AN EVALUATION OF THE ECONOMIC BENEFITS OF ACTIVE COOLING AND CARBON DIOXIDE ENRICHMENT OF GREENHOUSE CUCUMBERS

(Cucumis sativus L.)

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Marcus Johannes Aart Everardus van Heijst

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ABSTRACT

Cooling a greenhouse with a refrigeration system rather than conventional ventilation makes it possible to maximise the fractional enrichment time for carbon dioxide, and more importantly enrich during periods of high photosynthetically active radiation. Using conventional climate control methods, enrichment is limited to periods when the greenhouse is not being ventilated, thus reducing the potential enrichment time of the crop.

The objective of this study was to develop a simulation model of a greenhouse crop growing with a closed cycle climate control system, using a heat pump, with a reversible (dual) cycle, for heating and cooling.

A computer implemented mathematical model developed by Wells (1992) was modified to simulate cucumber crop growth in a greenhouse of commercial size and allowing certain parameters to be set. These parameters included: two types of control system, four levels of enrichment, three crop periods, and at two locations, Auckland and Christchurch. The three crop periods chosen were 26 Jan to 26 April, 25 May to 23 August, and 20 September to 19 December. The two types of control involved conventional fan ventialtion and electric heating, and closed cycle climate control using a reverse cycle heat pump. Greenhouse carbon dioxide enrichment levels used were 350, 600, 900, 1200 $\mu l.l^{-1}$. The two locations chosen were Auckland and Christchurch.

An economic analysis of the results was carried out calculating Annual Marginal Return (AMR) and Internal Rate of Return (IRR) for treatments compared to control.

It was concluded that carbon dioxide enrichment combined with conventional control is a worthwhile investment in Christchurch but less so in Auckland. Due to the high capital cost, carbon dioxide enrichment combined with closed cycle climate control is a less attractive investment. However, as considerable energy savings are possible with closed cycle climate control, it is worthwhile investigating other less expensive forms of closed cycle climate control. The economic feasibility of the application of this technology to other, higher value, crops is worthwhile investigating.

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This thesis is especially dedicated to Michelle who can now finally appreciate being married, my father and mother who can now have their house back again, and Nicole who has been a great inspiration. You have all been there to encourage me to complete this work.

Finally a word of advice to anyone considering doing one of these: Keep your head down, stick with it, and try to avoid doing things like getting married and taking on full time employment !

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1. History of Carbon Dioxide Enrichment.

The use of carbon dioxide enrichment for greenhouse crop production is by no means a new idea.

As early as 1888 the benefits of carbon dioxide were recognized and reported for practical greenhouse cultures in Germany, and a few years later in England (Wittwer, 1986).

Although the first experiments, by Brown and Escombe (1902), gave negative results with carbon dioxide enrichment; Demoussy (1904), later explained these effects to be due to impurities in the carbon dioxide supply. His experiments, with enrichment to 1500 $\mu l.l^{-1}$, produced an average increase in plant weight of 160%, varying from 97% for fuchsia to 262% for geranium. These results obtained are surprisingly close to those reported 80 years later (Lemon, 1983).

Trials conducted by Cummings and Jones (1918), in America for 7 years starting in 1909, showed favourable yield increases for many crops. Vegetable and fruit plants produced enhanced fruit and with greater abundance, while flower crops produced blossoms earlier and in greater profusion.

Contemporary with and subsequent to these trials, extensive studies were being carried out, with emphasis on enhancement of yield and harvest index of crops of economic importance, mainly in Europe and to some extent in the US carbon dioxide was obtained from burning charcoal, coal gas, paraffin, and purified gases from smelter furnaces. Some achieved a doubling and even tripling of tomato and cucumber yields.

Toxic substances in the carbon dioxide supply, due to inherent impurities, incomplete combustion, or improper application techniques, prevented carbon dioxide enrichment of greenhouse atmospheres from becoming a general practice, and many results achieved were of limited value due to poor experimental control.

From then on, the interest in carbon dioxide enrichment, both as a commercial practice and as a growth variable in scientific studies, followed an irregular pattern of peaks and troughs.

The 1920's to 1930's saw the first use of carbon dioxide enrichment commercially, mostly in Germany. However, as the problems of enrichment had not been overcome yet, and growers were affected by the poor economic situation due to World War II, interest in enrichment was soon to fade.

That is until about 1960 when, in the Netherlands, new greenhouse lettuce cultivars had been developed that grew faster under poor light conditions. These larger lettuce plants were more frost susceptible hence growers installed simple kerosene (paraffin) burners to prevent frost injury at night. As the burners had no chimneys the flue gases produced were released into the greenhouse atmosphere. When, in 1961, one particular grower in 's Gravenzande (Westland) also used the burners during daytime with the greenhouse ventilators shut, he found his lettuce to develop into a crop of unusually high weight and quality. Other growers noticed similar responses and within 1 year 4000 acres of lettuce in the Netherlands were being treated with carbon dioxide (Wittwer, 1986).

In that same year numerous European papers on carbon dioxide enrichment of greenhouse atmospheres were presented at the 16th International Horticultural Congress Meetings in Brussels, Belgium, followed by various publications in trade journals.

Simultaneous with these commercial developments Gaastra published results showing that elevated carbon dioxide concentrations, up to 1000 $\mu l.l^{-1}$, combined with higher temperatures and incident light caused an increase in yield of tomatoes and cucumbers (Gaastra, 1959).

The widespread use of carbon dioxide, at the time, has been attributed to a set of unusual circumstances which developed almost simultaneously (Wittwer, 1986):

1. A remarkable increase in yield, improved quality, and accelerated maturity was demonstrated for all flower and vegetable crops.
2. Safe economical and dependable combustion units became available which used natural gas or fuel oils of low sulphur content.
3. The development of combustion units, used also for greenhouse heating, was preceded by the use of relatively pure forms of carbon dioxide - dry ice, cylinder carbon dioxide, or low pressure liquid sources.
4. The economic returns exceeded by severalfold the cost of treatment.
5. carbon dioxide monitoring and measuring devices of simple design were developed and became available at a reasonable cost.
6. Modern developments in plastics enabled construction of greenhouses which were far more effective in containment of released carbon dioxide and, along with perforated plastic tubing, provided for effective distribution and circulation of the generated gas.
7. The introduction of carbon dioxide as a variable for the growth of greenhouse crops was accompanied by remarkable developments in other crop production technologies

The latest resurge in interest (late 1970's and early 1980's) has been prompted, in part, by the realization of the occurrence global climatic change due to the global increase in atmospheric carbon dioxide resulting from the greenhouse effect. Keeling (1983) suggested a rate of 1.5 - 2.0 $\mu l.l^{-1}$ increase in global atmospheric carbon dioxide content per year.

These recent studies into the effects of the elevated global carbon dioxide levels, and associated global warming, have caused an associated re-evaluation of the effects on plant life - the basis of all other life on earth. Although the effects are potentially harmful to most other life on earth, quite the opposite is true for plant life; as studies have already revealed that an increase in atmospheric temperature and carbon dioxide content can potentially lead to beneficial effects in crop responses.

Furthermore there have been recent technological and cultural developments and improvements (Mortensen, 1987):

- Introduction of high quality kerosene (<100 mg.l^{-1} sulphur content) and less leakage of propane from improved equipment.
- Increased use of pure, bottled carbon dioxide gas.
- Better control through the use of monitoring equipment.
- Improved greenhouse construction has lead to more gas-tight greenhouses causing higher carbon dioxide depletion by crops during periods of high light intensity.
- Reduction in carbon dioxide production by the growing media through the use of inorganic media.
- Higher knowledge base of plant responses to carbon dioxide enrichment.
- Increased competition within the greenhouse industry causing a greater emphasis on cost-efficient crop production.

With the ever increasing cost of energy and labour which is not matched by crop returns, it is increasingly important to grow a crop optimally not just in terms of yields achieved but also in terms of costs incurred. Hence recent research has tended to concentrate on growth optimisation.

The idea behind optimisation is that of each cultivation measure (e.g. carbon dioxide enrichment) the increase in financial yield (by enriching with carbon dioxide) must be greater than the extra costs incurred achieving the elevated yields (Nederhoff, 1988).

Udink ten Cate (1982) proposed to reduce the complexity of the greenhouse control system by developing a hierarchical control system, see Figure 1.1.

- The first level of the system involves the control of the average climate of the greenhouse.
- The second level describes short term overall plant responses with a time span of several minutes. (less than 24 hours).
- The third level concerns itself with the crop growth and development on a daily basis, i.e. time unit of one day. (greater than 24 hours).

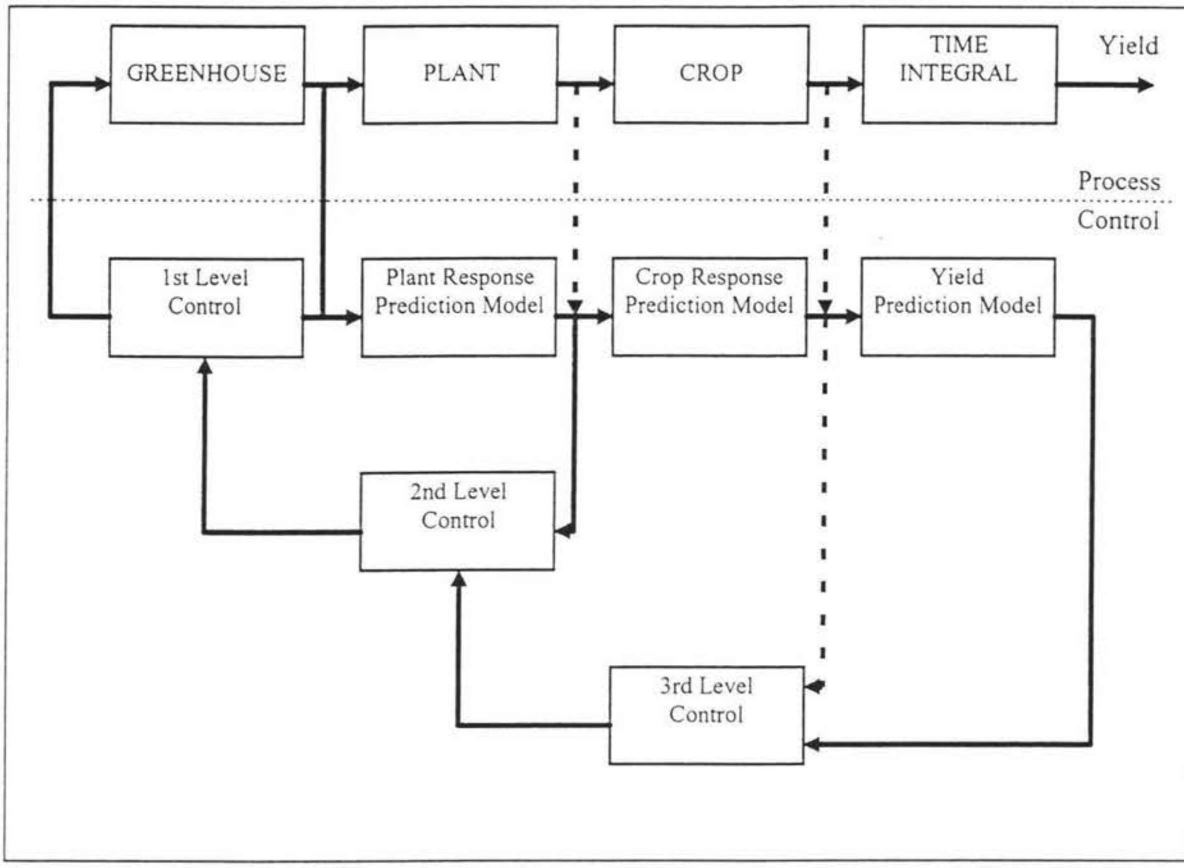

Figure 1.1 *Hierarchical model of crop growth (Udink ten Cate, 1983).*

It has been argued by several authors (Copet and Videau, 1981; Udink ten Cate and Challa, 1984) that optimal control of the greenhouse environment (level 1) can only be achieved if the set-point trajectories are determined from consideration of the short term plant responses (level 2) and the long term crop response and management (level 3).

This approach has become a benchmark for future research into greenhouse control optimisation as illustrated by Challa and Schapendonk (1986) who proposed a similar, adapted, hierarchical model for greenhouse control with carbon dioxide enrichment as a cost factor.

Although the model is incomplete, as it is difficult to incorporate temperature into optimisation models, it does illustrate the effect of carbon dioxide cost on optimisation; i.e. where carbon dioxide is supplied, and hence becomes a cost factor, control of other factors of production (ventilation rate, leaf area index, crop price index, etc.) become significantly more critical.

New Zealand growers today are becoming increasingly aware of the importance of carbon dioxide to greenhouse crop production (Anon., 1990a, 1990b; Collins, 1991; Anon. 1991a, 1991b).

There are generally three options available to growers for carbon dioxide enrichment:

Option 1. No additional enrichment. Here the grower relies on ventilation and ambient carbon dioxide levels. The greenhouse is ventilated whenever carbon dioxide levels within the greenhouse drop too low, or the temperature goes too high.

Option 2. Enrichment of the greenhouse atmosphere through combustion (e.g. of gas, kerosene, etc.), combined with heating. This method of enrichment can only be practised during the winter months, and to a limited extent on summer mornings. Otherwise option 1. is used to maintain carbon dioxide levels.

Option 3. Constant monitoring of the greenhouse atmosphere and enrichment with pure carbon dioxide. Enrichment of the greenhouse takes place whenever necessary, during periods when the greenhouse vents are closed. Growers enriching by this method usually enrich to carbon dioxide concentrations well above the current ambient level of 350 $\mu l.l^{-1}$ (e.g. 600-1000 $\mu l.l^{-1}$).

Because of the relative cost of pure carbon dioxide and the monitoring equipment necessary, option 3 is confined to properties of sufficient size able to absorb the extra capital and running costs associated with this intensive system.

In the current market climate of increasing competition and the push for more efficient production there is a trend toward greenhouse operations of larger size and using more sophisticated climate control systems. This has led to increasing use of option 3 by greenhouse growers. This option allows higher enrichment set-points to be maintained and provides the grower with more control over the greenhouse atmosphere.

2. PHYSIOLOGICAL EFFECTS OF CO_2 ON PLANTS

2.1 Introduction

Carbon dioxide serves as the primary substrate for photosynthesis in plants. "Photosynthesis is essentially the only mechanism of energy input into the living world" (Salisbury and Ross, 1978). It is the ability to photosynthesise that sets plants apart from all other organisms on earth.

The overall photosynthetic reaction can be summarised as follows:

$$CO_2 + H_2O \leftrightarrow CH_2O + O_2 \qquad (1)$$

The forward (rightward) reaction is light dependent, hence the name photo- (light) synthesis. It involves the oxidation of water (H_2O) and the reduction of carbon dioxide (CO_2) to form carbohydrates (CH_2O), the main form of biological energy storage - and oxygen (O_2) as a by-product.

It may be noted from (1) above that a reverse reaction is also possible, this is called respiration. Respiration involves the oxidation of carbohydrates, releasing energy and forming carbon dioxide. More importantly, however, respiration involves synthetic (anabolic) processes forming carbon skeleton intermediates for a large number of essential plant products (e.g. proteins, amino acids, chlorophyll, etc.) needed for growth of the plant.

All plants need a certain level of respiration for the maintenance of biological functions, this is termed maintenance respiration . However, for positive growth to occur the rate of photosynthesis must exceed respiration. The rates of these activities are determined by a variety of internal (biological) and external (environmental) factors. Internal factors are species dependent and determine how a plant will respond to a given set of conditions. The grower has no direct control over these factors apart from choosing different plant varieties or cultivars.

External factors may influence photosynthesis and respiration indirectly, for example by affecting hormone level or enzyme activity; or directly, for example by increasing the reaction rate through an increase in plant temperature. The grower, potentially, has a significant amount of control over the external factors of plant activity.

It is obvious that there is a close relationship between photosynthesis and growth. Therefore, it should also be apparent that the grower has the ability to vary crop growth through the modification of the crop environment.

Traditionally the only external growth factors manipulated by greenhouse growers have been temperature, irrigation, humidity, and light levels. One important external factor which was not often explored by greenhouse growers is greenhouse carbon dioxide level.

2.2 Carbon partitioning among vegetative organs

According to Acock and Pasternak (1986), one of the most obvious indications that carbon dioxide induces a change in plant anatomy or morphology is a change in the ratio of dry weights of organs on the plant.

A frequently reported ratio is the *root:shoot ratio* which has been shown to increase for a number of plants. Table 2.2 shows responses of specific plant species as cited in literature. The effect of carbon dioxide is larger with greater light flux density and greater plant age.

Mortensen (1987) stated that results from research indicate a need to increase nutrient levels for plants undergoing carbon dioxide enrichment, especially at high air humidity levels, in order to avoid nutrient deficiency.

2.2.1 The effect of carbon dioxide on root growth

Very little information is available on the effects of carbon dioxide on root growth. Though it has been shown that, for soybean, that there is a slight increase in weight per unit length with carbon dioxide enrichment (Acock and Paternak, 1986).

2.2.2 The effect of carbon dioxide on stem growth

carbon dioxide enrichment tends to increase mainly stem length and volume, but also to a certain extent stem density (Acock and Paternak, 1986).

2.2.3 The effect of carbon dioxide on leaf growth

Plants subjected to carbon dioxide enrichment have a lower *Specific Leaf Area* (SLA), that is a *lower leaf-area : leaf-weight ratio*, than plants grown in ambient carbon dioxide.

The extra dry matter produced in the leaf is not photosynthetically active even though there is often an increase in the number of mesophyll layers (which contain chloroplasts). This may be due to the masking effect of over-lapping layers.

This insufficient use of dry matter in leaves is seen as a gradual reduction in *Relative Growth Rate* (RGR) over the first few weeks of growth until the RGR in enriched plants is equal to, or less than the RGR in non-enriched plants.

Plant	Physical effect of carbon dioxide enrichment
Barley	Increase in root:shoot ratio Enhanced branching and tillering
Kale	Increase in root:shoot ratio
Maize	Increase in stem volume
Pea	Enhanced branching and tillering
Pine seedlings	Increase in stem volume
Radish	Increase in root:shoot ratio
Rice	Increase in root:shoot ratio Increase in fruit number and size
Rose	Enhanced branching and tillering
Soy Bean	Increase in stem volume Thicker leaves Enhanced branching and tillering Increase in fruit number
Sugar Beet	Increase in root:shoot ratio
Tomato	Decrease in time to anthesis Increase in earliness Increase in fruit number and size
Wheat	Increase in root:shoot ratio Enhanced branching and tillering Increase in fruit number and size

Table 2.2 *Table of the responses of specific plant species to carbon dioxide enrichment (Black, 1986).*

However, enriched plants do have a higher *Absolute Growth Rate* (AGR) than non-enriched plants. Hence, plants grown in carbon dioxide enriched atmospheres grow more, larger and thicker leaves with an extra palisade layer.

2.2.4 The effect of carbon dioxide on fruit formation and development

Plants typically initiate two to three times as many fruit as they can support. In a non-enriched atmosphere the excess fruit initiated are aborted, some fruit may even be prevented from initiating. A high carbon dioxide concentration may reduce the physiological stress on the plants and thus reduce the fruit abortion rate leading to a greater crop set. Furthermore, the increased carbon availability, in a high carbon dioxide environment, may enable plants to initiate or retain organs earlier in their lifecycle and thus induce *earliness*.

This may be especially important for greenhouse crop production in low winter light at high latitudes (e.g. Southern New Zealand). The earliness induced enables plants to set and ripen a few days earlier, which gives a disproportionately large increase in return on the crop.

It has been noted, for a number of species, that carbon dioxide enrichment enhances branching and tillering. This enables enriched plants to form full canopies in less time than the slower growing non-enriched plants. Also, the greater number of branches increases the number of potential flowering (and subsequently fruiting) sites.

As a result of the combined effect of the increased branching and the increased initiation/retention, higher carbon dioxide concentrations increase the number of such as temperature and humidity. It is interesting to note that carbon dioxide enrichment, in New Zealand, is currently used mainly on the commercial production of tomatoes, roses and cucumbers.

CROP	Mature Crops (Marketable Yield)		Immature Crops (Biomass)	
	Number of Results	Mean Increase (%)	Number of Results	Mean Increase (%)
Carnation	33	7	-	-
Chrysanthemum	66	6	-	-
Rose	24	27	-	-
Cucumber	31	43	26	46
Lettuce	54	35	7	68
Muskmelon	7	13	-	-
Capsicum	4	60	1	141
Strawberry	13	17	-	-
Tomato	131	17	24	52

Table 2.3 *Table showing mean percentage yield increase through carbon dioxide enrichment compared to control, for selected greenhouse crops (from Kimball, 1986).*

Kimball also showed that carbon dioxide had an overwhelmingly positive effect on yield. He states that of the 772 individual observations, only 66 yielded less than their respective controls (Kimball, 1986).

Flower crops gave an average yield increase of 12% as opposed to 29, 20, 41, 37, and 52% respectively for the combined mature and immature data of fruit, grain, leaf, legume seed, and root crops. This is easily explained as the flower yields were in terms of the number of blooms (an effect not greatly enhanced by enrichment) rather than weight. Kimball explains that even though the response of flowers to carbon dioxide enrichment is not as great, enrichment is still an economic practice because a 12% increase in a high-value crop will still return a profit. Also carbon dioxide will cause an increase in bloom quality in terms of bloom size (Kimball, 1986).

Mortensen's data suggest that in case of cut flowers the increase in weight is larger than the increase in the number of flowers, which is in line with Kimball's results. Mortensen's results also imply a greater effect on weight of foliage pot plants than leaf number and number of lateral breaks, with carbon dioxide enrichment (Mortensen, 1987).

Mortensen's (1987) results imply a very positive increase in plant dry/fresh weight and yield (marketable), with carbon dioxide enrichment, for vegetables. This is again in line with Kimball's results on vegetables.

In the results presented by Kimball root crops show the best response to enrichment (49 to 52%), which is in line with the theory that an improvement in the shoot environment benefits the roots relatively more (Kimball, 1986).

3. OUTLINE OF THE STUDY

This chapter will describe the background to the research presented in this thesis.

3.1 The 'Cucumber Model'

The research presented in this thesis serves as a continuation of initial work begun at Massey University which involved the development and verification of mathematical models of the dynamic response of a crop growing in a greenhouse environment (Wells, 1992).

The aim of the initial work was the development of a reliable model to simulate plant growth under variable structural control, environmental, and climatic parameters then implementing this model into suitable computer software.

After review of research into greenhouse modelling up to 1984, and considering the aims of the project in relation to greenhouse control, it was decided to base development on the most advanced work then available.

Wells noted two major short-comings of the existing models:

1. Many models ignored the effect of water vapour on the thermal capacity of the air.
2. No existing models treated the greenhouse structure as a separate entity from the greenhouse glazing. In preliminary work it was shown that only a model which treated the temperature of the greenhouse structure and the temperature of the glazing separately, could successfully simulate the rise of air temperature during the day; thus giving an accurate picture of the overall energy balance of the structure.

Based on this information the model to be developed was to be dynamic with analytical equations. The resulting equations of the model had to be easily computer implemented to allow for simulation.

The computer programming language chosen for implementation was the European Simulation Language or ESL (Hay et al, 1988). This language provides a number of procedures for solving differential equations, with inbuilt routines to deal with *discontinuities*. This latter ability was important as the model developed contained several discontinuities which needed to be dealt with.

Crop productivity was simulated and determined by combining an environment simulation model, a crop development model, and models of photosynthesis, respiration, and partitioning; then converting these models into ESL. This crop growth simulation model was used to predict the growth of a crop over one growing season and the results compared with actual data obtained from measurements carried out on a crop of cucumbers during a growing season, at the Massey University Plant Growth Unit (PGU).

As the two sets of results agreed to within experimental error, the model is considered to be a verified simulation model of greenhouse cucumber production. This means that the model gives a fair representation of real-time crop growth in a greenhouse.

The resulting model will be referred to in this thesis as *The Cucumber Model.*

For more details on the Cucumber Model refer to "Modelling The Greenhouse Environment And The Growth Of Cucumbers" (Wells, 1992).

3.2 Justification of the experiment

As illustrated in the previous two chapters the use of elevated carbon dioxide levels in a greenhouse has a potentially desirable effect on the performance of many commercially grown greenhouse crops. The problem to be overcome by the grower, however, is how to maintain elevated carbon dioxide levels within a greenhouse without sacrificing control over temperature. Conventional methods of combined carbon dioxide and temperature control have meant that in order to maintain optimum greenhouse temperatures, the grower has had to sacrifice carbon dioxide enrichment during the period of ventilation, thus reducing enrichment time. In order to maintain a predetermined carbon dioxide level during all the desired daylight hours it is necessary to employ a method of cooling without ventilation, that is a method of closed cycle cooling. For this reason, it was decided to undertake this current study into the economic evaluation of greenhouse closed cycle cooling with carbon dioxide enrichment.

The traditional view of closed cycle cooling with crop production has been that this form of control is only viable, or in fact necessary, at research institutions, and that it has no commercial viability. Due to this prejudiced view, combined with the negative aspect of the cost of the construction of an experimental greenhouse, no experiments on the commercial viability have yet been undertaken nationally or internationally. However, with the development of a verified crop model, the constraint of greenhouse construction has been removed. Now the effects of carbon dioxide and closed cycle cooling can be explored without a major cost or time constraint. A simulation of a season's growth can be accomplished on a computer in 2 to 10 hours (depending on computer performance), and is therefore an effective research tool.

3.3 Aim of the Experiment

The aim of this study was to carry out an economic evaluation of the use of carbon dioxide enrichment in a greenhouse while using closed cycle cooling for greenhouse climate control. This involved the use of a modified form of the cucumber simulation model, with climatic data from two different sites and a range of carbon dioxide set-points, to predict crop yield. Using information on market prices for cucumbers, marginal cost of running the greenhouse, and marginal capital cost of climate control and carbon dioxide injection equipment it was then possible to estimate the return to the grower.

3.4 Experimental Method

The existing model, developed by Dr. C.M. Wells (1992) was designed to simulate a real greenhouse with its crop. In order for this model to be useful in the current study, a number of modifications had to be made. The new model evolved from the original cucumber model had to be more flexible to allow the user to set inputs such as: the size of the greenhouse, the type of climate control, set-points for heating, cooling, humidity, and carbon dioxide level, and the amount of irrigation. It was also necessary to add new procedures to simulate the operation of the heat pump - refrigeration system used in the closed cycle system, electric heating, fan ventilation, carbon dioxide injection, and humidity control.

3.4.1 The 'KOMKOM' Model

The new model, dubbed the 'komkom' model (after the Dutch word for cucumber: *komkommer*), involved the following modifications to the original model developed by Dr. Wells;

- Greenhouse Size. The cucumber model was developed to simulate a $100m^2$ glasshouse; as this size is not commonly regarded as commercially viable for vegetable production, the greenhouse unit was enlarged to $990m^2$ (30 m by 33 m), or 11,000 ft^2. This also involved the generation of a new set of *light transmission tables* for the larger house. The tables were created using a computer program based on the work of Bellamy (1991) and modified by Wells (1992) - See Wells (1992) for details.

- Heating. Although the aim of this research is to evaluate closed cycle cooling systems, in order to provide a fair comparison of this new system with traditional methods of climate control it was deemed necessary to simulate the operation of a *control house* as a reference. The cucumber model allowed the energy input through heating to be read in through data files, but did not simulate the operation or control of the heater. Hence it was necessary to calculate the size of an appropriate heater for a $990m^2$ greenhouse. Then an algorithm was developed to simulate the operation of the heater within the greenhouse, this was then implemented into 'komkom'.

- Cooling. The $100m^2$ greenhouse at Massey PGU used natural ventilation for cooling. For optimum control of greenhouse temperature and carbon dioxide content it is advantageous to use fan ventilation in preference to natural ventilation due to the faster response to control, of greenhouse climate, achieved with forced ventilation. An algorithm for appropriately sized fan ventilators was developed and implemented into *komkom*.

- Carbon Dioxide Enrichment. The original model featured no carbon dioxide enrichment, nor was carbon dioxide level controlled in any way. Hence a control algorithm was developed and implemented for the simulation of carbon dioxide enrichment, to various set-points, in the greenhouse treatments other than the control.

- Heat Pump Climate Control. For the purpose of the research in this study the appropriate size of a dual cycle heat pump system was calculated and an algorithm developed to simulate its operation in the greenhouse. The heat pump type chosen is based on a *vapour compression* cycle using R22 refrigerant.

- Humidity Control. Humidity control was implemented for the simulations of closed cycle cooling as it was found that the inherent moisture removal rate through active cooling caused relative humidity to drop to sub-optimum levels. The humidity was raised through the simulation of a water vapour injection system.

- Air Circulation. In order to reduce air temperature stratification it is necessary to keep the greenhouse air well mixed. In the simulation of the conventionally controlled greenhouse the operation of clear perforated polythene ducting was included. A closed cycle cooling/heating system in a greenhouse inherently provides enough air circulation, through the action of the evaporator fans, to make further air circulation devices unnecessary, hence no ducting was included in the simulation of closed cycle climate control.

  Climatological Data. The original simulation model was based on a 100 m^2 greenhouse in Palmerston North. It was decided that simulations at Auckland and Christchurch would be more suitable as these areas are more favoured by growers in the greenhouse vegetable industry. Hence it was necessary to construct a new set of climatological data files based on meteorological information of the areas more favoured by greenhouse vegetable growers. The climatological data was available in the form of hourly meteorological data, for Auckland (Mangere) and Christchurch (Airport), recorded between November 1969 and October 1974, which had been extensively checked and corrected (Leslie and Trethowen, 1977). This data was converted into a one year, five minute, incremental data base representing an average year.

- Time and Duration of the Season Simulated. The cropping season in this study was taken to consist of three cropping cycles per year, arranged as follows:

	Transplant Date	Simulation Start Date	Simulation End Date
Crop 1	January 5	January 26	April 26
Crop 2	May 4	May 25	August 23
Crop 3	August 30	September 20	December 19

Each crop cycle was assumed to last for 112 days from transplanting to end of harvest. It was assumed that since carbon dioxide enrichment would only affect the weight of leaves during the early vegetative phase of the plant, and not the leaf area, there would be little gain from enriching in this early period. It was also assumed that all treatments, at a particular location would have similar energy demands, during the initial 21 day period, hence simulation was started 21 days after transplanting for each cropping cycle. The simulation run for each cropping cycle then continued for 91 days until the end of harvest. By varying the parameters in this model it was possible to execute a set of model runs, for crop production with conventional climate control and no carbon dioxide injection, conventional control with carbon dioxide injection, and closed cycle control with carbon dioxide injection, for each location, and for three different crop cycles.

3.4.2 Cropping Method

The features of the growing system simulated in the model were as follows:

Physical aspects of the growing system

The greenhouse design chosen was a multispan venlo type with metal framing and single skin plastic cladding. Dimensions, 30m by 33m.

Plants were planted in 6 litre bags.

Number of plants in the greenhouse per crop was 1400, or 1.41 plants per m^2.

Cultural aspects of the growing system

Plants were trained under a *modified umbrella system*.

One fruit was allowed to form on the 10th to 27th nodes of the main stem, and all nodes of the laterals. Thus the total potential number of fruit harvested per plant was 78. In reality harvested numbers will be less than this due to fruit abortion, or the stems not developing at the maximum rate.

Plants were provided with adequate moisture and nutrients via a trickle irrigation system.

Plant health was maintained such that negligible damage occurred through the effects of insects or pathogens.

3.4.3 Execution of Model Runs

In order to provide a balanced comparison between capital and running costs of various carbon dioxide enrichment systems it was decided to structure the model execution sets in the following way:

Group 1. Control Greenhouse. For this set of model executions the parameters were set for a greenhouse with:

- conventional fan cooling.
- conventional electric heating with fans and heating coils.
- air circulation by clear perforated ducts
- no carbon dioxide control.

Hence there is one set of results per crop cycle for this group.

Group 2. Conventional Greenhouse with pulsed carbon dioxide enrichment between 8am and 5pm *(Conventional Pulsing Control)*. For this set the model parameters were:

- Conventional fan cooling.
- Conventional electric heating with fans and heating coils.
- Air circulation by clear perforated ducts
- Carbon dioxide enrichment with pure carbon dioxide at set-points of 350, 600, 900, and 1200 $\mu l.l^{-1}$ taking place only when no ventilation was occurring.

Hence there are four sets of results for this group.

Group 3. Closed Cycle Greenhouse with heat pump climate control and continuous carbon dioxide enrichment between 8am and 5pm *(Closed Cycle Control)*. For this execution set the model parameters were set as:

- closed cycle heat pump system for heating and cooling control.
- humidity control with *cold steam* vapour injection.
- carbon dioxide enrichment with pure carbon dioxide at set-points of 350, 600, 900, and 1200 $\mu l.l^{-1}$, and continuous enrichment.

Hence there are four sets of results for this group.

There are a total of 9 sets for all three groups, these simulations were carried out over three crop periods and for two locations. Hence the total number of sets is 54.

3.5 ANALYSIS OF OUTPUT FROM MODEL RUNS

As part of execution the komkom model provides values from a series of output variables.

Output from model executions was restricted to variables pertinent to analysis of results (including climate variables; consumption of carbon dioxide; energy requirements for heating, cooling, and air circulation; and crop growth parameters).

The data was then converted to a form suitable for importing into commercial spreadsheet software for analysis. Combined with information on market prices for capital equipment, running costs, and produce prices, and economic analysis was then carried out, including expected Marginal Annual Return and Internal Rate of Return.

4. Description of Model - Changes to *Cucumber*

This chapter describes in more detail the changes that were made to the *Cucumber* model to develop the *KOMKOM* model.

The control of the heating system, fan ventilation system, and CO_2 enrichment were handled in a procedure called *CONTROL*.

The simulation of the heat pump climate control system was handled by the procedure *REFRIG*.

For details on these procedures refer to the code listing in Appendix A1.

The conversion of meteorological data into boundary files was performed by a program called *KOMMET*.

The conversion of output from *KOMKOM* into a format suitable for analysis with a spread sheet was performed by a program called *FILCH*.

4.1 The Heating System

As explained in the previous chapter, for our purposes the *KOMKOM* model needed to be able to simulate the operation of an appropriately sized heating system for the greenhouse.

The heating system simulated is a two-stage system. The following table shows the control logic for the heating system simulation - see Table 4.1

Ambient Temp. °C, Ta	Heating Stage One	Heating Stage Two
Ta ≤ Theat - HDB	On	On
Ta ≤ Theat	On	Off
Ta ≥ Theat	On	Off
Ta ≥ Theat + HDB	Off	Off
Note: Theat = Heating Setpoint, HDB = Heating Deadband		

***Table 4.1** Control Logic for the Heating System Simulation.*

The Heat Capacities for the heating stages are as follows:

- Stage One: 90 kW
- Stage Two: 60 kW

4.2 The Cooling System

The cooling system simulated in *KOMKOM* is a positive pressure fan ventilation system with perforated duct distribution.

The fans are arranged in two banks, allowing for two stages of operation. The control logic for the fan ventilation simulation was as follows:

Ambient Temp. °C, Ta	Fan Ventilation Stage One	Fan Ventilation Stage Two
Ta $\leq$ Tvent - FDB	Off	Off
Ta $\leq$ Tvent	On	Off
Ta $\geq$ Tvent	On	Off
Ta $\geq$ Tvent + FDB	On	On
Note: Tvent = Fan Ventilation Setpoint, FDB = Fan Ventilation Deadband		

Table 4.2 *Control Logic for the Fan Ventilation System Simulation.*

The capacities of the fan ventilation stages were as follows:

- Fan ventilation stage one: 20 air changes per hour
- Fan ventilation stage two: 30 air changes per hour

4.3 Carbon Dioxide Enrichment

CO_2 enrichment took place in all simulations except the control. Enrichment was set to take place between the hours of 8am and 5pm. In case of simulations for greenhouses featuring conventional control, enrichment took place only when no fan ventilation was occurring and if the ambient CO_2 level was below setpoint. If these conditions were met, enrichment took place at 10 mg $CO_2.m^{-2}.s^{-1}$.

4.4 Heat Pump Climate Control

The model used for the heat pump system in the simulation of closed cycle climate control, is based on a verified dynamic model developed for simulating a water chilling refrigeration plant using R22 (Darrow, 1990). This model consists of a number of differential and algebraic equations which are solved by analytical solution of numerical methods.

The model was developed to predict three parameters of a water chiller:

- Tank water temperature
- Condensation temperature
- Refrigerant evaporation temperature

Darrow obtained further equations, used to describe enthalpy, gamma, pressure and temperature relationships and specific volume from data published by Cleland (Cleland, 1985).

Darrow made certain assumptions made in the development of the model:

- There was no pressure drop in the pipe work.

- There were no external heat gains or losses in the system.
- Water in the tank was mixed perfectly.
- Super heat was constant through each model run.

A schematic diagram of the refrigeration plant simulated is shown in figure 4.1.

For the purpose of this research Darrow's model was modified to calculate only the temperatures of the condenser and the evaporator, and the heat transfer rates from the condenser and the evaporator. The heat transfer rates could be either positive or negative depending on the mode of the heat pump, that is heating or cooling of the greenhouse atmosphere.

The resulting model was coded into ESL in a procedure called *REFRIG*. See Appendix A1 for details. *REFRIG* also contains calculations to determine the sensible and latent heat loadings, on the greenhouse environment, by the heat pump system.

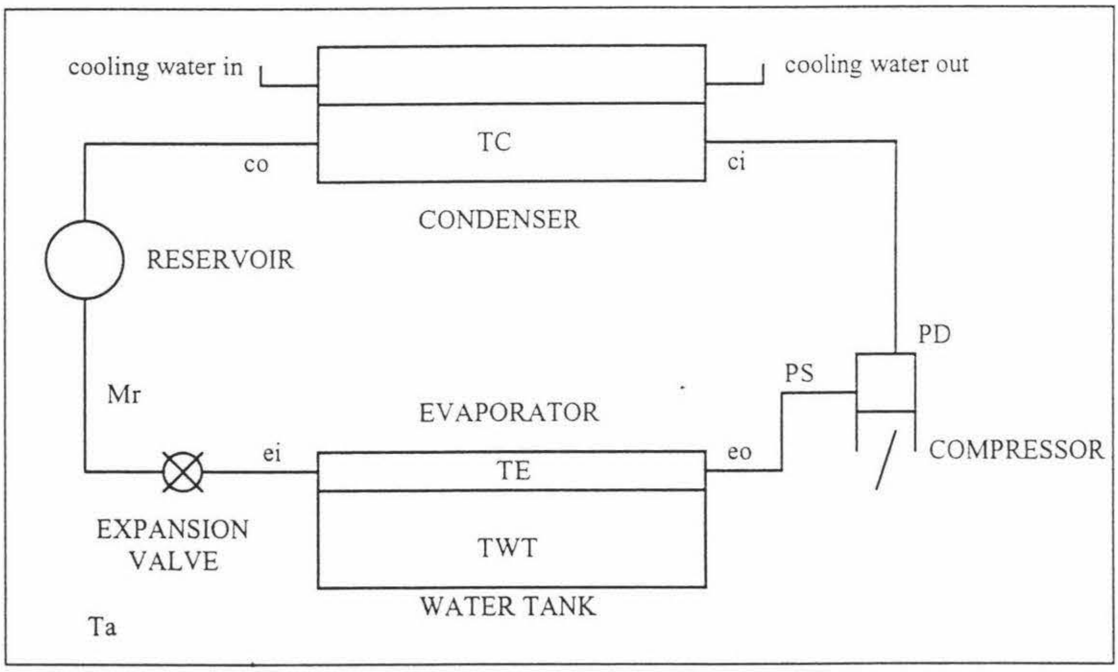

Figure 4.1 *Schematic Diagram of Darrow's Refrigeration Plant (Darrow, 1990)*

The calculations are carried out in the following steps:

1. Calculate the discharge and suction pressures:

$$Ps = \exp\frac{21.25384 - 2025.4518}{Tevap + 248.94}$$

where Tcond = Temperature of the condenser, °C; Tevap = Temperature of the evaporator, °C

2. Compression ratio;

$$CompRatio = \frac{Pd}{Ps}$$

3. Heat flow, ϕ;

$$dTC = Tcond - Tevap$$
$$G1 = 1.137423 - 1.50914 \times 10^{-3} \times Tevap - 5.59643 \times 10^{-6} \times Tevap^2$$
$$G2 = dTC\left(-8.74677 \times 10^{-6} \times Tevap - 1.4954710^{-7} \times Tevap^2\right)$$
$$G3 = 5.97029 \times 10^{-8} \times Tevap \times dTC^2 + 1.41458 \times 10^{-9} \times Tevap^2 \times dTC$$
$$G4 = 3.68417 \times 10^{-4} \times Superheat - 6.26076 \times 10^{-6} \times SuperHeat^2$$
$$G5 = 1.45839 \times 10^{-5} \times Tevap \times SuperHeat - 1.6573 \times 10^{-7} \times Tevap \times SuperHeat^2$$
$$G6 = -4.5258 \times 10^{-4} + G1 + G2 + G3$$
$$\phi = G6 \times (1 + G4 + G5)$$

where, *SuperHeat* = Vapour Superheat = 8.0 °C

4. Volumetric and mechanical efficiencies;

$$VolEff = 0.958 - 0.0327 \times CompRatio$$
$$MechEff = \frac{VolEff}{1.1}$$

In calculating the mechanical efficiency there is assumed to be a 10% loss due to factors not modelled.

