10 years.
TEMP3	Contains the total average frequencies of dusty days for winter for the 10 years.
TIM	Data array which contains the number of days in each month of the year.
TMEANC	Total mean cost to the enterprise for each replication ($/ha).
TOTSS	Pooled variance of total cost for all enterprises ($/ha).
TOTSSSC	Rolling total of variances of costs for all enterprises ($/ha).
TOTSYN	Rolling total of photosynthetic yield costs for all enterprises ($/ha).
TQUAN	Total quantity of road dust deposition for both sides of the road up to 500 metres away from the road (g). Note that these figures are for Becker's study and are used here to calculate the percentage deposition of road dust away from the roadway.
TSUM	Totals the level of road dust deposition on productive land for each metre away from the roadway (g).

UDENS	An array used to store the deposition density of road dust deposited on plant surfaces for each metre away from the roadway on the upwind side of the road (g/m^2).
UH	Used in the calculation of losses due to 'other' dust effects. Is equal to the percentage reduction selected times the area affected.
UURAN URN	Used to store number selected by random number generator.
VARCPU VARC	Weighted average costs that vary with yield ($/t).
WIN	Number of 'winter' days in the growing season.
WINTER	An array storing rainfall figures for each day from April to October inclusive, for a period of 10 years.
YON YON1	An array of logical assignment variables used to detect whether 'other' effects of road dust are expected to occur.
YPHEC	Yield per hectare for the enterprise (t).
ZO Z1	Logical assignment variables which are used to show whether the last 1 or 2 days have been dry or not.
ZBOL	Logical assignment variables used to signal whether the year is a leap year or not.

APPENDIX VII

RAINFALL DATA FILE MANAGEMENT

A data file called RAIN.DAT is read with subroutine RAIN.FOR and contains daily rainfall records (in units of 0.1 millimetres) for any particular locality, for a period of 10 years. These figures may be gained directly on request from the Meterological Department Office in Wellington for any region in New Zealand (in this study, figures for Tauranga Airport were used in examples).

The data for the 10 years are input to the file in a concurrent sequence with the following format:

i) 1st line - Year of Data, e.g. 1974
FORMAT (16X, I4).

ii) Following 31 lines - Daily rainfall figures for that year set out in monthly columns from January to December. FORMAT I1, 11 (2X, I4).

iii) Data for each of the nine following years, is then entered in a similar manner in the line immediately following the last line of the previous year's data.

A further point to note is that each monthly column must contain 31 rows of figures. Hence for months with less than 31 days in them, zeros should be inserted at the end to make up the 31. The reason for this system is to allow for simplicity of programming to read the file; although the zeros are not actually read by the rainfall subroutine and are not incorporated into the rainfall probability data.

APPENDIX VIII

MODEL OPERATING DESCRIPTION AND INSTRUCTIONS

1. Introduction

The Road Dust Model is an interactive modular simulation model written in FORTRAN 77. The model contains one main routine (DUST.FOR), eight subroutines and one data file (see Appendix V).

2. Operating the Model and User Input Requirements

2.1 Getting Started

Since the model is stored on computer in a non-compiled version, the user must first compile and link all routines. The model is then ready to run on a fully interactive basis in screen mode.

2.2 Running the Model and Data Input

After compiling the program, type the command; [RUN DUST (RETURN)]. This will signify the start of the interactive session. The total list of interactive questions (in order) which appear on the screen are outlined below. Note that each question answered must be followed by pressing the [RETURN] key:

1) TYPE THE ROAD NAME

   Type in the name of the road to be analysed.

2) WHAT IS THE TOTAL LENGTH OF ROAD (METRES)

   Type in the length of the road segment which is being analysed for road dust.

3) INPUT SPEED VARIABLES HIS, AVS, LOS (KM/HR)
Since the speed travelled along the road will vary considerably between different road users, input;

i) the estimated speed travelled by the fastest drivers [RETURN].
ii) the estimated speed travelled by average drivers [RETURN].
iii) the estimated speed travelled by slow drivers.

4) INPUT DAILY TRAFFIC COUNT VARIABLES HIT, AVT, LOT (NB: HIT, AVT AND LOT ARE THE HIGH, MEDIUM AND LOW ESTIMATES OF AVERAGE DAILY TRAFFIC COUNT FOR THE ROAD.)
To allow for daily variability in the number of cars travelling along any particular road, type in the estimated daily traffic count for:

i) busy days [RETURN]
ii) average days [RETURN]
iii) quiet days [RETURN].