5. Specific suction vapour volume;

$$V1 = \exp\left(-11.82344 + \frac{2390.321}{Tevap + 273.15}\right)$$
$$V2 = 1.01859 + 5.09433 \times 10^{-4} \times Tevap - 14.8464 \times 10^{-6} \times Tevap^2$$
$$V3 = V2 - 2.49547 \times 10^{-7} \times Tevap^3$$
$$V4 = V1 \times V3$$
$$V5 = 1 + 5.23275 \times 10^{-3} \times SuperHeat - 5.59394 \times 10^{-6} \times SuperHeat^2$$
$$V6 = 3.45555 \times 10^{-5} \times Tevap \times SuperHeat - 2.31649 \times 10^{-7} \times Tevap \times SuperHeat^2$$
$$V7 = 5.80303 \times 10^{-7} \times SuperHeat \times Tevap^2 - 3.20189 \times 10^{-9} \times Tevap^2 \times SuperHeat^2$$
$$SpecVol = V4 \times (V5 + V6 + V7)$$

6. Volumetric and Mass flow rates through compressor

$$VolFlow = SweptVol \times VolEff$$
$$MassFlow = \frac{VolFlow}{SpecVol}$$

where, SweptVol = 0.0292 for stage 1

0.0584 for stage 2

0.0292 for stage 3

7. Theoretical and Actual Compressor Power

$$PowerT = \frac{\phi}{\phi - 1} \times Ps \times SpecVol \times \left(Compratio^{\frac{\phi}{\phi-1}} - 1\right)$$

$$PowerA = \frac{PowerT}{MechEff}$$

8. Enthalpy of suction vapour

$$h1 = 250027.0 + 367.265 \times Tevap - 1.84133 \times Tevap^2 - 11.4556 \times 10^{-3} \times Tevap^3$$
$$h2 = 1.0 + 2.85446 \times 10^{-3} \times SuperHeat + 4.0129 \times 10^{-7} \times SuperHeat^2$$
$$h3 = 13.3612 10^{-6} \times Tevap \times SuperHeat - 8.11617 \times 10^{-8} \times Tevap \times SuperHeat^2$$
$$h4 = 14.1194 \times 10^{-8} \times SuperHeat \times Tevap^2 - 9.53294 \times 10^{-10} \times Tevap^2 \times SuperHeat^2$$
$$hevapo = h1 \times (h2 + h3 + h4) + 155482.0$$

9. The enthalpy of liquid entering the condenser

$$hcondi = hevapo + \frac{PowerT}{MassFlow}$$

10. Enthalpy of liquid leaving the condenser

The liquid leaving the condenser is assumed to be saturated

$$h5 = 1170.36 \times Tcond + 1.68674 \times Tcond^2 + 5.2703 \times 10^{-3} \times Tcond^3$$
$$hcondo = 200000.0 + h5$$

$$hevapi = hcondo$$

11. The heat flowrate from the evaporator and the condenser . These are equal to the mass flow rate multiplied by the difference in the enthalpy entering and leaving the evaporator and condenser respectively.

$$Qevap = MassFlow \times (hevapo - hevapi)$$
$$Qcond = MassFlow \times (hcondi - hcondo)$$

12a. If the heat pump is set to cool (Mode 1) then,

i) Calculate the heat flow rate from the evaporator by dividing the difference between the greenhouse ambient temperature and the evaporator temperature by the heat transfer coefficient of the evaporator.

$$Qevape = (Ta - Tevap) \times UAi$$

ii) Calculate the heat flow rate from the condenser by dividing the difference between the condenser temperature and the outside temperature by the heat transfer coefficient of the condenser.

$$Qconde = (Tcond - To) \times UAo$$

12b. Else, heat pump is set to heat (Mode 0)

i) Calculate the heat flow rate from the evaporator by dividing the difference between the evaporator temperature and the outside temperature the heat transfer coefficient of the condenser.

$$Qevape = (To - Tevap) \times UAo$$

ii) Calculate the heat flow rate from the condenser by dividing the difference between the greenhouse ambient temperature and the condenser by the heat transfer coefficient of the evaporator.

$$Qconde = (Tcond - Ta) \times UAi$$

13. Calculate the error for this differential step

$$Errore = Qevap - Qevape$$
$$Errorc = Qcond - Qconde$$

The loop is terminated if the error is less than 0.01, jumps to step 16.

If not then the procedure continues to the next step.

14. Increase the heat flow rates based on enthalpy by half the error

$$Qevap = Qevape + \frac{Errore}{2}$$
$$Qcond = Qconde + \frac{Errorc}{2}$$

15a. If the heat pump is set to cool (Mode 1) then;

i) Set the evaporator temperature to difference between the greenhouse ambient temperature and, the ratio of the heat flow rate of the evaporator and the heat transfer coefficient of the evaporator.

$$Tevap = Ta - \frac{Qevap}{UAi}$$

ii) Set the condenser temperature to the sum of the outside temperature, and the ratio of the heat flow rate of the condenser and the heat transfer coefficient of the condenser.

$$Tcond = To + \frac{Qcond}{UAo}$$

15b. Else, the heat pump is set to heat (Mode 0) then;

i) Set the evaporator temperature to the difference between the outside temperature, and the ratio between the heat flow rate from the evaporator and the heat transfer coefficient of the condenser.

$$Tevap = To - \frac{Qevap}{UAo}$$

ii) Set the condenser temperature to the sum of the greenhouse temperature, and the ratio between the heat flow rate from the condenser and the heat transfer coefficient of the evaporator.

$$Tcond = Ta + \frac{Qcond}{AUi}$$

16. Calculate sensible and latent heat components

i) Enthalpy of the inside air

$$Ha1 = Ta \times (Phia + Xa \times Cpv) + Xa \times 2501$$

$$Ha2 = Ha1 - CircRate \times \frac{Qevap}{da}$$

where; Phia = the thermal capacity of the dry fraction of the inside air per unit floor area

Xa = the moisture concentration of the inside air per unit floor area

Cpv = the specific heat capacity of water vapour

da = average depth (height) of the greenhouse inside airspace

$$pevap = 611.0 \times \exp\left(\frac{17.27 \times Tevap}{Tevap + 237.3}\right)$$

$$rhoevap = Ma \times \frac{P - pevap}{R \times (Tevap + 273.15)}$$

$$Xevap = \frac{rhoevap \times da \times Mw \times pevap}{Ma \times (P - pevap)}$$

$$Hevap = Tevap \times (Cpa \times rhoevap \times da + Xevap \times Cpv) + Xevap \times 2501$$

where; pevap = vapour pressure of the air at the evaporator

rhoevap = density of dry air at the evaporator

Ma = Molecular mass of dry air

Mw = Molecular mass of water

Xevap = concentration of moisture on the evaporator

Hevap = enthalpy of the air at the evaporator

ii) Compare the ratio between the inside and the evaporator enthalpies, set the ratio to a minimum of 0.0 or a maximum of 1.0

$$CF = \frac{Ha1 - Ha2}{Ha1 - Hevap}$$

IF CF > 1.0 THEN CF = 1.0

IF CF < 0.0 THEN CF = 0.0

iii) Calculate the new moisture concentration of the inside air based on the moisture concentration of the inside air before the effect of the heat pump is taken into account, and the moisture concentration of the air at the evaporator.

$$Xa2 = Xa - CF \times (Xa - Xevap)$$

iv) Calculate the rate of heat loss, and the rate of moisture loss through the heat pump, based on the heat pump mode (i.e. cooling or heating).

- If the heat pump is in cooling mode (Mode 1) then

$$Qref = \frac{Qevap}{Af}$$

$$fref = \frac{CircRate}{da} \times \frac{Xa - Xa2}{Af}$$

IF fref < 0.0 THEN fref = 0.0

- Else the heat pump is in heating mode, and

$$Qref = \frac{-Qcond}{Af}$$

$$fref = 0.0$$

This model was used to simulate the heat pump climate control system which was split into 3 banks of 102 kW, 204 kW, and 104 kW respectively, or 409.7 kW @ 25.8 °C T.D. (Temperature Differential - between refrigerant and air temperature) collectively.

Control of the heat pump banks was as follows (CDB1 and CDB2 are the first and second dead-band respectively):

<u>In Mode 1 - Cooling Mode</u>

Ambient Temp. °C, Ta	Cooling Stage One	Cooling Stage Two	Cooling Stage Three
Ta > Tcool	On	Off	Off
Ta > Tcool + CDB1	On	On	Off
Ta > Tcool + CDB1 + CDB2	On	On	On
Ta < Tcool + CDB1	On	On	Off
Ta < Tcool	On	Off	Off
Ta < Tcool - CDB1	Off	Off	Off
Tcool = Cooling set-point			

In Mode 0 - Heating Mode

Ambient Temp. °C, Ta	Heating Stage One	Heating Stage Two	Heating Stage Three
Ta < Theat	On	Off	Off
Ta < Theat - CDB1	On	On	Off
Ta < Theat - CDB1 - CDB2	On	On	On
Ta > Theat - CDB1	On	On	Off
Ta > Theat	On	Off	Off
Ta > Theat + CDB1	Off	Off	Off
Theat = Heating set-point			

4.5 Humidity Control

As explained in the previous chapter, it was found that the closed cycle climate control system caused high rates of moisture removal during cooling. Hence it was necessary to implement a form of humidity control. This was accomplished by injecting water at a fixed rate of 0.1 $g.m^{-2}.s^{-1}$ when the inside relative humidity dropped below setpoint (60% RH).

4.6 Air Circulation

During simulation air stratification was assumed to be negligible.

4.7 Climatological Data

As explained, the climatological data available was in the form of hourly data for two sites, Auckland (Mangere) and Christchurch (Airport). The data was structured as shown in table 4.2

74 11 20 5 20 92 10 12 6 33 37 246

YY MM DD HH DBT RH WS WD CC DRH DFH DIN

where, YY = Year
- MM = Month
- DD = Day
- HH = Hour
- DBT = Dry Bulb Temperature, °C x 10
- RH = Relative Humidity, %
- WS = Windspeed, knots
- WD = Wind Direction, to 16 compass points
- CC = Cloud Cover, on a scale of 0 - 8 (0 = cloudless)
- DRH = Direct Irradiance on a Horizontal surface, $W.m^{-2}$
- DFH = Diffuse Irradiance on a Horizontal surface, $W.m^{-2}$
- DIN = Direct Irradiance on a surface Normal to the solar beam, $W.m^{-2}$

Table 4.2 *Structure of met data (Leslie and Trethowen, 1977)*

From the data the average year chosen was 1971.

As the data was not in a format directly compatible with the *KOMKOM* model, it had to be converted. The conversion was carried out using a program written by the author in the *PASCAL*® programming language. The code for this program, called *KOMMET*, can be found in Appendix A2.

KOMMET performed the following tasks:

1. Converting the month and day data into Julian Day data.
2. Calculating wet bulb temperature from the dry bulb temperature and the relative humidity.
3. Convert the wind speed data from knots to $km.hr^{-1}$
4. Converting the cloud cover factor to a cloud cover fraction.
5. Calculating total global solar radiation on the horizontal, from the direct and diffuse irradiance on the horizontal.
6. Calculate the solar altitude and azimuth from the Julian day and location data.
7. Converting the hourly interval data into 5 minute interval data through linear interpolation.
8. Converting the total data base into boundary files representing a week each, hence 52 boundary files were created in total for each location, Auckland and Christchurch.

4.8 *Converting* KOMKOM *output*

KOMKOM uses many variables to describe the state of the system at any stage during the simulation. For the purpose of analysis it is important to select key variables which describe aspects of the system performance we are interested in. Hence, representative variables were chosen to be recorded and stored in data files for later manipulation at the analysis stage.

The data stored were grouped into three types:

COND - contains hourly data describing the physical state of the greenhouse atmosphere, hourly energy consumption by environmental modification equipment.

DDAT - contains daily data describing plant growth characteristics.

LEAF - contains daily data describing plant yield and daily energy consumption by environmental modification equipment.

As the model generally updates variables in steps of 5 minute intervals it was necessary to modify output from the model of the key variables to hourly and daily data. This was done by calculating the hourly / daily average or sum of each key variable, where appropriate.

The key variables chosen and their units are shown in the tables 4.3, 4.4, and 4.5.

Variable	Units
The Julian day	day
The hour of the day	hr
Average hourly internal temperature	°C
Average hourly internal CO_2 content	ppm
Average hourly relative humidity	%
Total hourly fan run (conventional system)	min/hr
Total hourly heater output (conventional system)	kW/hr
Total hourly CO_2 injection	mg/hr
Total hourly compressor output (closed cycle control system)	kW/hr
Total hourly gross photosynthesis	mg CO_2/m^2.hr
Total hourly maintenance respiration	mg CO_2/m^2.hr
Total hourly growth respiration	mg CO_2/m^2.hr

Table 4.3 Review of hourly based data file variables (data file COND)

Variable	Units
Julian day	day
Daily gross photosynthesis	mg CO^2/m^2.day mg
Daily maintenance respiration	CO_2/m^2.day
Daily growth respiration	mg CO_2/m^2.day
Daily weight of fruit	mg DM/plant
Daily weight of leaves	mg DM/plant
Daily weight of stems	mg DM/plant
Daily weight of roots	mg DM/plant
Daily specific leaf area (SLA)	-
Daily Leaf Area Index (LAI)	-

Table 4.4 Review of daily based data file variables (data file DDAT)

Variable	Units
Julian day	day
Daily internal light level	MJ/m^2
Average daily temperature	°C
Total leaf area	m_2/plant
Daily number of fruit aborted	number
Daily number of fruit harvested	number
Daily weight of fruit harvested	mg DM/plant
Daily total fan run (conventional control)	min/day
Daily total heat output (conventional control)	kW/day
Daily total CO_2 injected	mg/day
Daily total compressor output	kW/day

Table 4.6 Review of daily based data file variables (data file LEAF)

KOMKOM created a data file of each type for each week simulated. A sample of actual data output from *KOMKOM* is shown in figure 4.2.

333.0	34041.08	1314.985	7636.58	28602.6	20513.7	3387.2	4403.3	1.199	3.452
334.0	50614.26	1459.806	11073.63	45858.5	20531.7	3389.6	4406.4	1.201	3.464
335.0	55861.67	1797.936	13323.99	66618.1	20074.1	3391.9	4409.4	1.204	3.384
336.0	23472.38	1397.372	4854.99	74189.0	19986.7	3380.5	4394.7	1.209	3.415
337.0	47033.06	1420.249	8991.28	33207.7	19969.2	3380.5	4394.6	1.221	3.408
338.0	53243.14	1493.257	11161.84	50613.8	19934.4	3376.7	4389.6	1.221	3.409
339.0	56661.59	1797.870	11367.90	68338.1	19395.5	3369.7	4380.5	1.225	3.330

Figure 4.2 Example of data file DDAT output produced by KOMKOM.

As there are 13 weeks in each crop period simulated (91 days) this meant each simulation run produced 3 x 13 = 39 data files which would subsequently need to be analysed.

In order to reduce the number of data files and to change the data file format into one delimited for import into a spreadsheet, a program was written in the *GWBASIC®* programming language, called *FILCH* (FILe Change).

FILCH appended each set of 13 data files of a particular type, into one file. At the same time changing the format to suit the spreadsheet package used for analysis. A sample of the output produced by *FILCH* is shown in figure 4.3

Once each formatted data file was imported into the spreadsheet, the data could then easily be analysed and graphs printed showing trends in the key variables over the 91 days simulated.

An example of such a graph is shown in figure 4.4. This graph shows the changes in plant *Specific Leaf Area* (SLA) and *Leaf Area Ratio* (LAI) during the crop 3 period for a closed cycle cooled greenhouse enriched to 600 ppm situated in Christchurch.

Once all model runs were completed, and all data collected the results were analysed. A description of this analysis is given in the following chapter.

Day	FGrDave	FReDave	FCODave	WFruit	WLeaf	WStem	WRoot	SLA	LAI
263	784.46	23.422	33.1	0	843.4	109.5	142.4	0.462	0.088
264	1978.31	39.885	320.23	0	1355.6	190.9	248.2	0.426	0.082
265	631.73	44.14	4.77	0	1365	192.2	249.8	0.430	0.092
266	234.55	38.121	36.77	0	1437	201.5	262	0.459	0.114
267	533.07	43.48	80.11	0	1520.9	221.9	288.4	0.512	0.110
268	135.72	44.302	4.67	0	1530	223.1	290	0.515	0.147
269	749.2	60.333	132.12	0	1698.6	256.6	333.6	0.585	0.143

Figure 4.3 *Example of data file DDAT after formatting with* FILCH.

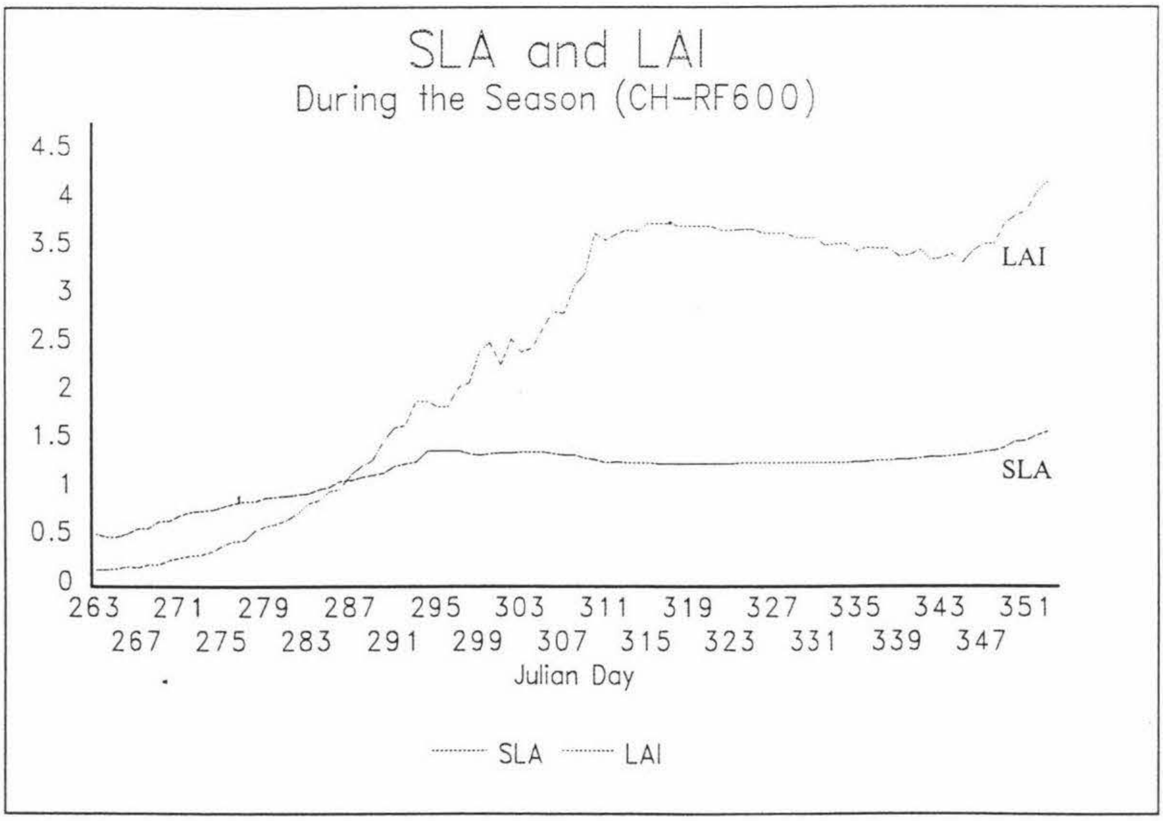

Figure 4.4 *Example of graphical representation of information in data file DDAT.*

5. RESULTS - ANALYSIS

Once the simulation runs were completed and the appropriate data files created, the results were analysed using commercially available spreadsheet software.

The results were analysed for the following aspects of enrichment.

- ENVIRONMENT
- Average Internal Greenhouse CO_2 Concentration
- CO_2 Consumption
- Electricity Consumption
- VARIATION IN CROP FACTORS
- Effect On Fruit Weight
- Effect on Fruit Number
- Fruit number harvested as a function of average carbon dioxide concentration
- Fruit number harvested and aborted as a function of carbon dioxide set-point

5.1 ENVIRONMENT

For a complete analysis of the effects of enrichment it is important to also include:

- Average internal greenhouse CO_2 concentration
- Amount of CO_2 used for enrichment
- Average internal greenhouse temperature
- Quantity of electricity used

5.1.1 Average Internal Greenhouse CO_2 Concentration.

The greenhouse modelled was enriched between the hours of 8 am and 5 p.m. During this period the greenhouse CO_2 level was expected to vary with plant activity and, in case of the conventionally controlled greenhouse, ventilation frequency and rate.

As explained, in order for the crop to gain maximum benefit from CO_2 enrichment, the crop must be exposed to a carbon dioxide level optimal for plant growth, and this level should remain as constant as possible. Obviously, where a greenhouse is cooled with conventional fan ventilation (*conventional pulsing control*), the carbon dioxide level inside the greenhouse is expected to vary significantly more than in a greenhouse with *closed cycle control* (no ventilation required).

In order to confirm this supposition, the average internal CO_2 level inside the greenhouse was analysed between the hours of 8am and 5pm (when enrichment took place).

The graphs in Figures 5.1, 5.2, and 5.3 show the actual average greenhouse carbon dioxide concentration (between 8am and 5pm) versus the set-point for crops 1, 2, and 3 respectively for a greenhouse located in Auckland. The Figures 5.4, 5.5, and 5.6 show the same for Christchurch.

On the graphs points are shown with horizontal bars indicating the mean greenhouse CO_2 concentration achieved (during the hours of enrichment), with the value of the mean shown beside the points. Also shown for each set-point is the variation in greenhouse CO_2 concentration using high-low bars. The bars show variation to one standard deviation either side of the mean.

The graphs can be analysed for three different effects:

- Effect due to method of control
- Effect due to season
- Effect due to location

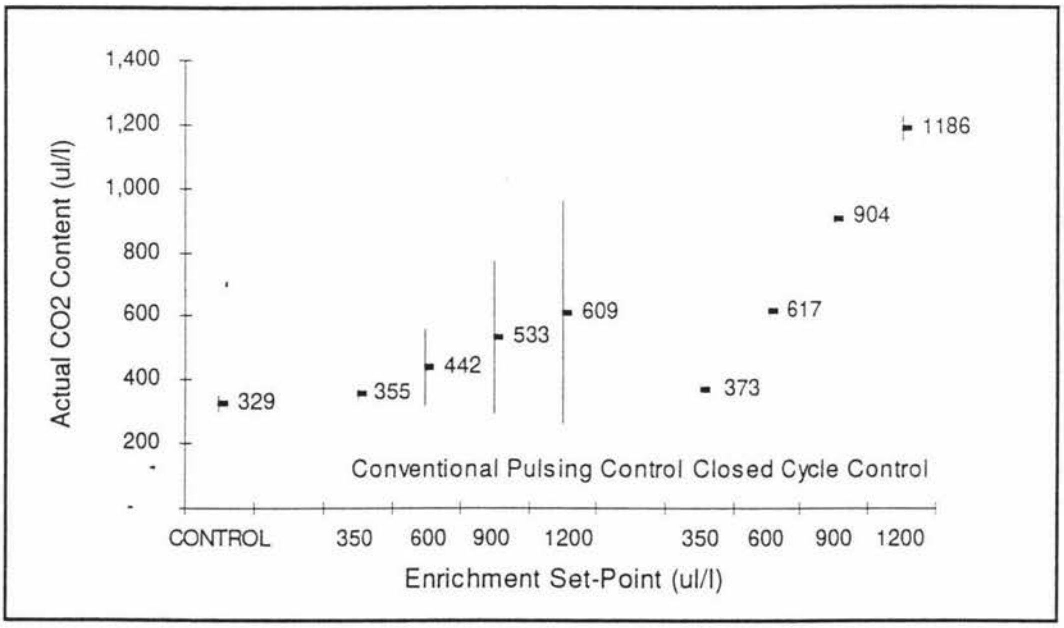

Figure 5.1 Average Greenhouse Carbon Dioxide Concentration, between 8am and 5pm, versus set-point for crop 1 (26 January to 26 April), AUCKLAND.

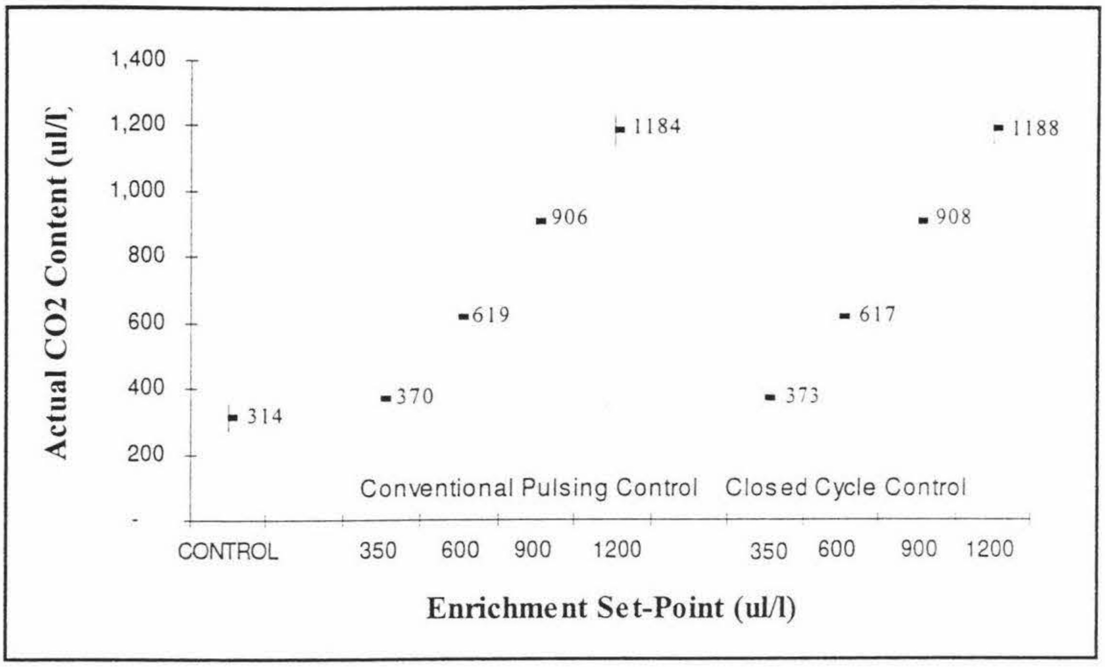

Figure 5.2 *Average Greenhouse Carbon Dioxide Concentration, between 8am and 5pm, versus set-point for crop 2 (25 May to 23 August), AUCKLAND.*

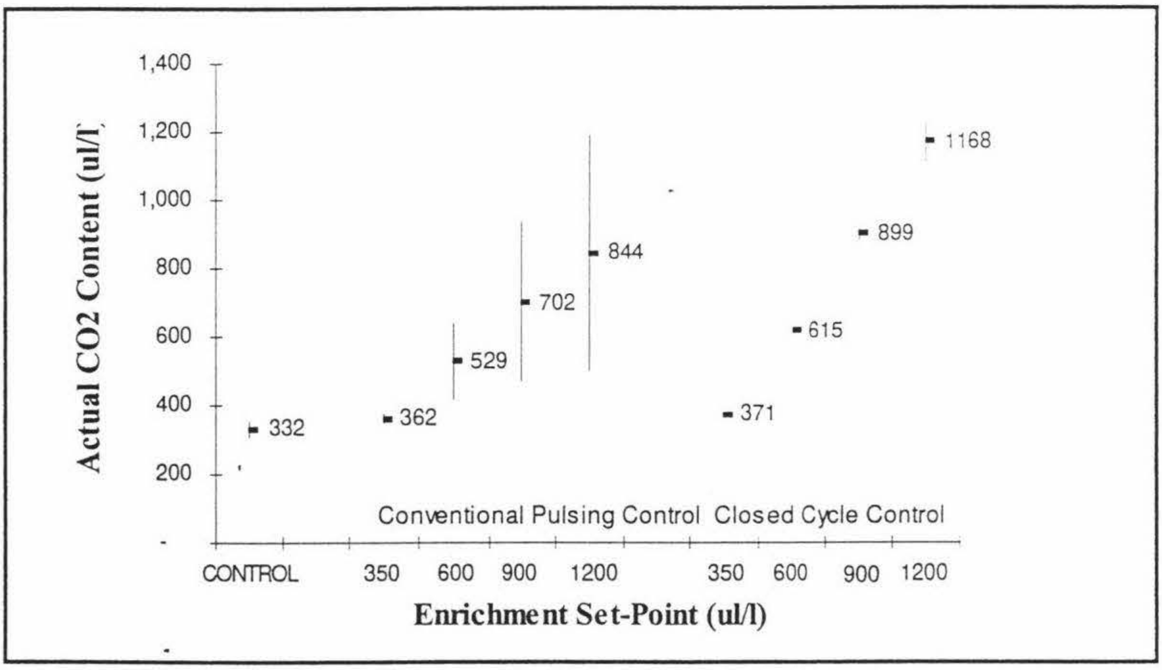

Figure 5.3 *Average Greenhouse Carbon Dioxide Concentration, between 8am and 5pm, versus set-point for crop 3 (20 September to 19 December), AUCKLAND.*

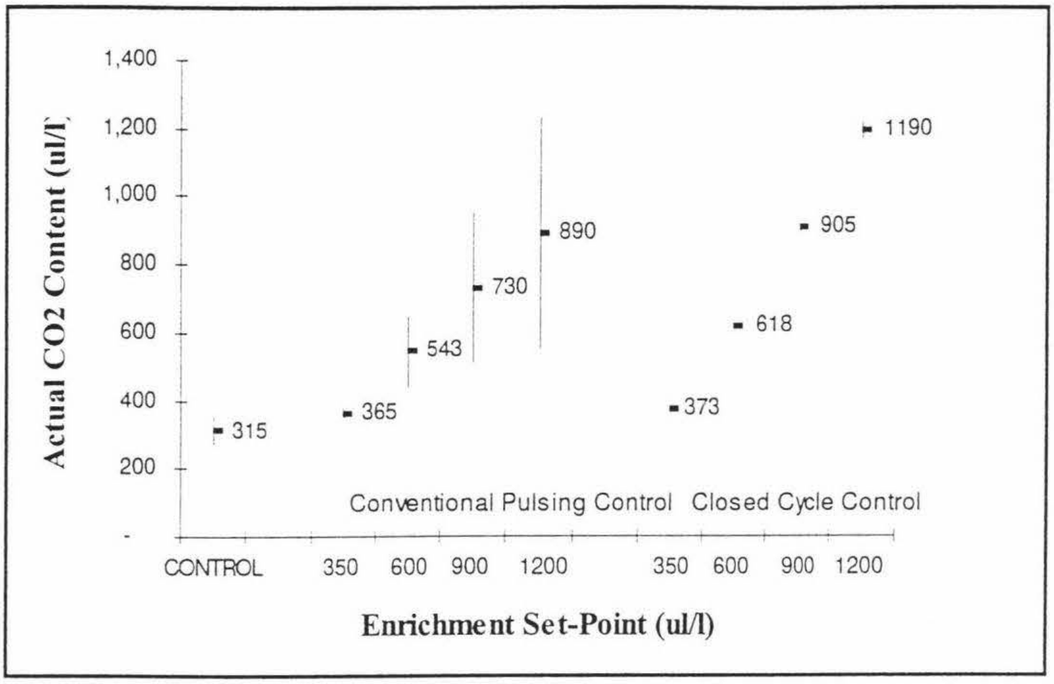

Figure 5.4 *Average Greenhouse Carbon Dioxide Concentration, between 8am and 5pm, versus set-point for crop 1 (26 January to 26 April), CHRISTCHURCH.*

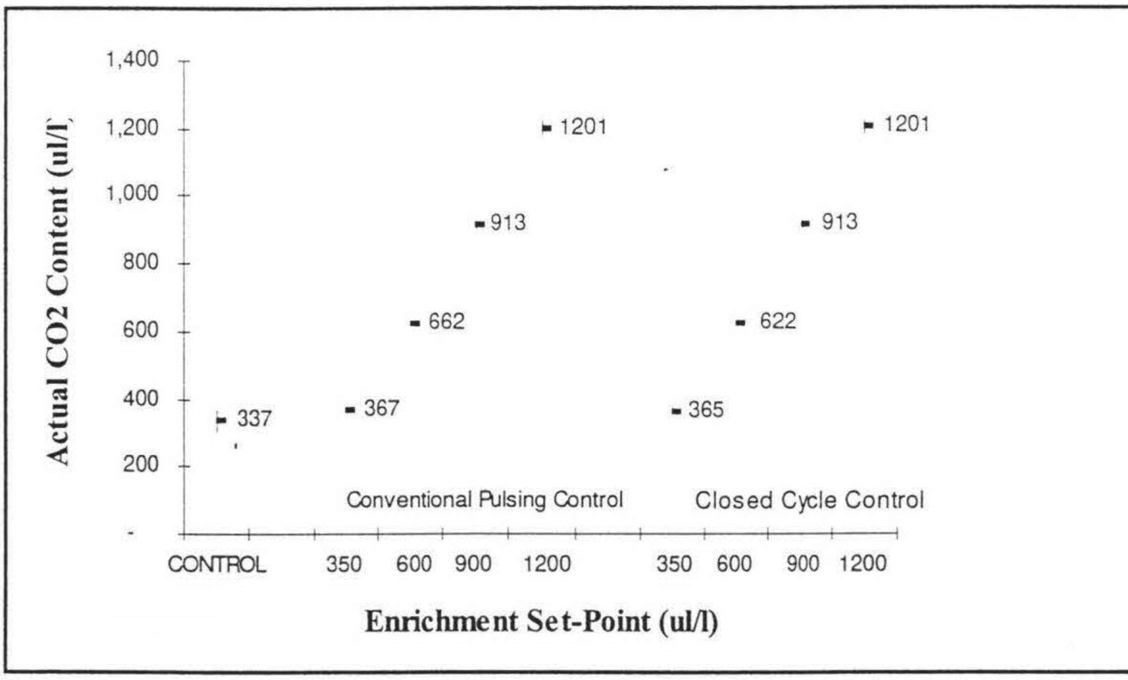

Figure 5.5 *Average Greenhouse Carbon Dioxide Concentration, between 8am and 5pm, versus set-point for crop 2 (25 May to 23 August), CHRISTCHURCH.*

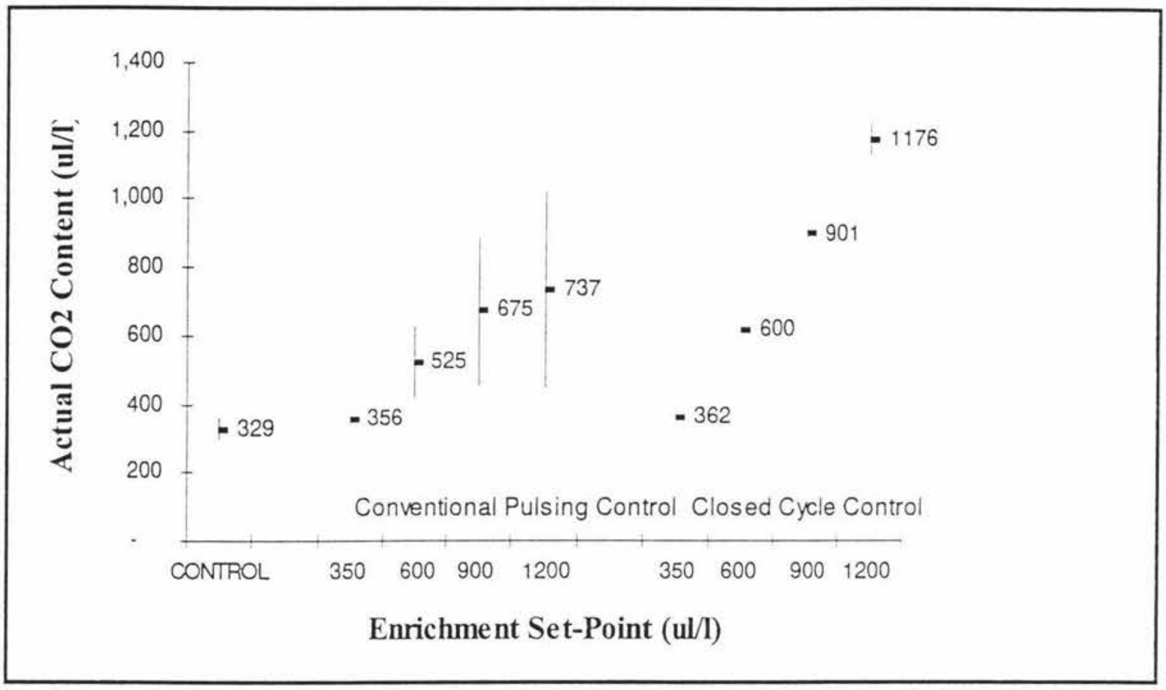

Figure 5.6 Average Greenhouse Carbon Dioxide Concentration, between 8am and 5pm, versus set-point for crop 3 (20 September to 19 December), CHRISTCHURCH.

Effect due to method of control.

Firstly looking at the graph in figure 5.1 the following can be noted.

In Auckland, for conventional control, the graph shows two main characteristics:

- A non-linear relationship between set-point and mean CO2 concentration.
- Increasing variation in average CO2 concentration with increasing set-point, particularly above the 350 µl/l set-point .

For closed cycle control there is a close correlation between set-point and mean CO2 concentration, with little variation from the mean at all setpoints.

These same characteristics are shown in the graph in Figure 5.3.

Effect due to season.

The effect due to season is best illustrated by comparing the graphs in Figures 5.1 and 5.3 with the graph in Figure 5.2.

The following can be shown: the graph in Figure 5.2 shows close correlation between set-point and mean CO2 concentration for both closed cycle and conventional control. This means a similar level pf control is achieved, with either system, during the second crop period. This is quite distinct from the level of controlled achieved by conventional control in crop 1 or crop 3 (Figures 5.1 and 5.3 respectively).

Effect due to Location

When comparing the trends in the graphs for Christchurch, shown in Figures 5.4 to 5.6 the following can be noted:

- Mean CO2 concentrations during all three crops show very similar trends to the same crop periods in Auckland, for both conventional control and closed cycle control.
- During crop 1 (Figure 5.4), with conventional control the greenhouse in Christchurch can maintain a mean CO2 concentration closer to set-point than the same greenhouse in Auckland (Figure 5.1). This relationship is reversed during crop 3, compare Figures 5.6 and 5.3.

The results are also shown in Table 5.1 for clarity.

TREATMENT		CROP 1 Mean	CROP 1 Standard Deviation	CROP 2 Mean	CROP 2 Standard Deviation	CROP 3 Mean	CROP 3 Standard Deviation
AUCKLAND							
Pulsing Control	control	329	25	314	42	332	23
	350	355	15	370	8	362	14
	600	442	119	619	5	529	112
	900	533	237	906	13	702	233
	1200	609	349	1,184	46	844	346
Closed Cycle Control	350	373	5	373	5	371	6
	600	617	5	617	5	615	6
	900	904	12	908	13	899	14
	1200	1,186	36	1,188	46	1,168	58
CHRISTCHURCH							
Pulsing Control	control	315	43	337	32	329	33
	350	365	13	367	8	356	11
	600	543	104	622	4	525	103
	900	730	220	913	10	675	217
	1200	890	340	1,201	21	737	286
Closed Cycle Control	350	373	5	365	7	362	4
	600	618	4	622	4	616	5
	900	905	11	913	10	901	12
	1200	1,190	24	1,201	21	1,176	45

Table 5.1 Average greenhouse carbon dioxide concentration, between 8am and 5pm, versus set-point. For all treatments, during three crop periods, and in two locations.

5.1.2 CO_2 Consumption.

An analysis CO_2 consumption versus the set-points for the two types of control at Auckland and Christchurch and for the three different crop periods is shown in Figures 5.7 to 5.9.

The graphs illustrate four different effects:

- Effect due to enrichment set-point
- Effect due to method of control
- Effect due to location
- Effect due to season

The effects will now be described:

Effect due to Enrichment Set-Point

Not surprisingly, the graphs show an increase in carbon dioxide consumption with each increase in enrichment set-point. This effect is apparent with either method of control, during each crop cycle, and at either location.

Effect due to method of control

AUCKLAND

Greenhouse simulations in Auckland show a higher consumption of carbon dioxide with closed cycle control compared with pulsing control during crops 1 and 3. The reverse is true during crop 2, when the carbon dioxide consumption with pulsing control slightly exceeds carbon dioxide consumption with closed cycle control.

CHRISTCHURCH

During crop 1 greenhouse simulations in Christchurch show marginally higher carbon dioxide consumption in closed cycle control compared with pulsing control. During crop 2 there is no significant difference in carbon dioxide consumption between the two methods of control.

During crop 3, however, carbon dioxide consumption in the greenhouse simulation using pulsing control show a significantly higher carbon dioxide consumption than the simulation using closed cycle control, at enrichment set-points above 350 ppm.

Effect due to Location

There is a distinct effect due to location shown in the graphs.

This effect can be attributed entirely to location and the local climatic conditions, as all other parameters in the simulations are kept equal.

During crops 1 and 3, simulations for Auckland show a consistently lower carbon dioxide consumption than Christchurch, with conventional control; and a consistently higher carbon dioxide consumption with closed cycle control. The differences become more pronounced as set-point increases.

The same pattern is shown during crop 2 with closed cycle control. However, with conventional control, simulations in Auckland show consistently higher carbon dioxide consumption than simulations in Christchurch.

Effect due to Season

The effect due to season is distinct; the quantity of carbon dioxide consumed occurs in the following order: the greatest quantity is during crop 3, then crop 1 and the least during crop 2.

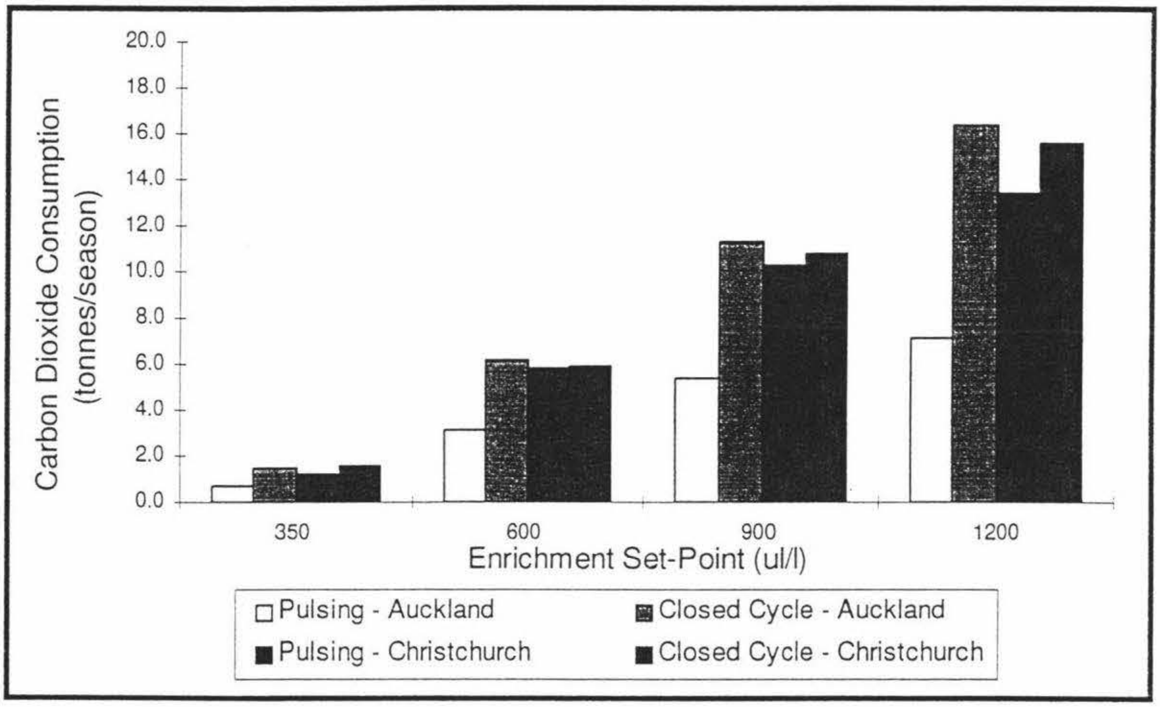

Figure 5.7 Seasonal Carbon Dioxide Consumption versus set-point, for crop 1 (26 January to 26 April).

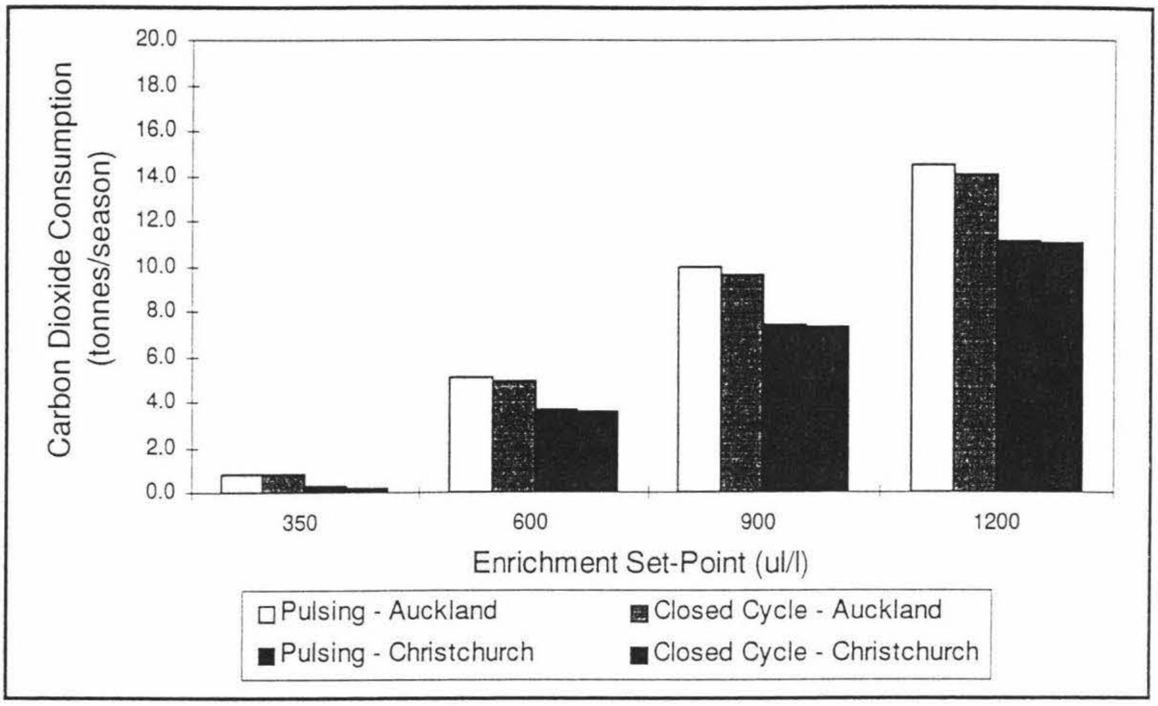

Figure 5.8 *Seasonal Carbon Dioxide Consumption versus set-point, for crop 2 (25 May to 23 August).*

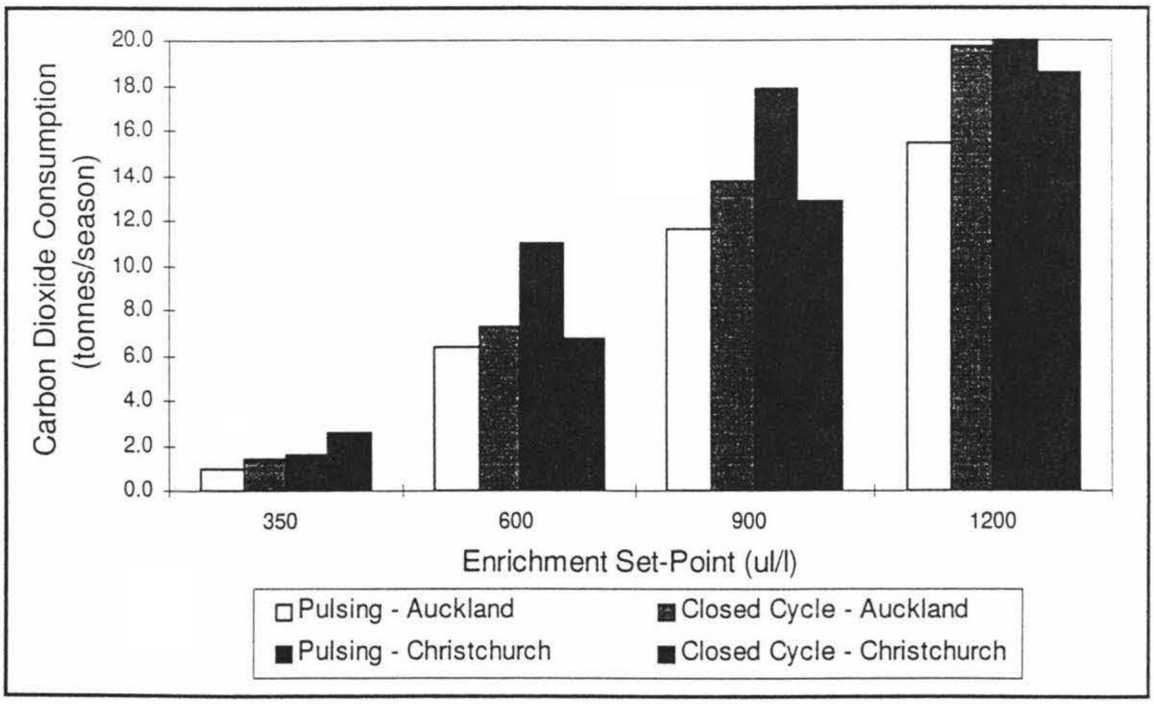

Figure 5.9 *Seasonal Carbon Dioxide Consumption versus set-point, for crop 3 (20 September to 19 December).*

5.1.3 Electricity Consumption

With two very different methods of climate control it is expected that there will be differences in energy consumption between simulations of conventional control and closed cycle control.

The two different systems of environment control will inherently vary in their power requirements and the distribution of total power consumption between heating and cooling.

The simulated electricity consumption for the various treatments is shown in graphs 5.10 to 5.13.

The first two graphs show electricity consumption for simulations in Auckland, the last two for Christchurch.

Exploring, again, the following effects:

- Effect due to enrichment set-point
- Effect due to method of control
- Effect due to season
- Effect due to location

Effect due to Enrichment Set-Point

The effect due to enrichment set-point is not shown to be significant in any treatment simulation.

Effect due to Method of Control

Looking at Figures 5.10 and 5.12, and comparing electricity use for cooling with the two methods of control it can be seen that conventional control demands an almost insignificant amount of energy compared with closed cycle control. Except during crop 2 where very little cooling takes place with either method of control.

When studying the energy requirement for heating (Figures 5.11 and 5.13), however, shows that conventional control uses more energy than closed cycle control, although the differences in energy requirements are not as great as with cooling.

Effect due to Season

In Auckland, crop 1 has the highest cooling requirement followed by crop 3, with crop 2 having a very low cooling requirement.

Not unexpectedly, the reverse is true for the heating requirement of the crops in Auckland. Crop 2 has a very high heating requirement, followed by crop 3, with crop 1 having a very low heating requirement.

In Christchurch, crop 3 has the highest energy requirement for cooling followed by crop 1. Crop 2 has no, or an insignificant, energy requirement for cooling.

The energy requirement for heating in Christchurch is very high during crop 2, followed by crop 3 and then crop 1. Energy requirement for the latter two crop periods are significantly lower than for crop 2.

Effect due to Location

First of all, when comparing energy requirements for cooling at Auckland and Christchurch (Figures 5.10 and 5.12) it can be seen that these are higher for Auckland than for Christchurch, during crops 1 and 2. During crop 3 there is no significant difference in energy requirement for cooling between the two sites.

Secondly, when comparing energy requirements for heating at the two sites (Figures 5.11 and 5.13) it is clear that in all cases there is a higher requirement in Christchurch compared with Auckland.

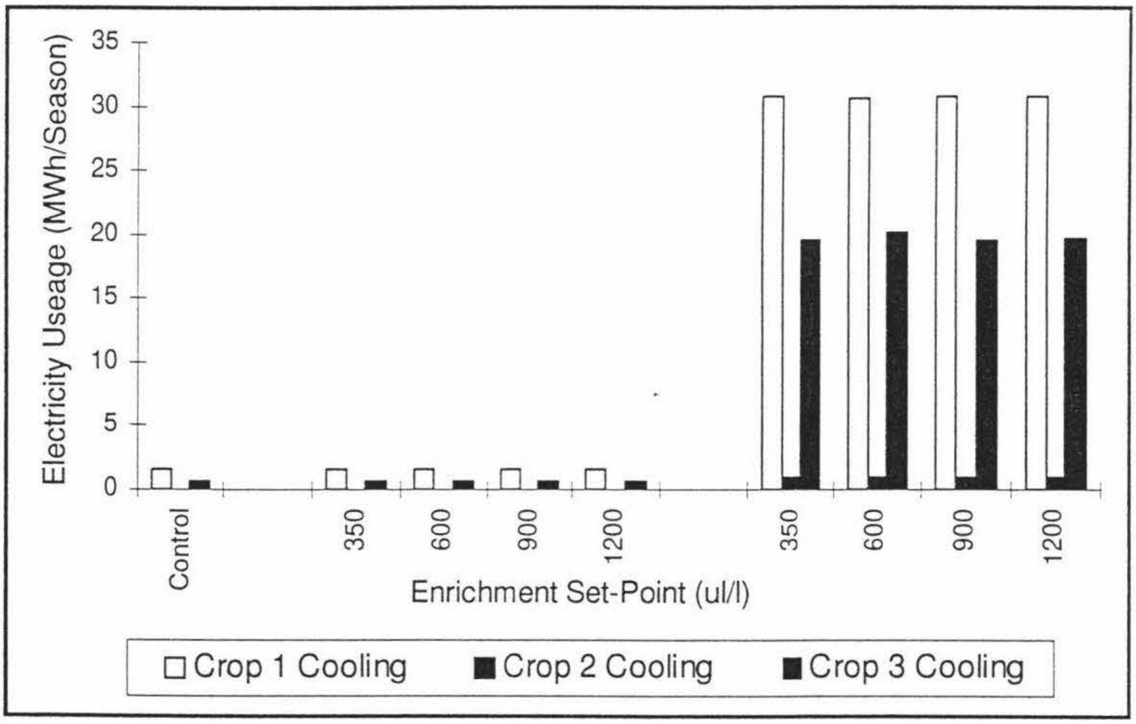

Figure 5.10 Electricity consumption for cooling as a function of greenhouse control, CO_2 set-point, and crop. Auckland.

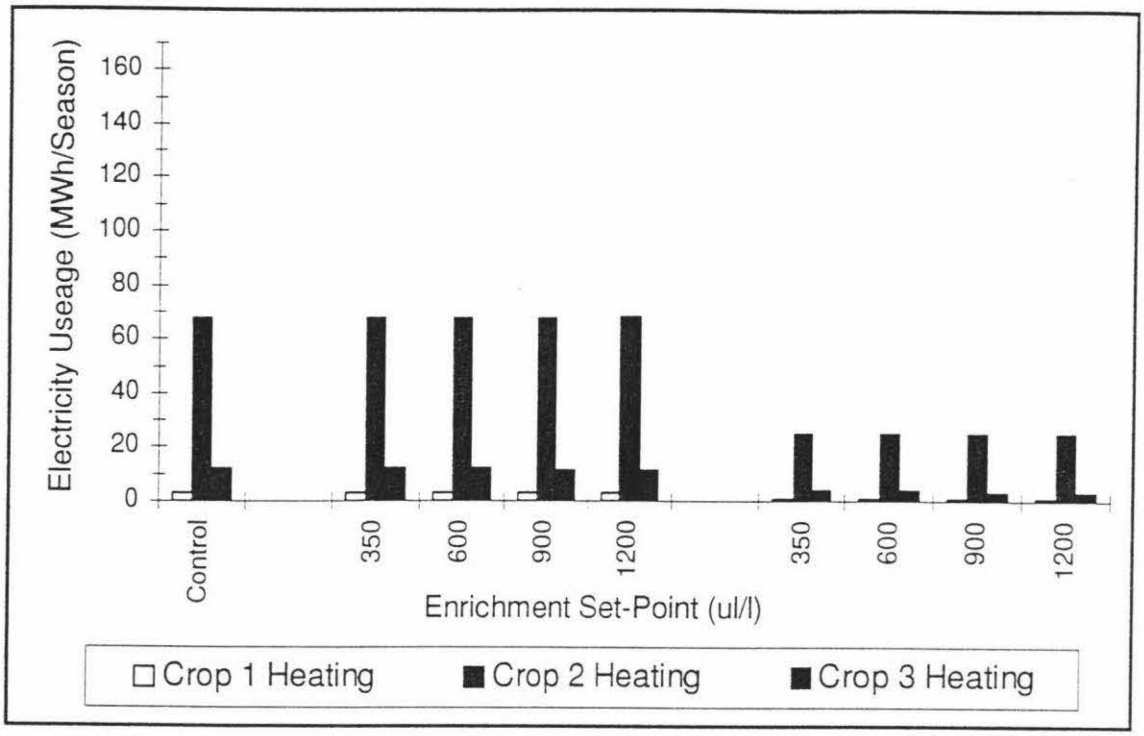

Figure 5.11 *Electricity consumption for heating as a function of greenhouse control, CO_2 set-point, and crop. Auckland.*

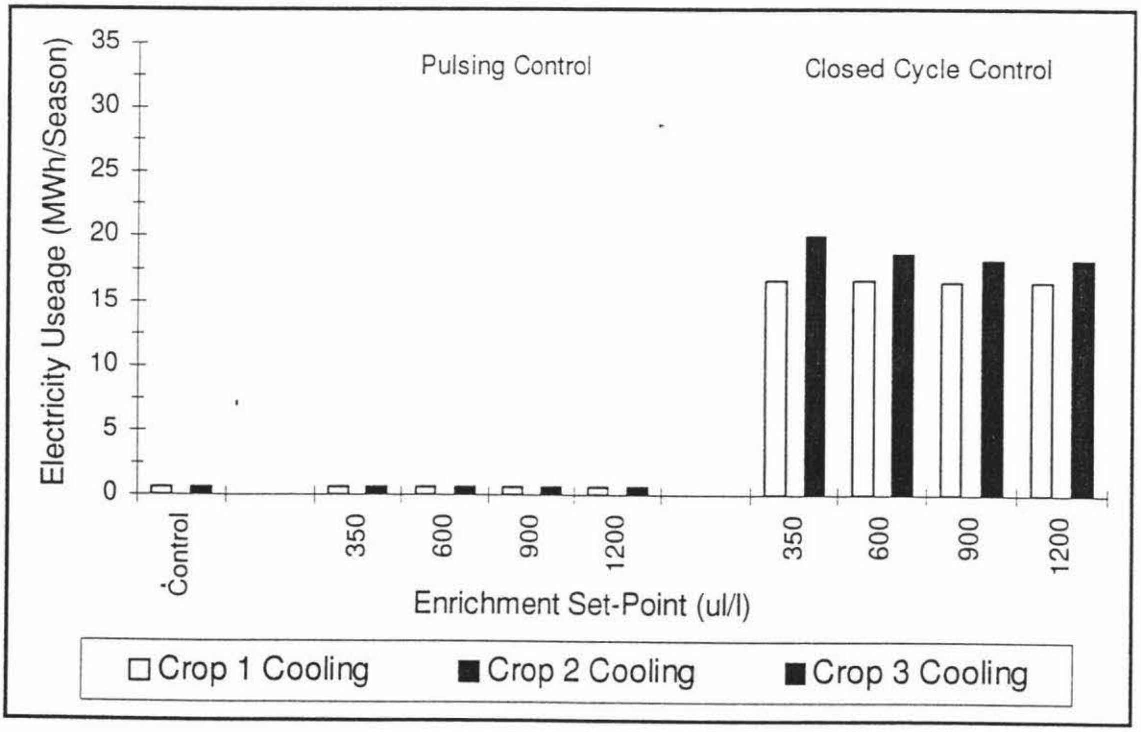

Figure 5.12 *Electricity consumption for cooling as a function of greenhouse control, CO2 set-point, and crop. Christchurch.*

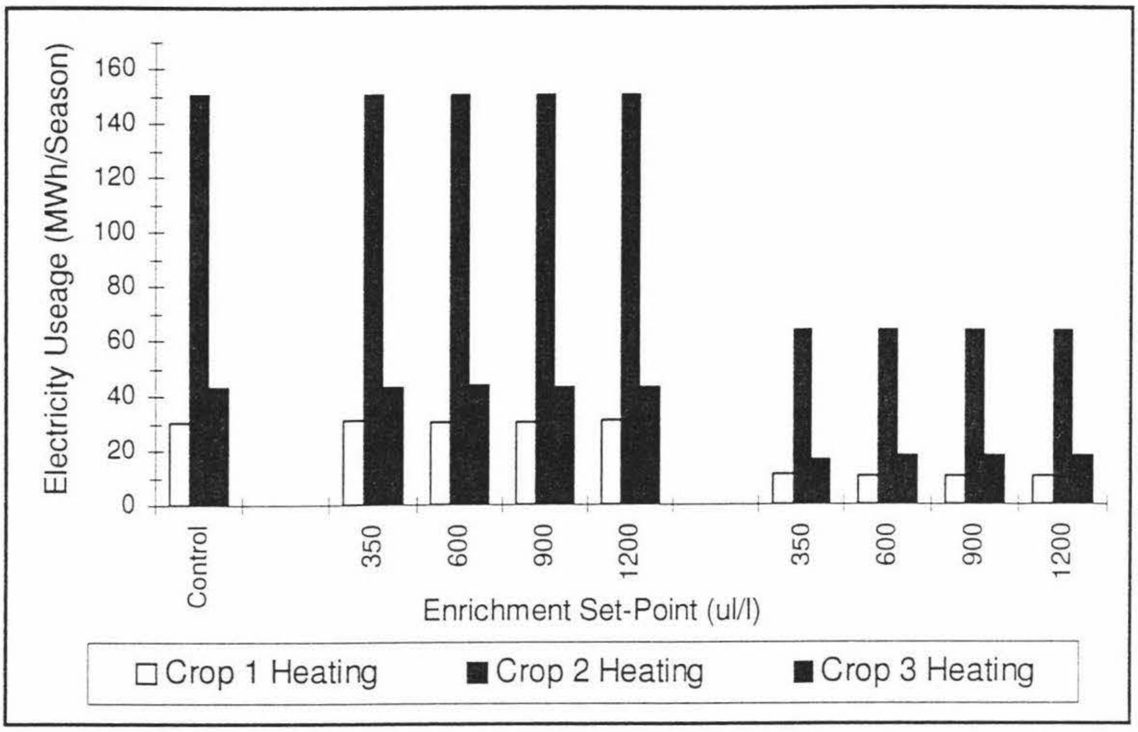

Figure 5.13 Electricity consumption for heating as a function of greenhouse control, CO_2 set-point, and crop. Christchurch.

5.2 VARIATION IN CROP FACTORS

The ultimate aim of growing a greenhouse crop with closed cycle climate control and CO_2 enrichment is to improve crop yields to the point where the extra returns achieved exceed the increase in costs incurred, hence maximising marginal return.

Already discussed have been the additional CO2, and electricity consumption required by greenhouses using closed cycle climate control, that is the additional costs incurred.

Now we need to look at the additional yield achieved as a result of the additional investment. Note that marginal capital expenditure will be discussed in the discussion, chapter 7.

In order to assess crop yield, we may consider two crop factors:

- Average fruit weight
- Average fruit number per plant.

5.2.1 Effect On Fruit Weight

An analysis of average fruit fresh weight as a function of average greenhouse CO_2 concentration was carried out. The results are shown in the graphs in Figures 5.14 to 5.17.

The results were again analysed in the following categories:

- Effect due to average carbon dioxide concentration.
- Effect due to method of control
- Effect due to season
- Effect due to location

Effect due to average carbon dioxide concentration.

With exceptions, the general trend is a very gradual increase in fruit fresh weight with an increase in average carbon dioxide concentration. This is particularly true at concentrations above 350 ppm during crop 1 and crop 3.

Effect due to method of control

As seen earlier the method of control has a marked effect on the average greenhouse carbon dioxide concentration, particularly during crops 1 and 3.

The effect due to method of control on fruit fresh weight is most noticeable during crop 1 and crop 3. With closed cycle control there appears to be a better correlation between average greenhouse carbon dioxide concentration and average seasonal fruit fresh weight, than with pulsing control.

During crop 2, this correlation is apparent in Auckland but not so in Christchurch.

Effect due to season

There is a marked effect due to season on the fruit fresh weight. Fruit produced during crop 2 was of significantly lower weight than fruit produced in either of the other two seasons.

The season also appeared to affect the general trend between average carbon dioxide concentration, particularly fruit grown during crop 2.

Differences in fruit fresh weight during crop 1 and crop 3 are minimal.

Effect due to location

Location, too seemed to have a marked effect on fruit fresh weight, and again particularly during crop 2.

In Auckland the average fruit fresh weight, during crop 2, tended to be higher than in Christchurch.

Differences in fruit fresh weight during crop 1 and crop 3 at the two sites are minimal.

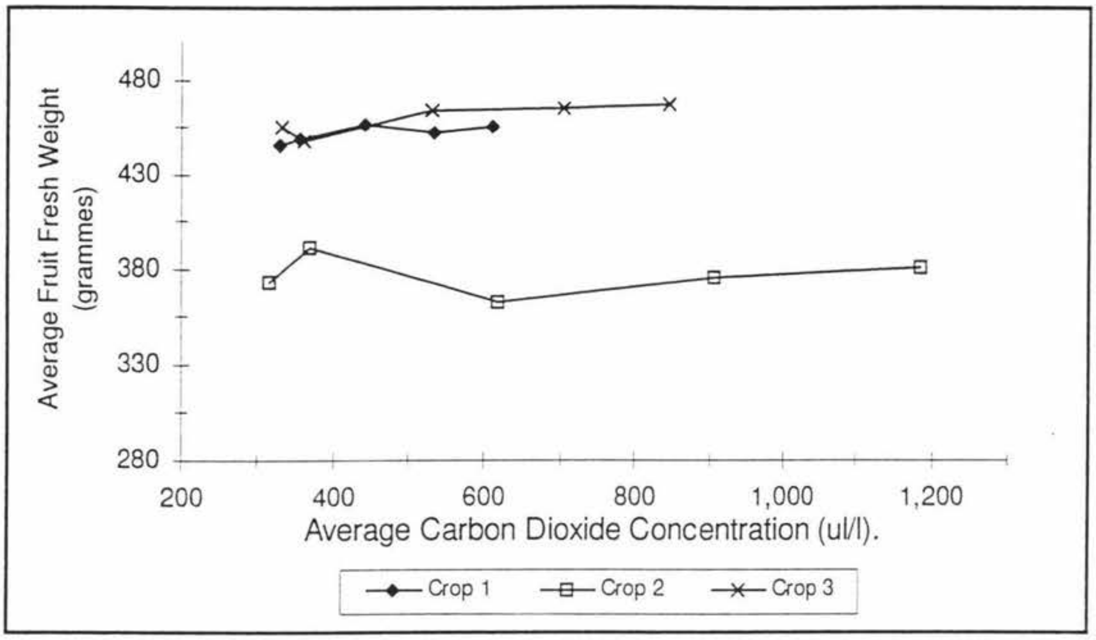

Figure 5.14 *Average Fruit Fresh Weight as a function of average CO_2 concentration, with Pulsing Control, in Auckland.*

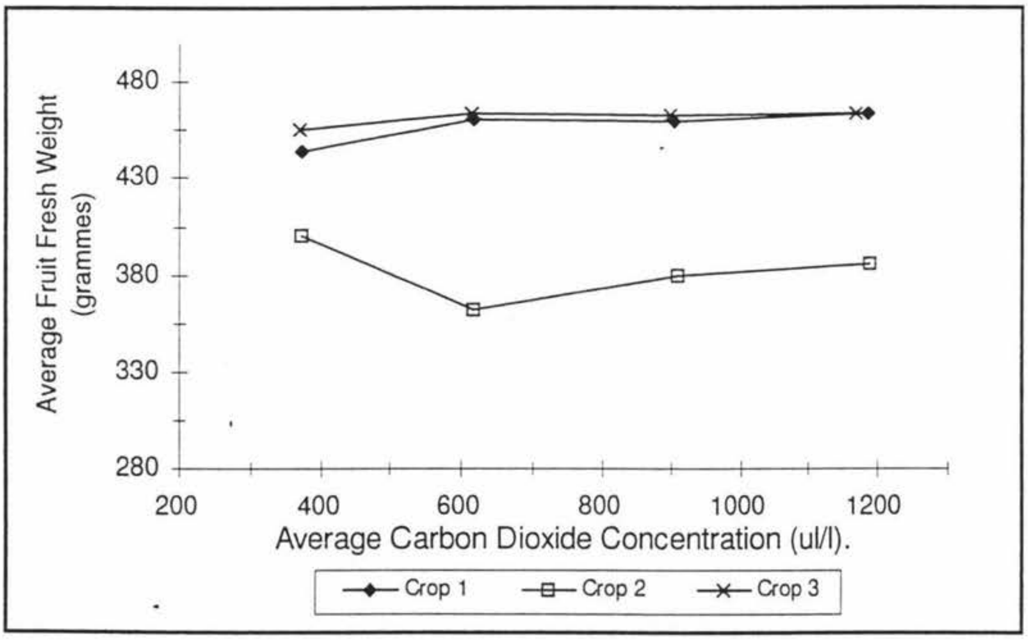

Figure 5.15 *Average Fruit Fresh Weight as a function of average CO_2 concentration, with Closed Cycle Control, in Auckland.*

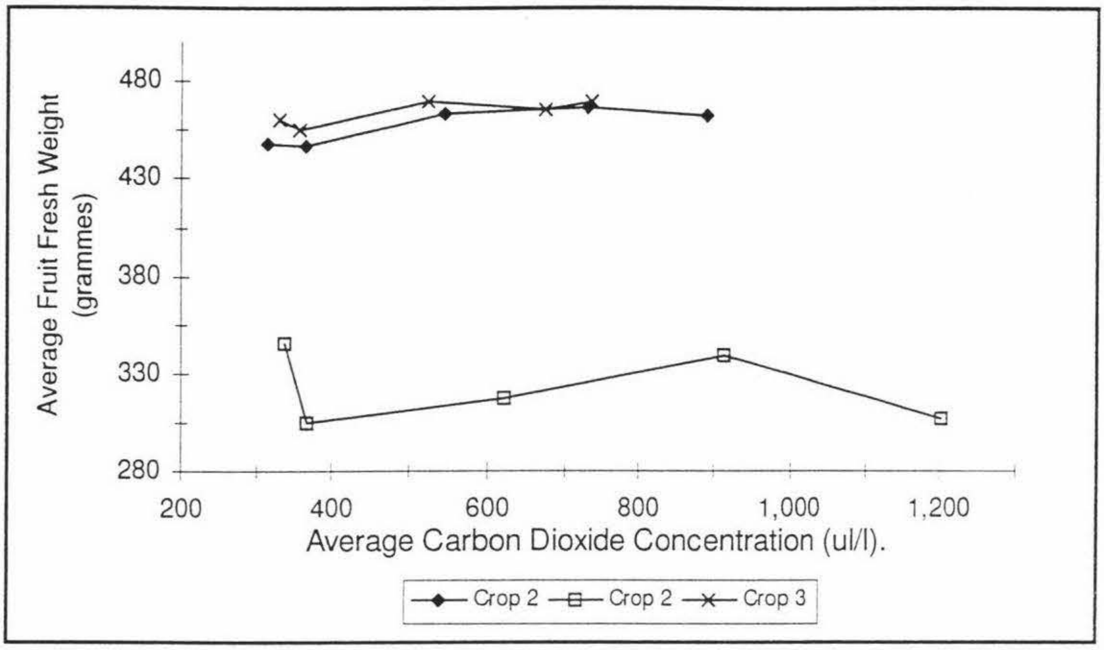

Figure 5.16 *Average Fruit Fresh Weight as a function of average CO_2 concentration, with Pulsing Control, in Christchurch.*

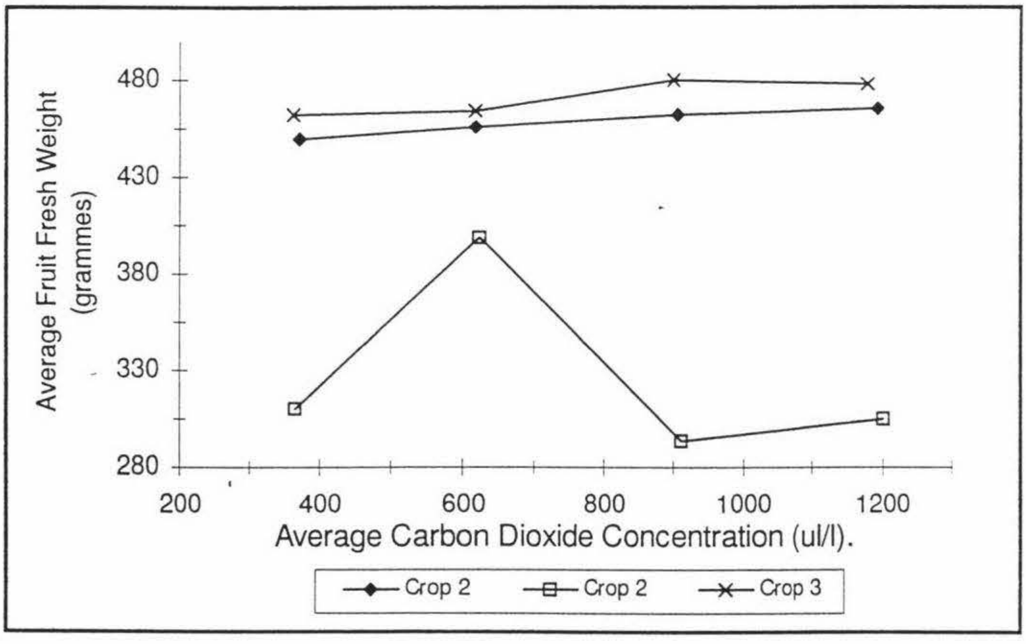

Figure 5.17 *Average Fruit Fresh Weight as a function of average CO_2 concentration, with Closed Cycle Control, in Christchurch.*

5.2.2 Effect on Fruit Number

In case of cucumbers the fruit number can be regarded as more important than fruit weight as this crop is sold by number (provided the fruit weight is above a set minimum), rather than weight. Hence it is appropriate to examine the effect of CO_2 enrichment on average fruit number per plant.

The results are presented here in two formats;

- Fruit number harvested per plant as a function of average carbon dioxide concentration.
- Fruit number harvested and fruit number aborted as a function of carbon dioxide set-point.

These results are depicted graphically in Figures 5.18 to 5.21, and Figures 5.22 to 5.25 respectively.

Fruit number harvested as a function of average carbon dioxide concentration.

These results can be arranged into the following effects:

- Effect due to average carbon dioxide concentration.
- Effect due to method of control
- Effect due to season
- Effect due to location

Effect due to average carbon dioxide concentration.

As expected, the general trend is an increase in fruit number with an increase in average carbon dioxide concentration.

The graphs depicting the effect of conventional control also include the results of the control simulations. These simulations have the lowest average carbon dioxide concentration, and in Christchurch also produce the lowest fruit number per plant in each crop.

The only exception appears to be with simulations carried using conventional control in Auckland (Figure 5.18). Here the effect due to average carbon dioxide concentration seems to be somewhat irregular.

Effect due to method of control

The general trend is a slight increase in fruit number per plant with closed cycle control when compared with conventional control, especially at higher average carbon dioxide concentrations.

Effect due to season

The greatest effect is due to the season, particularly when comparing crop 2 with crops 1 and 3. Crop 2 consistently produces significantly less fruit numbers than either of the other two crops, regardless of average carbon dioxide concentration, method of control, or location.

Small variations in fruit numbers produced do occur when comparing conventional control during crop 1 with crop 3 in both Auckland and Christchurch. When comparing closed cycle control during crop 1 and crop 3 there appears to be no significant difference.

Effect due to location

The effect due to location is most significant during crop 2. Simulations for crop 2 in Auckland consistently produce higher fruit numbers than simulations for crop 2 in Christchurch.

The next most significant effect is with conventional control and crops 1 and 3. These two crops produce consistently higher numbers in Christchurch compared with Auckland.

The effect due to location on fruit numbers with closed cycle control during crops 1 and 3 is not significant.

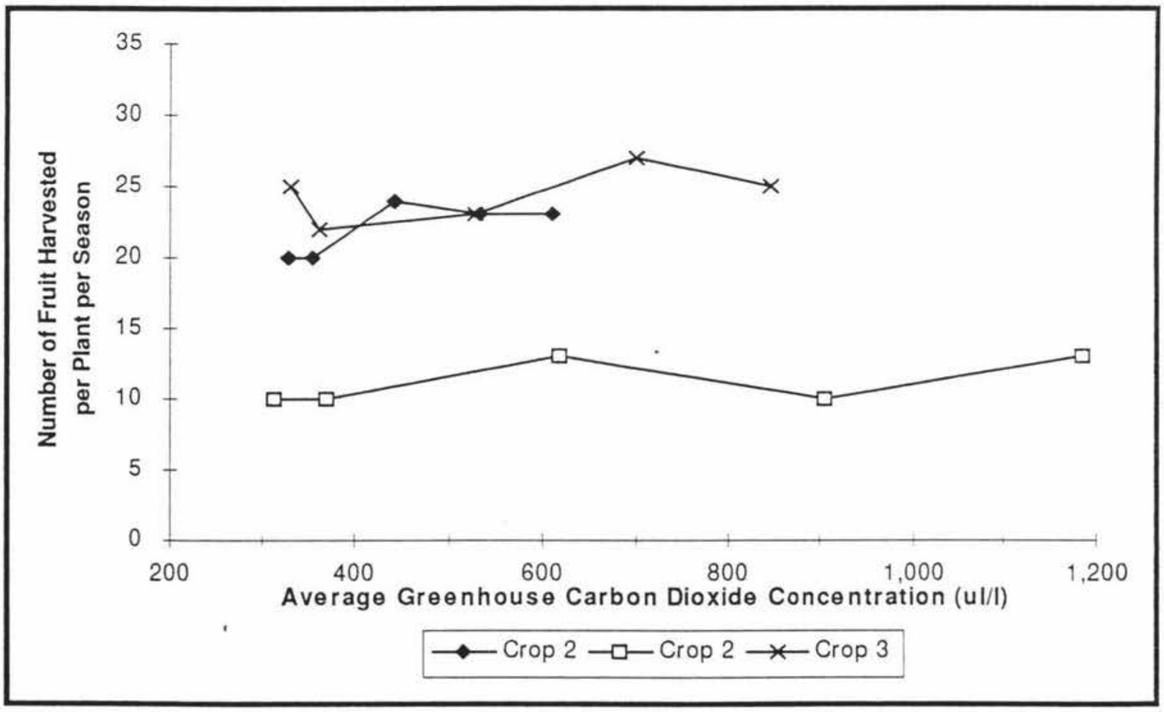

Figure 5.18 Fruit Number Harvested as a function of average CO_2 concentration, with Conventional-Control, in Auckland.

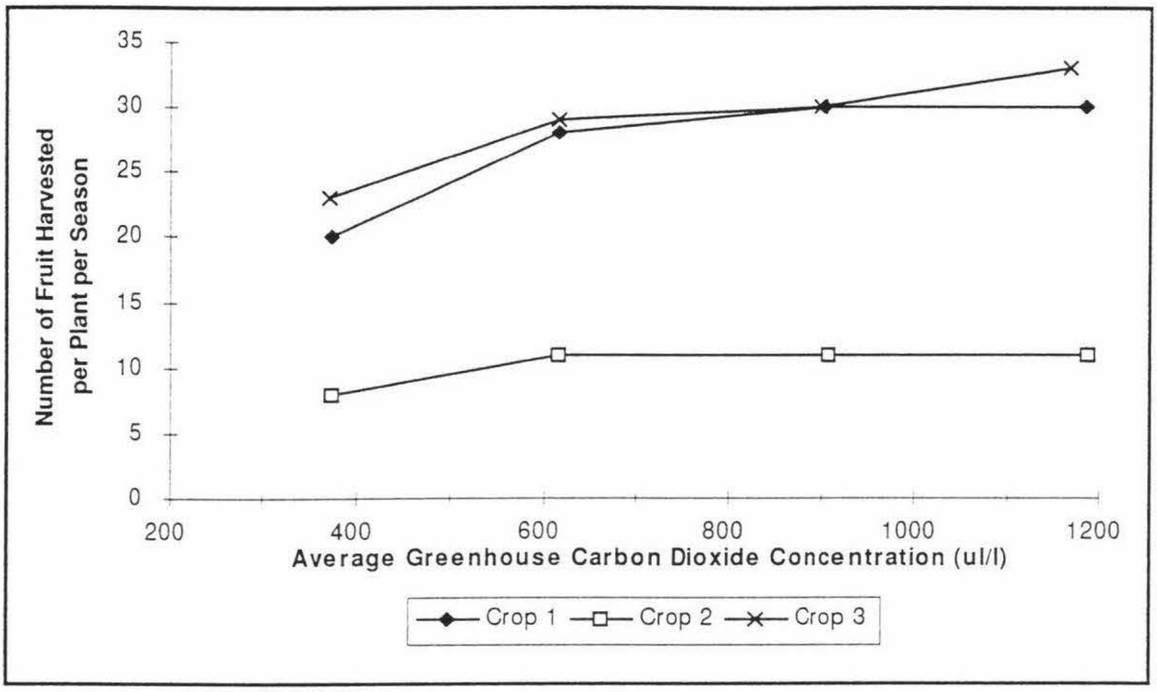

Figure 5.19 Fruit Number Harvested as a function of average CO_2 concentration, with Closed Cycle Control, in Auckland.

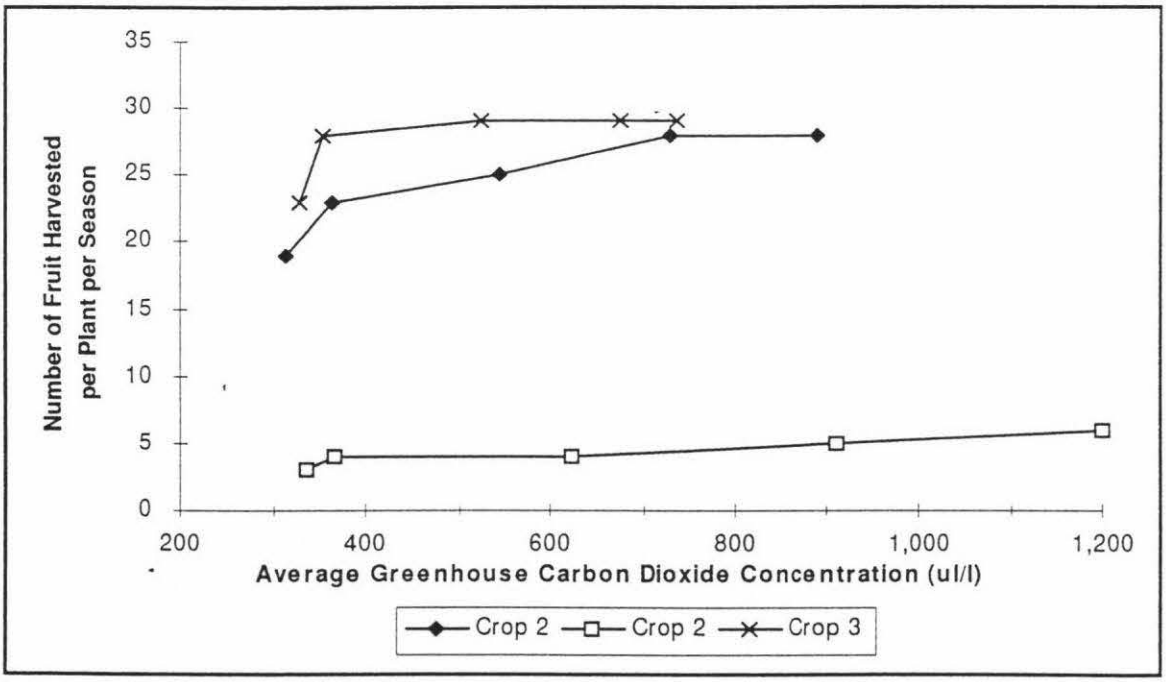

Figure 5.20 Fruit Number Harvested as a function of average CO_2 concentration, with Conventional Control, in Christchurch.