5) INPUT SILT CONTENT OF ROAD (as decimal fraction)
Type in the (decimal) fraction of silt in the roading material (i.e. all particles below 75 μm in diameter).

NOTE1: All of the above questions relate to the total length of the road segment being analysed. Those which follow are asked for each enterprise bordering the road.

6) INPUT THE ENTERPRISE TYPE (E.G. KIWIFRUIT, DAIRYING, ETC.)
Type in the name of the enterprise type.

7) DOES THE ENTERPRISE INVOLVE ANIMAL PRODUCTION? (YES/NO)
Key in the appropriate yes or no response.

<u>NOTE2</u>: The response to this question will signal the program into a later set of questions specific to either;

i) horticultural and arable (i.e. plant) enterprise types; or

ii) animal enterprise types.

8) INPUT THE DISTANCE (METRES) FROM THE ROAD CENTRE TO START OF PRODUCTIVE LAND. THE DISTANCE MUST BE GREATER THAN 0.
Type in the distance from the centre of the road to where the productive area of the enterprise starts.

9) IS THE ENTERPRISE ON THE PREVAILING UPWIND SIDE OF THE ROAD (YES/NO)? IF NO THEN IT MUST BE ON THE PREVAILING DOWNWIND SIDE OF THE ROAD
If the prevailing wind direction for the area blows from the road more onto the enterprise than away from it, then type in NO. Otherwise type in YES.

10) INPUT THE LENGTH OF ROAD FRONTAGE FOR THIS ENTERPRISE (METRES)
Type the distance in metres, for which the enterprise borders the road segment.

<u>NOTE3</u>: The questions which follow in the next section are asked only if a 'plant' enterprise type was signified earlier in question no. 7.

11) ARE THERE LOSSES ASSOCIATED WITH EXTRA PEST AND DISEASE INCIDENCE (YES/NO)?
Type whether you think that road dust causes extra problems of pest and disease damage to the enterprise (i.e. respond YES or NO).

<u>NOTE4</u>: The following sub-questions are dependent on YES responses. This also applies to questions 12, 13 and 14.

11a) ARE THEY YIELD LOSSES (YES/NO)?
Type whether you think that the pest and disease damage will cause a decrease in production yield.

11b) DO YOU WISH A HIGH ESTIMATE (YES) OR LOW ESTIMATE (NO)?
Type YES if you think that it may have a fairly significant effect on yield or NO, if a small effect.

11c) IS THERE DOWNGRADING (YES/NO)?
Type whether you think that the pest and disease damage will cause any produce to be downgraded.

11d) DO YOU WISH A HIGH ESTIMATE (YES) OR LOW ESTIMATE (NO)?
Type YES if you think that it may have a fairly significant effect on downgrading, or NO if a small effect.

12) ARE THERE COSTS FROM REDUCED POLLINATION (YES/NO)?
Type YES if you think that road dust may cause pollination problems for the enterprise. Otherwise NO.

12a) See 11a.
12b) See 11b.
12c) See 11c.
12d) See 11d.

13) IS THERE DOWNGRADING DUE TO DUST ON FRUIT (YES/NO)?
Type YES if you think that dust contamination on fruit is likely to cause produce to be downgraded.

13a) See 11b.

14) IS YIELD AFFECTED BY WEED INCIDENCE (YES/NO)?
Type YES if you think that road dust is likely to inhibit weed control to the extent of affecting crop yield.

14a) See 11b.

15) INPUT THE YIELD (TONNES) PER HECTARE FOR THIS ENTERPRISE
Type the expected yield per hectare for this enterprise type. Note that some averaged figures for a number of enterprise types are provided in Appendix IV, Table AIV.1.

16) INPUT THE WEIGHTED AVERAGE PRICE PER TONNE FOR PRODUCE FROM THIS ENTERPRISE (NB. WEIGHTED AVERAGE PRICE IS THE OVERALL AVERAGE PRICE WITH RESPECT TO THE PRICE AND PROPORTION OF EACH GRADE OR PRODUCE SOLD.)
Note that the weighted average price for a number of enterprise types is provided in Appendix III, Table AIII.1. In addition, the relative proportion of each grade for these enterprise types is shown in Appendix IV, Table AIV.4.

17) INPUT PRICE PER TONNE FOR PREMIUM GRADE (I.E. GENERALLY EXPORT GRADE)
Refer Appendix III, Table AIII.1.

18) INPUT PRICE PER TONNE FOR LOW GRADE (I.E. GENERALLY PROCESS GRADE)
Refer Appendix III, Table AIII.1

19) INPUT THE COSTS WHICH VARY WITH YIELD (PER TONNE) (E.G. FREIGHT, PACKAGING, ETC.)
These are the overall average variable costs with respect to the costs and proportion of each grade of produce sold. Costs for a range of enterprise types are also given in Appendix III, Table AIII.1.

20) INPUT COSTS WHICH VARY WITH YIELD FOR PREMIUM GRADE
Refer Appendix III, Table AIII.1.

21) INPUT COSTS WHICH VARY WITH YIELD FOR LOW GRADE
Refer Appendix III, Table AIII.1.

22) ARE THE PLANT LEAVES SMOOTH (NOT HAIRY) - (YES/NO)?
Hairy leaves will 'trap' dust much more readily than leaves with smooth surfaces. Type YES if the leaves are smooth and NO if hairy.

23) IS THE LAND PROTECTED FROM DUST BY A SHELTERBELT (YES/NO)?
Type YES if there is a shelterbelt along the enterprise border adjacent to the road being evaluated.

24) THE MONTHS FOR GROWING SEASON ARE ABBREVIATED AS: JAN, FEB, MAR, APR, MAY, JUN, JUL, AUG, SEP, OCT, NOV, DEC
IF THE GROWING SEASON IS THE COMPLETE YEAR INPUT JAN AS THE START AND DEC AS THE END. OTHERWISE INPUT START AND END NORMALLY.
FOR EXAMPLE MAR AUG
OR OCT MAR

24a) INPUT START OF GROWING SEASON
Type JAN for evergreen plant types or the first month of growth for deciduous.

24b) INPUT END OF GROWING SEASON
Type in DEC for evergreen plant types or the last month of growth for deciduous.

NOTE5: The program will now execute calculations for the particular enterprise. On completion of these calculations a screen prompt will then appear.

25) ARE THERE MORE ENTERPRISE EVALUATIONS REQUIRED (YES/NO)?
If there are no more enterprises along the road segment to be evaluated then type in NO. The program will then execute final calculations for the total road segment. These are then transferred to an output file called RES.DAT.
If more enterprises are to be evaluated then type in YES. The program will then begin a new set of questions for the next enterprise.

<u>NOTE6</u>: The questions to follow will be asked if an enterprise is an animal type enterprise. Note that questions 6 to 10 are common to all types of enterprise.

26) INPUT GROSS INCOME PER HECTARE ($)
The averaged gross incomes for a number of enterprise types are shown in Appendix III, Table AIII.2.

27) DO YOU WISH A HIGH OR LOW ESTIMATE OF YIELD REDUCTION (HI/LO)?
Type HI if think that road dust may have a fairly significant effect on the enterprise. Otherwise type LO if think that it will have little effect.

28) ARE THERE MORE ENTERPRISE EVALUATIONS REQUIRED (YES/NO)?
Refer to Question 25.

APPENDIX IX

OUTPUT FILE FOR CASE STUDY OF ROAD DUST COST ANALYSIS FOR A HYPOTHETICAL STRETCH OF ROAD

Output File for Case Study of Road Dust
Cost Analysis for a Hypothetical Stretch of Road

Road Dust Cost Evaluation

Road Name	:	ASTHMATIC ALLEY		
Length of Road Segment (metres)	:	1000		
Silt Content of Road	:	.060		
Traffic Count Variables (ave/day)	:	HIGH 270.	AVERAGE 250.	LOW 230.
Speed Variables (km/hr)	:	HIGH 90.	AVERAGE 70.	LOW 50.