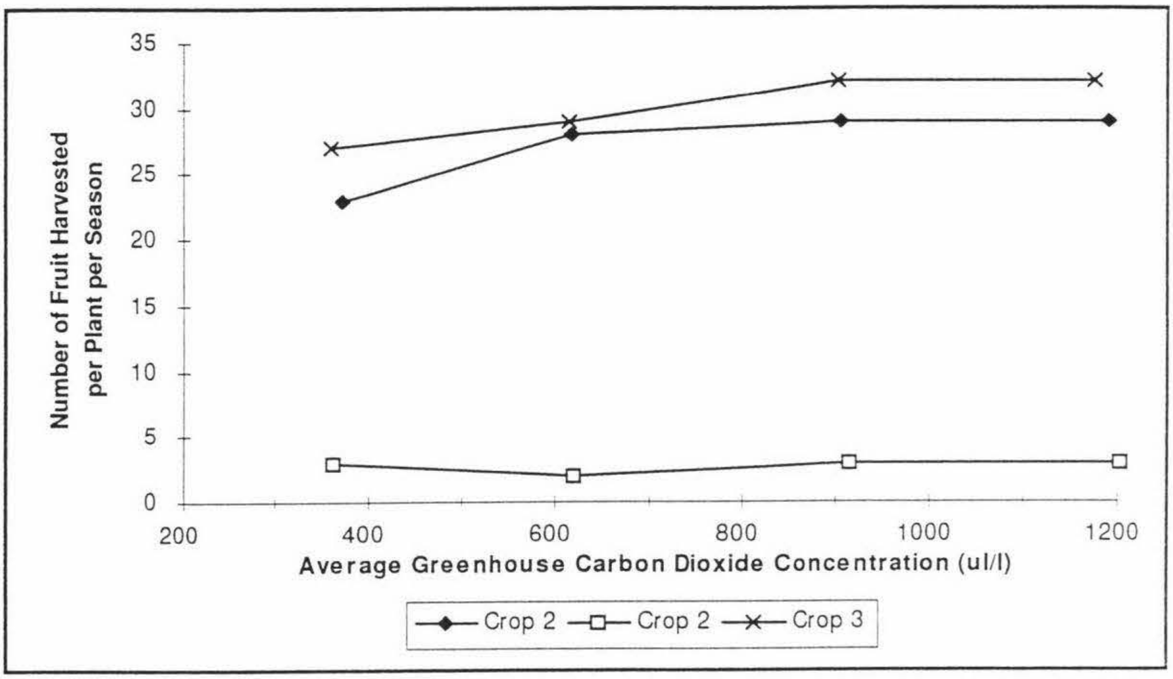

Figure 5.21 Fruit Number Harvested as a function of average CO_2 concentration, with Closed Cycle Control, in Christchurch.

Fruit number harvested and fruit number aborted as a function of carbon dioxide set-point.

The results are depicted in the graphs in Figures 5.22 to 5.25. Examining the graphs, the total height of the bars shown represents fruit number initiated. The total is split between number harvested and number aborted to the proportion of black area and white area respectively.

The results can be arranged into the following effects:

- Effect due to carbon dioxide enrichment set-point.
- Effect due to method of control
- Effect due to season
- Effect due to location

Effect due to carbon dioxide enrichment set-point.

There appears to be little influence on total number initiated by carbon dioxide set-point. In most cases the carbon dioxide set-point causes no change in total fruit number initiated.

As discussed previously, the carbon dioxide set-point tends to cause an increase in fruit number harvested. Subsequently, this means that there is a reduction in fruit number aborted, as there tends to be little change in total number initiated.

Effect due to method of control

The general trend is an increase in total fruit number harvested when moving from conventional control to closed cycle control.

In most cases there is a reduction in total fruit number aborted per plant. The effect of control on total fruit number initiated is a tendency to reduce to this number.

Effect due to season

Again, the greatest effect on fruit numbers is due to season. During crop 2 there are fewer fruit initiated, harvested, and aborted, than during either crop 1 or crop 3. This is true for both locations.

During crop 3 there are generally more fruit harvested, less fruit aborted, and less fruit initiated than during crop 1.

Effect due to Location

The effect due to location is variable. During crop 1 there are fewer fruit initiated in Christchurch compared to Auckland. However, there are more fruit harvested with conventional control in Christchurch, yet there is no significant difference with closed cycle control in Christchurch, when compared to Auckland.

During crop 2 there are fewer fruit initiated and fewer fruit harvested in Christchurch with either method of control.

During crop 3 there are fewer fruit initiated in Christchurch. The fruit number harvested in Christchurch, compared with Auckland, follows the same trend as during crop 1.

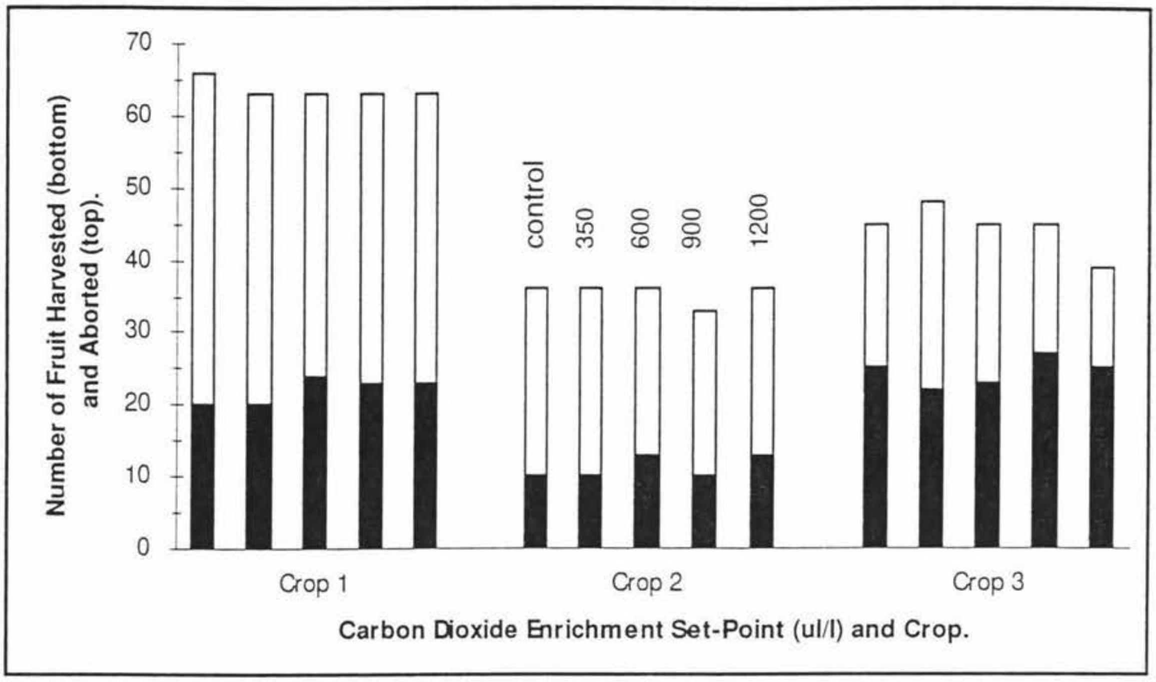

Figure 5.22 *Fruit Number Harvested and Aborted as a function of CO_2 Enrichment Set-Point, with Conventional Control, in Auckland.*

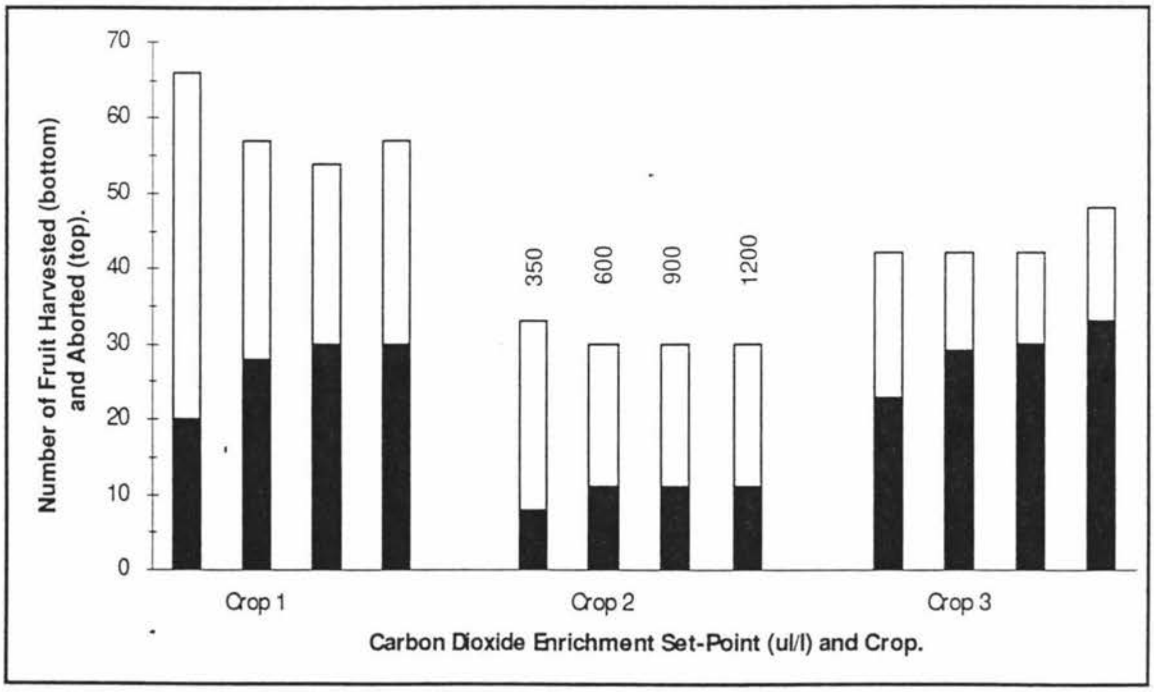

Figure 5.23 *Fruit Number Harvested as a function of average CO_2 concentration, with Closed Cycle Control, in Auckland.*

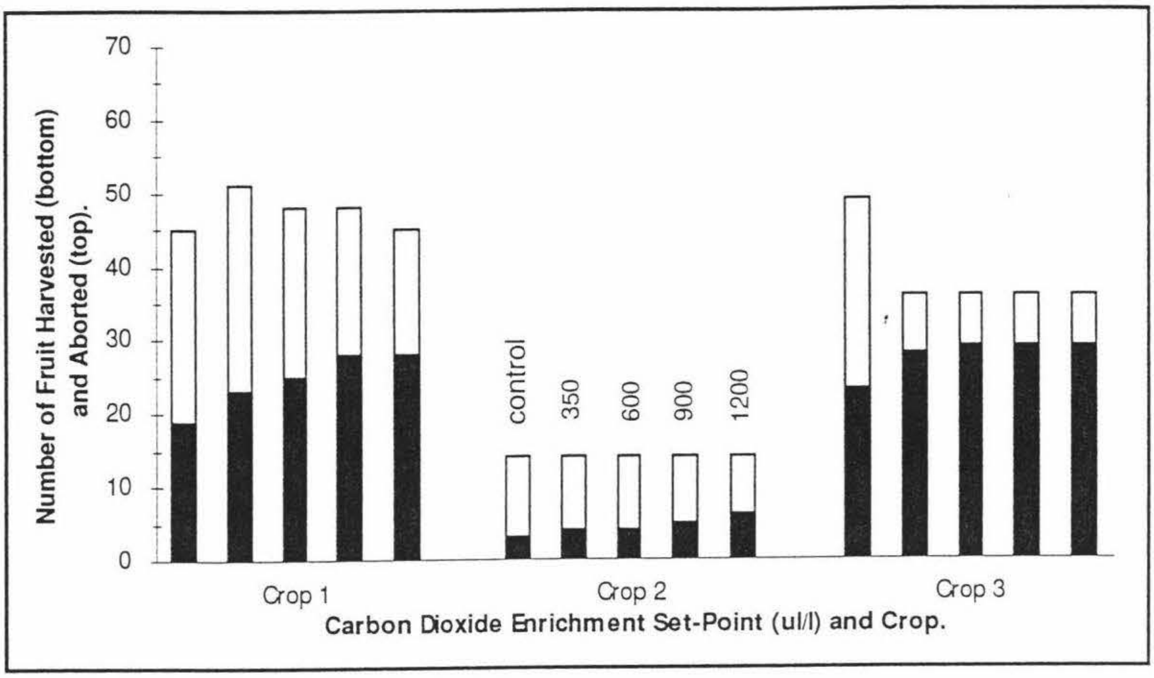

Figure 5.24 *Fruit Number Harvested and Aborted as a function of CO_2 Set-Point, with Conventional Control, in Christchurch.*

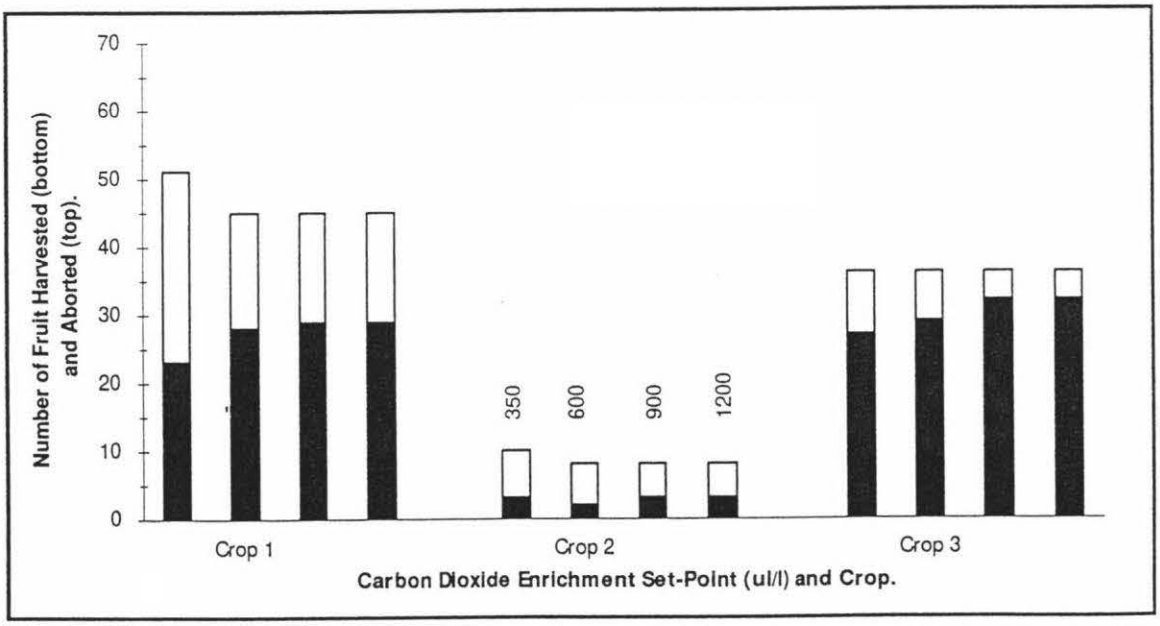

Figure 5.25 *Fruit Number Harvested and Aborted as a function of CO_2 Set-Point, with Closed Cycle Control, in Christchurch.*

The effects noted in this chapter will now be discussed in chapter 6, followed by an economic analysis of the results.

6. RESULTS - DISCUSSION

The previous chapter outlined the analysis of the results highlighting trends. The purpose of this chapter is to discuss the trends observed and provide explanation of the causes of these trends. The discussions are then followed by an economic analysis of the results.

The discussion is set out in the same way as the analysis in the previous chapter. That is:

- Environment

    Average Internal Greenhouse CO_2 Concentration.

    CO_2 Consumption.

    Electricity Consumption

- Variation in crop factors

    Effect On Fruit Weight

    Effect on Fruit Number

        As a function of average carbon dioxide concentration.

        As a function of carbon dioxide set-point.

- Economic Analysis

6.1 Environment

6.1.1 Average Internal Greenhouse CO_2 Concentration.

In a greenhouse with pulsing control the non-linear relationship between carbon dioxide setpoint and mean CO_2 concentration is due to the fact that ventilation must be started for the purpose of climate control. In doing so, the elevated greenhouse carbon dioxide concentration quickly falls back to ambient (approximately 350 ppm). With a set carbon dioxide injection rate, a certain period of time is needed to again raise the greenhouse carbon dioxide concentration back to set-point. This period of time will be longer at higher set-points, hence the difference between carbon dioxide set-point and actual mean greenhouse carbon dioxide concentration can be expected to be greater as the set-point is increased.

With closed cycle control no ventilation is necessary, hence there will be little variation in mean greenhouse carbon dioxide concentration.

This effect is more pronounced in periods of warmer weather, and hence higher ventilation frequency. This is the case during crops 1 and 3. The fan run results can be seen in Table 6.1

Conversely, in cooler seasons the mean greenhouse CO_2 concentration is expected to more closely match the carbon dioxide set-point. This is the case during crop 2. As can be seen in Table 6.1, the fan run for this period is very low when compared to the fan run for crop 1 or crop 3.

Obviously temperatures during the three seasons will be determined by the climate at the location in question. For example, in Christchurch where the summer and autumn are cooler than in Auckland, the ventilation frequency is lower hence the mean CO_2 concentration in the greenhouse is higher. This can be seen in the graphs for crop 1.

For crop 3 (Spring), the ventilation frequency in Christchurch is similar to frequency in Auckland, as is shown in Table 6.1. The fan run for bank 1 in Christchurch is lower than bank 1 in Auckland.

However, the average CO_2 concentration for Auckland is higher than for Christchurch. The explanation for this is found when comparing the fan run for bank 2 for Auckland and Christchurch. In Christchurch the latter bank exhibits a greater fan run than in Auckland. Whatsmore, the total quantity of CO_2 consumed in Christchurch during crop 3 is also higher than in Auckland, see Table 6.10 and 6.11.

This means that when ventilation is necessary in Christchurch the temperatures are more extreme than in Auckland and the larger fans in bank two are necessary to cool the greenhouse, hence it is more difficult to maintain the carbon dioxide set-point.

	Auckland		Christchurch	
	Fan Bank 1	Fan Bank 2	Fan Bank 1	Fan Bank 2
Crop 1 Control	36,875	7,296	16,010	1,600
350	36,892	7,295	16,101	1,609
600	36,940	7,297	16,038	1,602
900	36,924	7,305	16,035	1,597
1200	36,940	7,304	16,109	1,610
Crop 2 Control	434	-	2	-
350	435	-	2	-
600	442	-	2	-
900	442	-	1	-
1200	444	-	1	-
Crop 3 Control	17,885	119	14,874	1,247
350	17,926	94	14,948	1,247
600	17,899	82	14,999	1,262
900	17,796	81	14,846	1,247
1200	17,786	79	14,852	1,246

Table 6.1 Table of Fan Run results for greenhouses with pulsing control (figures in total minutes per season)

6.1.2 CO_2 Consumption

Obviously, there will be an increase in carbon dioxide consumption with each increase in set-point, as more carbon dioxide will need to be injected in order to maintain the higher set-points.

The effect due to climate overrides the effect due to control. This is apparent when comparing carbon dioxide consumption during the three crop periods. During crop 1, more carbon dioxide is consumed with closed cycle control than with pulsing control as the high ventilation requirement (see Table 6.1) results in a low fractional enrichment time.

However, during crop 2 (Winter), the cooler temperatures mean that the fractional enrichment time with pulsing control is almost 100% hence there is only a small difference in the mean carbon dioxide concentration between a greenhouse with closed cycle control and a greenhouse with pulsing control. The need for ventilation, however small it may be, has meant that the greenhouses with pulsing control consumed a little more carbon dioxide than greenhouses with closed cycle control.

When studying the results for crop 3 the effect due to location becomes apparent. In Auckland the temperatures during Spring result in lower fractional enrichment time than for example during crop 2. Hence the carbon dioxide consumption is lower with pulsing control than with closed cycle control.

However in Christchurch, despite the lower fractional enrichment time, the carbon dioxide consumption for pulsing control is higher than for closed cycle control. This is due to the fact that the local climate causes greater temperature variations during periods of enrichment than is the case in Auckland, as can be observed from the greenhouse mean and standard deviation temperatures depicted in the table in Table 6.2.

As explained earlier, this results in a greater fan run for fan bank 2, and hence a greater loss of carbon dioxide during enrichment, exceeding the carbon dioxide consumption with closed cycle control.

		AUCKLAND		CHRISTCHURCH	
		Mean Temp.	Stand. Dev	Mean Temp.	Stand. Dev
CROP 1	PULSING	24.26	1.91	22.88	2.25
	CLOSED CYCLE	26.36	2.76	24.47	3.63
CROP 2	PULSING	20.22	1.90	18.82	0.94
	CLOSED CYCLE	20.09	2.57	18.05	0.80
CROP 3	PULSING	22.99	1.95	22.50	2.46
	CLOSED CYCLE	24.85	3.49	24.29	3.95

Table 6.2 *Mean greenhouse Temperature (°C) and Standard Deviation (°C) for the period of enrichment, i.e. between 8am and 5pm, for Auckland and Christchurch, with two methods of control, and during three crop cycles.*

6.1.3 Electricity Consumption

The effect on electricity consumption due to enrichment set-point is not significant. This indicates that the increased plant activity due to increased carbon dioxide concentration has no significant effect on energy required to maintain a set greenhouse climate.

The effect on electricity consumption due to method of control is significant. For cooling there is a greater energy requirement for closed cycle control than for pulsing control, despite the very high efficiency of closed cycle control. This is because the energy requirement of fans is considerably higher than for heat pumps. Of course the level of cooling achieved with fan ventilation is also a lot lower than with closed cycle heat pump cooling.

With closed cycle control, electricity consumption for heating is significantly less than consumption with pulsing control using electric heating. This is a result of the greater efficiency of heat pumps in heating when compared with electric heaters.

For Auckland, comparing the effect due to season the order of energy required for cooling goes from crop 1 through to crop 3, with crop 1 having the highest cooling requirement. This is understandable, as crop 1 represents growth mainly during Summer, crop 2 represents Spring, and crop 3 represents Winter.

The effect due to location overrides this pattern. For Christchurch the cooling requirement during crop 3 is greater than during crop 1. As discussed earlier, this is explained by the temperature variations which are prominent at this location during crop 3.

The energy requirement for heating is greatest during crop 2, then crop 3, and lowest for crop 1; at both Auckland and Christchurch as a result of then climatic conditions during those periods.

6.2 Variation in Crop Factors

The following sections will explore the effects observed on two crop factors, namely:

- Effect on Fruit Weight
- Effect on Fruit Number

6.2.1 Effect on Fruit Weight

A general trend of an increase in fruit fresh weight with an increase in average greenhouse carbon dioxide concentration is expected as the elevated carbon dioxide levels encourage greater assimilation and hence greater fruit weight.

The table in Table 6.3 best explains the effect due to method of control on average fruit fresh weight in terms of average carbon dioxide concentration. It can be noted that in all cases the correlation coefficient is higher with closed cycle control than with pulsing control. This would suggest that with closed cycle control average seasonal fruit fresh weight is more dependent on average seasonal greenhouse carbon dioxide concentration than with pulsing control.

The lower fruit fresh weight achieved during crop 2, when compared with crops 1 and 3 is probably due to the lower light levels and the resulting reduction in assimilation possible. Table 6.4 shows the average seasonal photosynthetically active radiation (PAR) for the three crop periods. It can be clearly seen that light levels during crop 2 are significantly less than during either of the other crop periods. Hence it is likely that the light level during crop 2 is the most limiting factor for growth.

The consistently higher average seasonal fruit fresh weight achieved during crop 3 compared to crop 1, however small it may be, could be attributed to the respective average seasonal PAR during those periods also.

			AUCKLAND	CHRISTCHURCH
Crop 1	Pulsing Control	Corr. Coeff.	0.73	0.81
		Intercept	418.81	440.20
		Gradient	0.06	0.03
	Closed Cycle Control	Corr. Coeff.	0.84	0.99
		Intercept	432.09	443.73
		Gradient	0.02	0.02
Crop 2	Pulsing Control	Corr. Coeff.	0.31	-0.23
		Intercept	334.81	330.76
		Gradient	0.08	-0.01
	Closed Cycle Control	Corr. Coeff.	-0.18	-0.34
		Intercept	387.50	362.60
		Gradient	0.04	-0.05
Crop 3	Pulsing Control	Corr. Coeff.	0.85	0.81
		Intercept	440.74	450.11
		Gradient	0.03	0.03
	Closed Cycle Control	Corr. Coeff.	0.74	0.88
		Intercept	443.99	453.71
		Gradient	0.02	0.02

Table 6.3 Regression analysis of average seasonal fruit fresh weight ($g.fruit^{-1}.season^{-1}$) with respect to average seasonal greenhouse CO_2 concentration ($\mu l.l^{-1}$).

The effect due to location on the average seasonal fruit fresh weight appears to be most prominent during crop 2. Comparing the difference in average seasonal PAR for Auckland and Christchurch during this period, Christchurch receives 28% less PAR than Auckland and this is likely to be the largest contributing factor to the difference in result. This point is further reinforced by the results presented in Table 6.4. This table shows a regression analysis between average seasonal fruit fresh weight and average seasonal greenhouse carbon dioxide concentration. The table clearly shows that during crop 2 the correlation coefficient is low for Christchurch, hence this indicates that some factor other than average carbon dioxide concentration is responsible for the trend in fruit fresh weight

	AUCKLAND	CHRISTCHURCH
CROP 1	5.18	4.72
CROP 2	2.48	1.78
CROP 3	6.14	6.45

Table 6.4 Average daily photosynthetically active solar radiation, or PAR ($J.m^{-2}.d^{-1}$).

6.2.2 Effect on Fruit Number

Fruit Number as a result of average carbon dioxide concentration.

As discussed in 6.2.2 total seasonal fruit number harvested per plant is a more appropriate way to determine crop yield in cucumber production.

The effect due to average seasonal greenhouse carbon dioxide concentration is generally an increase in fruit number produced with an increase in average carbon dioxide concentration. This is expected, particularly in periods when carbon dioxide is likely to be the most limiting factor for growth such as during crop 1 and crop 3 (Summer/Autumn and Spring respectively). Hence, the correlation coefficient between total seasonal fruit number harvested per plant and average seasonal greenhouse carbon dioxide concentration is also expected to be the highest during these crop periods. This is confirmed a regression analysis is performed on the results from the simulation runs, as presented in Table 6.5. This table shows generally a higher correlation coefficient for treatments in both Auckland and Christchurch during crop1 and crop3 when compared to crop 2 .

The effect due to control of a slight increase in fruit number harvested per plant is clear when looking at Table 6.5. The figure shows higher correlations with closed cycle control when compared with pulsing control during crop 1 and crop 3. Furthermore, in most cases the gradients for closed cycle control are higher than for pulsing control which indicates that there is a greater response in fruit number produced per plant to carbon dioxide enrichment with closed cycle control. This is expected as greater control on carbon dioxide concentration is possible with closed cycle control compared to pulsing control, especially during crop 1 and crop 3.

Table 6.5 shows that the effect due to season is generally a lower correlation coefficient for crop 2 compared to crop1 and crop 3. This is despite the higher fractional enrichment time possible during crop 2. Again the most likely explanation is that light is the most limiting factor for fruit number production during crop 2.

Despite the low correlation for some of the results, there is a distinct pattern in the intercept figures between results for Auckland and results for Christchurch. The intercepts are lower for Christchurch than for Auckland during crop 2 yet they are higher during crop 1 and crop 3. The differences are the greatest during crop 2 (approximately 70%), this is in line with the lower fruit number achieved in Christchurch compared to Auckland. This latter effect is most likely due to the significantly lower light levels in Christchurch during winter compared with Auckland.

The differences in fruit number production between Christchurch and Auckland are not as significant during crop 1 and crop 3 (approximately 15% and 33% respectively).

Another trend to be noted is, in most cases, a lower gradient for Christchurch compared with Auckland, during crop 1 and crop 3. This means a lower response to carbon dioxide enrichment in Christchurch compared to Auckland.

			AUCKLAND	CHRISTCHURCH
Crop 1	Pulsing Control	Correl. Coeff.	0.60	0.96
		Intercept	17.91	19.49
		Gradient	0.0095	0.0103
	Closed Cycle Control	Correl. Coeff.	0.85	0.83
		Intercept	18.15	22.03
		Gradient	0.0115	0.0068
Crop 2	Pulsing Control	Correl. Coeff.	0.43	0.95
		Intercept	9.87	2.79
		Gradient	0.0021	0.0025
	Closed Cycle Control	Correl. Coeff.	0.75	0.28
		Intercept	7.79	2.45
		Gradient	0.0032	0.0004
Crop 3	Pulsing Control	Correl. Coeff.	0.78	0.85
		Intercept	19.20	27.31
		Gradient	0.0083	0.0025
	Closed Cycle Control	Correl. Coeff.	0.95	0.95
		Intercept	20.00	24.97
		Gradient	0.0115	0.0066

Table 6.5. Regression Analysis of Total Seasonal Fruit Number Harvested per plant with respect to Average Seasonal Greenhouse Carbon Dioxide Concentration.

Fruit Number as a result of carbon dioxide set-point.

Regression analyses of the results of fruit number per plant with respect to carbon dioxide setpoint were carried out. The analyses are presented in Tables 6.6, 6.7, and 6.8 for total fruit number harvested, aborted, and initiated respectively.

The effect due carbon dioxide setpoint on fruit number harvested is expected to be similar to the effect due to average greenhouse carbon dioxide concentration. This appears the to be the case, as is illustrated by comparing Table 6.5 with Table 6.6. The two tables show very similar results.

In 6.2.2 a lack of distinct trend in total fruit number initiated with respect to carbon dioxide setpoint was noted. This is confirmed by Table 6.8. The correlation coefficients vary between -0.94 and +0.79 with a number of treatments returning a 0 correlation coefficient. Hence it is assumed that total fruit number initiated is likely to be related to a factor other than carbon dioxide setpoint.

The analysis for total fruit number aborted, as shown in Table 6.7. The distinct negative correlations indicate that total fruit number aborted is inversely proportional to carbon dioxide setpoint. This is confirmed by the negative values for the gradients.

As stated in 6.2.2 there is a tendency to increase total fruit number harvested as the method of control changes from pulsing control to closed cycle control. This is reflected in the regression analysis in terms of the gradients for the relevant curves. In all but one case the gradient increases, that is a better response to carbon dioxide setpoint increases. The exception is during crop 2 in Christchurch, when the gradient decreases significantly.

The increases are most likely to be the result of a more constant elevated carbon dioxide level in the greenhouse possible with closed cycle control. The reduction experienced in Christchurch during crop 2 is difficult to explain, however the very low correlation figure shown for closed cycle control indicates that the total fruit number harvested per plant is more likely to be due to a factor other than carbon dioxide setpoint.

The reduction in total fruit number aborted when changing from pulsing to closed cycle control, is also reflected in Table 6.7 in four of the six cases, in terms of a decrease in gradient. The exceptions are again during crop 2 in Christchurch, but also during crop 3 in Auckland. As there is no definite trend in the total fruit number initiated, and this number is most likely to remain constant, the decrease in fruit number aborted would seem logical with the trend of increase in the fruit number harvested.

In the case of crop 2 in Christchurch, there is little difference in gradient. While in the case of crop 3 in Auckland is a little more difficult to explain, although there does appear to be an increase in fruit number initiated.

The effect due to season is again the most prominent, this is reflected in Tables 6.6 through 6.8 in lower intercepts, gradients, or both for any treatment during crop 2 compared with treatments in crop 1 or crop 3. This indicates a lower response to carbon dioxide setpoint in terms of total fruit number harvested, aborted, and initiated during crop 2. Again climatic conditions are the likely cause of the differences.

The tables also show an increase in intercepts, gradients, or both for fruit number harvested during crop 3 compared with crop 1. This indicates a higher response to carbon dioxide setpoint during crop 3. The reverse tends to be true for fruit number aborted, indicating a higher number aborted during crop 1 when compared to crop 3.

The effect due to location described in 6.2.2 is reflected in the tables as follows; The higher total fruit number initiated in Auckland compared to Christchurch is reflected in higher intercepts for Auckland, although there is no change with increasing carbon dioxide setpoint. The higher number harvested with conventional control in Christchurch compared to Auckland is reflected in higher a higher intercept and gradient for Christchurch.

For closed cycle control the intercept for total fruit number harvested in Christchurch is higher but the gradient is lower than for Auckland. This indicates a higher initial fruit number harvested at lower carbon dioxide setpoints, but a lower response to setpoint increase in Christchurch compared to Auckland.

The differences in fruit number harvested and fruit number initiated during crop 2 in Christchurch compared to Auckland is reflected in significantly lower intercepts for Christchurch. The reason for this trend is likely to be again the lower light levels in Christchurch compared to Auckland during this period.

During crop 3 the fruit number initiated in Christchurch appears to be unrelated to carbon dioxide setpoint. The fruit number initiated in Auckland is higher with a negative trend with increasing carbon dioxide setpoint under pulsing control, and a positive trend with closed cycle control.

During crop 3 the total fruit number harvested is initially higher in Christchurch with either method of control, however the response to carbon dioxide setpoint increase is greater in Auckland. This would seem to suggest that carbon dioxide is a more limiting factor in Auckland than in Christchurch for fruit number harvested.

			AUCKLAND	CHRISTCHURCH
Crop 1	Pulsing Control	Correl. Coeff.	0.56	0.94
		Intercept	20.49	21.22
		Gradient	0.0026	0.0063
	Closed Cycle Control	Correl. Coeff.	0.85	0.83
		Intercept	18.66	22.31
		Gradient	0.0109	0.0065
Crop 2	Pulsing Control	Correl. Coeff.	0.43	0.96
		Intercept	9.95	2.85
		Gradient	0.0020	0.0025
	Closed Cycle Control	Correl. Coeff.	0.75	0.29
		Intercept	7.93	2.45
		Gradient	0.0030	0.0004
Crop 3	Pulsing Control	Correl. Coeff.	0.75	0.75
		Intercept	20.81	27.98
		Gradient	0.0045	0.0010
	Closed Cycle Control	Correl. Coeff.	0.94	0.94
		Intercept	20.57	25.22
		Gradient	0.0107	0.0063

Table 6.6 Regression Analysis of Total Seasonal Fruit Number Harvested per plant with respect to Carbon Dioxide Setpoint.

			AUCKLAND	CHRISTCHURCH
Crop 1	Pulsing	Correl. Coeff.	- 0.56	- 0.98
	Control	Intercept	42.51	31.56
		Gradient	- 0.0026	- 0.0125
	Closed	Correl. Coeff.	- 0.79	- 0.79
	Cycle	Intercept	47.57	28.83
	Control	Gradient	- 0.0211	- 0.0126
Crop 2	Pulsing	Correl. Coeff.	- 0.75	- 0.96
	Control	Intercept	26.07	11.15
		Gradient	- 0.0030	- 0.0025
	Closed	Correl. Coeff.	- 0.75	- 0.93
	Cycle	Intercept	25.14	7.60
	Control	Gradient	- 0.0061	- 0.0024
Crop 3	Pulsing	Correl. Coeff.	- 1.00	- 0.75
	Control	Intercept	30.68	8.02
		Gradient	- 0.0140	- 0.0010
	Closed	Correl. Coeff.	- 0.51	- 0.94
	Cycle	Intercept	18.01	10.78
	Control	Gradient	- 0.0043	- 0.0063

Table 6.7 Regression Analysis of Total Seasonal Fruit Number Aborted per plant with respect to Carbon Dioxide Setpoint.

			AUCKLAND	CHRISTCHURCH
Crop 1	Pulsing	Correl. Coeff.	-	- 0.94
	Control	Intercept	63.00	52.78
		Gradient	-	- 0.0063
	Closed	Correl. Coeff.	- 0.72	- 0.75
	Cycle	Intercept	66.23	51.14
	Control	Gradient	- 0.0101	- 0.0061
Crop 2	Pulsing	Correl. Coeff.	- 0.25	-
	Control	Intercept	36.02	14.00
		Gradient	- 0.0010	-
	Closed	Correl. Coeff.	- 0.75	- 0.75
	Cycle	Intercept	33.07	10.05
	Control	Gradient	- 0.0030	- 0.0020
Crop 3	Pulsing	Correl. Coeff.	- 0.93	-
	Control	Intercept	51.49	36.00
		Gradient	- 0.0095	-
	Closed	Correl. Coeff.	0.79	-
	Cycle	Intercept	38.58	36.00
	Control	Gradient	0.0065	-

Table 6.8 Regression Analysis of Total Seasonal Fruit Number Initiated per plant with respect to Carbon Dioxide Setpoint.

6.3 Economic Analysis of Enrichment

The economic analysis of the experiment results is split into two categories:

- An analysis of the capital cost of enrichment equipment.
- An analysis of the returns and running costs expected with enrichment.

In order to simplify analysis, the economic analysis is based on a marginal analysis of costs and returns associated with enrichment. This means that costs and returns common to control and treatments have been negated. These include the following:

- Basic greenhouse construction; including the greenhouse structure, irrigation system, and greenhouse maintenance.
- Crop establishment and maintenance costs; plant support structures, media preparation, planting costs, harvesting costs.
- Labour costs involved with the above.

6.3.1 Capital Costs

Table 6.9 shows an analysis of the capital costs associated with the treatments. The prices quoted in the table are exclusive of G.S.T. and current in 1992 as quoted by relevant commercial suppliers of the equipment and services.

As explained in chapter 4, control for heating and cooling was arranged in banks. One bank would switch on when the greenhouse temperature reached the first set-point and successive banks would switch on when the greenhouse temperature exceeded the first set-point was and successive setpoints were reached. The aim of this set-up was to reduce hunting (on and off) of heating or cooling equipment as the control attempts to maintain the relevant set-point.

Conventional Control

The Heating System

As described in 4.1 the heating system was arranged in two banks;

Bank One: Three 30 kW heaters

Bank Two: Two 30 kW heaters

The ducting, and control equipment for the heaters is represented as *accessories* in Table 6.9.

Table 6.9. Capital Cost of Environmental Control Equipment for the Test Greenhouse.

Capital cost of a conventionally control greenhouse

		Cost per unit	Sub-Total	Total
• Heating:	Units of 30 kW each	1,872		
	for 5 units		9,360	
	Control, per unit	-192		
	for 5 units		960	
	Accessories, per unit	74		
	for 5 units		370	
				10,690
• Cooling:	Fan units of 760 mm each	998		
	for 4 units		3,992	
	Fan units of 1220 mm each	1,560		
	for 2 units		3,120	
	Gravity Shutters, for 760mm fans	300		
	for 4 units		1,200	
	Gravity Shutters, for 1220mm fans	400		
	for 4 units		1,600	
				9,912
• Circulation:	Fan unit of 760 mm	998		
	Ducting, PE of 30m length	50		
				1,048
• Installation and connection				10,000
				$31,650

Capital cost of carbon dioxide enrichment equipment

	Sub-Total	Total
• Concrete pad and support structure	1,000	
• Gas analyzer	3,000	
• Solenoids, relays and PVC pipes	4,500	
• Wiring	1,000	
		$9,500

Capital cost of a greenhouse fitted with a closed cycle, heat-pump, cooling system

	Cost per unit	Totals
Option 1, Heat-pump with a screw compressor.		
• Evaporators, 2.950mm • 0.685mm	4,000	
for 8 units		32,000
• Screw Compressor	60,000	
110 kW motor	8000	
Liquid Receiver	3,000	
		71,000
• Cross-over valve		5,000
• Plumbing		3,000
• Electrical		20,000
		$131,000
Option 2, Heat-pump with piston compressors.		
• Evaporators, 2.950mm • 0.685mm	4,000	
for 8 units		32,000
• Piston Compressor	8,300	
for 4 units		33200
• 30 kW motor	2,500	
for 4 units	3,000	10,000
• Cross-over valve	5,000	
for 3 units		15,000
• Plumbing		3,000
• Electrical		20,000
		$113,200

The Cooling System

As described in 4.2 the fan ventilation system also consisted of two banks;

Bank One: Four 760mm fans with 550 Watt electric motors each providing 20 airchanges per hour.

Bank Two: Two 1220mm fans with 1,100 Watt electric motors each providing 30 airchanges per hour.

The greenhouse used in the simulations has a total volume of 2,821.5 m^3. Hence, the fan capacities were as follows:

Bank One: 56,430 m^3/hr

Bank Two: 84,645 m^3/hr

The Air Circulation System

As well as heating and cooling control, the conventional house also needed circulation equipment within the house. For this purpose one 760 mm fan and perforated ducting running the length of the house was used.

The Carbon Dioxide Enrichment System

The carbon dioxide enrichment system consisted of an injector set to inject pure carbon dioxide at the rate of 10 mg CO_2.m-2.s-1 or 594 g of CO_2 per minute, a controller used to set the enrichment set-point, and a monitoring device capable of measuring the actual greenhouse carbon dioxide level.

In the analysis of costs and returns, in the next section, the payback periods for a conventionally controlled greenhouse is calculated by assuming the additional capital cost to consist of the carbon dioxide enrichment equipment only, i.e. $9500.

Closed Cycle Control System

The Heat Pump System

The capital cost of a heat-pump system, for closed cycle control, is split into two options: first option is a system using a single, variable load, screw compressor to drive three banks of evaporators and condensers, this forms a comparison with the second option of a system with independent piston compressors for each bank.

The heat-pump system was split into three banks: the first consisting of two double-duty condenser/evaporator units providing 23.85 kW of cooling capacity at 6°C T.D. (temperature difference between refrigerant and air temperature), and could serve as both condenser or evaporator as required in case of heating or cooling. The second bank consisting of four units, and the third bank again of two units.

Total cooling power for the heat-pump system is rated at 411.8 kW @ 25.9 °C T.D. for the screw compressor system at full capacity (split into banks of 103 kW, 206 kW, and 103 kW each), or 409.7 kW @ 25.8 °C T.D. for the four piston compressors combined (power of individual banks is 102 kW, 204 kW, and 104 kW each).

It is clear from the costings shown in Table 6.9 that there is no cost saving in combining the compressor power, of four piston compressors, into one screw compressor. This meant that all further analysis is done assuming the heat pump system was driven by four piston compressors.

The payback periods for closed cycle control is calculated by reducing the total cost of the heat-pump system by the cost of the conventional control, which is not needed, and added to this is the cost of the CO_2 enrichment equipment. Hence the total cost of a closed cycle control system with enrichment is :

$ 113,200 - $ 31,650 + $ 9,500 = $ 108,850

The Humidity Control System

As explained in 4.5, with the heat pump system operating humidity control was necessary to replace the moisture removed by the heat pump system. This humidity control took the form of a 'cold steam' injection system which would inject water vapour at the rate of 0.1 $g.m^{-2}.s^{-1}$ or 99 g.s-1 when the greenhouse relative humidity dropped below 60%.

The system consisted of a water vapour injection device, a controller, and a relative humidity sensing device.

The Air Circulation System

Air stratification within the greenhouse using closed cycle control was minimised with the operation of the evaporator fans.

6.3.2 Income and Running Costs

Tables 6.10 and 6.11 show a breakdown of the running costs associated with treatments at Auckland and Christchurch respectively.

The seasonal costs shown do not represent complete costs of production, instead they serve as base figures for the marginal costs/returns of production with enrichment.

The value per fruit shown were based on information published in the Horticultural News by Turners and Growers during 1994 and 1995 The values used are shown in Table 6.12. The average monthly prices shown are for carton quantities. The column headed 'max' indicates the maximum price achieved per

Table 6.10 Seasonal Income, Running Costs, and Returns associated with various treatments, AUCKLAND.