ENTERPRISE ANALYSIS

NO. 1

ENTERPRISE TYPE	:	KIWIFRUIT
SIDE OF ROAD	:	DOWNWIND
ROAD FRONTAGE (M)	:	100.
PROTECTED BY SHELTER BELTS	:	YES
YIELD PER HECTARE(T)	:	21.
WEIGHTED AVERAGE PRICE($/T)	:	1496.
PREMIUM GRADE PRICE($/T)	:	1750.
LOW GRADE PRICE($/T)	:	350.
WEIGHTED AVERAGE COSTS THAT VARY WITH YIELD ($/T)	:	916.0
COSTS THAT VARY WITH YIELD FOR PREMIUM GRADE ($/T)	:	1059.0
COSTS THAT VARY WITH YIELD FOR LOW GRADE ($/T)	:	315.0

COSTS OF DUST EFFECT :

	MEAN % LOSS	MEAN TOTAL COST
PHOTOSYNTHETIC YIELD LOSSES	0.31	71.30

OTHER ESTIMATES OF COST	ESTIMATED LEVEL OF % LOSS (HI/LO/NIL)
PESTS AND DISEASE	
- YIELD ?	LOW
- DOWNGRADING ?	HIGH
REDUCED POLLINATION	
- YIELD ?	LOW
- DOWNGRADING ?	HIGH
DOWNGRADING FROM DUSTY FRUIT ?	HIGH
EXTRA WEED YIELD EFFECT ?	NIL

ENTERPRISE TOTAL MEAN COST	:	1087.95
STANDARD DEVIATION OF COST	:	97.97

ENTERPRISE ANALYSIS

NO. 2

SIDE OF ROAD	:	DOWNWIND
ROAD FRONTAGE (M)	:	100.
PROTECTED BY SHELTER BELTS	:	YES
YIELD PER HECTARE(T)	:	7.
WEIGHTED AVERAGE PRICE($/T)	:	4709.
PREMIUM GRADE PRICE($/T)	:	5000.
LOW GRADE PRICE($/T)	:	2000.
WEIGHTED AVERAGE COSTS THAT VARY WITH YIELD ($/T)	:	2029.0
COSTS THAT VARY WITH YIELD FOR PREMIUM GRADE ($/T)	:	2289.0
COSTS THAT VARY WITH YIELD FOR LOW GRADE ($/T)	:	1249.0

COSTS OF DUST EFFECT :

	MEAN % LOSS	MEAN TOTAL COST
PHOTOSYNTHETIC YIELD LOSSES	0.34	120.67

OTHER ESTIMATES OF COST	ESTIMATED LEVEL OF % LOSS (HI/LO/NIL)
PESTS AND DISEASE	
- YIELD ?	LOW
- DOWNGRADING ?	HIGH
REDUCED POLLINATION	
- YIELD ?	HIGH
- DOWNGRADING ?	LOW
DOWNGRADING FROM DUSTY FRUIT ?	HIGH
EXTRA WEED YIELD EFFECT ?	LOW

ENTERPRISE TOTAL MEAN COST	:	1485.25
STANDARD DEVIATION OF COST	:	166.20

ENTERPRISE ANALYSIS

NO. 3

ENTERPRISE TYPE	: PEACHES
SIDE OF ROAD	: DOWNWIND
ROAD FRONTAGE (M)	: 100.
PROTECTED BY SHELTER BELTS	: YES
YIELD PER HECTARE(T)	: 23.
WEIGHTED AVERAGE PRICE($/T)	: 453.
PREMIUM GRADE PRICE($/T)	: 1100.
LOW GRADE PRICE($/T)	: 300.
WEIGHTED AVERAGE COSTS THAT VARY WITH YIELD ($/T)	: 171.0
COSTS THAT VARY WITH YIELD FOR PREMIUM GRADE ($/T)	: 624.0
COSTS THAT VARY WITH YIELD FOR LOW GRADE ($/T)	: 104.0

COSTS OF DUST EFFECT :

	MEAN % LOSS	MEAN TOTAL COST
PHOTOSYNTHETIC YIELD LOSSES	0.23	27.88

OTHER ESTIMATES OF COST	ESTIMATED LEVEL OF % LOSS (HI/LO/NIL)
PESTS AND DISEASE	
- YIELD ?	LOW
- DOWNGRADING ?	HIGH
REDUCED POLLINATION	
- YIELD ?	NIL
- DOWNGRADING ?	NIL
DOWNGRADING FROM DUSTY FRUIT ?	HIGH
EXTRA WEED YIELD EFFECT ?	NIL