Crop Period (Julian Days)	Treatment	Enrichment Setpoint	Fruit Harvested (number)	Seasonal Income ($)	Seasonal Costs: Carbon Dioxide ($)	Heating ($)	Cooling ($)	Air Circulation ($)	Condenser ($)	Seasonal Return: Absolute ($)	Marginal ($)
	Control		20	17,640		141	81	60		17,358	
	Conventional	350	20	17,640	1,464	140	81	60		15,895	(1,463)
	Pulsing	600	24	21,168	2,439	142	81	60		18,445	1,087
Crop 1	Control	900	23	20,286	3,354	142	81	60		16,649	(710)
Period:		1200	23	20,286	4,036	142	81	60		15,967	(1,392)
26 - 116											
	Closed	350	20	17,640	1,806	40	1,534	240	243	13,778	(3,581)
	Cycle	600	28	24,696	3,672	39	1,526	240	243	18,976	1,617
	Control	900	30	26,460	5,739	40	1,533	240	243	18,665	1,307
		1200	30	26,460	7,732	41	1,536	240	243	16,668	(690)
	Control		10	15,680		3,398	1	60		12,221	
	Conventional	350	10	15,680	1,507	3,397	1	60		10,715	(1,506)
	Pulsing	600	13	20,384	3,237	3,404	1	60		13,683	1,462
Crop 2	Control	900	10	15,680	5,185	3,403	1	60		7,031	(5,190)
Period:		1200	13	20,384	7,003	3,404	1	60		9,916	(2,305)
145 - 235											
	Closed	350	8	12,544	1,502	1,256	51	240	243	9,252	(2,969)
	Cycle	600	11	17,248	3,158	1,255	51	240	243	12,301	80
	Control	900	11	17,248	5,057	1,253	50	240	243	10,404	(1,817)
		1200	11	17,248	6,802	1,256	51	240	243	8,656	(3,565)
	Control		25	24,850		590	33	60		24,166	
	Conventional	350	22	21,868	1,584	597	33	60		19,594	(4,572)
	Pulsing	600	23	22,862	3,756	596	33	60		18,417	(5,749)
Crop 3	Control	900	27	26,838	5,861	574	33	60		20,311	(3,855)
Period:		1200	25	24,850	7,371	566	33	60		16,820	(7,346)
	Closed	350	23	22,862	1,786	173	977	240	243	19,443	(4,723)
	Cycle	600	29	28,826	4,109	175	1,006	240	243	23,053	(1,113)
	Control	900	30	29,820	6,727	168	973	240	243	21,468	(2,698)
		1200	33	32,802	9,078	168	979	240	243	22,095	(2,072)

Annual Return

Pulsing ($)	Closed Cycle ($)
1,087	1,617
1,462	80
(3,855)	(1,113)
(1,307)	584

Internal Rate of Return
(10 Years)

Pulsing	Closed Cycle
N/A	N/A

Table 6.11 Seasonal Income, Running Costs, and Returns associated with various treatments, CHRISTCHURCH.

Crop Period (Julian Days)	Treatment	Enrichment Setpoint	Fruit Harvested (number)	Seasonal Income ($)	Seasonal Costs: Carbon Dioxide ($)	Heating ($)	Cooling ($)	Air Circulation ($)	Condenser ($)	Seasonal Return: Absolute ($)	Marginal ($)
	Control	.	19	16,758		1,675	81	123		14,879	
	Pulsing	350	23	20,286	1,676	1,713	82	123		16,693	1,814
	"	600	25	22,050	3,532	1,688	81	123		16,626	1,747
Crop 1	"	900	28	24,696	5,288	1,686	81	123		17,519	2,640
Period:	"	1200	28	24,696	6,570	1,701	82	123		16,221	1,342
26 - 116	Closed Cycle	350	23	20,286	1,814	595	2,095	490	496	14,796	(83)
	"	600	28	24,696	3,555	591	2,094	490	496	17,471	2,592
	"	900	29	25,578	5,521	583	2,064	490	496	16,425	1,546
	"	1200	29	25,578	7,439	584	2,066	490	496	14,504	(375)
	Control		3	4,704		8,309	9	123		(3,736)	
	Pulsing	350	4	6,272	1,320	8,307	9	123		(3,486)	250
	"	600	4	6,272	2,648	8,305	9	123		(4,813)	(1,077)
Crop 2	"	900	5	7,840	4,167	8,307	5	123		(4,761)	(1,025)
Period:	"	1200	6	9,408	5,659	8,306	5	123		(4,683)	(948)
145 - 235	Closed Cycle	350	3	4,704	1,275	3,500	-	490	496	(1,057)	2,679
	"	600	2	3,136	2,617	3,500	-	490	496	(3,966)	(230)
	"	900	3	4,704	4,121	3,499	-	490	496	(3,902)	(166)
	"	1200	3	4,704	5,606	3,499	-	490	496	(5,386)	(1,650)
	Control		23	22,862		2,378	74	123	-	20,287	
	Pulsing	350	28	27,832	1,844	2,390	75	123		23,401	3,114
	"	600	29	28,826	5,598	2,401	75	123		20,630	343
Crop 3	"	900	29	28,826	8,362	2,385	74	123		17,882	(2,406)
Period:	"	1200	29	28,826	9,198	2,384	74	123		17,048	(3,239)
263 - 353	Closed Cycle	350	27	26,838	2,235	903	2,521	490	496	20,194	(93)
	"	600	29	28,826	3,919	990	2,346	490	496	20,585	298
	"	900	32	31,808	6,369	975	2,281	490	496	21,198	910
	"	1200	32	31,808	8,636	975	2,283	490	496	18,928	(1,359)

Annual Return

Pulsing ($)	Closed Cycle ($)
2,640	2,592
250	2,679
3,114	910
6,003	6,181

Internal Rate of Return (10 Years)

Pulsing	Closed Cycle
62.7%	N/A

carton of fruit for any given month in 1994 or 1995. The price shown for December was calculated through linear interpolation between November and January. For the calculation of average seasonal price per fruit the number of fruit per carton was assumed to be 25. The commission charged by the auctioneers was assumed to be 10%. The cost of harvesting, wrapping, packing, and packaging was assumed to total $0.15 per fruit. Transport is not included as this will vary widely between growers.

The resulting average price achieved per fruit is $0.63, $1.12, and $0.71 for Crop1, Crop 2, and Crop3 respectively.

The cost of pure carbon dioxide in bulk was taken to be $0.40 per kilogram, with an additional supply charge of $400 per month, for both Auckland and Christchurch.

The cost of electrical energy was calculated in the following manner, after consultation with local Electricity Supply Authorities. For Auckland all electrical consumption was available at a bulk tariff of 5 cents per unit. In Christchurch different tariffs where available. Heat pump cooling (assumed to be day time consumption) was charged at an on-demand tariff of 12.6 cents per unit. Heating (assumed to be night-time consumption) was charged at a night tariff of 5.5 cents per unit. Air circulation was charged at 10.2 cents per unit. Note, these rates were valid in 1992.

The cost of heating the greenhouse treatments in Christchurch were 2.5 to 12 times the cost of the same treatments in Auckland. This is due to differences in energy consumption (see Chapter 5), not tariff differences.

However, the situation with respect to cooling is different. Despite the treatments in Auckland requiring considerably more energy for cooling than the treatments in Christchurch, the cost of cooling in Christchurch was consistently higher than in Auckland. A similar pattern emerged for the cost of air circulation. These differences are attributable to the differences in tariffs for the two locations. As a result there are significantly higher operating costs associated with all treatments in Christchurch compared to Auckland.

	$/Carton			
	1994	1995	Max	KomKom
Jan		22.96	22.96	0.918
Feb		19.32	19.32	0.773
Mar		17.40	17.40	0.696
Apr	17.85	27.07	27.07	1.083
May	24.16	31.11	31.11	1.244
Jun	34.38	29.44	34.38	1.375
Jul	39.87	38.92	39.87	1.595
Aug	28.96	26.27	28.96	1.158
Sep	32.24	27.56	32.24	1.290
Oct	26.18	15.58	26.18	1.047
Nov	18.56		18.56	0.742
Dec			20.76	0.830

	Crop 1	Crop 2	Crop 3
Av. per Season	0.84	1.39	0.93
- Commission	0.08	0.14	0.09
- Costs	0.13	0.13	0.13
= Nett	0.63	1.12	0.71

Table 6.12 Monthly average price per carton of cucumbers (left), and calculation of average seasonal price per cucumber (right).

6.3.3 Returns and Internal Rate of Return

The Seasonal 'Absolute' Returns (SAR) were calculated by taking the income and subtracting from this the sum of all costs. The SAR figure is in itself meaningless without comparison with the control. Hence the Seasonal Marginal Returns (SMR) were calculated by taking the difference between the SAR for each treatment and the SAR for the control.

The Annual Marginal Returns (AMR) were calculated by taking the sum of the greatest SMR for each crop period under each type of control.

The Internal Rate of Return (IRR) for each treatment was calculated assuming an economic life of ten years for each system. While a properly maintained system may in fact have a longer service life than this, it was felt that discounting over ten years was a suitable compromise between short and long term investment considerations. Where the AMR is zero or negative, no internal rate of return can be calculated and N/A is entered in the table. An IRR of 10% or greater is a level at which an investment yielding this return is considered attractive.

The marginal establishment cost of the conventionally controlled enrichment schemes was taken to include only the capital cost of the carbon dioxide enrichment equipment ($9,500). For the closed cycle systems the marginal capital cost was calculated as the difference between the cost of a closed cycle system and a conventional control system plus the carbon dioxide enrichment equipment ($113,200 - $31,650 + $9,500 = $91,050).

At both locations, treatments with closed cycle control gave a greater AMR than treatments with conventional control.

In fact, in Auckland the AMR for conventionally controlled treatments (pulsing control) is negative. This indicates it would be uneconomic for a grower to consider carbon dioxide enrichment in the conventionally controlled greenhouse simulated.

Although the AMR is positive for treatments in Auckland with closed cycle control, the IRR is zero or negative as the AMR is not sufficient to provide a payback on the cost of equipment over a ten year period. Hence, in Auckland it would be uneconomic for a greenhouse grower to consider carbon dioxide enrichment and closed cycle control equipment in the greenhouse simulated.

Despite the higher running costs, comparing Tables 6.10 and 6.11 it is clear that treatments in Christchurch provide greater AMR than in Auckland. The IRR for the conventionally controlled greenhouse is 62.7% which indicates that carbon dioxide enrichment would be an attractive investment with the greenhouse simulated. Despite the relatively high AMR for closed cycle control of $ 6,181, this is not sufficient to provide a payback for the equipment over a ten year period and hence the IRR is less than zero. This means that investment in the closed cycle control system and carbon dioxide enrichment equipment is not attractive to a grower with the greenhouse simulated.

6.3.4 Price Variability

In order to study the effects of price, a sensitivity analysis has been carried out, the results of which are shown in Tables 6.13 and 6.14.

The effect of change in fruit price was calculated by changing the fruit price achieved, during each crop period, in steps of 10% both in the positive and the negative direction from the initial prices. The seasonal marginal return for each treatment was then recalculated. The AMR for each step and each type of control was derived from the sum of the highest seasonal marginal returns for each type of control. The IRR was then calculated for each step and each type of control from the respective AMRs.

Note, where the yield achieved by a treatment is the same as the yield for the control, there will be no effect on AMR by a change in fruit price as this change affects both the treatment and the control to the same degree (e.g. conventional control with 350 ppm setpoint for crop 1 in Auckland, Figure 6.12).

Firstly, looking at Auckland (Table 6.13) with conventional control, a positive AMR is possible only when prices achieved are lifted by 20%. A positive IRR is not achieved until prices are lifted by 30%, the resulting IRR is then 13.1% which would make carbon dioxide enrichment an attractive investment for a greenhouse grower using conventional control in the greenhouse simulated.

The treatments using closed cycle control in Auckland provide a net positive AMR with the initial fruit prices used. The AMR needs to be at least $ 9,105 for an IRR of 0%. Even with the highest increase in fruit price of 50% the AMR is only $ 8,485 hence a greater increase in AMR is needed to return a positive IRR. In fact, further calculations have indicated that fruit prices would have to lift by 90% in order to provide a AMR sufficient to raise IRR to over 10%, the IRR is then 11.6%.

In Christchurch the figures are quite different. With conventional control a positive AMR is predicted even if fruit prices fall by 50%, the AMR is then $ 145 which is not sufficient to provide a payback on the investment in carbon dioxide enrichment equipment and hence IRR is less than zero. For a positive IRR fruit prices cannot fall below 60% of initial prices (i.e. a drop of 40%), the AMR is then $ 1,151 and the IRR is 3.7%. For an IRR of greater than 10%, the fruit prices cannot fall below 70% (i.e. a drop of 30%), the AMR is then $ 2,158 and the IRR is 18.6% which would make carbon dioxide enrichment an attractive investment for a greenhouse grower with conventional control in the greenhouse simulated.

With closed cycle control in Christchurch a positive AMR is predicted with fruit prices at 60% of initial. However, the prices would need to lift by 20% for an AMR of greater than $ 9,105, and hence a positive IRR. At this level, the AMR is $ 9,558 and the IRR is 0.9%. A lift in fruit prices by greater than 50% is needed to return an IRR of greater than 10%. Further calculations have shown that a lift in prices by 60% would return an AMR of $16,312 and an IRR of 12.3%.

Table 6.13 Sensitivity Analysis of Marginal and Internal Rate of Return to Average Seasonal Fruit Price, AUCKLAND.

Enrichment Setpoint		Fruit Harvested (number)	Marginal Average Seasonal Returns, with respect to the control										
			Change in Price per Fruit from Seasonal Average										
			- 50 %	- 40 %	- 30 %	- 20 %	- 10 %	0 %	+ 10 %	+ 20 %	+ 30 %	+ 40 %	+ 50 %
Control	0	20	$ 0.32	$ 0.38	$ 0.44	$ 0.50	$ 0.57	$ 0.63	$ 0.69	$ 0.76	$ 0.82	$ 0.88	$ 0.95
Conventiona	350	20	(1,463)	(1,463)	(1,463)	(1,463)	(1,463)	(1,463)	(1,463)	(1,463)	(1,463)	(1,463)	(1,463)
Pulsing	600	24	(677)	(324)	29	381	734	1,087	1,440	1,793	2,145	2,498	2,851
Control	900	23	(2,033)	(1,768)	(1,503)	(1,239)	(974)	(710)	(445)	(180)	84	349	613
	1200	23	(2,715)	(2,450)	(2,185)	(1,921)	(1,656)	(1,392)	(1,127)	(862)	(598)	(333)	(69)
Closed	350	20	(3,581)	(3,581)	(3,581)	(3,581)	(3,581)	(3,581)	(3,581)	(3,581)	(3,581)	(3,581)	(3,581)
Cycle	600	28	(1,911)	(1,205)	(499)	206	912	1,617	2,323	3,029	3,734	4,440	5,145
Control	900	30	(3,103)	(2,221)	(1,339)	(457)	425	1,307	2,189	3,071	3,953	4,835	5,717
	1200	30	(5,100)	(4,218)	(3,336)	(2,454)	(1,572)	(690)	192	1,074	1,956	2,838	3,720
Control	0	10	0.56	0.67	0.78	0.90	1.01	1.12	1.23	1.34	1.46	1.57	1.68
Conventiona	350	10	(1,506)	(1,506)	(1,506)	(1,506)	(1,506)	(1,506)	(1,506)	(1,506)	(1,506)	(1,506)	(1,506)
Pulsing	600	13	(890)	(420)	51	521	991	1,462	1,932	2,403	2,873	3,343	3,814
Control	900	10	(5,190)	(5,190)	(5,190)	(5,190)	(5,190)	(5,190)	(5,190)	(5,190)	(5,190)	(5,190)	(5,190)
	1200	13	(4,657)	(4,187)	(3,716)	(3,246)	(2,776)	(2,305)	(1,835)	(1,364)	(894)	(424)	47
Closed	350	8	(1,401)	(1,715)	(2,029)	(2,342)	(2,656)	(2,969)	(3,283)	(3,597)	(3,910)	(4,224)	(4,537)
Cycle	600	11	(704)	(548)	(391)	(234)	(77)	80	236	393	550	707	864
Control	900	11	(2,601)	(2,444)	(2,287)	(2,130)	(1,974)	(1,817)	(1,660)	(1,503)	(1,346)	(1,190)	(1,033)
	1200	11	(4,349)	(4,192)	(4,035)	(3,878)	(3,721)	(3,565)	(3,408)	(3,251)	(3,094)	(2,937)	(2,781)
Control	0	25	0.36	0.43	0.50	0.57	0.64	0.71	0.78	0.85	0.92	0.99	1.07
Conventiona	350	22	(3,081)	(3,380)	(3,678)	(3,976)	(4,274)	(4,572)	(4,871)	(5,169)	(5,467)	(5,765)	(6,063)
Pulsing	600	23	(4,755)	(4,954)	(5,153)	(5,352)	(5,551)	(5,749)	(5,948)	(6,147)	(6,346)	(6,545)	(6,743)
Control	900	27	(4,849)	(4,651)	(4,452)	(4,253)	(4,054)	(3,855)	(3,657)	(3,458)	(3,259)	(3,060)	(2,861)
	1200	25	(7,346)	(7,346)	(7,346)	(7,346)	(7,346)	(7,346)	(7,346)	(7,346)	(7,346)	(7,346)	(7,346)
Closed	350	23	(3,729)	(3,928)	(4,127)	(4,326)	(4,525)	(4,723)	(4,922)	(5,121)	(5,320)	(5,519)	(5,717)
Cycle	600	29	(3,101)	(2,704)	(2,306)	(1,909)	(1,511)	(1,113)	(716)	(318)	79	477	875
Control	900	30	(5,183)	(4,686)	(4,189)	(3,692)	(3,195)	(2,698)	(2,201)	(1,704)	(1,207)	(710)	(213)
	1200	33	(6,048)	(5,252)	(4,457)	(3,662)	(2,867)	(2,072)	(1,276)	(481)	314	1,109	1,904

Determination of Internal Rate of Return for most positive marginal return with Conventional Control.

Best Seasonal	(677)	(324)	29	381	734	1,087	1,440	1,793	2,145	2,498	2,851
Marginal	(890)	(420)	51	521	991	1,462	1,932	2,403	2,873	3,343	3,814
Return	(3,081)	(3,380)	(3,678)	(3,976)	(4,054)	(3,855)	(3,657)	(3,458)	(3,259)	(3,060)	(2,861)
Per Annum	(4,649)	(4,124)	(3,599)	(3,074)	(2,329)	(1,307)	(285)	737	1,759	2,781	3,803
Marginal Cost of Control	9,500	9,500	9,500	9,500	9,500	9,500	9,500	9,500	9,500	9,500	9,500
Internal Rate of Return	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	13.1%	26.5%	38.5%

Determination of Internal Rate of Return for most positive marginal return with Closed Cycle Control.

Best Seasonal	(1,911)	(1,205)	(499)	206	912	1,617	2,323	3,071	3,953	4,835	5,717
Marginal	(704)	(548)	(391)	(234)	(77)	80	236	393	550	707	864
Return	(3,101)	(2,704)	(2,306)	(1,909)	(1,511)	(1,113)	(716)	(318)	314	1,109	1,904
Per Annum	(5,716)	(4,456)	(3,196)	(1,936)	(676)	584	1,844	3,146	4,817	6,651	8,485
Marginal Cost of Control	91,050	91,050	91,050	91,050	91,050	91,050	91,050	91,050	91,050	91,050	91,050
Internal Rate of Return	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 6.14 Sensitivity Analysis of Marginal and Internal Rate of Return to Average Seasonal Fruit Price, CHRISTCHURCH.

Enrichment Setpoint		Fruit Harvested (number)	Average Seasonal Marginal Return with Respect to Control: Change in Price per Fruit from Seasonal Average										
			- 50 %	- 40 %	- 30 %	- 20 %	- 10 %	0 %	+ 10 %	+ 20 %	+ 30 %	+ 40 %	+ 50 %
Control	0	19	$ 0.32	$ 0.38	$ 0.44	$ 0.50	$ 0.57	$ 0.63	$ 0.69	$ 0.76	$ 0.82	$ 0.88	$ 0.95
Conventio	350	23	50	402	755	1,108	1,461	1,814	2,166	2,519	2,872	3,225	3,578
Pulsing	600	25	(899)	(370)	159	688	1,217	1,747	2,276	2,805	3,334	3,863	4,393
Control	900	28	(1,329)	(536)	258	1,052	1,846	2,640	3,433	4,227	5,021	5,815	6,609
	1200	28	(2,627)	(1,834)	(1,040)	(246)	548	1,342	2,135	2,929	3,723	4,517	5,311
Closed	350	23	(1,847)	(1,494)	(1,141)	(789)	(436)	(83)	270	623	975	1,328	1,681
Cycle	600	28	(1,377)	(584)	210	1,004	1,798	2,592	3,385	4,179	4,973	5,767	6,561
Control	900	29	(2,864)	(1,982)	(1,100)	(218)	664	1,546	2,428	3,310	4,192	5,074	5,956
	1200	29	(4,785)	(3,903)	(3,021)	(2,139)	(1,257)	(375)	507	1,389	2,271	3,153	4,035
Control	0	3	0.56	0.67	0.78	0.90	1.01	1.12	1.23	1.34	1.46	1.57	1.68
Conventio	350	4	(534)	(378)	(221)	(64)	93	250	406	563	720	877	1,034
Pulsing	600	4	(1,861)	(1,704)	(1,547)	(1,391)	(1,234)	(1,077)	(920)	(763)	(607)	(450)	(293)
Control	900	5	(2,593)	(2,280)	(1,966)	(1,653)	(1,339)	(1,025)	(712)	(398)	(85)	229	543
	1200	6	(3,300)	(2,829)	(2,359)	(1,888)	(1,418)	(948)	(477)	(7)	464	934	1,404
Closed	350	3	2,679	2,679	2,679	2,679	2,679	2,679	2,679	2,679	2,679	2,679	2,679
Cycle	600	2	554	397	240	83	(74)	(230)	(387)	(544)	(701)	(858)	(1,014)
Control	900	3	(166)	(166)	(166)	(166)	(166)	(166)	(166)	(166)	(166)	(166)	(166)
	1200	3	(1,650)	(1,650)	(1,650)	(1,650)	(1,650)	(1,650)	(1,650)	(1,650)	(1,650)	(1,650)	(1,650)
Control	0	23	0.36	0.43	0.50	0.57	0.64	0.71	0.78	0.85	0.92	0.99	1.07
Conventio	350	28	629	1,126	1,623	2,120	2,617	3,114	3,611	4,108	4,605	5,102	5,599
Pulsing	600	29	(2,639)	(2,043)	(1,447)	(850)	(254)	343	939	1,535	2,132	2,728	3,325
Control	900	29	(5,388)	(4,791)	(4,195)	(3,598)	(3,002)	(2,406)	(1,809)	(1,213)	(616)	(20)	576
	1200	29	(6,221)	(5,625)	(5,029)	(4,432)	(3,836)	(3,239)	(2,643)	(2,047)	(1,450)	(854)	(257)
		0											
Closed	350	27	(2,081)	(1,683)	(1,286)	(888)	(490)	(93)	305	702	1,100	1,498	1,895
Cycle	600	29	(2,684)	(2,088)	(1,491)	(895)	(299)	298	894	1,491	2,087	2,683	3,280
Control	900	32	(3,563)	(2,668)	(1,773)	(879)	16	910	1,805	2,700	3,594	4,489	5,383
	1200	32	(5,832)	(4,937)	(4,042)	(3,148)	(2,253)	(1,359)	(464)	431	1,325	2,220	3,114

Determination of Internal Rate of Return for most positive marginal return with Conventional Control.

Best Seasonal	50	402	755	1,108	1,846	2,640	3,433	4,227	5,021	5,815	6,609
Marginal	(534)	(378)	(221)	(64)	93	250	406	563	720	934	1,404
Return	629	1,126	1,623	2,120	2,617	3,114	3,611	4,108	4,605	5,102	5,599
Per Annum	145	1,151	2,158	3,164	4,556	6,003	7,451	8,899	10,346	11,851	13,612
Marginal Cost of Control	9,500	9,500	9,500	9,500	9,500	9,500	9,500	9,500	9,500	9,500	9,500
Internal Rate of Return	N/A	3.7%	18.6%	31.1%	46.9%	62.7%	78.2%	93.5%	108.8%	124.7%	143.3%

Determination of Internal Rate of Return for most positive marginal return with Closed Cycle Control.

Best Seasonal	(1,377)	(584)	210	1,004	1,798	2,592	3,385	4,179	4,973	5,767	6,561
Marginal	2,679	2,679	2,679	2,679	2,679	2,679	2,679	2,679	2,679	2,679	2,679
Return	(2,081)	(1,683)	(1,286)	(879)	16	910	1,805	2,700	3,594	4,489	5,383
Per Annum	(779)	412	1,604	2,805	4,493	6,181	7,870	9,558	11,247	12,935	14,623
Marginal Cost of Control	91,050	91,050	91,050	91,050	91,050	91,050	91,050	91,050	91,050	91,050	91,050
Internal Rate of Return	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1%	4%	7%	10%

It can be concluded that a grower in Auckland with conventional control in the greenhouse simulated would need to consider the investment in carbon dioxide enrichment equipment carefully as an IRR of greater than 10% is predicted only if average fruit prices achieved lift by approximately 30% for the term of the payback period of 10 years.

Investment in closed cycle control and carbon dioxide enrichment equipment is an even less attractive consideration as average fruit prices achieved would need to lift by approximately 90%, for the 10 year payback period term, in order to yield an IRR of at least 10%.

However, a grower with the greenhouse simulated in Christchurch and conventional control should consider investing in carbon dioxide enrichment equipment as it will provide an attractive payback with initial fruit prices and even sustain a drop in fruit prices achieved, by as much as 30%, while still providing an attractive payback with an IRR of more than 10%.

The decision to invest in closed cycle control and carbon dioxide enrichment should be taken very cautiously as a satisfactory IRR of greater than 10% is not reached unless average fruit prices achieved lift by approximately 60% or more compared to the 1994 - 1995 average. And this would need to be sustained for 10 years.

Therefore for a grower with the greenhouse simulated, carbon dioxide enrichment is a more stable investment in Christchurch compared with Auckland, based on fluctuations in average seasonal fruit price achieved. This is particularly the case with conventional control equipment. With closed cycle control the investment can only be considered if a significant lift in prices achieved is forecast, and maintained for the ten year payback period.

Note also, with each 10% change in fruit price achieved the effect on IRR results are greater with conventional control than with closed cycle control.

6.3.5 Yield Variability

In order to investigate the effect of variation in fruit yield achieved, a sensitivity analysis based on change in fruit yield, from the yield achieved in the simulations, was carried out. The results are shown in Tables 6.15 and 6.16.

To calculate the effect of change in yield, the yield achieved with each treatment during each crop period and at each location, was varied by a step of one fruit in each direction (positive and negative) from the yield results in the simulations. The range over which fruit yield was varied was -3 to +3. As we were interested in the varying effects of the treatments with respect to control, the yield of the control treatment was not varied.

With each change in yield, the seasonal marginal return for each treatment was re-calculated. The new AMR figures for both conventional control and closed cycle control were derived from the sum of the greatest SMR's. Based on each AMR, the resulting IRR was then calculated.

Table 6.15 Sensitivity Analysis of Marginal and Internal Rate of Return to Average Seasonal Fruit Yield, AUCKLAND.

Enrichment Setpoint		Fruit Harvested (number)	Marginal Average Seasonal Returns, with Respect to Control.						
			Change in Fruit Number per Plant						
			-3.	-2.	-1.	0	+1.	+2.	+3.
Control	0	20	Average Seasonal Fruit Price:			$ 0.63			
Conventio	350	20	(4,109)	(3,227)	(2,345)	(1,463)	(581)	301	1,183
Pulsing	600	24	(1,559)	(677)	205	1,087	1,969	2,851	3,733
Control	900	23	(3,356)	(2,474)	(1,592)	(710)	172	1,054	1,936
	1200	23	(4,038)	(3,156)	(2,274)	(1,392)	(510)	372	1,254
Closed	350	20	(6,227)	(5,345)	(4,463)	(3,581)	(2,699)	(1,817)	(935)
Cycle	600	28	(1,029)	(147)	735	1,617	2,499	3,381	4,263
Control	900	30	(1,339)	(457)	425	1,307	2,189	3,071	3,953
	1200	30	(3,336)	(2,454)	(1,572)	(690)	192	1,074	1,956
Control	0	10	Average Seasonal Fruit Price:			$ 1.12			
Conventio	350	10	(6,210)	(4,642)	(3,074)	(1,506)	62	1,630	3,198
Pulsing	600	13	(3,242)	(1,674)	(106)	1,462	3,030	4,598	6,166
Control	900	10	(9,894)	(8,326)	(6,758)	(5,190)	(3,622)	(2,054)	(486)
	1200	13	(7,009)	(5,441)	(3,873)	(2,305)	(737)	831	2,399
Closed	350	8	(7,673)	(6,105)	(4,537)	(2,969)	(1,401)	167	1,735
Cycle	600	11	(4,624)	(3,056)	(1,488)	80	1,648	3,216	4,784
Control	900	11	(6,521)	(4,953)	(3,385)	(1,817)	(249)	1,319	2,887
	1200	11	(8,269)	(6,701)	(5,133)	(3,565)	(1,997)	(429)	1,139
Control	0	24	Average Seasonal Fruit Price:			$ 0.71			
Conventio	350	22	(6,560)	(5,566)	(4,572)	(3,578)	(2,584)	(1,590)	(596)
Pulsing	600	23	(7,737)	(6,743)	(5,749)	(4,755)	(3,761)	(2,767)	(1,773)
Control	900	27	(5,843)	(4,849)	(3,855)	(2,861)	(1,867)	(873)	121
	1200	27	(7,346)	(6,352)	(5,358)	(4,364)	(3,370)	(2,376)	(1,382)
Closed	350	25	(4,723)	(3,729)	(2,735)	(1,741)	(747)	247	1,241
Cycle	600	29	(3,101)	(2,107)	(1,113)	(119)	875	1,869	2,863
Control	900	30	(4,686)	(3,692)	(2,698)	(1,704)	(710)	284	1,278
	1200	33	(4,060)	(3,066)	(2,072)	(1,078)	(84)	910	1,904

Determination of Internal Rate of Return for most positive marginal return with Conventional Con

Best Seasonal	(1,559)	(677)	205	1,087	1,969	2,851	3,733
Marginal	(3,242)	(1,674)	(106)	1,462	3,030	4,598	6,166
Return	(5,843)	(4,849)	(3,855)	(2,861)	(1,867)	(873)	121
Per Annum	(10,645)	(7,201)	(3,757)	(313)	3,131	6,575	10,019
Marginal Cost of Control	9,500	9,500	9,500	9,500	9,500	9,500	9,500
Internal Rate of Return	N/A	N/A	N/A	N/A	30.7%	68.8%	105.4%

Determination of Internal Rate of Return for most positive marginal return with Closed Cycle Cont

Best Seasonal	(1,029)	(147)	735	1,617	2,499	3,381	4,263
Marginal	(1,029)	(147)	735	1,617	2,499	3,381	4,263
Return	(3,101)	(2,107)	(1,113)	(119)	875	1,869	2,863
Per Annum	(5,158)	(2,400)	358	3,116	5,874	8,632	11,390
Marginal Cost of Control	91,050	91,050	91,050	91,050	91,050	91,050	91,050
Internal Rate of Return	N/A	N/A	N/A	N/A	N/A	N/A	4.3%

Table 6.16 Sensitivity Analysis of Marginal and Internal Rate of Return to Average Seasonal Fruit Yield, CHRISTCHURCH.

Enrichment Setpoint		Fruit Harvested (number)	Marginal Average Seasonal Returns, with Respect to Control.						
			Change in Fruit Number per Plant						
			-3.	-2.	-1.	0	+1.	+2.	+3.
Control	0	19	Average Seasonal Fruit Price:		$	0.63			
Conventio	350	23	(832)	50	932	1,814	2,696	3,578	4,460
Pulsing	600	25	(899)	(17)	865	1,747	2,629	3,511	4,393
Control	900	28	(6)	876	1,758	2,640	3,522	4,404	5,286
	1200	28	(1,304)	(422)	460	1,342	2,224	3,106	3,988
Closed	350	23	(2,729)	(1,847)	(965)	(83)	799	1,681	2,563
Cycle	600	28	(54)	828	1,710	2,592	3,474	4,356	5,238
Control	900	29	(1,100)	(218)	664	1,546	2,428	3,310	4,192
	1200	29	(3,021)	(2,139)	(1,257)	(375)	507	1,389	2,271
Control	0	3	Average Seasonal Fruit Price:		$	1.12			
Conventio	350	4	(4,454)	(2,886)	(1,318)	250	1,818	3,386	4,954
Pulsing	600	4	(5,781)	(4,213)	(2,645)	(1,077)	491	2,059	3,627
Control	900	5	(5,729)	(4,161)	(2,593)	(1,025)	543	2,111	3,679
	1200	6	(5,652)	(4,084)	(2,516)	(948)	620	2,188	3,756
Closed	350	3	(2,025)	(457)	1,111	2,679	4,247	5,815	7,383
Cycle	600	2	(4,934)	(3,366)	(1,798)	(230)	1,338	2,906	4,474
Control	900	3	(4,870)	(3,302)	(1,734)	(166)	1,402	2,970	4,538
	1200	3	(6,354)	(4,786)	(3,218)	(1,650)	(82)	1,486	3,054
Control	0	23	Average Seasonal Fruit Price:		$	0.71			
Conventio	350	28	132	1,126	2,120	3,114	4,108	5,102	6,096
Pulsing	600	29	(2,639)	(1,645)	(651)	343	1,337	2,331	3,325
Control	900	29	(5,388)	(4,394)	(3,400)	(2,406)	(1,412)	(418)	576
	1200	29	(6,221)	(5,227)	(4,233)	(3,239)	(2,245)	(1,251)	(257)
Closed	350	27	(3,075)	(2,081)	(1,087)	(93)	901	1,895	2,889
Cycle	600	29	(2,684)	(1,690)	(696)	298	1,292	2,286	3,280
Control	900	32	(2,072)	(1,078)	(84)	910	1,904	2,898	3,892
	1200	32	(4,341)	(3,347)	(2,353)	(1,359)	(365)	629	1,623

Determination of Internal Rate of Return for most positive marginal return with Conventional Cont

Best Seasonal	(6)	876	1,758	2,640	3,522	4,404	5,286
Marginal	(4,454)	(2,886)	(1,318)	250	1,818	3,386	4,954
Return	132	1,126	2,120	3,114	4,108	5,102	6,096
Per Annum	(4,329)	(885)	2,559	6,003	9,447	12,891	16,335
Marginal Cost of Control	9,500	9,500	9,500	9,500	9,500	9,500	9,500
Internal Rate of Return	N/A	N/A	23.7%	62.7%	99.3%	135.7%	171.9%

Determination of Internal Rate of Return for most positive marginal return with Closed Cycle Cont

Best Seasonal	(54)	828	1,710	2,592	3,474	4,356	5,238
Marginal	(54)	828	1,710	2,592	3,474	4,356	5,238
Return	(2,072)	(1,078)	(84)	910	1,904	2,898	3,892
Per Annum	(2,180)	578	3,336	6,094	8,852	11,610	14,368
Marginal Cost of Control	91,050	91,050	91,050	91,050	91,050	91,050	91,050
Internal Rate of Return	N/A	N/A	N/A	N/A	N/A	4.7%	9.3%

In Auckland, in a greenhouse with conventional control a positive AMR and IRR are not achieved until fruit yield is lifted by 1, at which level the AMR and IRR are $ 3,131 and 30.7% respectively. These returns would make carbon dioxide enrichment an attractive investment for a greenhouse grower with the greenhouse simulated.

With closed cycle control, a positive AMR is returned with fruit yield reduced by -1. Below this yield, the AMR becomes negative.

The IRR is positive only when yield is increased by 3 fruit. At this level the IRR is 4.3% which is still not high enough to consider closed cycle control and carbon dioxide enrichment an attractive investment for a grower with the greenhouse simulated. Further calculations show that a lift in yield of 5 fruit is needed in order to increase IRR above 10%, at this level the IRR is 13.2%.

The greenhouse with conventional control in Christchurch returned a positive AMR and IRR with a reduction in yield up to -1. At this point the AMR and IRR are $ 2,559 and 23.7% respectively, both become negative with any further reduction in fruit yield.

The IRR is greater than 10% and hence carbon dioxide enrichment is an attractive proposition even if yield drops by 1 fruit.

With closed cycle control, the greenhouse in Christchurch returned positive AMR's for reductions down to -2 fruit. IRR, however, was not positive until fruit yield was lifted by 2 fruit, at which level the IRR was 4.7%. In order to return an IRR of greater than 10%, further calculations show that the fruit yield would need to lift by 4, at this level the AMR is $17,126 and the IRR is 13.5%.

Hence, closed cycle control and carbon dioxide enrichment becomes an attractive investment option only if fruit yield is lifted by 4 fruit per plant, and sustained at this level for at least the ten year payback period.

In both Auckland and Christchurch, each unit change in fruit yield achieved causes a greater effect on IRR in a greenhouse with a conventional control system compared with a greenhouse with a closed cycle control system.

As with the fruit price sensitivity analysis, the simulated greenhouse located in Christchurch is more stable with variation in fruit yield than the same greenhouse located in Auckland.

At neither location is closed cycle control and carbon dioxide enrichment an attractive investment option unless fruit yield is lifted significantly from that simulated, and maintained at this level for at least 10 years.

Comparing the average seasonal fruit price sensitivity analysis with the seasonal fruit yield sensitivity analysis it can be seen that unit change in fruit yield has a greater effect on AMR and IRR than each 10% change in fruit price achieved.

7. CONCLUSIONS AND RECOMMENDATIONS

It can be noted from the previous section that the results of the simulation trials are quite variable and depend on the type of treatment and the location of the greenhouse. Based on the simulation results only, the following conclusions can be drawn from the study regarding the enrichment of greenhouse cucumbers with carbon dioxide under New Zealand conditions.

- The capital cost of carbon dioxide enrichment equipment in combination with conventional control is relatively low and can be easily justified in Christchurch, where generally cooler outside temperatures will result in longer enrichment times than in Auckland. In Auckland the justification is less tenable and is sensitive to the accuracy of the model to predict fruit production, and also the to possible fluctuations in average seasonal fruit price achieved.
- The capital cost of a closed cycle system using a heat pump for heating and cooling is relatively high and can only be considered in combination with carbon dioxide enrichment. In Christchurch the results look more promising than in Auckland, because of the considerable energy saving possible with closed cycle climate control compared to conventional climate control (see Table 7.1). Furthermore, carbon dioxide enrichment in Christchurch results in significantly increased production compared to Auckland. In Auckland this system does not look as promising since the capital cost for closed cycle control is high and there is no significant lift in yield from conventional control.
- Since the capital cost of the heat pump is a major factor for the closed cycle enrichment system it would be worth investigating other less expensive forms of closed cycle cooling. These would include ice-bank storage systems, to decrease the size of the compressor needed, and large area plate heat exchangers used in conjunction with thermal storage (either rock beds or solar ponds).
- Variation in yield per plant has a greater effect on returns than 10% change in produce price.
- Although, no conclusions can be drawn from this study as to the likely benefits of this technology for other crops it is worthwhile exploring the economic benefits of this technology when applied to other, higher value, greenhouse crops . This will only be possible when the simulation model has been suitably adapted to other crops.

	Auckland	Christchurch
Conventional Climate Control	84.8	226.1
Closed Cycle Climate Control	80.7	126.9

Table 7.1 *Table showing the total annual energy requirement for cooling and heating of the greenhouse simulated, with two types of control and at two locations (figures in Mwh).*

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APPENDIX

PROGRAM LISTINGS AND DATA FILES

GREENHOUSE SIMULATION MODEL

Changes made to the *CUCUMBER* model (Wells, 1992) are highlighted in bold.

The *KOMKOM* greenhouse simulation model, written in the ESL (Hay et al, 1988) programming language is listed in the following sections.

- The input data file SIMPUT is listed in section A16
- The initial plant data file INPUT14.CEL is listed in section A17
- The direct and diffuse transmission and absorption data for the greenhouse SKY and DIFF are listed in sections A19 and A20 respectively.