ENTERPRISE TOTAL MEAN COST : 334.22
STANDARD DEVIATION OF COST : 34.98

ENTERPRISE ANALYSIS

NO. 4

SIDE OF ROAD	:	DOWNWIND
ROAD FRONTAGE (M)	:	100.
PROTECTED BY SHELTER BELTS	:	YES
YIELD PER HECTARE(T)	:	20.
WEIGHTED AVERAGE PRICE($/T)	:	3951.
PREMIUM GRADE PRICE($/T)	:	4230.
LOW GRADE PRICE($/T)	:	2834.
WEIGHTED AVERAGE COSTS THAT VARY WITH YIELD ($/T)	:	564.0
COSTS THAT VARY WITH YIELD FOR PREMIUM GRADE ($/T)	:	564.0
COSTS THAT VARY WITH YIELD FOR LOW GRADE ($/T)	:	564.0

COSTS OF DUST EFFECT :

	MEAN % LOSS	MEAN TOTAL COST
PHOTOSYNTHETIC YIELD LOSSES	0.24	311.52

OTHER ESTIMATES OF COST	ESTIMATED LEVEL OF % LOSS (HI/LO/NIL)
PESTS AND DISEASE	
- YIELD ?	LOW
- DOWNGRADING ?	HIGH
REDUCED POLLINATION	
- YIELD ?	NIL
- DOWNGRADING ?	NIL
DOWNGRADING FROM DUSTY FRUIT ?	LOW
EXTRA WEED YIELD EFFECT ?	NIL

ENTERPRISE TOTAL MEAN COST	:	1750.77
STANDARD DEVIATION OF COST	:	442.14

ENTERPRISE ANALYSIS

NO. 5

ENTERPRISE TYPE	:	ORANGES
SIDE OF ROAD	:	DOWNWIND
ROAD FRONTAGE (M)	:	100.
PROTECTED BY SHELTER BELTS	:	YES
YIELD PER HECTARE(T)	:	51.
WEIGHTED AVERAGE PRICE($/T)	:	485.
PREMIUM GRADE PRICE($/T)	:	485.
LOW GRADE PRICE($/T)	:	485.
WEIGHTED AVERAGE COSTS THAT VARY WITH YIELD ($/T)	:	76.0
COSTS THAT VARY WITH YIELD FOR PREMIUM GRADE ($/T)	:	76.0
COSTS THAT VARY WITH YIELD FOR LOW GRADE ($/T)	:	76.0

COSTS OF DUST EFFECT :

	MEAN % LOSS	MEAN TOTAL COST
PHOTOSYNTHETIC YIELD LOSSES	0.25	98.15

OTHER ESTIMATES OF COST	ESTIMATED LEVEL OF % LOSS (HI/LO/NIL)
PESTS AND DISEASE - YIELD ?	LOW
- DOWNGRADING ?	LOW
REDUCED POLLINATION - YIELD ?	NIL
- DOWNGRADING ?	NIL
DOWNGRADING FROM DUSTY FRUIT ?	LOW
EXTRA WEED YIELD EFFECT ?	NIL

ENTERPRISE TOTAL MEAN COST : 296.31
STANDARD DEVIATION OF COST : 136.99

ENTERPRISE ANALYSIS

NO. 6

ENTERPRISE TYPE

SIDE OF ROAD : DOWNWIND

ROAD FRONTAGE (M) : 100.

PROTECTED BY SHELTER BELTS : YES

YIELD PER HECTARE(T) : 7.

WEIGHTED AVERAGE PRICE($/T) : 2996.

PREMIUM GRADE PRICE($/T) : 3855.

LOW GRADE PRICE($/T) : 1677.

WEIGHTED AVERAGE COSTS THAT VARY WITH YIELD ($/T) : 685.0

COSTS THAT VARY WITH YIELD FOR PREMIUM GRADE ($/T) : 1353.0

COSTS THAT VARY WITH YIELD FOR LOW GRADE ($/T) : 312.0

COSTS OF DUST EFFECT :

	MEAN % LOSS	MEAN TOTAL COST
PHOTOSYNTHETIC YIELD LOSSES	0.15	47.47

OTHER ESTIMATES OF COST	ESTIMATED LEVEL OF % LOSS (HI/LO/NIL)
PESTS AND DISEASE - YIELD ?	LOW
- DOWNGRADING ?	NIL
REDUCED POLLINATION - YIELD ?	NIL
- DOWNGRADING ?	NIL
DOWNGRADING FROM DUSTY FRUIT ?	HIGH
EXTRA WEED YIELD EFFECT ?	LOW