A1 Main Simulation Model

```
--
-- File KOMKOM.ESL
--
----------------------------------------------------------------------
-- ESL Simulation program KOMKOMMER
-- Simulates greenhouse environment and cucumber growth
----------------------------------------------------------------------
-
-- Begin the simulation
--
  STUDY
--
-- Include models, subroutines, and functions from other files
--
-- Global Variables
  INCLUDE "GLOBAL";
-- Properties of Soil
  INCLUDE "SOIL";
-- Function interpolater
  INCLUDE "GEN2";
-- Control routines
  INCLUDE "CONTROL";
-- Read input files and set up initial data
  INCLUDE "INDATA";
```

```
-- Calculate data that varies daily
  INCLUDE "VARIDATA";
-- Convective heat transfer coefficients
  INCLUDE "CONVHT";
-- Solar radiation partitioning, transmission, absorption
  INCLUDE "SOLAR";
-- Refrigeration Submodel
  INCLUDE "REFRIG";
-- Greenhouse Energy and Mass Balance Model
  INCLUDE "GEMB";
-- Crop photosysnthesis
  INCLUDE "PHOTOSYN";
-- Crop growth and respiration
  INCLUDE "GROWTH";
-- Crop development (daily)
  INCLUDE "DEVELOP";
-- Hourly data output
  INCLUDE "HOUTPUT";
-- Daily data output
  INCLUDE "DOUTPUT";
--
--EXPERIMENT
--
USE GLOBAL;
--
-- Simulation variables for the greenhouse model
--
  REAL : Tgi/18.3/,Xgi/0.0/;
  REAL : Tsi/19.0/;
  REAL : Tai/21.1/,Xai/45.0/;
  REAL : Tci/20.0/,Xci;
  REAL : Tmi/22.7/,Xmi;
  REAL : Tfi/24.0/,T1i/24.0/,T2i/24.0/,T3i/24.0/,T4i/24.0/,T5i/22.0/;
  REAL : XCO2ai,XCO2i;
--
  REAL : Tg,Xg;
  REAL : Ts;
  REAL : Ta,Xa;
  REAL : Tc,Xc;
  REAL : Tm,Xm;
  REAL : Tf,T1,T2,T3,T4,T5;
  REAL : XCO2a;
  REAL : T1evap/5.0/,T1cond/35.0/;
```

```
  REAL : T2evap/5.0/,T2cond/35.0/;
  REAL : T3evap/5.0/,T3cond/35.0/;
--
-- Input and output file specifiers
--
  CHARACTER : Filename(20);
  INTEGER : Err,IJ,Num1,Num2;
--
  FILE : Infile,Out1,Out2,Out3,Out4;
--
-- Read and calculate input parameters
--
  INDATA;
  VARIDATA;
--
-- Initialize crop and root medium moisture content
-- Initialize carbon dioxide content
--
  Xmi := 0.9*Xmmax;
  Xci := 0.9*Xcmax;
  XCO2ai := da*ChiCO2a;
--
-- MAIN LOOP FOR READING BOUNDAY CONDITION FILES
--
  FOR IJ := 14..26 LOOP
--
-- Open output files and input files
--
  Num1 := INT(IJ/10) + 48;
  Num2 := IJ - (Num1 - 48)*10 + 48;
--
-- Hourly output of environment and control parameters
--
  Filename(1..14) := "c:\output\cond";
  Filename(15) := ACHAR(Num1);
  Filename(16) := ACHAR(Num2);
  Filename(17..19) := ".AK";
  REWRITE Out1,Filename;
--
-- Daily output of yield and control variables
--
  Filename(11..14) := "leaf";
  REWRITE Out4,Filename;
```

```
--
-- Daily output of crop growth parameters
--
  Filename(11..14) := "ddat";
  REWRITE Out2,Filename;
--
-- 5 minute boundary value inputs. 1 week in each file
--
  Filename(1..14) := "c:\input\bound";
  OPEN Infile,Filename;
--
-- Beginning of loop to read boundary file
--
  WHILE Day <= 365.0 LOOP
--
-- Set simulation finish time TFIN to 300 seconds (= 5 minutes).
-- Set communication interval CINT to be 30 seconds for control
-- Force maximum simulation step to be 30 seconds (NSTEP = 1)
--
  TFIN := 300;
  CINT := 30;
  NSTEP := 1.0;
--
-- Read Boundary values from Infile
-- Year, Day, Hour, Minute, Outside Dry Bulb Temp, Outside Wet Bulb
Temp
-- Deep Ground Temp, Outside Wind Speed, Global Solar Radiation,
-- Solar Altitude, Solar Azimuth, Opening of Top Ventilators,
-- Opening of Bottom Ventilators, Heater Input,
-- Heater Temperature Diff, Irrigation Amount
--
  READ InFile,Y,Day,Hr,Min,To,Tow,Td,Uo,Sg,SAlt,SAzi,
            Cloud,IOSTAT=Err;
--
-- On end of file terminate this loop
--
  TERMINATE Err /= 0;
--
-- Period of simulation
--
  IF (Day >= 145) AND (Day <= 235) THEN
--
-- Scale input values
```

```
--
  To := To/10.0;
  Tow := Tow/10.0;
  Td := Td/10.0;
  Uo := Uo/100.0;
  Cloud := Cloud/1000;
--
-- To pick or not to pick
--
  IF (Hr = 9.0) AND (Min = 0.0) THEN
    PickTime := TRUE;
  ELSE
    PickTime := FALSE;
  END_IF;
--
-- Calculate solar radiation transmission and absorption and
-- gross photosynthesis
--
  IF (Sg = 0.0) OR (SAlt <= 0.0) THEN
    Bg := 0.0; Bs :=0.0; Bc := 0.0; Bm := 0.0; Bf := 0.0;
    Bcave := 0.0; Bpar := 0.0; FGross := 0.0; Assim := 0.0;
    firr := 0.0;
  ELSE
    SOLAR;
    PHOTOSYN(:=Tci);
    firr := 0.0;
    IF (psim<-1.5) THEN firr := 500*Nplant/(TFIN*Af); END_IF;
  END_IF;
--
-- Calculate Maintenance and Growth Respiration;
--
  GROWTH(:=Tci);
--
-- Select appropriate simulation algoritmn
-- Night : 2nd order Runge-Kutta with fixed step length
-- Day : 4th/5th order Runge-Kutta with variable step length
--
  IF (Sg = 0.0) THEN ALGO := 3; ELSE ALGO := 1; END_IF;
--
-- Change between day and night setpoints
--
  IF (Hr>=DaySet) AND (Hr<=NightSet) THEN Theat := Theatd;
   ELSE Theat := Theatn; END_IF;
```

```
--
-- Call the Greenhouse Energy and Mass Balance Model
--
  GEMB(Tg,Ts,Ta,Tc,Tm,Tf,T1,T2,T3,T4,T5,Xg,Xa,Xc,Xm,XCO2a,
  T1evap,T2evap,T3evap,T1cond,T2cond,T3cond :=
  Tgi,Tsi,Tai,Tci,Tmi,Tfi,T1i,T2i,T3i,T4i,T5i,
  Xgi,Xai,Xci,Xmi,XCO2ai,T1evap,T2evap,T3evap,T1cond,T2cond,T3cond);
--
-- Calculate RH and wet bulb temperature at end of period
--
  psat := 611.0*exp(17.27*Ta/(Ta+237.3));
  RH := 100.0*pa/psat;
  Taw := Ta - ((psat - pa)/((psat*Lamd*Mw)/(R*(Ta + 273.15)**2.0) +
         Gamma));
  CO2a := XCO2a*1e3*R*(Ta+273.15)/(da*1.52*Ma*(P-pa));
--
-- Average FGross, FResp, FCO2prod
--
  FGrHave := FGrHave + FGross*300;
  FReHave := FReHave + FResp*300;
  FCOHave := FCOHave + FCO2prod*300;
  TaHave := TaHave +Ta;
  RHHave := RHHave + RH;
--
-- Output hourly average data
--
  IF (Min = 55.0) THEN HOUTPUT(:=Ta,Tc,Out1); END_IF;
--
-- Update initial conditions for next simulation period
--
    Tgi := Tg;  Tsi := Ts;  Tai := Ta;  Tci := Tc;  Tmi := Tm;
    Tfi := Tf;  T1i := T1;  T2i := T2;  T3i := T3;  T4i := T4;
    T5i := T5;
    Xgi := Xg;  Xai := Xa;  Xci := Xc;  Xmi := Xm; XCO2ai := XCO2a;
    T1evapi := T1evap; T2evapi := T2evap; T3evapi := T3evap;
    T1condi := T1cond; T2condi := T2cond; T3condi := T3cond;
--
-- Sum for Average Leaf Temp and incident PAR
--
   TSum := TSum + Tci;
   LSum := LSum + Bpar;
   Count := Count + 1.0;
--
```

```
-- At end of day
--
  IF (Hr = 23) AND (Min = 55.0) THEN
--
-- Update LAI by growing the leaves (development)
--
    DEVELOP;
--
--   Daily output of variables
--
    DOUTPUT(:=Out2,Out4);
--
-- Update parameters affected by growth of plants
--
    VARIDATA;
--
  END_IF; -- End of day loop
--
  END_IF; -- Day loop
--
  END_LOOP;
--
-- At end of week close input and output files
--
  CLOSE Infile;
  CLOSE Out1;
  CLOSE Out2;
  CLOSE Out4;
--
-- End of loop for week of boundary condition data
--
  END_LOOP;
--
-- When all input weeks processed end of simulation
--
  PRINT ".                  -----  STUDY COMPLETED  -----";
--
  END_STUDY
--
```

A2 Global Variables

```
--
-- File GLOBAL.ESL
```

```
--
-- Global variables used in the simulation model KOMKOMMER
-------------------------------------------------------------------
  PACKAGE GLOBAL;
-------------------------------------------------------------------
-- ESL Package GLOBAL
--------------------------------------------------------------------
-
-- Universal constants
--
 CONSTANT REAL : Gamma/66.0/,R/8.31/,Mw/18.0/,Ma/29.0/,Sigma/5.67e-8/;
--
-- Densities
--
  CONSTANT REAL : rhow/1.0e6/,rhoq/2.66e6/,rhocl/2.65e6/,rhoom/1.3e6/;
--
-- Specific heat capacities
--
  CONSTANT REAL : Cpq/0.8/,Cpcl/0.9/,Cpom/1.92/,Cpw/4.18/,Cpv/1.88/;
--
-- Latent heat of vaporization of water
--
  REAL : Lamd/2450.0/,Theta;
--
-- Solar Constant
--
  CONSTANT REAL : Ssc/1360.0/;
--
  CONSTANT REAL : Pi/3.14159/;
--
-- Barometric pressure and outside CO2 concentration
--
  CONSTANT REAL : P/101325.0/,CO2o/350.0/;
--
-- Greenhouse dimensions
--
  REAL : Length,Width,Gutter,Ridge,Spans,Offset,BagD,BagH;
--
-- Volumes (m3)
--
  REAL : Va,Vgb,Vs;
--
-- Areas (m2)
```

```
--
  REAL : Aroof,Awall,Aend,Agable,Ag,Agb,As,Amtop,Amside,Am,Af;
--
-- Component thicknesses (m)
--
  REAL : dgl,da,df,d1,d2,d3,d4,d5;
--
-- Densities (g/m3)
--
  REAL : rhogl,rhogb,rhos,rhoa,rhof,rho1,rho2,rho3,rho4,rho5;
--
-- Heat capacity area densities (J/m2 floor.K)
--
  REAL : Phig,Phis,Phia,Phic,Phim,Phif,Phi1,Phi2,Phi3,Phi4,Phi5;
--
-- Volumetric fractions in media,floor and soil
-- (quartz, clay, organic, water)
--
  REAL : xqm,xqf,xq1,xq2,xq3,xq4,xq5;
  REAL : xclm/0.0/,xclf,xcl1,xcl2,xcl3,xcl4,xcl5;
  REAL : xomm,xomf,xom1,xom2,xom3,xom4,xom5;
  REAL : xwm,xwf,xw1,xw2,xw3,xw4,xw5;
--
-- Moisture density of floor and soil layers (g H2O/m2 floor)
--
  REAL : Xf,X1,X2,X3,X4,X5;
--
-- Maximum moisture density of crop and media (g H2O/m2 floor)
--
  REAL : Xcmax,Xmmax;
  REAL : FBark/0.5/,Field;
--
-- Absolute Humidity (g/m3)
--
  REAL : Chio,Chig,Chiamax,Chia,Chic,Chim,ChiCO2o,ChiCO2a/1440.0/;
--
-- Specific heat capacities (J/g.K)
--
  REAL : Cpo/1.01/,Cpgl,Cpgb,Cps,Cpa/1.01/;
--
-- Surface emissivities
--
  REAL : eg,es,ec,em,ef;
```

```
--
-- Media, floor and soil thermal conductivities (W/m °C)
--
  REAL : km,kf,k1,k2,k3,k4,k5;
--
-- Date, time and boundary conditions
--
  REAL : Y,Day,Hr,Min;
  REAL : To,Tow,Td,Uo,Sg;
  REAL : SAlt,SAzi;
  REAL : Top,Bot,Ht,delT,Irr;
--
  REAL : Tave,Todw,Tsky,Th,esky,po,Taw,pa,psat,RH,VPD,Bcave,Bpar;
  REAL : CO2hTot,CO2a,CO2i;
  REAL : TSum/0.0/,LSum/0.0/;
--
-- Area Indices (m2/m2 floor)
--
  REAL : GAI,SAI,FAI,MAI,LAI;
--
  REAL : Lg,Lf,Lc/0.1/;
  REAL : Ua/0.20/;
--
-- View Factors
--
  REAL : Fmm,Fss,Taucb,Fcc,Fgsky,Fmf,Fmc,Fms,Fmg;
  REAL : Ffm,Ffc,Ffs,Ffg;
  REAL : Fcf,Fcm,Fcs,Fcg,Fsf,Fsm,Fsc,Fsg;
  REAL : SFgsky,SFsg,SFcg,SFcs,SFmg,SFms,SFmc;
  REAL : SFfg,SFfs,SFfc,SFfm;
--
-- Hydraulic capacities and conductivity
--
  REAL : Capc/0.014/,Capm/0.4/,Kmc/0.004/;
--
-- Variables for light transmission
--
  REAL : Tau(0..9,0..36),Alpha(0..9,0..36);
  REAL : Cloud/0.65/;
  REAL : Az,Div;
  REAL : Sx,So,Sdf,Sdr,Sp,Sn,Sc;
  REAL : Corr,SinB,CosB,Cos90B,RR,K,Kt,Kd;
  REAL : Spdr,Spdf,Sndr,Sndf;
```

```
  REAL : Agdr,Agdf,Taugdr,Taugdf;
  REAL : Asdr,Asdf;
  REAL : X,LAM,Sigp,Sign;
  REAL : Rhophor,Rhonhor,Rhopdf,Rhondf,Rhopdr,Rhondr;
  REAL : Rhocpdf,Rhocndf,Rhocpdr,Rhocndr;
  REAL : Acpdf,Acndf,Acpdr,Acndr;
  REAL : Taucpdf,Taucndf,Taucpdr,Taucndr;
  REAL : Kbdf,Kbdr,Kpdf,Kpdr,Kndf,Kndr;
  REAL : Afp/0.8/,Afn/0.8/;
--
-- Water holding capacities, miscellaneous variables
--
  REAL : WHCc/19.0/,WHCm;
  REAL : SBlock,Nplant,DMt;
--
-- Heat and Mass Transfer Coefficients
--
  REAL : hCgo,hCga,hCsa,hCcat,hCcab,hCca,hCma,hCfa,hao;
  REAL : hRgsky,hRsg,hRhg,hRhs,hRcg,hRcs,hRch,hRmg,hRms,hRmh,hRmc;
  REAL : hRfg,hRfs,hRfh,hRfc,hRfm;
  REAL : hGsg/0.6/,hGfm,hGf1,hG12,hG23,hG34,hG45,hG5d;
  REAL : rao,rVga,rVe,rVi,rVma;
  REAL : Infil,N;
--
-- Energy & Mass Flows
--
  REAL : Bg,Bs,Bc,Bm,Bf;
  REAL : Cgo,Cga,Csa,Cca,Cma,Cfa,Cao,Cht;
  REAL : Gsg,Gfm,Gf1,G12,G23,G34,G45,G5d;
  REAL : Rgsky,Rsg,Rcg,Rcs,Rmg,Rms,Rmc;
  REAL : Rfg,Rfs,Rfc,Rfm;
  REAL : LEga,LEca,LEma,LEao;
  REAL : Edrip,Eirr,Eup,Edrn;
  REAL : Qr;
  REAL : f,fprod,fga,fdrip,fca,fma,firr,fup,fdrn,fao,fr,fhum;
--
-- Water potentials
--
  REAL : Psic,Psim;
--
-- Variables for plant development model
--
-- Function table for dependence of N on leaf number (main stem)
```

```
--
  INTEGER: TabNuM/7/;
  CONSTANT REAL: NuTabM(2,7)/
    1.0,0.70, 5.0,1.0, 10.0,1.25, 15.0,1.50,
    20.0,1.45, 25.0,1.40, 30.0,1.00/;
--
-- Function table for dependence of Nu on Leaf number (Laterals)
--
  INTEGER: TabNuL/7/;
  CONSTANT REAL: NuTabL(2,7)/
  1.0,0.55, 5.0,0.90, 10.0,0.65, 15.0,0.50,
  20.0,0.50, 25.0,0.50, 30.0,0.50/;
--
-- Function Table for dependence of Leaf maintenance respiration
--  on fruit weight
--
  INTEGER: TabLeaf/5/;
  CONSTANT REAL: LeafTab(2,5)/
  0.0,3.0, 1.0,2.4, 2.0,2.1, 3.0,1.5, 4.0,0.6/;
--
-- Constants for plant development model
--
  REAL: NecroM/40.0/,NecroL/20.0/;
  REAL: DFactM/3.0/,DFactL/4.0/;
  REAL: Prune/334.0/;
  REAL: Pinch/304.0/;
  REAL: TopNode/27.0/;
  REAL: Laterals/3.0/;
  REAL: Init/49.0/;
  REAL: FactorM/44000.0/;
  REAL: FactorL/32000.0/;
--
  REAL: PMain/1.0/,PLat/1.0/;
  REAL: PMaini,PLati,KMain,KLat,A,B,UMain,ULat;
  REAL: dAdP,dBdP,dUdP;
  REAL: AreaM,AreaL,AREA,AREAi;
  REAL: LN,Light,Temp,LFact,Age,Nu,FDC,RGR;
  REAL: FruitM,FruitL,FruFactM,FruFactL;
  REAL: AEM,AEL,NCMi,NCLi;
  REAL: NM(30),NL(30);
  REAL: NCM(30),LM(30),ARM(30),ARMi(30);
  REAL: NCL(20),LL(20),ARL(20),ARLi(30);
--
```

```
  INTEGER: Startday/263/;
  INTEGER: NoLM,NoLL,NOL;
--
-- Variables for growth and respiratin models
--
  REAL : dAREA,dA1,SLA;
  REAL : PGRleaf,PGRstem,PGRroot,PGRfruit;
  REAL : Preqleaf,Preqstem,Preqroot,Preqfruit;
  REAL : PGRfruM(10..30),PGRfruL(20);
  REAL : Assim,RespMain,PRequired,Reserve/10.0/,Ratio,ResL;
  REAL : Wleaf,Wstem,Wroot,Wfruit,WfruitM,WfruitL,WfruitH/0.0/;
  REAL : WfruM(10..30),WfruL(20);
  REAL : TFruM(10..30),TFruL(20);
  REAL : AgeFruM(10..30),AgeFruL(20);
  REAL : CO2pleaf,CO2pstem,CO2proot,CO2pfruit,CO2prod,LostFresh;
  INTEGER : NofruitH/0/,NofruitA/0/;
--
-- Parameters for fruit abortion and removal
--
  LOGICAL : PickTime/FALSE/;
  LOGICAL : AbortM(10..30),AbortL(20),HarvM(10..30),HarvL(20);
--
--
-- CO2 production rates during growth
--
  CONSTANT REAL : CO2leaf/0.243/;
  CONSTANT REAL : CO2stem/0.386/;
  CONSTANT REAL : CO2root/0.425/;
  CONSTANT REAL : CO2fruit/0.458/;
--
-- Assimilate requirement ratios
--
  CONSTANT REAL : ARleaf/0.795/;
  CONSTANT REAL : ARstem/1.150/;
  CONSTANT REAL : ARroot/1.217/;
  CONSTANT REAL : ARfruit/1.515/;
  CONSTANT REAL : MaxGRleaf/1.0/;
  CONSTANT REAL : MaxGRfru/0.06/;
--
-- Maintenance respiration parameters
--
  CONSTANT REAL : Q10/2.0/;
  CONSTANT REAL : TempRef/25.0/;
  CONSTANT REAL : MainRoot/3.33E-7/;
```

```
  CONSTANT REAL : MainStem/3.06E-7/;
  CONSTANT REAL : MainLeaf/3.33E-7/;
  CONSTANT REAL : MainFru/1.39E-7/;
--
  REAL : PickW/17000.0/;
--
  INTEGER : Picking(1..50),PDay/1/,NoPicks;
  REAL : WeightP(1..50),AbortAge/12.0/,RemAge/20.0/,RemW/10000.0/;
--
  REAL : Ttot;
--
-- Crop growth variables
--
  REAL : MesCond,rm,EPC,Compoint,Eff,RespD;
  REAL : FNCO2,FNmax,FGmax,FGross,FGShd,FGSun,FGs,FG;
  REAL : Fvent,FResp,FCO2prod,Finj;
  REAL : VisDif,VisTot,VisDir,VisShd,VisPer,VisSun;
  REAL : LAIC,FracSun;
  INTEGER : I1,I2;
--
-- Capacities of Heating, Fan, and CO2 Systems
--
  CONSTANT REAL : HeatCap1/100000.0/,HeatCap2/150000.0/;
  CONSTANT REAL : Airflow1/20.0/,Airflow2/30.0/;
  CONSTANT REAL : InjectRate/10.0/;
--
-- Set points
--
  CONSTANT REAL : Theatd/18.0/,Theatn/15.0/,Tvent/25.0/,Tcool/27.0/;
  REAL : CO2set;
  CONSTANT REAL : HDB/2.0/,FDB/2.0/,CDB1/2.0/,CDB2/1.0/,RHDB/5.0/;
  CONSTANT REAL : DaySet/8.0/,NightSet/16.0/,RHset/60.0/;
  REAL : Theat;
  LOGICAL : Heat1On/FALSE/,Heat2On/FALSE/,Fan1On/FALSE/,Fan2On/FALSE/;
  LOGICAL : heatOn,FanOn,VentOn;
  LOGICAL : RefrigOn,Refrig1On,Refrig2On,Refrig3On;
  LOGICAL : CO2On;
  INTEGER : Mode;
--
-- Refrigeration plant definition
--
  REAL: RTF1_h,RTF2_h,HUse1_h,HUse2_h,RTC_h;
```

```
  REAL: RTF1_d,RTF2_d,HUse1_d,HUse2_d,RTC_d;
  REAL: SCP1h_h,SCP1h_d;
  REAL: SCP2h_h,SCP2h_d;
  REAL: SCP3h_h,SCP3h_d;
  REAL: SCP1c_h,SCP1c_d;
  REAL: SCP2c_h,SCP2c_d;
  REAL: SCP3c_h,SCP3c_d;
  REAL : FGrHave,FReHave,FCOHave;
  REAL : FGrDave,FReDave,FCODave;
  REAL : TaHave,RHHave;
--
-- Global counters
--
  INTEGER : Err,I,J;
  REAL : Count;
--
  END;
--
```

A3 Function Interpolator

```
--
-- File GEN2.ESL
--
---------------------------------------------------------------------
PROCEDURE GEN2(INTEGER: N;REAL: TABLE(2,*),x)RETURN REAL;
---------------------------------------------------------------------
-- Modified from original ESL submodel AFGEN2
---------------------------------------------------------------------
-- Searches a table of x-y coordinate values and finds
-- which values span the input of x and performs a second
-- order interpolation to obtain a value for y.
-- Over any segment, a number of simple polynomial fits
-- is found and the interpolated function, y, is a
-- weighted average over two of these; the weighting
-- being a function of the independent variable.
-- The weighting function has a zero slope at the points
-- where the interpolating polynomials switch over. In
-- the range TABLE(1,i) to TABLE(1,i+1), two quadratics
-- are used; Qn fits TABLE(2,i-1), TABLE(2,i) and
-- TABLE(2,i+1) and Q1n fits TABLE(2,i),
```

```
-- TABLE(2,i+1) and TABLE(2,i+2). Qn and Q1n overlap in the
-- range TABLE(1,i) to TABLE(1,i+1). In this range,
--
--    y = w*Qn+(1-w)*Q1n
--
-- where,
--
-- w = 1 - 3*s**2 + 2*s**3, is the weighting function,
-- s = (x - TABLE(1,i))/(TABLE(1,i + 1) - TABLE(1,i)),
--      the independent variable,
--
-- s has a normalised range [0,1] and,
-- w(0) = w(1) = w'(0) = w'(1) = 0.0.
--
-- The calling sequence is:
--
--    GEN2(N,TABLE,x)
--
-- where,
--
-- N is the number of elements in the array,
-- TABLE is the table of values which represents a two row
--         n column matrix;
--         row 1 represents the input values and which
--         must be in ascending order,
--         row 2 represents the corresponding function values
-- x is the input value.
--
-- The output is an algebraic variable.
--
---------------------------------------------------------------------
  REAL: Qn,Qna,Qnb,Qnc;
  REAL: Q1n,Q1na,Q1nb,Q1nc,Ycalc;
  REAL: su/0.0/,sl/0.0/,s/0.0/,w/0.0/;
  INTEGER: i;
--
  IF x < TABLE(1,1) THEN
    Ycalc:= TABLE(2,1);
  ELSE_IF x >= TABLE(1,N) THEN
    Ycalc:= TABLE(2,N);
  ELSE
    i := N;
    WHILE x < TABLE(1,i) LOOP
      i:= i - 1;
```

```
    END_LOOP;
    WHILE x >= TABLE(1,i + 1) LOOP
      i:= i + 1;
    END_LOOP;
    s:= (x - TABLE(1,i))/(TABLE(1,i + 1) - TABLE(1,i));
    IF s < 1.0e-12 THEN
      w:= 1.0;
    ELSE
      w:= 1.0 - s*s*(3.0 - 2.0*s);
    END_IF;
    IF i = 1 THEN
--
-- take Qn as line Qn=TABLE(2,1)
--
      Qna:= TABLE(2,1);Qnb:= 0.0;Qnc:= 0.0;
    ELSE
      sl := - (TABLE(1,i) - TABLE(1,i - 1))/(TABLE(1,i + 1) -
             TABLE(1,i));
      Qna:= TABLE(2,i);
      Qnc:= ((sl*TABLE(2,i + 1) - TABLE(2,i - 1))/(1.0 - sl) +
             Qna)/sl;
        Qnb:= TABLE(2,i + 1) - Qna - Qnc;
      END_IF;
      IF i = N - 1  THEN
--
-- take Q1n as line Q1n = TABLE(2,N)
--
      Q1na:= TABLE(2,N);Q1nb:= 0.0;Q1nc:= 0.0;
    ELSE
      su:= (TABLE(1,i + 2) - TABLE(1,i))/(TABLE(1,i + 1) -
           TABLE(1,i));
      Q1na:= TABLE(2,i);
      Q1nc:= ((su*TABLE(2,i + 1) - TABLE(2,i + 2))/(1.0 - su) +
              Q1na)/su;
      Q1nb:= TABLE(2,i + 1) - Q1na - Q1nc;
    END_IF;
    Qn:= Qna + s*(Qnb + s*Qnc);
    Q1n:= Q1na + s*(Q1nb + s*Q1nc);
    Ycalc:= Qn*w + Q1n*(1.0 - w);
  END_IF;
--
  RETURN Ycalc;
--
END GEN2;
```

```
--
```

A4 Soil Thermal Properties Routine

```
--
-- File SOIL.ESL
--
-----------------------------------------------------------------
PROCEDURE SOIL (REAL : xq,xc,xo,xw,fc) RETURN REAL;
-----------------------------------------------------------------
-- ESL Subroutine to find soil thermal conductivity using method
-- of ten Berge (1986) based on De Vries (1963)
-- Inputs xq = volume fraction of quartz minerals
--        xc = volume fraction of clay minerals
--        xo = volume fraction of organic material
--        xw = volume fraction of water
--        fc = volume fraction of water at field capacity
-----------------------------------------------------------------
--
-- Thermal conductivies of soil components
--
   CONSTANT REAL : kq8.8/,kc/0.9/,ko/1.92/,kw/0.57/,ka/0.025/;
--
   REAL : xa,e,ga,k02,k05,kfcsa,kfsa,kfcsw,kfsw,k;
   REAL : faw,fqw,fcw,fow,fww,faa,fqa,fca;foa,fwa;
--
-- Air content and porosity
  xa := 1 - xq - xc - xo - xw;
  e := xa + xw;
--
-- Depolarization factor for ellispsoid
--
  IF xw > fc THEN
    ga := 0.333 - (xa/e)*0.298;
  ELSE
    ga := 0.013 + (xw/fc)*0.085;
  END_IF;
  faw := 0.333*(2.0/(1.0 + ((ka/kw)-1.0)*ga) +
         1.0/(1.0 + ((ka/kw) - 1.0)*(1.0 - 2.0*ga)));
  fqw := 0.333*(2.0/(1.0 + ((kq/kw) - 1.0)*ga) +
         1.0/(1.0 + ((kq/kw) - 1.0)*(1.0 - 2.0*ga)));
  fcw := 0.333*(2.0/(1.0 + ((kc/kw) - 1.0)*ga) +
         1.0/(1.0 + ((kc/kw) - 1.0)*(1.0 - 2.0*ga)));
```

```
  fow := 0.333*(2.0/(1.0 + ((ko/kw) - 1.0)*ga) +
         1.0/(1.0 + ((ko/kw) - 1.0)*(1.0 - 2.0*ga)));
  fww := 1.0;
  faa := 1.0;
  fqa := 0.333*(2.0/(1.0 + ((kq/ka) - 1.0)*ga) +
         1.0/(1.0 + ((kq/ka) - 1.0)*(1.0 - 2.0*ga)));
  fca := 0.333*(2.0/(1.0+((kc/ka) - 1.0)*ga) +
         1.0/(1.0 + ((kc/ka) - 1.0)*(1.0 - 2.0*ga)));
  foa := 0.333*(2.0/(1.0 + ((ko/ka) - 1.0)*ga) +
         1.0/(1.0 + ((ko/ka) - 1.0)*(1.0 - 2.0*ga)));
  fwa := 0.333*(2.0/(1.0+((kw/ka)-1.0)*ga) +
         1.0/(1.0 + ((kw/ka) - 1.0)*(1.0 - 2.0*ga)));
  k02 := 1.25*(fwa*0.02*kw + fqa*xq*kq + fca*xc*kc + foa*xo*ko +
         faa*(e - 0.02)*ka)/(fwa*0.02 + fqa*xq + fca*xc + foa*xo +
faa*(e - 0.02));
  k05 := (fww*0.05*kw + fqw*xq*kq + fcw*xc*kc + fow*xo*ko + faw*(e -
           0.02)*ka)/(fww*0.05 + fqw*xq + fcw*xc + fow*xo + faw*(e -
           0.02));
  kfcsa := fqa*xq*kq + fca*xc*kc + foa*xo*ko;
  kfsa := fqa*xq + fca*xc + foa*xo;
  kfcsw := fqw*xq*kq + fcw*xc*kc + fow*xo*ko;
  kfsw := fqw*xq + fcw*xc + fow*xo;
--
  IF xw < 0.02 THEN
-- Air is continuous medium
   k := 1.25*(fwa*xw*kw + kfcsa + faa*xa*ka)/(fwa*xw + kfsa + faa*xa);
  ELSE_IF xw > 0.05 THEN
-- Water is continuous medium
    k := (fww*xw*kw + kfcsw+faw*xa*ka)/(fww*xw + kfsw + faw*xa);
  ELSE
-- Interpolate between xw = 0.02 and xw = 0.05
    k := k02 +' (xw - 0.02)*(k05 - k02)/0.03;
  END_IF;
  RETURN k;
--
END SOIL;
--
```

A5 Convective Heat Transfer Coefficient Routine

```
--
-- File CONVHT.ESL
--
```

```
-----------------------------------------------------------------
PROCEDURE CONVHT(REAL: U,D,Ts,Ta,Side) RETURN REAL;
-----------------------------------------------------------------
-
-- ESL Subroutine CONVHT
-- Calculates the Nusselt number based on correlations from
-- Monteith and Unsworth (1989) and returns the
-- convective heat transfer coefficient (W/m2.K)
-- Inputs U = wind speed (m/s)
--        D = characteristic dimension (m)
--       Ts = Surface temperature (°C)
--       Ta = Air temperature (°C)
--     Side = code for side of surface in question
--           > 0 top side
--           < 0 bottom side
--           = 0 vertical surface
-----------------------------------------------------------------
-
  CONSTANT REAL : g/9.81/;
  CONSTANT REAL : v0/13.3E-6/;
  CONSTANT REAL : K0/18.1E-6/;
  REAL: Tm,Corr,K,v,Re,Gr,Bound,A,B,m,n,Nufor,Nufre,Nu,h;
  LOGICAL : Stable,Forced, Free;
--
  Free   := FALSE;
  Forced := FALSE;
  Stable := FALSE;
--
-- Check for stable conditions
--
  IF ((Side < 0) AND (Ts > Ta)) OR ((Side > 0) AND (Ts < Ta)) THEN
    Stable := TRUE;
  END_IF;
--
-- Calculate RE and GR
--
  Tm := (Ts + Ta)/2.0;
  Corr := 1.0 + 0.007*Tm;
  K := 1200.0*K0*Corr;
  v := v0*Corr;
  Re := U*D/v;
  Gr := g*D*D*D*ABS(Ts - Ta)/((Tm + 273.15)*v*v);
  IF Re = 0.0 THEN Bound := 100.0;
  ELSE Bound := Gr/(Re*Re);
```

```
  END_IF;
--
-- Test for transition region
--
  IF Bound < 10.0 THEN
    Forced:= TRUE;
  END_IF;
--
  IF Bound > 0.33 THEN
    Free := TRUE;
  END_IF;
--
-- Forced convection parameters
--
  IF Forced THEN
    IF Re > 2E4 THEN
      A := 0.032;
      n := 0.8;
    ELSE
      A := 0.60;
      n := 0.5;
    END_IF;
  ELSE
     A := 0.00;
     n := 1.0;
  END_IF;
--
-- Free convection parameters
--
  IF Free THEN
    IF Side = 0 THEN
      IF Gr > 1E9 THEN
        B := 0.11;
        m := 0.33;
      ELSE
        B := 0.58;
        m := 0.25;
      END_IF;
    ELSE
      IF Stable THEN
        B := 0.23;
        m := 0.25;
      ELSE_IF Gr > 1E5 THEN
        B := 0.13;
```

```
        m := 0.33;
      ELSE
        B := 0.50;
        m := 0.25;
      END_IF;
    END_IF;
  ELSE
        B := 0.00;
        m := 1.0;
  END_IF;
--
-- Calculate Nussult numbers
--
  Nufor := A*Re**n;
  Nufre := B*Gr**m;
  Nu := (Nufor**3.0 + Nufre**3.0)**(1.0/3.0);
--
-- Convective heat transfer coefficient
--
  h := Nu*K/D;
  RETURN h;
--
END CONVHT;
--
```

A6 Data Input and Initialization Routine

```
--
-- File INDATA.ESL
--
---------------------------------------------------------------------
PROCEDURE INDATA;
---------------------------------------------------------------------
-
-- ESL Subroutine INDATA
-- Reads input data from:
--         DIFF = diffuse radiation transmission and absorption
--          SKY = direct radiation transmission and absorption
-- INPUT14.CEL = initial cell counts for all leaves
--  SIMPUT.NEW = simulation parameters
-- Initializes simulation parameters
---------------------------------------------------------------------
-
```

```
USE GLOBAL;
--
  REAL : Dummy;
--
  FILE : Tranfile,Datafile,Leafile;
--
-- Read light transmission table (diffuse and direct light)
--
  OPEN Tranfile, "c:\input\diff.";
  READ Tranfile;
  READ Tranfile,Tau(0,0),Alpha(0,0);
  CLOSE Tranfile;
--
  OPEN Tranfile,"c:\input\sky.";
  READ Tranfile;
  FOR I := 1..9 LOOP
    FOR J := 1..I*4 LOOP
      READ Tranfile,Tau(I,J),Alpha(I,J);
    END_LOOP;
  END_LOOP;
  CLOSE Tranfile;
--
-- Read initial leaf cell numbers
--
  OPEN Leafile, "c:\input\input14.cel";
  READ Leafile,Dummy,PMain,PLat,AREA,AREAi;
  FOR I := 1..30 LOOP
    READ Leafile,NCM(I);
  END_LOOP;
  FOR I := 1..20 LOOP
    READ Leafile,NCL(I);
  END_LOOP;
  CLOSE Leafile;
--
-- Read greenhouse parameters
--
  OPEN Datafile, "c:\input\simput.new";
  READ Datafile;
  READ Datafile;
  READ Datafile;
  READ Datafile;
  READ Datafile,Length,Width,Gutter,Ridge,Spans;
  READ Datafile;
```

```
  READ Datafile,Offset;
  READ Datafile;
  READ Datafile,rhogl,rhogb,rhos;
  READ Datafile;
  READ Datafile,Cpgl,Cpgb,Cps;
  READ Datafile;
  READ Datafile,xqf,xq1,xq2,xq3,xq4,xq5;
  READ Datafile;
  READ Datafile,xclf,xcl1,xcl2,xcl3,xcl4,xcl5;
  READ Datafile;
  READ Datafile,xomf,xom1,xom2,xom3,xom4,xom5;
  READ Datafile;
  READ Datafile,xwf,xw1,xw2,xw3,xw4,xw5;
  READ Datafile;
  READ Datafile,eg,es,ec,em,ef;
  READ Datafile;
  READ Datafile,dgl,df,d1,d2,d3,d4,d5;
  READ Datafile;
  READ Datafile,Vgb,Vs;
  READ Datafile;
  READ Datafile,As,Fss,SBlock;
  READ Datafile;
  READ Datafile,Nplant,BagD,BagH,Fmm;
  READ Datafile;
  READ Datafile,X,Sigp,Sign;
  READ Datafile;
  READ Datafile,HeatOn,FanOn,VentOn,RefrigOn,CO2On;
  READ Datafile;
  READ Datafile,CO2set;
  CLOSE Datafile;
--
-- Calculate Surface Areas
--
  Af := Length*Width;
  Aroof := Spans*Length*(Sqrt((Width/Spans)**2.0+((Ridge -
                Gutter)*2.0)**2.0));
  Awall := 2.0*Length*Gutter;
  Aend := 2.0*Width*Gutter;
  Agable := Width*(Ridge - Gutter);
  Ag := Aroof + Awall + Aend + Agable;
  Amtop := Nplant*Pi*BagD*BagD/4.0;
  Amside := Nplant*Pi*BagD*BagH;
  Am := Amtop + Amside;
```

```
--
-- Area Indices (m2/m2 floor)
--
  GAI := Ag/Af;
  SAI := As/Af;
  MAI := Am/Af;
  FAI := (Af - Amtop)/Af;
--
-- Greenhouse Volume and Average Greenhouse height (m)
--
  Va := Af*(Ridge + Gutter)/2.0;
--
-- Characteristic dimensions
--
  Lf := (Length+Width)/2.0;
  Lg := Gutter + Aroof/(2.0*Length);
--
-- Moisture content of floor and soil layers (g H2O/m2 floor)
--
  Xf := df*xwf*rhow;
  X1 := d1*xw1*rhow;
  X2 := d2*xw2*rhow;
  X3 := d3*xw3*rhow;
  X4 := d4*xw4*rhow;
  X5 := d5*xw5*rhow;
--
-- Fraction of quartz minerals and organic matter in the root medium
--
  xqm := (0.37 - 0.06*(Fbark - 0.5) - 0.56*(Fbark - 0.5)**2.0)*(1.0 -
          FBark);
  xomm := (0.37 - 0.06*(Fbark - 0.5) - 0.56*(Fbark - 0.5)**2.0)*FBark;
--
-- water holding capacity, field capacity, and maximum water
-- concentration of root medium
--
-- Heat Capacities (solid portions) (J/m2 floor.K)
--
  Phig := GAI*dgl*rhogl*Cpgl + Vgb*rhogb*Cpgb/Af;
  Phis := Vs*rhos*Cps/Af;
  Phim := Amtop*BagH*(xomm*rhoom*Cpom + xqm*rhoq*Cpq)/Af;
  Phif := df*(xqf*rhoq*Cpq + xclf*rhocl*Cpcl + xomf*rhoom*Cpom);
  Phi1 := d1*(xq1*rhoq*Cpq + xcl1*rhocl*Cpcl + xom1*rhoom*Cpom);
  Phi2 := d2*(xq2*rhoq*Cpq + xcl2*rhocl*Cpcl + xom2*rhoom*Cpom);
```

```
  Phi3 := d3*(xq3*rhoq*Cpq + xcl3*rhocl*Cpcl + xom3*rhoom*Cpom);
  Phi4 := d4*(xq4*rhoq*Cpq + xcl4*rhocl*Cpcl + xom4*rhoom*Cpom);
  Phi5 := d5*(xq5*rhoq*Cpq + xcl5*rhocl*Cpcl + xom5*rhoom*Cpom);
--
  WHCm := (0.55 - 0.60*Fbark + 2.6*FBark*FBark);
  Field := WHCm*(xqm*rhoq + xomm*rhoom)/rhow;
  Xmmax := WHCm*Amtop*BagH*(xomm*rhoom + xqm*rhoq)/Af;
--
-- Intialize fruit variables
--
  FOR I := 10..30 LOOP
    AbortM(I) := FALSE;
    HarvM(I) := FALSE;
    WfruM(I) := 0.0;
    TFruM(I) := 0.0;
  END_LOOP;
  FOR I := 1..20 LOOP
    AbortL(I) := FALSE;
    HarvL(I) := FALSE;
    WfruL(I) := 0.0;
    TFruL(I) := 0.0;
  END_LOOP;
--
-- Generate Nu tables.
--
  FOR I:=1..30 LOOP
    LN:=I;
    NM(I) := GEN2(TabNuM,NuTabM(1..2,1..TabNuM),LN);
  END_LOOP;
--
  FOR I:=1..20 LOOP
    LN:=I;
    NL(I) := GEN2(TabNuL,NuTabL(1..2,1..TabNuL),LN);
  END_LOOP;
--
-- Thermal conductivities of floor and soil layers
--
  kf := SOIL(xqf,xclf,xomf,xwf,0.09);
  k1 := SOIL(xq1,xcl1,xom1,xw1,0.09);
  k2 := SOIL(xq2,xcl2,xom2,xw2,0.09);
  k3 := SOIL(xq3,xcl3,xom3,xw3,0.09);
  k4 := SOIL(xq4,xcl4,xom4,xw4,0.09);
  k5 := SOIL(xq5,xcl5,xom5,xw5,0.09);
```

```
--
-- Initialize LAI and plant organ dry weights
--
  LAI := AREA*Nplant/(Af*10000.0);
  Wleaf := LAI*Af*20000.0/Nplant;
  Wstem := (10.0/77.0)*Wleaf;
  Wroot := (13.0/77.0)*Wleaf;
  WFruit := 0.0;
--
-- Initialize total dry matter of crop, heat capacity,
-- and maximum water holding capacity (concentration)
--
  DMt := (Wleaf+Wstem+Wroot+WFruit)/1000.0;
  Phic := DMt*Nplant*Cpom/Af;
  Xcmax := WHCc*DMt*Nplant/Af;
--
-- Initialize potential growth rates and potential assimilate
-- requirements of plant organs
--
  dAREA := (AREA - AREAi)/86400.0;
  PGRleaf := MaxGRleaf*dAREA;
  PGRstem := (10.0/77.0)*PGRleaf;
  PGRroot := (13.0/77.0)*PGRleaf;
  Preqleaf := PGRleaf*ARLeaf;
  Preqstem := PGRstem*ARstem;
  Preqroot := PGRroot*ARroot;
  PGRfruit := 0.0;
  Preqfruit := 0.0;
--
-- Read in picking times
--
  FOR I := 1..50 LOOP
    Picking(I) := 0;
    WeightP(I) := PickW;
  END_LOOP;
  OPEN Datafile, "c:\input\pickfile.";
  READ Datafile;
  READ Datafile,NoPicks;
  FOR I := 1..NoPicks LOOP
    READ Datafile,Picking(I),WeightP(I);
  END_LOOP;
  CLOSE Datafile;
--
```

```
END INDATA;
--
```

A7 Daily Variable Parameter Routine

```
-- .
-- File VARIDATA.ESL
--
---------------------------------------------------------------------
PROCEDURE VARIDATA;
----------------------------------------------------------------------
-
-- ESL Subroutine VARIDATA
-- Updates simulation parameters which vary on a daily basis
----------------------------------------------------------------------
-
USE GLOBAL;
--
-- Average depth of air accounting for growth of crop
--
  da := Va/Af - (Amtop*BagH)/Af - LAI*0.002 - Vgb/Af - Vs/Af;
--
-- Diffuse Radiation extinction coefficients, reflectivities,
-- transmissivities and apsorptivities
--
  LAM := X + 1.774*(X + 1.182)**(-0.733);
  Kbdf := 0.83 + 0.115*LOG(X) - 0.077*LOG(LAI) +
          0.053*LOG(X)*LOG(LAI);
  Kpdf := Kbdf*SQRT(1.0 - Sigp);
  Kndf := Kbdf*SQRT(1.0 - Sign);
  Rhophor := (1.0 - SQRT(1.0 - Sigp))/(1.0 + SQRT(1.0 - Sigp));
  Rhonhor := (1.0 - SQRT(1.0 - Sign))/(1.0 + SQRT(1.0 - Sign));
  Rhopdf := (0.90 + 0.075*LOG(X))*Rhophor;
  Rhondf := (0.90 + 0.075*LOG(X))*Rhonhor;
  Rhocpdf := Rhopdf - (Rhopdf + Afp - 1.0)*EXP(-2.0*Kpdf*LAI);
  Rhocndf := Rhondf - (Rhondf + Afn - 1.0)*EXP(-2.0*Kndf*LAI);
  Taucpdf := (1.0 - Rhocpdf)*EXP(-Kpdf*LAI);
  Taucndf := (1.0 - Rhocndf)*EXP(-Kndf*LAI);
  Acpdf := 1.0 - Rhocpdf - Taucpdf;
  Acndf := 1.0 - Rhocndf - Taucndf;
--
-- View Factors
--
```

```
  Taucb := exp(-Kbdf*LAI);
  Fcc := 1.0 - (1.0 - Taucb)/LAI;
  Fgsky := 0.60;
  Fmf := (1.0 - (Fmm*Am/Amside))/2.0;
  Fmc := (1.0 - Fmm - Fmf)*(1.0 - Taucb);
  Fms := (1.0 - Fmm - Fmf)*Taucb*SBlock;
  Fmg := (1.0 - Fmm - Fmf)*Taucb*(1.0 - SBlock);
  Ffm := Fmf*MAI/FAI;
  Ffc := (1.0 - Ffm)*(1.0 - Taucb);
  Ffs := (1.0 - Ffm)*Taucb*SBlock;
  Ffg := (1.0 - Ffm)*Taucb*(1.0 - SBlock);
  Fcf := Ffc*FAI/(2.0*LAI);
  Fcm := Fmc*MAI/(2.0*LAI);
  Fcs := (1.0 - Fcc - Fcm - Fcf)*SBlock;
  Fcg := (1.0 - Fcc - Fcm - Fcf)*(1.0 - SBlock);
  Fsf := Ffs*FAI/SAI;
  Fsm := Fms*MAI/SAI;
  Fsc := Fcs*2.0*LAI/SAI;
  Fsg := 1.0 - Fss - Fsc - Fsm - Fsf;
--
-- Script F factors for radiative transfers
--
  SFgsky := eg*Fgsky;
  SFsg := 1.0/((1.0 - es)/es + 1.0/Fsg + SAI*(1.0 - eg)/(GAI*eg));
  SFcg := 1.0/((1.0 - ec)/ec + 1.0/Fcg + 2.0*LAI*(1.0 - eg)/(GAI*eg));
  SFcs := 1.0/((1.0 - ec)/ec + 1.0/Fcs + 2.0*LAI*(1.0 - es)/(SAI*es));
  SFmg := 1.0/((1.0 - em)/em + 1.0/Fmg + MAI*(1.0 - eg)/(GAI*eg));
  SFms := 1.0/((1.0 - em)/em + 1.0/Fms + MAI*(1.0 - es)/(SAI*es));
  SFmc := 1.0/((1.0 - em)/em + 1.0/Fmc + MAI*(1.0 - ec)/(2.0*LAI*ec));
  SFfg := 1.0/((1.0 - ef)/ef + 1.0/Ffg + FAI*(1.0 - eg)/(GAI*eg));
  SFfs := 1.0/((1.0 - ef)/ef + 1.0/Ffs + FAI*(1.0 - es)/(SAI*es));
  SFfc := 1.0/((1.0 - ef)/ef + 1.0/Ffc + FAI*(1.0 - ec)/(2.0*LAI*ec));
  SFfm := 1.0/((1.0 - ef)/ef + 1.0/Ffm + FAI*(1.0 - em)/(MAI*em));
--
END VARIDATA;
--
```

A8 Solar Radiation Partitioning Routine

```
--
-- File SOLAR.ESL
--
-----------------------------------------------------------------
```

```
PROCEDURE SOLAR;
----------------------------------------------------------------------
-- ESL Subroutine SOLAR
-- Separates solar radiation into direct, diffuse, PAR, and NIR
-- components and calculates the solar absorption at the glazing,
-- structure, crop, root medium and floor
----------------------------------------------------------------------
USE GLOBAL;
--
--  Determine solar radiation components
--
     SinB := SIN(SAlt*Pi/180.0);
     CosB := COS(SAlt*Pi/180.0);
     Cos90B := COS((90-SAlt)*Pi/180.0);
     Sx := Ssc*(1.0 + 0.033*COS(2.0*Pi*Day/365.0));
     RR := 0.847 - 1.61*SinB + 1.04*SinB**2.0;
     K := (1.47 - RR)/1.66;
     So := Sx*SinB;
     Kt := Sg/So;
     IF Kt <= 0.22 THEN
       Kd := 1;
     ELSE_IF Kt <= 0.35 THEN
       Kd := 1.0 - 6.4*(Kt - 0.22)**2.0;
     ELSE_IF Kt <= K THEN
       Kd := 1.47 - 1.66*Kt;
     ELSE
       Kd := RR;
     END_IF;
     Sdf := Sg*Kd;
     Sdr := Sg - Sdf;
     Corr := (1.0 - Kd**2.0)*Cos90B**2.0*CosB**3.0;
     Sc := Sdf*(Corr/(1.0 + Corr));
     Sdr := Sdr + Sc;
     Sdf := Sdf - Sc;
     Sp := Sg*(0.6 - 0.1*(1.0 - Kd**2.0));
     Sn := Sg - Sp;
     Spdf := Sp*(1.0 + 0.3*(1.0 - Kd**2.0)*(Sdf/Sg));
     IF Spdf > Sp THEN Spdf := Sp; END_IF;
     IF Spdf > Sdf THEN Spdf := Sdf; END_IF;
     Spdr := Sp - Spdf;
     Sndf := Sdf - Spdf;
     Sndr := Sn - Sndf;
--
```

```
-- Transmission of greenhouse.  Absorption of glazing and structure
--
    I := 9 - INT(SAlt/10.0 - 0.01);
    Div := 90.0/I;
    Az := SAzi - Offset;
    IF Az < 0.0 THEN Az := 360.0 + Az; END_IF;
    J := INT(Az/Div) + 1;
    Taugdr := Tau(I,J)*0.90;
    Taugdf := Tau(0,0)*0.90;
    Agdr := Alpha(I,J)*0.56 + Tau(I,J)*0.1;
    Agdf := Alpha(0,0)*0.56 + Tau(0,0)*0.1;
    Asdr := Alpha(I,J)*0.44;
    Asdf := Alpha(0,0)*0.44;
--
-- Crop extinction coefficients, reflectivities, and absorptivities
-- for direct radiation
--
    Kbdr := SQRT(X*X + (CosB/SinB)**2.0)/LAM;
    Kpdr := Kbdr*SQRT(1.0 - Sigp);
    Kndr := Kbdr*SQRT(1.0 - Sign);
    Rhopdr := Rhophor*2.0*Kpdr/(1.0+Kpdr);
    Rhondr := Rhonhor*2.0*Kndr/(1.0+Kndr);
    Rhocpdr := Rhopdr -  (Rhopdr + Afp - 1.0)*EXP(-2.0*Kpdr*LAI);
    Rhocndr := Rhondr -  (Rhondr + Afn - 1.0)*EXP(-2.0*Kndr*LAI);
    Taucpdr := (1.0 - Rhocpdr)*EXP(-Kpdr*LAI);
    Taucndr := (1.0 - Rhocndr)*EXP(-Kndr*LAI);
    Acpdr := 1.0 - Rhocpdr - Taucpdr;
    Acndr := 1.0 - Rhocndr - Taucndr;
--
-- Solar radiation absorption by glazing, structure, crop, root medium
-- and floor
--
    Bg := Agdr*Sdr + Agdf*Sdf;
    Bs := Asdr*Sdr + Asdf*Sdf;
    Bc := Acpdr*Taugdr*Spdr + Acpdf*Taugdf*Spdf +
          Acndr*Taugdr*Sndr + Acndf*Taugdf*Sndf;
    Bcave := Bc/(2.0*LAI);
    Bpar := Taugdr*Spdr + Taugdf*Spdf;
    Bm := (Afp*Taucpdr*Taugdr*Spdr + Afp*Taucpdf*Taugdf*Spdf +
           Afn*Taucndr*Taugdr*Sndr + Afn*Taucndf*Taugdf*Sndf)*
           (1.0 - FAI);
    Bf := (Afp*Taucpdr*Taugdr*Spdr + Afp*Taucpdf*Taugdf*Spdf +
           Afn*Taucndr*Taugdr*Sndr + Afn*Taucndf*Taugdf*Sndf)*FAI;
```

```
--
END SOLAR;
--
```

A9 Crop Development Model

```
--
-- File DEVELOP.ESL
--
-- Contains the subroutine for leaf and plant development
--
----------------------------------------------------------------------
PROCEDURE RGRt(REAL:P,K,A,B,U,dAdP,dBdP,dUdP,LN) RETURN REAL;
----------------------------------------------------------------------
--
-- ESL Subroutine RGRt
-- Finds the relative growth rate of a leaf
-- Inputs P = plastochron age
--        Q = relative growth rate (plastochrons per plastochron)
--        A = parameter A from Horie's model
--        B = parameter B from Horie's model
--        U = number of unfolding leaf
--     dAdP = rate of change of A on plastochron basis
--     dBdP = rate of change of B on plastochron basis
--     dUdP = rate of change of U on plastochron basis
--       LN = leaf number
----------------------------------------------------------------------
-
  REAL: RGR;
--
  IF LN >= P THEN RGR := 0.0;
  ELSE_IF LN >= U THEN RGR := A+dAdP*(P-LN);
  ELSE RGR := A+dAdP*(P-U)+dBdP*(U-LN)+dUdP*(B-A);
  END_IF;
  RETURN K*RGR;
--
END RGRt;
--
----------------------------------------------------------------------
PROCEDURE dFdT(REAL:U,Nu,LN) RETURN REAL;
----------------------------------------------------------------------
-
-- ESL Subroutine dFdT
```

```
-- Calculates the rate of change of fraction of
-- dividing cells in a leaf
-- Inputs U = number of unfolding leaf
--        N = parameter determining rate of maturation of a leaf
--       LN = leaf number
------------------------------------------------------------------------
-
  REAL: F;
--
  IF U - LN < 0.0 THEN F := 1.0;
  ELSE_IF U - LN < Nu THEN F := (1.0 - (U - LN)/Nu);
  ELSE  F := 0.0;
  END_IF;
  RETURN F;
--
END dFdT;
--
-----------------------------------------------------------------------
PROCEDURE LEAF(REAL: NC,L,INC,RGR,FDC);
------------------------------------------------------------------------
-
-- ESL Subroutine LEAF
-- Analytical integration of the D.E. describing the relative
-- number of cells along the mid-rib of a leaf
-- Also return leaf length (cm)
-- Inputs INC = initial relative number of cells
--        RGR = relative growth rate of leaf
--        FDC = fraction of deviding cells in the leaf
-- Outputs NC = final relative number of cells
--           L = length of leaf
-----------------------------------------------------------------------
--
  NC := INC*EXP(RGR*FDC);
  L := 0.1*NC*(4.0 - 3.0*FDC);
--
END LEAF;
--
-----------------------------------------------------------------------
PROCEDURE STEM(REAL: P,K,A,B,U,dAdP,dBdP,dUdP,
                     IP,Age,Light,Temp,Init,Factor);
------------------------------------------------------------------------
-
-- ESL Subroutine STEM
```

```
-- Calculates the plastochron age of a stem by analytical
-- integrations of the D.E. for node initiation rate
-- Also relative growth of the stem on a plastochron basis
-- Values of model parameters A & B and number of unfolding leaf U
-- Rates of change of A, B and U
-- Inputs IP = initial plastochron age
--       Age = plastochron age of main stem ( used for laterals)
--     Light = average daily light intensity
--      Temp = average daily temperature
--      Init = age to initiate stem
--    Factor = reduction factor accounting for presence of fruit
-- Outputs P = final plastochron age
--         Q = rate relative growth rate of stem
--         A = a parameter used in the model
--         B = a parameter used in the model
--         U = The number of the leaf which is unfolding
--      dAdP = rate of change of A on a plastochron basis
--      dBdP = rate of change of B on a plastochron basis
--      dUdP = rate of change fo U on a plastochron basis
-------------------------------------------------------------------
-- Constant Parameters for Node development sub-model
-- from Horie et al, 1976.
--
  CONSTANT REAL: As/0.22/,Ad/1.17/,La/5.7/;
  CONSTANT REAL: Bs/0.34/,Bd/2.07/,Lb/8.0/;
  CONSTANT REAL: Cs/3.30/,Cd/3.30/,Lc/10.0/;
  CONSTANT REAL: Lp/3.0/;
--
-- Function table for temperature dependence of node formation rate
--
  INTEGER: TabT/5/;
  CONSTANT REAL: TempTab(2,5)/
    0.0,0.0, 12.0,0.0, 18.0,0.8, 24.0,1.0, 40.0,1.0/;
--
-- Function table for light dependence of node formation rate
--
  INTEGER: TabL/5/;
  CONSTANT REAL: LightTab(2,5)/
    0.0,0.584, 1.0,0.8, 2.0,0.95, 4.0,1.0, 10.0,1.0/;
--
  REAL: KSTemp,KSLight,Ks,Nu,LFact,C,dCdP;
--
-- Find Stationary rate of node formation
--
```

```
  KsTemp := GEN2(TabT,TempTab,Temp);
  KsLight := GEN2(TabL,LightTab,Light);
  Ks := KsTemp*KsLight*Factor;
--
-- Actual rate of node formation
--
  K := Ks*(1.0 - EXP(-P/Lp));
--
-- Solve the differential equation for P.
--
  IF Age > Init THEN
    P := Lp*LOG(EXP(Ks/Lp)*(EXP(IP/Lp) - 1.0) + 1.0);
  ELSE
    P := IP;
  END_IF;
--
-- Calculate rates of change of parameters on Plastachron basis
--
  A := As + Ad*exp(-P/La);
  B := Bs + Bd*exp(-P/Lb);
  C := Cs - Cd*exp(-P/Lc);
  U := P - C/A;
  dAdP := (As - A)/La;
  dBdP := (Bs - B)/Lb;
  dCdP := (Cs - C)/Lc;
  dUdP := 1.0 - (A*dCdP - C*dAdP)/(A*A);
--
END STEM;
--
----------------------------------------------------------------------
PROCEDURE DEVELOP;
-----------------------------------------------------------------------
-
-- ESL Subroutine DEVELOP
-- Determines the development of the stem and laterals
-- and the individual leaf expansions
-- Based on leaf expension determines potential growth rates of
-- dry matter in leaves, stem, and root and potential assimilate
-- requirements
----------------------------------------------------------------------
USE GLOBAL;
--
  REAL : Zero/0.0/;
```

```
--
  AREAi := AREA;
--
-- Average Light and Temp
-- Reset Integrators
--
  Light := LSum*0.0864/Count;
  Temp := TSum/Count;
  TSum := 0.0;
  LSum := 0.0;
  Count := 0.0;
--
  LFact := 2.9 + 0.49*Light;
  FruFactM := 1.0 - (WfruitM/FactorM)**2.0;
  IF FruFactM < 0.0 THEN FruFactM := 0.0; END_IF;
  FruFactL := 1.0 - (WFruitL/(Laterals*FactorL))**2.0;
  IF FruFactL < 0.0 THEN FruFactL := 0.0; END_IF;
--
-- Invoke Stem Model for development of main stem
--
  PMaini := PMain;
  Age := PMain;
  STEM(PMain,KMain,A,B,UMain,dAdP,dBdP,dUdP,
       PMaini,Age,Light,Temp,Zero,FruFactM);
--
-- Calculate growth of individual leaves on main stem and total
-- leaf area
--
  AreaM := 0.0;
  NoLM := 0;
--
  FOR I := 1..30 LOOP
    LN := I;
    Nu:=NM(I)*LFact;
    RGR := RGRt(PMain,KMain,A,B,UMain,dAdP,dBdP,dUdP,LN);
    FDC := dFdT(UMain,Nu,LN);
    NCMi := NCM(I);
    LEAF(NCM(I),LM(I),NCMi,RGR,FDC);
    PREPARE "MAIN",Day,I,RGR,FDC,NCMi;
    IF (PMain - LN*DfactM > NecroM) OR
       ((Day >= Pinch) AND (LN > TopNode)) OR
       (LN >= PMain) THEN
      LM(I) := 0.0;
      ARM(I) := 0.0;
```

```
    ELSE
      IF LN <= UMain THEN NoLM := NoLM + 1; END_IF;
      AEM := LM(I)*LM(I);
      IF AEM <= 100 THEN ARM(I):= 0.524*AEM;
      ELSE ARM(I):=0.688*AEM-16.4;
      END_IF;
    END_IF;
    AreaM:=AreaM+ARM(I);
  END_LOOP;
--
-- Invoke Stem Model for developement of laterals
--
  PLati := PLat;
  STEM(PLat,KLat,A,B,ULat,dAdP,dBdP,dUdP,
       PLati,Age,Light,Temp,Init,FruFactL);
--
  AreaL := 0.0;
  NoLL := 0;
--
  FOR I := 1..20 LOOP
    LN := I;
    Nu:=NL(I)*LFact;
    RGR := RGRt(PLat,KLat,A,B,ULat,dAdP,dBdP,dUdP,LN);
    FDC := dFdT(ULat,Nu,LN);
    NCLi := NCL(I);
    LEAF(NCL(I),LL(I),NCLi,RGR,FDC);
    IF (PLat - LN*DfactL > NecroL) OR
       (LN >= PLat) THEN
      LL(I) := 0.0;
      ARL(I) := 0.0;
    ELSE
      IF LN <= ULat THEN NoLL := NoLL + INT(Laterals); END_IF;
      AEL := LL(I)*LL(I);
      IF AEL <= 100 THEN ARL(I):= 0.524*AEL;
      ELSE ARL(I):=0.688*AEL-16.4;
      END_IF;
    END_IF;
    AreaL := AreaL + ARL(I)*Laterals;
  END_LOOP;
--
  AREA := AreaM + AreaL;
  LAI := AREA*Nplant/(Af*10000.0);
  NOL := NoLM + NoLL;
--
```

```
  Lc := SQRT((AREA/NOL)/0.68)/100.0;
--
-- Calculate potential growth rates for leaves, stem, and roots
--
  PGRleaf := 0.0;
  FOR I := 1..30 LOOP
    dAl := ARM(I) - ARMi(I);
    IF dAl > 0.0 THEN
      PGRleaf := PGRleaf + MaxGRleaf*dAl/86400.0;
    ELSE
      Wleaf := Wleaf + dAl/SLA;
    END_IF;
    ARMi(I) := ARM(I);
  END_LOOP;
  FOR I := 1..20 LOOP
    dAl := ARL(I) - ARLi(I);
    IF dAl > 0.0 THEN
      PGRleaf := PGRleaf + MaxGRleaf*dAl/86400.0;
    ELSE
      Wleaf := Wleaf + dAl/SLA;
    END_IF;
    ARLi(I) := ARL(I);
  END_LOOP;
--
  PGRstem := (10.0/77.0)*PGRleaf;
  PGRroot := (13.0/77.0)*PGRleaf;
  Preqleaf := PGRleaf*ARLeaf;
  Preqstem := PGRstem*ARstem;
  Preqroot := PGRroot*ARroot;
--
END DEVELOP;
--
```

A10 Photosynthesis Routine

```
--
-- File PHOTOSYN.ESL
--
-----------------------------------------------------------------
PROCEDURE PHOTOSYN(REAL : Tci);
-----------------------------------------------------------------
-
-- ESL Subroutine PHOTOSYN
```

```
-- Calculates the gross photosynthesis using the model of Gijzen &
-- ten Cate (1988) by using Gaussian integration across leaf angle
-- classes and height within the crop canopy
----------------------------------------------------------------------
USE GLOBAL;
--
-- Table of variation of endogenous photosynthetic capacity
--
  CONSTANT REAL : EPCTab(2,5)/
     0.0,0.0, 5.0,0.0, 30.0,2.0, 40.0,0.0, 100.0,0.0/;
--
-- Table of variation of mesophyll conductance with temperature
--
  CONSTANT REAL : MesTab(2,5)/
     0.0,0.0, 5.0,0.0, 25.0,0.004, 40.0,0.0, 100.0,0.0/;
--
-- Constants for photosynthesis model
--
  CONSTANT REAL : Q10Comp/1.7/,Q10Resp/2.0/,Eff0/0.017/;
  CONSTANT REAL : RespD20/0.05/,Comp25/40.0/;
--
-- Parameters for Gaussian Integration
--
  CONSTANT REAL : XGauss(3)/0.1127, 0.5000, 0.8873/;
  CONSTANT REAL : WGauss(3)/0.2778, 0.4444, 0.2778/;
--
-- Calculate photosynthetic capacity parameters
-- Dark respiration
--
  RespD := RespD20*Q10Resp**(0.1*(Tci - 20.0));
--
-- Mesophyll resistance
--
   MesCond := GEN2(5,MesTab(1..2,1..5),Tci);
    IF (MesCond < 0.000001) THEN rm := 3.0E30; ELSE rm := 1.0/MesCond;
END_IF;
--
-- Endogenous photosynthetic capacity
--
   EPC := GEN2(5,EPCTab(1..2,1..5),Tci);
--
-- CO2 compensation point
--
```

```
   Compoint := Comp25*Q10Comp**(0.1*(Tci - 25.0));
--
-- Initial light use efficiency and max photosynthesis for CO2
limitation
--
   IF (CO2a > Compoint) THEN
     Eff := Eff0*(CO2a - Compoint)/(CO2a + 2.0*Compoint);
     FNCO2 := 1.83*(CO2a - Compoint)/(rm + 1.36*rVe + 1.6*rVi);
   ELSE Eff := 0.0; FNCO2 := 0.0;
   END_IF;
--
--Maximum net photosynthesis
--
   IF (EPC < 0.000001) THEN FNmax := 0.0;
   ELSE FNmax := EPC*(1.0 - EXP(-FNCO2/EPC));
   END_IF;
--
-- Maximum Gross Photosynthesis
--
   FGmax := FNmax + RespD;
--
-- Reduction of FGmax by high reserve levels
--
   ResL := Reserve/(Wleaf+Wstem+Wroot);
   IF (ResL < 0.40) THEN
     FGmax := FGmax;
   ELSE_IF (ResL < 0.45) THEN
     FGmax := FGmax*(10.0-ResL*20.0);
   ELSE
     FGmax := 0.000001;
   END_IF;
--
-- Gaussian Integration in crop canopy profile
-- Calculate the gross photosynthetic rate
--
   FGross := 0.0;
--
-- Loop for 3 heights in canopy
--
   FOR I1 := 1..3 LOOP
     LAIC := LAI*XGauss(I1);
--
-- Components of visible (PAR) radiation
```

```
--
     VisDif := (1.0 - Rhocpdf)*Taugdf*Spdf*Kpdf*EXP(-Kpdf*LAIC);
     VisTot := (1.0 - Rhocpdr)*Taugdr*Spdr*Kpdr*EXP(-Kpdr*LAIC);
     VisDir := (1.0 - Sigp)*Taugdr*Spdr*Kbdr*EXP(-Kbdr*LAIC);
     VisShd := VisDif+VisTot-VisDir;
--
-- Photosynthesis of shaded leaves
--
     FGShd := Fgmax*(1.0 - EXP(-VisShd*Eff/FGmax));
     VisPer := (1.0 - Sigp)*Taugdr*Spdr/SinB;
--
-- Loop over leaf angle distribution for photsynthesis of sunlit leaves
--
     FGSun := 0.0;
     FOR I2 := 1..3 LOOP
       VisSun := VisShd + VisPer*XGauss(I2);
       FGs := FGmax*(1.0 - EXP(-VisSun*Eff/FGmax));
       FGSun := FGSun + FGs*WGauss(I2);
     END_LOOP;
--
-- Fraction of sunlit leaves at each height in canopy
--
     FracSun := EXP(-Kbdr*LAIC);
--
-- Total photosynthesis in leaf layer
--
     FG := FracSun*FGSun + (1.0 - FracSun)*FGShd;
--
-- Gaussian integration
--
     FGross := FGross + FG*WGauss(I1);
   END_LOOP;
--
-- Gross photosynthesis per unit floor area
--
   FGross := FGross*LAI;
--
-- Gross photosynthesis (assimilation) per plant
--
   Assim := FGross*Af/Nplant;
--
END PHOTOSYN;
--
```

A11 Crop Growth and Respiration Routines

```
--
-- File GROWTH.ESL
--
-----------------------------------------------------------------------
PROCEDURE GROWTH(REAL : Tci);
------------------------------------------------------------------------
-
-- ESL Subroutine GROWTH
-- Calculate the maintenance and growth respiration, reserve level,
-- and partitioning
-- Input Tci = crop temperature
-----------------------------------------------------------------------
USE GLOBAL;
--
  REAL : Factor;
  INTEGER : LastFM;
--
-- Calculate Maintenance Respiration
--
  RespMain := (Wroot*MainRoot + Wstem*MainStem + Wleaf*MainLeaf +
               Wfruit*MainFru)*Q10**(0.1*(Tci - TempRef));
  FResp := RespMain*Nplant/Af;
--
-- Calculate Reserve levels of carbohydrate
--
  Reserve := Reserve + (Assim - RespMain)*300.0*30.0/44.0;
  IF Reserve < 0.0 THEN
    Wleaf := Wleaf + Reserve*0.77/1.8;
    Wstem := Wstem + Reserve*0.10/1.8;
    Wroot := Wroot + Reserve*0.13/1.8;
    Reserve := 0.0;
  END_IF;
--
-- Calculate growth of fruit
--
  LostFresh := 0.0;
  PGRfruit := 0.0;
  IF DAY >= Pinch THEN
    LastFM := INT(TopNode);
  ELSE
```

```
    LastFM := 30;
  END_IF;
--
-- Loop for main stem
--
  FOR I := 10..LastFM LOOP
    IF (NOT AbortM(I)) AND (NOT HarvM(I)) AND (I <= UMain) THEN
      TFruM(I) := TFruM(I) + 1.0;
      AgeFruM(I) := TFruM(I)/288.0;
      Factor := EXP(-0.6*(AgeFruM(I)-15.0));
      PGRFruM(I) := MaxGRFru*4.0*Factor/((1.0+Factor)**2.0);
      PGRfruit := PGRfruit + PGRFruM(I);
    ELSE
      PGRFruM(I) := 0.0;
    END_IF;
  END_LOOP;
--
-- Loop for laterals
--
  FOR I := 1.. 20 LOOP
    IF (NOT AbortL(I)) AND (NOT HarvL(I)) AND (I <= ULat) THEN
      TFruL(I) := TFruL(I) + 1.0;
      AgeFruL(I) := TFruL(I)/288.0;
      Factor := EXP(-0.6*(AgeFruL(I) - 15.0));
      PGRFruL(I) := MaxGRFru*4.0*Factor/((1.0 + Factor)**2.0);
      PGRfruit := PGRfruit + PGRFruL(I)*Laterals;
    ELSE
      PGRFruL(I) := 0.0;
    END_IF;
  END_LOOP;
--
-- Potential assimilate requirement for fruit growth
--
  Preqfruit := PGRfruit*ARfruit;
--
-- Assimilate requirements for potential growth per second
--
  PRequired := Preqleaf + Preqstem + Preqroot + Preqfruit;
--
-- Convert to 5 minute requirement
--
  PRequired := PRequired*300.0;
--
```

```
-- Ratio of reserve to requirements
--
  IF Reserve < PRequired THEN
    Ratio := Reserve/PRequired;
    Reserve := 0.0;
  ELSE
    Ratio := 1.0;
    Reserve := Reserve - Prequired;
  END_IF;
--
-- Growth of organs and CO2 production (growth respiration)
--
  Wleaf := Wleaf + Ratio*PGRleaf*300.0;
  CO2pLeaf := Ratio*PGRleaf*CO2leaf;
  Wstem := Wstem + Ratio*PGRstem*300.0;
  CO2pStem := Ratio*PGRstem*CO2stem;
  Wroot := Wroot + Ratio*PGRroot*300.0;
  CO2pRoot := Ratio*PGRroot*CO2root;
  CO2pfruit := Ratio*PGRfruit*CO2fruit;
--
-- Growth of individual fruit, abortion and picking
--
-- Loop for main stem
--
  WfruitM := 0.0;
--
  FOR I := 10..LastFM LOOP
    IF (NOT AbortM(I)) AND (NOT HarvM(I)) THEN
      WfruM(I) := WfruM(I) + Ratio*PGRfruM(I)*300.0;
      WfruitM := WfruitM + WfruM(I);
      IF (PickTime) THEN
        IF (WFruM(I) >=PickW)
         OR ((AgeFruM(I) >= RemAge) AND (WFruM(I) >=RemW)) THEN
        HarvM(I) := TRUE;
          WfruitH := WfruitH + WfruM(I);
          NoFruitH := NoFruitH + 1;
        LostFresh := LostFresh + WfruM(I)*0.96/(1000.0*0.04);
        ELSE_IF (AgeFruM(I) >=RemAge) AND (WFruM(I) < RemW) THEN
          AbortM(I) := TRUE;
          NofruitA := NoFruitA + 1;
        LostFresh := LostFresh + WfruM(I)*0.96/(1000.0*0.04);
      END_IF;
      END_IF;
      IF (AgeFruM(I) >= AbortAge) AND (WfruM(I) < 0.2*PickW) THEN
```

```
        AbortM(I) := TRUE;
        NofruitA := NoFruitA + 1;
      END_IF;
    ELSE
      WfruM(I) := 0.0;
    END_IF;
  END_LOOP;
--
-- Loop for laterals
--
  WFruitL := 0.0;
--
  FOR I := 1..20 LOOP
    IF (NOT AbortL(I)) AND (NOT HarvL(I)) THEN
      WfruL(I) := WfruL(I) + Ratio*PGRfruL(I)*300.0;
      WfruitL := WfruitL + WfruL(I)*Laterals;
      IF (PickTime) THEN
        IF (WFruL(I) >=PickW)
         OR ((AgeFruL(I) >= RemAge) AND (WFruL(I) >= RemW)) THEN
        HarvL(I) := TRUE;
          WfruitH := WfruitH + WfruL(I)*Laterals;
          NoFruitH := NoFruitH + INT(Laterals);
        LostFresh := LostFresh + Laterals*WfruL(I)*0.96/(1000.0*0.04);
        ELSE_IF (AgeFruL(I) >=RemAge) AND (WFruL(I) < RemW) THEN
          AbortL(I) := TRUE;
          NofruitA := NoFruitA + INT(Laterals);
        LostFresh := LostFresh + Laterals*WfruL(I)*0.96/(1000.0*0.04);
      END_IF;
      END_IF;
      IF (AgeFruL(I) >= AbortAge) AND (WfruL(I) < 0.2*PickW) THEN
        AbortL(I) := TRUE;
        NofruitA := NoFruitA + INT(Laterals);
      END_IF;
    ELSE
      WfruL(I) := 0.0;
    END_IF;
  END_LOOP;
--

-- Add total fruit weight
--
  WFruit := WfruitM + WfruitL;
--
-- Total CO2 production and loss of fresh weight per second
```

```
--
  CO2prod := CO2pLeaf + CO2pStem + CO2pRoot + CO2pFruit;
  FCO2prod := CO2prod*Nplant/Af;
  LostFresh := LostFresh/300.0;
--
-- Specific leaf area
--
  SLA := AREA/Wleaf;
--
-- Total crop dry matter, dry matter heat capacity,
-- and maximum water holding capacity
--
  DMt := (Wleaf+Wstem+Wroot+WFruit)/1000.0;
  Phic := DMt*Nplant*Cpom/Af;
  Xcmax := WHCc*DMt*Nplant/Af;
--
END GROWTH;
--
```