ENTERPRISE TOTAL MEAN COST : 506.05
STANDARD DEVIATION OF COST : 57.68

NO. 7

ENTERPRISE TYPE	:	KIWIFRUIT
SIDE OF ROAD	:	DOWNWIND
ROAD FRONTAGE (M)	:	50.
PROTECTED BY SHELTER BELTS	:	YES
YIELD PER HECTARE(T)	:	21.
WEIGHTED AVERAGE PRICE($/T)	:	1496.
PREMIUM GRADE PRICE($/T)	:	1750.
LOW GRADE PRICE($/T)	:	350.
WEIGHTED AVERAGE COSTS THAT VARY WITH YIELD ($/T)	:	916.0
COSTS THAT VARY WITH YIELD FOR PREMIUM GRADE ($/T)	:	1059.0
COSTS THAT VARY WITH YIELD FOR LOW GRADE ($/T)	:	315.0

COSTS OF DUST EFFECT :

	MEAN % LOSS	MEAN TOTAL COST
PHOTOSYNTHETIC YIELD LOSSES	0.29	33.71

OTHER ESTIMATES OF COST	ESTIMATED LEVEL OF % LOSS (HI/LO/NIL)
PESTS AND DISEASE	
- YIELD ?	LOW
- DOWNGRADING ?	HIGH
REDUCED POLLINATION	
- YIELD ?	LOW
- DOWNGRADING ?	HIGH
DOWNGRADING FROM DUSTY FRUIT ?	HIGH
EXTRA WEED YIELD EFFECT ?	NIL

ENTERPRISE TOTAL MEAN COST	:	542.03
STANDARD DEVIATION OF COST	:	49.59

ENTERPRISE ANALYSIS

NO. 8

ENTERPRISE TYPE :DAIRYING

SIDE OF ROAD	:	DOWNWIND
ROAD FRONTAGE (M)	:	200.
COSTS ESTIMATED AT THE HIGHER LEVEL OF	:	0.020
TOTAL ENTERPRISE COST IS($)	:	184.86

ENTERPRISE ANALYSIS

NO. 9

ENTERPRISE TYPE	:	AVOCADOS
SIDE OF ROAD	:	UPWIND
ROAD FRONTAGE (M)	:	100.
PROTECTED BY SHELTER BELTS	:	YES
YIELD PER HECTARE(T)	:	20.
WEIGHTED AVERAGE PRICE($/T)	:	3951.
PREMIUM GRADE PRICE($/T)	:	4230.
LOW GRADE PRICE($/T)	:	2834.
WEIGHTED AVERAGE COSTS THAT VARY WITH YIELD ($/T)	:	564.0
COSTS THAT VARY WITH YIELD FOR PREMIUM GRADE ($/T)	:	564.0
COSTS THAT VARY WITH YIELD FOR LOW GRADE ($/T)	:	564.0

COSTS OF DUST EFFECT :

	MEAN % LOSS	MEAN TOTAL COST
PHOTOSYNTHETIC YIELD LOSSES	0.22	74.80

OTHER ESTIMATES OF COST	ESTIMATED LEVEL OF % LOSS (HI/LO/NIL)
PESTS AND DISEASE - YIELD ?	LOW
- DOWNGRADING ?	HIGH
REDUCED POLLINATION - YIELD ?	NIL
- DOWNGRADING ?	NIL
DOWNGRADING FROM DUSTY FRUIT ?	LOW
EXTRA WEED YIELD EFFECT ?	NIL

ENTERPRISE TOTAL MEAN COST	:	453.55
STANDARD DEVIATION OF COST	:	105.67

ENTERPRISE ANALYSIS

NO. 10

SIDE OF ROAD	: UPWIND
ROAD FRONTAGE (M)	: 100.
PROTECTED BY SHELTER BELTS	: YES
YIELD PER HECTARE(T)	: 168.
WEIGHTED AVERAGE PRICE($/T)	: 319.
PREMIUM GRADE PRICE($/T)	: 460.
LOW GRADE PRICE($/T)	: 100.
WEIGHTED AVERAGE COSTS THAT VARY WITH YIELD ($/T)	: 68.0
COSTS THAT VARY WITH YIELD FOR PREMIUM GRADE ($/T)	: 68.0
COSTS THAT VARY WITH YIELD FOR LOW GRADE ($/T)	: 68.0

COSTS OF DUST EFFECT :

	MEAN % LOSS	MEAN TOTAL COST
PHOTOSYNTHETIC YIELD LOSSES	0.26	54.41

OTHER ESTIMATES OF COST	ESTIMATED LEVEL OF % LOSS (HI/LO/NIL)
PESTS AND DISEASE - YIELD ?	LOW
- DOWNGRADING ?	HIGH
REDUCED POLLINATION - YIELD ?	NIL
- DOWNGRADING ?	NIL
DOWNGRADING FROM DUSTY FRUIT ?	LOW
EXTRA WEED YIELD EFFECT ?	NIL

ENTERPRISE TOTAL MEAN COST	: 613.43
STANDARD DEVIATION OF COST	: 76.23

ENTERPRISE ANALYSIS

NO.11

ENTERPRISE TYPE	:ASPARAGUS
SIDE OF ROAD	: UPWIND
ROAD FRONTAGE (M)	: 100.
PROTECTED BY SHELTER BELTS	: YES
YIELD PER HECTARE(T)	: 7.
WEIGHTED AVERAGE PRICE($/T)	: 2996.
PREMIUM GRADE PRICE($/T)	: 3855.
LOW GRADE PRICE($/T)	: 1677.
WEIGHTED AVERAGE COSTS THAT VARY WITH YIELD ($/T)	: 685.0
COSTS THAT VARY WITH YIELD FOR PREMIUM GRADE ($/T)	: 1353.0
COSTS THAT VARY WITH YIELD FOR LOW GRADE ($/T)	: 312.0

COSTS OF DUST EFFECT :

	MEAN % LOSS	MEAN TOTAL COST
PHOTOSYNTHETIC YIELD LOSSES	0.13	10.77

OTHER ESTIMATES OF COST	ESTIMATED LEVEL OF % LOSS (HI/LO/NIL)
PESTS AND DISEASE	
- YIELD ?	LOW
- DOWNGRADING ?	NIL
REDUCED POLLINATION	
- YIELD ?	NIL
- DOWNGRADING ?	NIL
DOWNGRADING FROM DUSTY FRUIT ?	HIGH
EXTRA WEED YIELD EFFECT ?	LOW

ENTERPRISE TOTAL MEAN COST	: 131.45
STANDARD DEVIATION OF COST	: 12.91

ENTERPRISE ANALYSIS

NO.12

SIDE OF ROAD	:	UPWIND
ROAD FRONTAGE (M)	:	100.
PROTECTED BY SHELTER BELTS	:	YES
YIELD PER HECTARE(T)	:	21.
WEIGHTED AVERAGE PRICE($/T)	:	1496.
PREMIUM GRADE PRICE($/T)	:	1750.
LOW GRADE PRICE($/T)	:	350.
WEIGHTED AVERAGE COSTS THAT VARY WITH YIELD ($/T)	:	916.0
COSTS THAT VARY WITH YIELD FOR PREMIUM GRADE ($/T)	:	1059.0
COSTS THAT VARY WITH YIELD FOR LOW GRADE ($/T)	:	315.0

COSTS OF DUST EFFECT :

	MEAN % LOSS	MEAN TOTAL COST
PHOTOSYNTHETIC YIELD LOSSES	0.26	15.92

OTHER ESTIMATES OF COST	ESTIMATED LEVEL OF % LOSS (HI/LO/NIL)
PESTS AND DISEASE	
- YIELD ?	LOW
- DOWNGRADING ?	HIGH
REDUCED POLLINATION	
- YIELD ?	LOW
- DOWNGRADING ?	HIGH
DOWNGRADING FROM DUSTY FRUIT ?	HIGH
EXTRA WEED YIELD EFFECT ?	NIL

ENTERPRISE TOTAL MEAN COST	:	283.46
STANDARD DEVIATION OF COST	:	23.49

ENTERPRISE ANALYSIS

NO. 13

ENTERPRISE TYPE	:	ORANGES
SIDE OF ROAD	:	UPWIND
ROAD FRONTAGE (M)	:	100.
PROTECTED BY SHELTER BELTS	:	YES
YIELD PER HECTARE(T)	:	51.
WEIGHTED AVERAGE PRICE($/T)	:	485.
PREMIUM GRADE PRICE($/T)	:	485.
LOW GRADE PRICE($/T)	:	485.
WEIGHTED AVERAGE COSTS THAT VARY WITH YIELD ($/T)	:	76.0
COSTS THAT VARY WITH YIELD FOR PREMIUM GRADE ($/T)	:	76.0
COSTS THAT VARY WITH YIELD FOR LOW GRADE ($/T)	:	76.0