A12 Greenhouse Energy and Mass Balance Model

```
--
-- File GEMB.ESL
--
----------------------------------------------------------------------
MODEL GEMB(REAL : Tg,Ts,Ta,Tc,Tm,Tf,T1,T2,T3,T4,T5,Xg,Xa,Xc,Xm,XCO2a,
                  T1evap,T2evap,T3evap,T1cond,T2cond,T3cond:=
           REAL : Tgi,Tsi,Tai,Tci,Tmi,Tfi,T1i,T2i,T3i,T4i,T5i,
                  Xgi,Xai,Xci,Xmi,XCO2ai,
                  T1evapi,T2evapi,T3evapi,T1condi,T2condi,T3condi);
----------------------------------------------------------------------
-
-- ESL model GEMB (Greenhouse Energy & Mass Balances)
--
-- Dynamiç simulation of the greenhouse environmental state variables.
-- Enthalpy of glazing, structure, crop, root media, soil layers,
-- and air.
-- Water content of glazing, crop, root media and air.
-- Water content of glazing, crop, root media and air.
-- Inputs Tgi = initial temperature of glazing
--        Tsi = initial temperature of structure
--        Tai = initial temperature of inside air
--        Tci = initial temperature of crop
```

```
--        Tmi = initial temperature of root medium
--        Tfi = initial temperature of floor
--        T1i = initial temperature of soil layer 1
--        T2i = initial temperature of soil layer 2
--        T3i = initial temperature of soil layer 3
--        T4i = initial temperature of soil layer 4
--        T5i = initial temperature of soil layer 5
--    T1evapi = initial temperature of evaporator 1
--    T2evapi = initial temperature of evaporator 2
--    T3evapi = initial temperature of evaporator 3
--        Xgi = initial moisture concentration on glazing
--        Xai = initial moisture content of inside air
--        Xmi = initial moisture content of root medium
--        Xci = initial moisture content of crop
--     XCO2ai = initial CO2 concentration of inside air
-- Outputs Tg = final temperature of structure
--         Ts = final temperature of structure
--         Ta = final temperature of inside air
--         Tc = final temperature of crop
--         Tm = final temperature of root medium
--         Tf = final temperature of floor
--         T1 = final temperature of soil layer 1
--         T2 = final temperature of soil layer 2
--         T3 = final temperature of soil layer 3
--         T4 = final temperature of soil layer 4
--         T5 = final temperature of soil layer 5
--     T1evap = final temperature of evaporator 1
--     T2evap = final temperature of evaporator 2
--     T3evap = final temperature of evaporator 3
--         Xg = final moisture concentration on glazing
--         Xa = final moisture content of inside air
--         Xm = final moisture content of root medium
--         Xc = final moisture content of crop
--      XCO2a = final CO2 concentration of inside air
---------------------------------------------------------------
USE GLOBAL;
--
-- Enthalpies
--
  REAL : Hg,Hs,Ha,Hc,Hm,Hf;
  REAL : H1,H2,H3,H4,H5;
  REAL : Tlast/0.0/;
  REAL : Power1A,Power2A,Power3A;
```

```
  REAL : Qr1,Qr2,Qr3,fr1,fr2,fr3;
  REAL : ATemp,AX;
--
  REAL : Swept1Vol/0.0292/,UAe1/4280.0/,UAc1/5630.0/;
  REAL : Swept2Vol/0.0584/,UAe2/8560.0/,UAc2/11260.0/;
  REAL : Swept3Vol/0.0292/,UAe3/4280.0/,UAc3/5630.0/;
--
  REAL : Circ1Rate/4.5/,Circ2Rate/9.0/,Circ3Rate/4.5/;
--
NOSORT;
INITIAL
--
--  Initialize dynamic variables
--
  Tg := Tgi;  Ts := Tsi;  Ta := Tai;  Tc := Tci;  Tm := Tmi;
  Tf := Tfi;  T1 := T1i;  T2 := T2i;  T3 := T3i;  T4 := T4i;
  T5 := T5i;
  Xg := Xgi; Xa := Xai; Xc := Xci; Xm := Xmi;
  XCO2a := XCO2ai;
  T1evap := T1evapi; T2evap := T2evapi; T3evap := T3evapi;
  T1cond := T1condi; T2cond := T2condi; T3cond := T3condi;
--
-- Determine the sky temperature
--
  po := 611.0*exp(17.27*Tow/(Tow + 237.3)) - Gamma*(To - Tow);
  IF po < 0.0 THEN po := 0.0; END_IF;
  Todw := (237.3*ALOG(po/611.0))/(17.27 - ALOG(po/611.0));
  IF Sg = 0.0 THEN esky := 0.741 + 0.0062*Todw;
  ELSE esky := 0.727 + 0.006*Todw;
  END_IF;
  esky := esky + Cloud*(1.0 - esky - 8.0/(To + 273.15));
  Tsky := (To+273.15)*esky**0.25-273.15;
--
-- Outside CO2 concentration
--
  Chio := Mw*po/(R*(To + 273.15));
  ChiCO2o := (CO2o/1e3)*1.52*Ma*(P-po)/(R*(To + 273.15));
--
-- inside air parameters
--
  rhoa := Ma*(P - pa)/(R*(Ta + 273.15));
  Phia := rhoa*da*Cpa;
  Theta := rhoa*Cpa;
```

```
--
-- Initial enthalpy contents
--
  Hg := Tg*(Phig + Xg*Cpw);
  Hs := Ts*(Phis);
  Ha := Ta*(Phia + Xa*Cpv) + 2501*Xa;
  Hc := Tc*(Phic + Xc*Cpw);
  Hm := Tm*(Phim + Xm*Cpw);
  Hf := Tf*(Phif + Xf*Cpw);
  H1 := T1*(Phi1 + X1*Cpw);
  H2 := T2*(Phi2 + X2*Cpw);
  H3 := T3*(Phi3 + X3*Cpw);
  H4 := T4*(Phi4 + X4*Cpw);
  H5 := T5*(Phi5 + X5*Cpw);
--
-- Initial water potentials
--
  Psic := -(1.0 - Xc/Xcmax)/Capc;
  Psim := -(1.0 - Xm/Xmmax)/Capm;
--
-- Convective heat transfer coefficients
--
  hCgo := CONVHT(Uo,Lf,Tg,To,1.0);
  hCga := CONVHT(Ua,Lg,Tg,Ta,0.0);
  hCsa := CONVHT(Ua,1.0,Ts,Ta,1.0);
  hCca := CONVHT(Ua,Lc,Tc,Ta,1.0);
  hCfa := CONVHT(Ua,Lf,Tf,Ta,1.0);
  hCma := hCfa;
--
-- Conductance between floor and soil layers (W/m2.K)
--
  xwm := Xm*Af/(Amtop*BagH*rhow);
  km := SOIL(xqm,xclm,xomm,xwm,Field);
  hGfm := 2.0/(BagH/km + df/kf);
  hGf1 := 2.0/(df/kf + d1/k1);
  hG12 := 2.0/(d1/k1 + d2/k2);
  hG23 := 2.0/(d2/k2 + d3/k3);
  hG34 := 2.0/(d3/k3 + d4/k4);
  hG45 := 2.0/(d4/k4 + d5/k5);
  hG5d := 2.0*k5/d5;
--
-- Equivalent radiative heat transfer coefficients (W.m2.K)
--
  Tave := (Tg + Tsky)/2.0;
```

```
  hRgsky := 4.0*SFgsky*Sigma*(Tave+273.15)**3.0;
  Tave := (Ts + Tg)/2.0;
  hRsg := 4.0*SFsg*Sigma*(Tave+273.15)**3.0;
  Tave := (Tc + Tg)/2.0;
  hRcg := 4.0*SFcg*Sigma*(Tave+273.15)**3.0;
  Tave := (Tc + Ts)/2.0;
  hRcs := 4.0*SFcs*Sigma*(Tave+273.15)**3.0;
  Tave := (Tm + Tg)/2.0;
  hRmg := 4.0*SFmg*Sigma*(Tave+273.15)**3.0;
  Tave := (Tm + Ts)/2.0;
  hRms := 4.0*SFms*Sigma*(Tave+273.15)**3.0;
  Tave := (Tm + Tc)/2.0;
  hRmc := 4.0*SFmc*Sigma*(Tave+273.15)**3.0;
  Tave := (Tf + Tg)/2.0;
  hRfg := 4.0*SFfg*Sigma*(Tave+273.15)**3.0;
  Tave := (Tf + Ts)/2.0;
  hRfs := 4.0*SFfs*Sigma*(Tave+273.15)**3.0;
  Tave := (Tf + Tc)/2.0;
  hRfc := 4.0*SFfc*Sigma*(Tave+273.15)**3.0;
  Tave := (Tf + Tm)/2.0;
  hRfm := 4.0*SFfm*Sigma*(Tave+273.15)**3.0;
--
-- Infiltration rate (airchange rate per hour)
--
  Infil := 0.77*Uo + 0.14*SQRT(ABS(Ta - To));
--
-- Advective heat transfer coefficient (W/m2 floor.K)
--
  hao := Phia*Infil/3600.0;
  rao := Theta/hao;
--
-- Leaf internal resistance
--
  VPD := 611.0*exp(17.27*Tc/(Tc+237.3)) - pa;
  IF (Sg <= 0.0) THEN
    rVi := 15.0*(1.0 + 0.162*VPD)*(1.0 + 0.0012*(Tc - 30.0)**2.0);
  ELSE
    rVi := 15.0*(1.0 + 0.162*VPD*exp(-0.055*Bcave))*
                 (1.0 + 0.0012*(Tc - 30.0)**2.0);
  END_IF;
--
-- Evaporative heat transfer coefficinets (W/m2.K) (0.93 from
-- Lewis number)
```

```
--
  rVga := 0.93*Theta/hCga;
  rVe := 0.93*Theta/HCca;
  rVma := 0.93*Theta/hCma;
--
DYNAMIC
--
-- Convective heat transfer rates
--
  Cgo := hCgo*GAI*(Tg - To);
  Cga := hCga*GAI*(Tg - Ta);
  Csa := hCsa*SAI*(Ts - Ta);
  Cca := hCca*2.0*LAI*(Tc - Ta);
  Cma := hCma*MAI*(Tm - Ta);
  Cfa := hCfa*FAI*(Tf - Ta);
  Cao := hao*(Ta - To);
--
-- Conductive heat transfer rates
--
  Gsg := hGsg*SAI*(Ts - Tg);
  Gfm := hGfm*(1.0 - FAI)*(Tf - Tm);
  Gf1 := hGf1*(Tf - T1);
  G12 := hG12*(T1 - T2);
  G23 := hG23*(T2 - T3);
  G34 := hG34*(T3 - T4);
  G45 := hG45*(T4 - T5);
  G5d := hG5d*(T5 - Td);
--
-- Radiative heat transfer rates
--
  Rgsky := hRgsky*GAI*(Tg - Tsky);
  Rsg := hRsg*SAI*(Ts - Tg);
  Rcg := hRcg*2.0*LAI*(Tc - Tg);
  Rcs := hRcs*2.0*LAI*(Tc - Ts);
  Rmg := hRmg*MAI*(Tm - Tg);
  Rms := hRms*MAI*(Tm - Ts);
  Rmc := hRmc*MAI*(Tm - Tc);
  Rfg := hRfg*FAI*(Tf - Tg);
  Rfs := hRfs*FAI*(Tf - Ts);
  Rfc := hRfc*FAI*(Tf - Tc);
  Rfm := hRfm*FAI*(Tf - Tm);
--
-- Evaporative mass transfer rates
```

```
--
  Chig := (Mw*611.0*exp(17.27*Tg/(Tg + 237.3)))/(R*(Tg + 273.15));
  Chic := (Mw*611.0*exp(17.27*Tc/(Tc + 237.3)))/(R*(Tc + 273.15));
  Chim := (Mw*611.0*exp(17.27*Tm/(Tm + 237.3)))/(R*(Tm + 273.15));
  Chiamax := (Mw*611.0*exp(17.27*Ta/(Ta + 237.3)))/(R*(Ta + 273.15));
  Chia := Xa/da;
  f := (GAI/rVga)*(Chig - Chia);
  fga := IF (Xg <= 0.0) AND (f > 0.0) THEN 0.0 ELSE f;
  f := (2.0*LAI/(rVi + rVe))*(Chic - Chia);
  fca := IF (Xc <= 0.0) AND (f > 0.0) THEN 0.0 ELSE f;
  f := ((1.0 - FAI)/rVma)*(Chim - Chia);
  fma := IF (Xm <= 0.0) AND (f > 0.0) THEN 0.0 ELSE f;
  fprod := fga + fca + fma;
--
-- Advective mass transfer rates
--
  f := (Chia - Chio)/rao;
  fao := IF (Chia >= Chiamax) AND (f < fprod) THEN fprod*1.05
         ELSE_IF (Chia <= Chio) AND (f > fprod) THEN fprod*0.95
         ELSE f;
  fdrip := IF (Xg > 0.0002*GAI*rhow) AND (fga < 0.0) THEN -fga ELSE
            0.0;
  fdrn := IF Xm > Xmmax THEN firr ELSE 0.0;
  fup := IF (Psim > Psic) THEN Kmc*(Psim - Psic) ELSE 0.0;
--
-- Latent Heat Transfer Rates
--
  LEga := fga*Lamd;
  LEca := fca*Lamd;
  LEma := fma*Lamd;
  LEao := fao*Lamd;
--
  Edrip := fdrip*Cpw*Tg;
  Eirr := firr*Cpw*Td;
  Eup := fup*Cpw*Tm;
  Edrn := fdrn*Cpw*Tm;
--

-- CO2 exchange
--
  Fvent := (ChiCO2a - ChiCO2o)/rao;
--
-- Call the refrigeration procedures
```

```
--
   Power1A := 0.0;
   Power2A := 0.0;
   Power3A := 0.0;
   Qr := 0.0;
   fr := 0.0;
   ATemp := Ta;
   AX := Xa;
--
PROCEDURAL;
--
  IF Refrig1On THEN
   REFRIG(Swept1Vol,UAe1,UAc1,T1evap,T1cond,Circ1Rate,Qr1,fr1,ATemp,AX,
        Power1A);
   Qr := Qr1;
   fr := fr1;
  END_IF;
--
  IF Refrig2On THEN
   REFRIG(Swept2Vol,UAe2,UAc2,T2evap,T2cond,Circ2Rate,Qr2,fr2,ATemp,AX,
        Power2A);
   Qr := Qr + Qr2;
   fr := fr + fr2;
  END_IF;
--
  IF Refrig3On THEN
   REFRIG(Swept3Vol,UAe3,UAc3,T3evap,T3cond,Circ3Rate,Qr3,fr3,ATemp,AX,
        Power3A);
   Qr := Qr + Qr3;
   fr := fr + fr3;
  END_IF;
END_PROCEDURAL;
--
-- Dynamic Equations
--
  Hg' := Bg - Cgo - Cga + Gsg - Rgsky + Rsg + Rcg + Rmg + Rfg
            - LEga - Edrip;
  Hs' := Bs - Csa - Gsg - Rsg + Rcs + Rms + Rfs;
  Ha' := Cga + Csa + Cca + Cma + Cfa + Cht - Cao + LEga + LEca
         + LEma - LEao - Qr;
  Hc' := Bc - Cca - Rcg - Rcs + Rmc + Rfc - LEca + Eup;
  Hm' := Bm - Cma + Gfm - Rmg - Rms - Rmc + Rfm
```

```
            - LEma + Eirr - Eup - Edrn;
  Hf' := Bf - Cfa - Gfm - Gf1 - Rfg - Rfs - Rfc - Rfm;
  H1' := Gf1 - G12;
  H2' := G12 - G23;
  H3' := G23 - G34;
  H4' := G34 - G45;
  H5' := G45 - G5d;
--
  Xg' := - fga - fdrip;
  Xa' := fga + fca + fma - fao - fr + fhum;
  Xc' := fup - fca - LostFresh;
  Xm' := firr - fma - fup - fdrn;
--
  XCO2a' := FResp + FCO2prod + Finj - FGross - Fvent;
--
STEP
--
-- Calculate temperatures
--
  Tg := Hg/(Phig + Xg*Cpw);
  Ts := Hs/(Phis);
  Ta := (Ha - Xa*2501)/(Phia + Xa*Cpv);
  Tc := Hc/(Phic + Xc*Cpw);
  Tm := Hm/(Phim + Xm*Cpw);
  Tf := Hf/(Phif + Xf*Cpw);
  T1 := H1/(Phi1 + X1*Cpw);
  T2 := H2/(Phi2 + X2*Cpw);
  T3 := H3/(Phi3 + X3*Cpw);
  T4 := H4/(Phi4 + X4*Cpw);
  T5 := H5/(Phi5 + X5*Cpw);
--
-- Calculate water potentials
--
  Psic := -(1.0 - Xc/Xcmax)/Capc;
  Psim := -(1.0 - Xm/Xmmax)/Capm;
--
-- Update inside air parameters
--
  IF Xa < 0.0 THEN pa := 0.0;
  ELSE pa := (Xa*R*(Ta + 273.15))/(Mw*da);
  END_IF;
  rhoa := Ma*(P - pa)/(R*(Ta + 273.15));
  Phia := rhoa*da*Cpa;
```

```
  Theta := rhoa*Cpa;
--
-- CO2 concentration
--
  ChiCO2a := XCO2a/da;
  CO2a := XCO2a*1e3*R*(Ta + 273.15)/(da*1.52*Ma*(P - pa));
  CO2hTot := CO2hTot + CO2a*(T - Tlast);
--
-- Summation of compressor use
--
  IF Mode = 0 THEN
   SCP1h_h := SCP1h_h + Power1A*(T - Tlast)/1000;
   SCP2h_h := SCP2h_h + Power2A*(T - Tlast)/1000;
   SCP3h_h := SCP3h_h + Power3A*(T - Tlast)/1000;
  ELSE
   SCP1c_h := SCP1c_h + Power1A*(T - Tlast)/1000;
   SCP2c_h := SCP2c_h + Power2A*(T - Tlast)/1000;
   SCP3c_h := SCP3c_h + Power3A*(T - Tlast)/1000;
  END_IF;
  Tlast := T;
--
COMMUNICATION
--
  psat := 611.0*exp(17.27*Ta/(Ta + 237.3));
  RH := 100.0*pa/psat;
--
-- If not the end of the last simulation step then check control
--
  IF (T /= TFIN) THEN
    CONTROL(:= Ta, CINT);
  END_IF;
--
END GEMB;
--
```

A13 Heat Pump Simulation Model

```
--
-- File REFRIG.ESL
--
-----------------------------------------------------------------
```

```
PROCEDURE REFRIG(REAL : SweptVol,UAi,UAo,Tevap,Tcond,CircRate,
                        Qref,fref,Ta,Xa,PowerA);
------------------------------------------------------------------
USE GLOBAL;
--
  REAL : GAM,VolEff,MechEff,SpecVol,Qevap,Qcond,Qevape,Qconde;
  REAL : Pd,Ps,CompRatio;
  REAL : VolFlow,MassFlow;
  REAL : hcondi,hcondo,hevapi,hevapo,Tevapi,Tcondi;
  REAL : PowerT;
  REAL : Errore,Errorc;
  REAL : Ha1,Ha2,Xa2,Hevap,Xevap,pevap,rhoevap,CF;
  REAL : h1,h2,h3,h4,h5;
  REAL : dTC,G1,G2,G3,G4,G5,G6;
  REAL : V1,V2,V3,V4,V5,V6,V7;
  REAL : SuperHeat;
  CONSTANT REAL : RefErr/0.01/;
  INTEGER : RCount;
--
-- Discharge and suction Pressures
--
  SuperHeat := 8.0;
  RCount := 0;
--
  LOOP
--
  Pd := EXP(21.25384 - 2025.4518/(Tcond + 248.94));
  Ps := EXP(21.25384 - 2025.4518/(Tevap + 248.94));
  CompRatio := Pd/Ps;
--
-- Calculate Gamma
--
  dTC := Tcond - Tevap;
  G1 := 1.137423 - 1.50914E-3*Tevap - 5.59643E-6*Tevap**2.0;
  G2 := (-8.74677E-6*Tevap - 1.49547E-7*Tevap**2.0)*dTC;
  G3 := 5.97029E-8*Tevap*dTC**2.0 + 1.41458E-9*Tevap**2.0*dTC;
  G4 := 3.68417E-4*SuperHeat - 6.26076E-6*SuperHeat**2.0;
  G5 := 1.45839E-5*Tevap*SuperHeat - 1.6573E-7*Tevap*SuperHeat**2.0;
  G6 := -4.5258E-4*dTC + G1 + G2 + G3;
  GAM := G6*(1.0 + G4 + G5);
--
-- Volumetric Efficiency
```

```
--
  VolEff := 0.958 - 0.0327*CompRatio;
  MechEff := VolEff/1.1;
--
-- Calculate Specific volume of suction vapour
--
  V1 := exp(-11.82344 + 2390.321/(Tevap + 273.15));
  V2 := 1.01859 + 5.09433E-4*Tevap - 14.8464E-6*Tevap**2.0;
  V3 := V2 - 2.49547E-7*Tevap**3.0;
  V4 := V1*V3;
  V5 := 1.0 + 5.23275E-3*SuperHeat - 5.59394E-6*SuperHeat**2.0;
  V6 := 3.45555E - 5*Tevap*SuperHeat -
        2.31649E-7*Tevap*SuperHeat**2.0;
  V7 := 5.80303E - 7*SuperHeat*Tevap**2.0 -
        3.20189E - 9*Tevap**2.0*SuperHeat**2.0;
  SpecVol := V4*(V5 + V6 + V7);
--
-- Calculate Volumetric and Mass flow rates through compressor
--
  VolFlow := SweptVol*VolEff;
  Massflow := VolFlow/SpecVol;
--
-- Theoretical and Actual Compressor Power
--
  PowerT := GAM/(GAM - 1.0)*Ps*SpecVol*((CompRatio**((GAM - 1.0)/GAM))
            - 1.0);
  PowerA := PowerT/MechEff;
--
-- Calculate enthalpy of suction vapour
--
  h1 := 250027.0 + 367.265*Tevap - 1.84133*Tevap**2.0 -
        11.4556E-3*Tevap**3.0;
  h2 := 1.0 + 2.85446E-3*SuperHeat + 4.0129E-7*SuperHeat**2.0;
  h3 := 13.3612E-6*Tevap*SuperHeat - 8.11617E-8*Tevap*SuperHeat**2.0;
  h4 := 14.1194E-8*SuperHeat*Tevap**2.0 -
        9.53294E-10*Tevap**2.0*SuperHeat**2.0;
  hevapo := h1*(h2 + h3 + h4)+155482.0;
--
-- Calculate enthalpy of liquid entering the condenser
--
  hcondi := hevapo + PowerT/MassFlow;
--
```

```
-- Calculate enthalpy of liquid leaving condenser (assuming saturated)
--
  h5 := 1170.36*Tcond + 1.68674*Tcond**2.0 + 5.2703E-3*Tcond**3.0;
  hcondo := 200000.0 + h5;
--
  hevapi := hcondo;
--
  Qevap := MassFlow*(hevapo - hevapi);
  Qcond := MassFlow*(hcondi - hcondo);
--
  IF Mode = 1 THEN
    Qevape := (Ta - Tevap)*UAi;
    Qconde := (Tcond - To)*UAo;
  ELSE
    Qevape := (To - Tevap)*UAo;
    Qconde := (Tcond - Ta)*UAi;
  END_IF;
--
  Errore := Qevap - Qevape;
  Errorc := Qcond - Qconde;
--
  RCount := RCount + 1;
--
--  tabulate Rcount,tevap,tcond,Qevap,Qevape,Qcond,Qconde;
--
  TERMINATE ((ABS(Errore/Qevap) < RefErr) AND
             (ABS(Errorc/Qcond) < RefErr));
--
  Qevap := Qevape + Errore/2.0;
  Qcond := Qconde + Errorc/2.0;
  IF Mode = 1 THEN
    Tevap := Ta - Qevap/Uai;
    Tcond := To + Qcond/UAo;
  ELSE
    Tevap := To - Qevap/Uao;
    Tcond := Ta + Qcond/UAi;
  END_IF;
--
  END_LOOP;
--
-- Calculate sensible and latent heat components
--
```

```
  Ha1 := Ta*(Phia + Xa*Cpv) + Xa*2501;
  Ha2 := Ha1 - CircRate*Qevap/da;
--
  pevap := 611.0*exp(17.27*Tevap/(Tevap + 237.3));
  rhoevap := Ma*(P - pevap)/(R*(Tevap + 273.15));
  Xevap := rhoevap*da*Mw*pevap/(Ma*(P - pevap));
  Hevap := Tevap*(Cpa*rhoevap*da + Xevap*Cpv) + Xevap*2501;
--
  CF := (Ha1 - Ha2)/(Ha1 - Hevap);
  IF CF > 1.0 THEN CF := 1.0; END_IF;
  IF CF < 0.0 THEN CF := 0.0; END_IF;
--
  Xa2 := Xa - CF*(Xa - Xevap);
--
  IF Mode = 1 THEN
    Qref := Qevap/Af;
    fref := (CircRate/da)*(Xa - Xa2)/Af;
    IF fref < 0.0 THEN fref := 0.0; END_IF;
  ELSE
    Qref := -Qcond/Af;
    fref := 0.0;
  END_IF;
--
END REFRIG;
--
```

A14 Hourly Output Procedure

```
--
-- File HOUTPUT.ESL
--
-----------------------------------------------------------------------
PROCEDURE HOUTPUT(REAL : Ta,Tc;FILE : Out1);
-----------------------------------------------------------------------
USE GLOBAL;
--
  CO2hTot := CO2hTot/3600;
  TaHave := TaHave/12;
  RHHave := RHHave/12;
--
  PRINT Out1,Day:6.1,Hr:6.1,TaHave:6.1,CO2hTot:8.1,RHHave:6.1,
       RTF1_h:10.2,RTF2_h:10.2,HUse1_h:10.2,HUse2_h:10.2,RTC_h:10.2,
```

```
        SCP1h_h:10.2,SCP2h_h:10.2,SCP3h_h:10.2,
        SCP1c_h:10.2,SCP2c_h:10.2,SCP3c_h:10.2,
        FGrHave:10.3,FReHave:10.3,FCOHave:10.3;
--
  TABULATE Day,Hr;
--
-- Sum Daily Values
--
  FGrDave := FGrDave + FGrHave;
  FReDave := FReDave + FReHave;
  FCODave := FCODave + FCOHave;
   RTF1_d :=  RTF1_d + RTF1_h;
   RTF2_d :=  RTF2_d + RTF2_h;
  HUse1_d := HUse1_d + HUse1_h;
  HUse2_d := HUse2_d + HUse2_h;
    RTC_d :=   RTC_d + RTC_h;
  SCP1h_d := SCP1h_d + SCP1h_h;
  SCP2h_d := SCP2h_d + SCP2h_h;
  SCP3h_d := SCP3h_d + SCP3h_h;
  SCP1c_d := SCP1c_d + SCP1c_h;
  SCP2c_d := SCP2c_d + SCP2c_h;
  SCP3c_d := SCP3c_d + SCP3c_h;
--
-- Reset hourly averages
--
   TaHave := 0.0;
  CO2hTot := 0.0;
   RHHave := 0.0;
  FGrHave := 0.0;
  FReHave := 0.0;
  FCOHave := 0.0;
   RTF1_h := 0.0;
   RTF2_h := 0.0;
    RTC_h := 0.0;
  HUse1_h := 0.0;
  HUse2_h := 0.0;
  SCP1h_h := 0.0;
  SCP2h_h := 0.0;
  SCP3h_h := 0.0;
  SCP1c_h := 0.0;
  SCP2c_h := 0.0;
  SCP3c_h := 0.0;
```

```
--
END HOUTPUT;
--
```

A15 Daily Output Procedure

```
--
-- File DOUTPUT.ESL
--
-------------------------------------------------------------------
PROCEDURE DOUTPUT(FILE : Out2,Out4);
-------------------------------------------------------------------
USE GLOBAL;
--
  TABULATE Day,FGrDave,FReDave,FCODave,Wfruit,Wleaf,Wstem,Wroot,
           SLA,LAI;
--
  PRINT Out2,Day:6.1,FGrDave:10.2,FReDave:10.3,FCODave:10.2,
        Wfruit:8.1,Wleaf:8.1,Wstem:8.1,Wroot:8.1,SLA:8.3,LAI:8.3;
--
  TABULATE Day,Light,Temp,AREA,NoFruitA,NoFruitH,WfruitH,
           RTF1_d,RTF2_d,HUse1_d,HUse2_d,RTC_d;
--
 PRINT Out4,Day:6.1,Light:6.1,Temp:6.1,AREA:9.1,NoFruitA:6,NofruitH:6,
       WfruitH:10.1,RTF1_d:10.1,RTF2_d:10.1,HUse1_d:10.1,HUse2_d:10.1,
        RTC_d:10.1,SCP1h_d:10.1,SCP2h_d:10.1,SCP3h_d:10.1,
        SCP1c_d:10.1,SCP2c_d:10.1,SCP3c_d:10.1;
--
-- Reset Daily Variables
--
   RTF1_d := 0.0;
   RTF2_d := 0.0;
  HUse1_d := 0.0;
  HUse2_d := 0.0;
  R  TC_d := 0.0;
  SCP1h_d := 0.0;
  SCP2h_d := 0.0;
  SCP3h_d := 0.0;
  SCP1c_d := 0.0;
  SCP2c_d := 0.0;
  SCP3c_d := 0.0;
```

```
  FGrDave := 0.0;
  FReDave := 0.0;
  FCODave := 0.0;
--
END DOUTPUT;
--
```

A16 Simulation Input File

The simulation input file SIMPUT.NEW is listed below

```
Input data for greenhouse energy mass balance model
Minimum no integration steps,Alogrithm
10 1
Greenhouse Cardinal Dimensions (Length, Width, Gutter Height, Ridge
Height, No of Spans)
33.0 30.0 2.1 3.6 5.0
Offset of Greenhouse minor axis from North South
0.0
Densities (g.m-3) (glazing, glazing bars, structure)
2.7e6 2.7e6 7.8e6
Heat Capacities (J.g-1.K-1) (Glazing, glazing bars, structure)
0.84 0.89 0.47
Volume fractions of quartz in floor and soil layers
0.20 0.20 0.20 0.20 0.20 0.30 0.30 0.30 0.30 0.35 0.35
Volume fractions of clay minerals floor and in soil layers
0.15 0.15 0.15 0.15 0.15 0.30 0.30 0.30 0.30 0.35 0.35
Volume fraction of organic matter in floor and soil layers
0.30 0.30 0.30 0.30 0.30 0.05 0.05 0.05 0.05 0.0 0.0
Volume fraction of water in floor and soil layers
0.35 0.35 0.35 0.35 0.35 0.35 0.30 0.30 0.30 0.25 0.25
Emissivities (Glazing, structure, crop, media, floor)
0.98 0.98 0.98 0.98 0.85
Thickness of glazing, floor and soil layers (m)
0.003 0.01 0.02 0.04 0.08 0.16 0.32
Total Volume of glazing bars, structural elements (m3)
0.47 1.13
Surface area of structure(m2), view factor (Fss), Radiation
Blockage(SBlock)
716.0 0.3 0.15
Number of plants, diameter and height of media bags and sel view
factor (Fmm)
```

```
1386.0 0.2 0.2 0.24
Leaf inclination parameter and Scattering coefficient in PAR and NIR
1.0 0.2 0.8
Control Switches Heaters, Fans, NatVent, Refrig, CO2
TRUE TRUE FALSE FALSE TRUE
Setpoint for CO2 enrichment
350.0
```

A17 Initial Plant Data

The initial plant input file INPUT14.CEL is listed below. The first row is respectively plastochron index of main stem, plastochron index of lateral (1.0 implies not initiated), total leaf area (cm^2), total leaf area one day previously. The remaining column data is the relative cell count along the mid-rib of 30 leaves on the main stem, and 20 leaves on the lateral. A value of 1.0 implies that the leaf has not yet initiated.

```
48   17.2    1.0    389.7   310.1
31.6
27.9
35.2
44.7
41.4
29.7
19.0
12.7
 9.7
 7.4
 5.7
 4.3
 3.2
 2.4
 1.8
 1.4
 1.0
 1.0
 1.0
 1.0
 1.0
 1.0
 1.0
 1.0
 1.0
 1.0
```

```
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
1.0
```

A18 The Light Transmission Model

The Main Light Transmission Program, GST2.F, Ray Tracing Subroutine, RAY.F, Transmission Subroutine, TRANS.F, and Diffuse Light Transmission Program, DIFF2.F remain unchanged from that described in Wells (1992).

The data, however, was changed to the following;

A19 The Direct Light Transmission and Absorption Data

The direct light transmission and absorption input file SKY is listed below. The columns are respectively transmissivity, absorptivity, solar elevation sector, and solar azimuth sector.

```
DATA FOR TRIAL GREENHOUSE IN PALM NTH
   0.768   0.151     1     1
   0.768   0.151     1     2
   0.768   0.151     1     3
```

0.768	0.151	1	4
0.765	0.158	2	1
0.764	0.158	2	2
0.764	0.158	2	3
0.765	0.158	2	4
0.765	0.158	2	5
0.764	0.158	2	6
0.764	0.158	2	7
0.765	0.158	2	8
0.759	0.168	3	1
0.758	0.170	3	2
0.759	0.167	3	3
0.759	0.167	3	4
0.758	0.170	3	5
0.759	0.168	3	6
0.759	0.168	3	7
0.758	0.170	3	8
0.759	0.167	3	9
0.759	0.167	3	10
0.758	0.170	3	11
0.759	0.168	3	12
0.724	0.208	4	1
0.723	0.210	4	2
0.724	0.208	4	3
0.726	0.202	4	4
0.726	0.202	4	5
0.724	0.208	4	6
0.723	0.210	4	7
0.724	0.208	4	8
0.724	0.208	4	9
0.723	0.210	4	10
0.724	0.208	4	11
0.726	0.202	4	12
0.726	0.202	4	13
0.724	0.208	4	14
0.723	0.210	4	15
0.724	0.208	4	16
0.693	0.242	5	1
0.686	0.251	5	2
0.687	0.253	5	3
0.686	0.244	5	4
0.687	0.236	5	5

0.687	0.236	5	6
0.686	0.244	5	7
0.687	0.253	5	8
0.686	0.251	5	9
0.693	0.242	5	10
0.693	0.242	5	11
0.686	0.251	5	12
0.687	0.253	5	13
0.686	0.244	5	14
0.687	0.236	5	15
0.687	0.236	5	16
0.686	0.244	5	17
0.687	0.253	5	18
0.686	0.251	5	19
0.693	0.242	5	20
0.693	0.257	6	1
0.689	0.266	6	2
0.678	0.275	6	3
0.659	0.279	6	4
0.653	0.266	6	5
0.650	0.253	6	6
0.650	0.253	6	7
0.653	0.266	6	8
0.659	0.279	6	9
0.678	0.275	6	10
0.689	0.266	6	11
0.693	0.257	6	12
0.693	0.257	6	13
0.689	0.266	6	14
0.678	0.275	6	15
0.659	0.279	6	16
0.653	0.266	6	17
0.650	0.253	6	18
0.650	0.253	6	19
0.653	0.266	6	20
0.659	0.279	6	21
0.678	0.275	6	22
0.689	0.266	6	23
0.693	0.257	6	24
0.699	0.284	7	1
0.698	0.292	7	2
0.691	0.297	7	3

0.670	0.303	7	4
0.638	0.304	7	5
0.608	0.291	7	6
0.592	0.265	7	7
0.592	0.265	7	8
0.608	0.291	7	9
0.638	0.304	7	10
0.670	0.303	7	11
0.691	0.297	7	12
0.698	0.292	7	13
0.699	0.284	7	14
0.699	0.284	7	15
0.698	0.292	7	16
0.691	0.297	7	17
0.670	0.303	7	18
0.638	0.304	7	19
0.608	0.291	7	20
0.592	0.265	7	21
0.592	0.265	7	22
0.608	0.291	7	23
0.638	0.304	7	24
0.670	0.303	7	25
0.691	0.297	7	26
0.698	0.292	7	27
0.699	0.284	7	28
0.678	0.392	8	1
0.682	0.399	8	2
0.694	0.399	8	3
0.693	0.382	8	4
0.666	0.362	8	5
0.640	0.337	8	6
0.559	0.316	8	7
0.516	0.270	8	8
0.516	0.270	8	9
0.559	0.316	8	10
0.640	0.337	8	11
0.666	0.362	8	12
0.693	0.382	8	13
0.694	0.399	8	14
0.682	0.399	8	15
0.678	0.392	8	16
0.678	0.392	8	17

0.682	0.399	8	18
0.694	0.399	8	19
0.693	0.382	8	20
0.666	0.362	8	21
0.640	0.337	8	22
0.559	0.316	8	23
0.516	0.270	8	24
0.516	0.270	8	25
0.559	0.316	8	26
0.640	0.337	8	27
0.666	0.362	8	28
0.693	0.382	8	29
0.694	0.399	8	30
0.682	0.399	8	31
0.678	0.392	8	32
0.877	0.753	9	1
0.874	0.784	9	2
0.881	0.823	9	3
0.878	0.809	9	4
0.878	0.772	9	5
0.878	0.682	9	6
0.829	0.580	9	7
0.753	0.452	9	8
0.708	0.342	9	9
0.708	0.342	9	10
0.753	0.452	9	11
0.829	0.580	9	12
0.878	0.682	9	13
0.878	0.772	9	14
0.878	0.809	9	15
0.881	0.823	9	16
0.874	0.784	9	17
0.877	0.753	9	18
0.877	0.753	9	19
0.874	0.784	9	20
0.881	0.823	9	21
0.878	0.809	9	22
0.878	0.772	9	23
0.878	0.682	9	24
0.829	0.580	9	25
0.753	0.452	9	26
0.708	0.342	9	27

0.708	0.342	9	28
0.753	0.452	9	29
0.829	0.580	9	30
0.878	0.682	9	31
0.878	0.772	9	32
0.878	0.809	9	33
0.881	0.823	9	34
0.874	0.784	9	35
0.877	0.753	9	36

A20 Diffuse Light Transmission and Absorption Data

The diffuse light transmission and absorption input file DIFF is listed below. The columns are respectively transmissivity and absorptivity.

```
DIFFUSE TRANSMISSIVITY FOR UNIFORM OVERCAST SKY
 0.706  0.250
DIFFUSE TRANSMISSIVITY FOR STANDARD OVERCAST SKY
 0.711  0.233
SOLAR ALT 85.00 AZI 45.00 B=  20.098
 0.741  0.223
SOLAR ALT 75.00 AZI 22.50 B=  17.539
 0.753  0.244
SOLAR ALT 75.00 AZI 67.50 B=  17.539
 0.775  0.248
SOLAR ALT 65.00 AZI 15.00 B=  16.899
 0.747  0.263
SOLAR ALT 65.00 AZI 45.00 B=  16.745
 0.762  0.266
SOLAR ALT 65.00 AZI 75.00 B=  16.899
 0.760  0.262
SOLAR ALT 55.00 AZI 11.25 B=  16.226
 0.739  0.287
SOLAR ALT 55.00 AZI 33.75 B=  16.069
 0.751  0.292
SOLAR ALT 55.00 AZI 56.25 B=  16.069
 0.747  0.287
SOLAR ALT 55.00 AZI 78.75 B=  16.226
 0.743  0.281
SOLAR ALT 45.00 AZI  9.00 B=  15.231
 0.733  0.316
```

```
SOLAR ALT 45.00 AZI 27.00 B=  15.119
 0.747  0.322
SOLAR ALT 45.00 AZI 45.00 B=  15.054
 0.739  0.319
SOLAR ALT 45.00 AZI 63.00 B=  15.119
 0.730  0.310
SOLAR ALT 45.00 AZI 81.00 B=  15.231
 0.724  0.302
SOLAR ALT 35.00 AZI  7.50 B=  13.688
 0.735  0.352
SOLAR ALT 35.00 AZI 22.50 B=  13.619
 0.752  0.360
SOLAR ALT 35.00 AZI 37.50 B=  13.553
 0.744  0.357
SOLAR ALT 35.00 AZI 52.50 B=  13.553
 0.731  0.349
SOLAR ALT 35.00 AZI 67.50 B=  13.619
 0.715  0.335
SOLAR ALT 35.00 AZI 82.50 B=  13.688
 0.704  0.322
SOLAR ALT 25.00 AZI  6.43 B=  11.272
 0.745  0.408
SOLAR ALT 25.00 AZI 19.29 B=  11.234
 0.769  0.420
SOLAR ALT 25.00 AZI 32.14 B=  11.189
 0.764  0.417
SOLAR ALT 25.00 AZI 45.00 B=  11.169
 0.752  0.405
SOLAR ALT 25.00 AZI 57.86 B=  11.189
 0.733  0.386
SOLAR ALT 25.00 AZI 70.71 B=  11.234
 0.707  0.362
SOLAR ALT 25.00 AZI 83.57 B=  11.272
 0.689  0.343
SOLAR ALT 15.00 AZI  5.62 B=   7.479
 0.784  0.509
SOLAR ALT 15.00 AZI 16.88 B=   7.463
 0.820  0.535
SOLAR ALT 15.00 AZI 28.13 B=   7.441
 0.819  0.535
SOLAR ALT 15.00 AZI 39.38 B=   7.425
 0.812  0.522
```

```
SOLAR ALT 15.00 AZI 50.63 B=   7.425
 0.798  0.494
SOLAR ALT 15.00 AZI 61.88 B=   7.441
 0.770  0.454
SOLAR ALT 15.00 AZI 73.13 B=   7.463
 0.737  0.409
SOLAR ALT 15.00 AZI 84.38 B=   7.479
 0.712  0.375
SOLAR ALT  5.00 AZI  5.00 B=   2.170
 0.823  0.587
SOLAR ALT  5.00 AZI 15.00 B=   2.168
 0.909  0.668
SOLAR ALT  5.00 AZI 25.00 B=   2.164
 0.909  0.672
SOLAR ALT  5.00 AZI 35.00 B=   2.161
 0.907  0.663
SOLAR ALT  5.00 AZI 45.00 B=   2.160
 0.898  0.633
SOLAR ALT  5.00 AZI 55.00 B=   2.161
 0.880  0.587
SOLAR ALT  5.00 AZI 65.00 B=   2.164
 0.848  0.528
SOLAR ALT  5.00 AZI 75.00 B=   2.168
 0.810  0.468
SOLAR ALT  5.00 AZI 85.00 B=   2.170
 0.785  0.427
```

A21 KomMet File Change Program

The following program written in PASCAL was used to convert the SUSTEP/CLIMDATA (Leslie and Trethowen, 1977) meteorological data file into Boundary files suitable for reading into *KOMKOM*.

```
Program KomMet (input,output);
{***************************************************************
 * MvH Komkom input File Create v1.0                            *
 * This Program reads in SUSTEP/CLIMDATA data and processes that *
 * data into KOMKOM boundary files                               *
 ***************************************************************}

{ Define variables }
const
   Month : array [1..12] of integer =
           (0,31,59,90,120,151,181,212,243,273,304,334);
   deg : real = 0.01745329252; {=pi/180}
var
   datfile, filein, fileout : text;
   flin, InDat, InFile, OutWK : string[30];
   digit : char;
   chWK, numstr, FileNam : string[5];

   Yri,Moi, Dayi, Hri, Tdbi, RHi,
   IDiri, IDifi, waste : integer;
   Twbi, Tdi, Uoi, cloudi, Sgi, SAlti, SAzii : real;

   WK, WDay, min, WHr, MinLoop, lcount, count, temp, c :integer;
   bflag : boolean;
   esat, ea : real;
   Yr1,Mo1, Day1, Hr1, Tdb1, RH1,
   IDir1, IDif1 :integer;
   Twb1, Td1, Uo1, cloud1, Sg1, SAlt1, SAzi1 : real;

   Yr, Day, Hr, Tdb, Twb, Td, RH, Uo, cloud,
   Sg, SAlt, SAzi, Lat, Long : real;

   NZDT, NZST, LongCor, LCT, EOT, B, LST,
   DFN, HourAngle, SolDec, iAlt, coAlt, siAlt, iA, Hrc, Dayc : real;
   Tground : array [1..12] of real;
   s1, lin : real;

   error : boolean;
```

```
{ Setup files and read in data from .DAT file }
procedure Initialise;
begin
  deg := pi/180;
  bflag := false;
  writeln('Initialising');
  FileNam := 'CHCH1';
  InFile := 'c:\met\'+FileNam+'.MET';
  InDat := 'c:\met\'+FileNam+'.DAT';
  writeln (InDat);
  assign (datfile,InDat);
  reset (datfile);
  for count := 1 to 12 do read(datfile,Tground[count]);
  read(datfile,Lat);
  read(datfile,Long);
  close (datfile);
end {Initialise};

{ Open Files }
procedure OpenFile;
begin
     assign (filein,InFile);
     reset (filein);

end {OpenFile};

{ In case of error close files and report error }
procedure FileError;
     begin
       write (count);
       close (filein);
       close (fileout);
       writeln ('A File Error Has Occurred !');
       writeln (error);
       Halt(1)
end {FileError};

{ File reading function }
Function NumProc(DigitNum: integer): integer;
begin
     count := 1;
     numstr := '';
     repeat
```

```
          read (filein,digit);
          numstr := numstr + digit;
          inc (count);
      until count = DigitNum + 1;
        val(numstr,temp,c);
        NumProc := temp;
 end {NumProc};

 { Function to calculate Wet-Bulb Temperature from Relative Humidity
   and Dry Bulb Temperature }
 function CalcTw(T : real; H : integer): real;
  begin
    esat := 611*exp(17.27*T/(T + 237.3));
    ea := (esat*H)/100;
    CalcTw := T - ((esat - ea)/((esat*44100)/(8.31*SQR(T +
               273.15))+66));
end {CalcTw};

{ Procedure to calculate Solar Azimuth and Solar Altitude from time
  of day and Julian day}
procedure SolCalc;
  begin
    NZDT := Hrc + min/60;
    NZST := NZDT;
    LongCor := 4*(Long - 180);
    LCT := NZST + LongCor/60;
    B := (360*(Dayc - 81))/364;
    EOT := 9.87*sin(2*B*deg) - 7.53*cos(B*deg) - 1.5*sin(B*deg);
    LST := LCT - EOT/60;
    DFN := 12 - LST;
    HourAngle := -DFN*15;
    SolDec := 23.45*sin((360*((284+Dayc)/365))*deg);
    iAlt := sin(Lat*deg)*sin(SolDec*deg) +
             cos(Lat*deg)*cos(SolDec*deg)*cos(HourAngle*deg);
    coAlt := SQRT(1 - SQR(iAlt));
    SAlt := arctan(iAlt/coAlt)/deg;
    iA := (sin(SolDec*deg)-
          sin(Lat*deg)*sin(SAlt*deg))/(cos(Lat*deg)*cos(SAlt*deg));
    siAlt := SQRT(1 - SQR(iA));
    SAzi := arctan(siAlt/iA)/deg;
    if (Sazi<0) then Sazi := Sazi + 180;
    if (sin(HourAngle*deg)>=0) then Sazi := -Sazi;
end {SolCalc};
```

```
  { Linear Regression Function to derive 5-minute steps from 60-minute
    data }
  function LinReg(l1, l2 : real;step : integer): real;
    begin
      lin := step/60;
      LinReg := l1 + (l2 - l1)*lin;
  end {LinReg};

{ Main Loop }
begin
  Initialise;
  OpenFile;
    min    := 0;
    Yri    := NumProc(2);
    Moi    := NumProc(2);
    Dayi   := NumProc(2);
    Dayi   := Month[Moi] + Dayi;
    Hri    := NumProc(2);
    Tdbi   := NumProc(3);
    RHi    := NumProc(3);
    Twbi   := CalcTw(Tdbi,RHi);
    Uoi    := NumProc(3);
    Uoi    := Uoi/2;
    waste  := NumProc(3);
    cloudi := NumProc(2);
    cloudi := cloudi/8;
    IDiri  := NumProc(4);
    IDifi  := NumProc(4);
    Sgi    := IDiri + IDifi;
    Tdi    := Tground[Moi];
    waste  := NumProc(4);

    readln(filein);
    Hrc    := Hri;
    Dayc   := Dayi;

    SolCalc;
    SAlti  := SAlt;
    SAzii  := SAzi;

  while not EOF(filein) do
  begin
    for WK := 11 to 28 do
    begin
```

```
writeln ('Processing Bound',WK);
str(WK,chWK);
OutWK := 'c:\input\bound'+chWK+'.CH';
assign (fileout,OutWK);
rewrite (fileout);
writeln (fileout);

for WDay := 1 to 7 do
begin
  writeln (' Day ',Dayi);

  for WHr := 0 to 23 do
  begin
    writeln (fileout,yri,' ',Dayi,' ',Hri:2,' ',min:2,' ',
             Tdbi,'0 ',Twbi*10:3:0,' ',Tdi*10:3:0,' ',
             Uoi*100:4:0,' ',Sgi:4:0,' ', Salti:4:0,' ',
             SAzii:4:0,' ',cloudi*1000:4:0);
    min    := 0;
    Yr1    := NumProc(2);
    Mo1    := NumProc(2);
    Day1   := NumProc(2);
    Day1   := Month[Mo1] + Day1;
    Hr1    := NumProc(2);
    Tdb1   := NumProc(3);
    RH1    := NumProc(3);
    Twb1   := CalcTw(Tdb1,RH1);
    Uo1    := NumProc(3);
    Uo1    := Uo1/2;
    waste  := NumProc(3);
    cloud1 := NumProc(2);
    cloud1 := cloud1/8;
    IDir1  := NumProc(4);
    IDif1  := NumProc(4);
    Sg1    := IDir1 + IDif1;
    Td1    := Tground[Mo1];
    waste  := NumProc(4);

    readln (filein);
    Hrc   := Hr1;
    Dayc  := Day1;

    SolCalc;
    SAlt1 := SAlt;
    SAzi1 := SAzi;
```

```
        for MinLoop := 1 to 11 do
        begin
          min    := MinLoop*5;
          Tdb    := LinReg(Tdbi,Tdb1,min);
          Twb    := LinReg(Twbi,Twb1,min);
          Uo     := LinReg(Uoi,Uo1,min);
          cloud  := LinReg(cloudi,cloud1,min);
          Sg     := LinReg(Sgi,Sg1,min);
          Td     := LinReg(Tdi,Td1,min);
          Hrc    := Hri;
          Dayc   := Dayi;
          SolCalc;
          writeln (fileout,Yri,' ',Dayi,' ',Hri:2,' ',min:2,' ',
                   round(Tdb*10):3,' ',round(Twb*10):3,' ',
                   round(Td*10):3,' ',round(Uo*100):4,' ',Sg:4:0,
                   ' ',SAlt:4:0,' ',SAzi:4:0,' ',
                   round(cloud*1000):4);
        end {MinLoop};
    min     := 0;
    Moi     := Mo1;
    Dayi    := Day1;
    Hri     := Hr1;
    Tdbi    := Tdb1;
    RHi     := RH1;
    Twbi    := Twb1;
    Uoi     := Uo1;
    cloudi  := cloud1;
    Sgi     := Sg1;
    Tdi     := Td1;
    SAlti   := SAlt1;
    SAzii , := SAzi1;

    end {WHr};

  end {WDay};
  writeln ('Closed File');
  {$I-}
  close (fileout);
  {$I+}
  if IOResult <> 0 then writeln ('File Close ',WK,'failure');

end {WK};
```

```
  end {EOF loop};
close (filein);
end.
```