COSTS OF DUST EFFECT :

	MEAN % LOSS	MEAN TOTAL COST
PHOTOSYNTHETIC YIELD LOSSES	0.26	26.61

OTHER ESTIMATES OF COST	ESTIMATED LEVEL OF % LOSS (HI/LO/NIL)
PESTS AND DISEASE	
- YIELD ?	HIGH
- DOWNGRADING ?	LOW
REDUCED POLLINATION	
- YIELD ?	NIL
- DOWNGRADING ?	NIL
DOWNGRADING FROM DUSTY FRUIT ?	LOW
EXTRA WEED YIELD EFFECT ?	NIL

ENTERPRISE TOTAL MEAN COST	:	130.91
STANDARD DEVIATION OF COST	:	36.16

ENTERPRISE ANALYSIS

NO. 14

SIDE OF ROAD	:	UPWIND
ROAD FRONTAGE (M)	:	150.
PROTECTED BY SHELTER BELTS	:	NO
YIELD PER HECTARE(T)	:	16.
WEIGHTED AVERAGE PRICE($/T)	:	337.
PREMIUM GRADE PRICE($/T)	:	337.
LOW GRADE PRICE($/T)	:	337.
WEIGHTED AVERAGE COSTS THAT VARY WITH YIELD ($/T)	:	78.0
COSTS THAT VARY WITH YIELD FOR PREMIUM GRADE ($/T)	:	78.0
COSTS THAT VARY WITH YIELD FOR LOW GRADE ($/T)	:	78.0

COSTS OF DUST EFFECT :

	MEAN % LOSS	MEAN TOTAL COST
PHOTOSYNTHETIC YIELD LOSSES	0.35	10.92

OTHER ESTIMATES OF COST	ESTIMATED LEVEL OF % LOSS (HI/LO/NIL)
PESTS AND DISEASE	
- YIELD ?	LOW
- DOWNGRADING ?	NIL
REDUCED POLLINATION	
- YIELD ?	NIL
- DOWNGRADING ?	NIL
DOWNGRADING FROM DUSTY FRUIT ?	NIL
EXTRA WEED YIELD EFFECT ?	LOW

ENTERPRISE TOTAL MEAN COST	:	42.00
STANDARD DEVIATION OF COST	:	14.85

NO. 15

ENTERPRISE TYPE	:	MAIZE
SIDE OF ROAD	:	UPWIND
ROAD FRONTAGE (M)	:	200.
PROTECTED BY SHELTER BELTS	:	NO
YIELD PER HECTARE(T)	:	8.
WEIGHTED AVERAGE PRICE($/T)	:	233.
PREMIUM GRADE PRICE($/T)	:	233.
LOW GRADE PRICE($/T)	:	233.
WEIGHTED AVERAGE COSTS THAT VARY WITH YIELD ($/T)	:	52.0
COSTS THAT VARY WITH YIELD FOR PREMIUM GRADE ($/T)	:	52.0
COSTS THAT VARY WITH YIELD FOR LOW GRADE ($/T)	:	52.0

COSTS OF DUST EFFECT :

	MEAN % LOSS	MEAN TOTAL COST
PHOTOSYNTHETIC YIELD LOSSES	0.37	5.31

OTHER ESTIMATES OF COST	ESTIMATED LEVEL OF % LOSS (HI/LO/NIL)
PESTS AND DISEASE - YIELD ?	HIGH
- DOWNGRADING ?	NIL
REDUCED POLLINATION - YIELD ?	NIL
- DOWNGRADING ?	NIL
DOWNGRADING FROM DUSTY FRUIT ?	NIL
EXTRA WEED YIELD EFFECT ?	LOW

ENTERPRISE TOTAL MEAN COST	:	27.03
STANDARD DEVIATION OF COST	:	7.51

SUMMARY OF DUST COSTS

NUMBER OF ENTERPRISES IS	:	15
THE MEAN TOTAL COST IS	:	7684.418
THE STD. OF TOTAL COST IS	:	136.681
THE PRESENT VALUE OF COST	:	58448.305