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

(Cucumis sativus L.)

A thesis
presented in partial fulfilment
of the requirements for the degree
of
Masterate
in
Horticultural Science
at
Massey University

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1996

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 ventilation 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 $\mu\text{l.l}^{-1}$. 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.

ACKNOWLEDGMENTS

I would like to thank my chief supervisor, Dr. Colin Wells for guiding me through the work, and my co-supervisors, Dr. Nevin Amos, Dr. Cliff Studman, and Dr. Gavin Wall of the Department of Agricultural Engineering, Massey University. Although this thesis has been a long time coming to completion my supervisors have supported me all the way.

I would also like to thank the staff in the Department who have always been ready to help me out.

I would also like to mention a word in the memory of Mr. Jack Tyler, thanks for listening and thanks for the advice. May your soul rest in peace, Jack.

Funding for the purchase of a computer and the research carried out came principally from Electricorp Marketing. Other funding was provided by the C. Alma Baker Trust and the Helen E. Akers Trust.

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 $1500 \mu\text{l.l}^{-1}$, 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 $1000 \mu\text{l.l}^{-1}$, 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 resurgence in interest (late 1970's and early 1980's) has been prompted, in part, by the realization of the occurrence of global climatic change due to the global increase in atmospheric carbon dioxide resulting from the greenhouse effect. Keeling (1983) suggested a rate of $1.5 - 2.0 \mu\text{l.l}^{-1}$ 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 ($<100 \text{ mg.l}^{-1}$ 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 led 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).

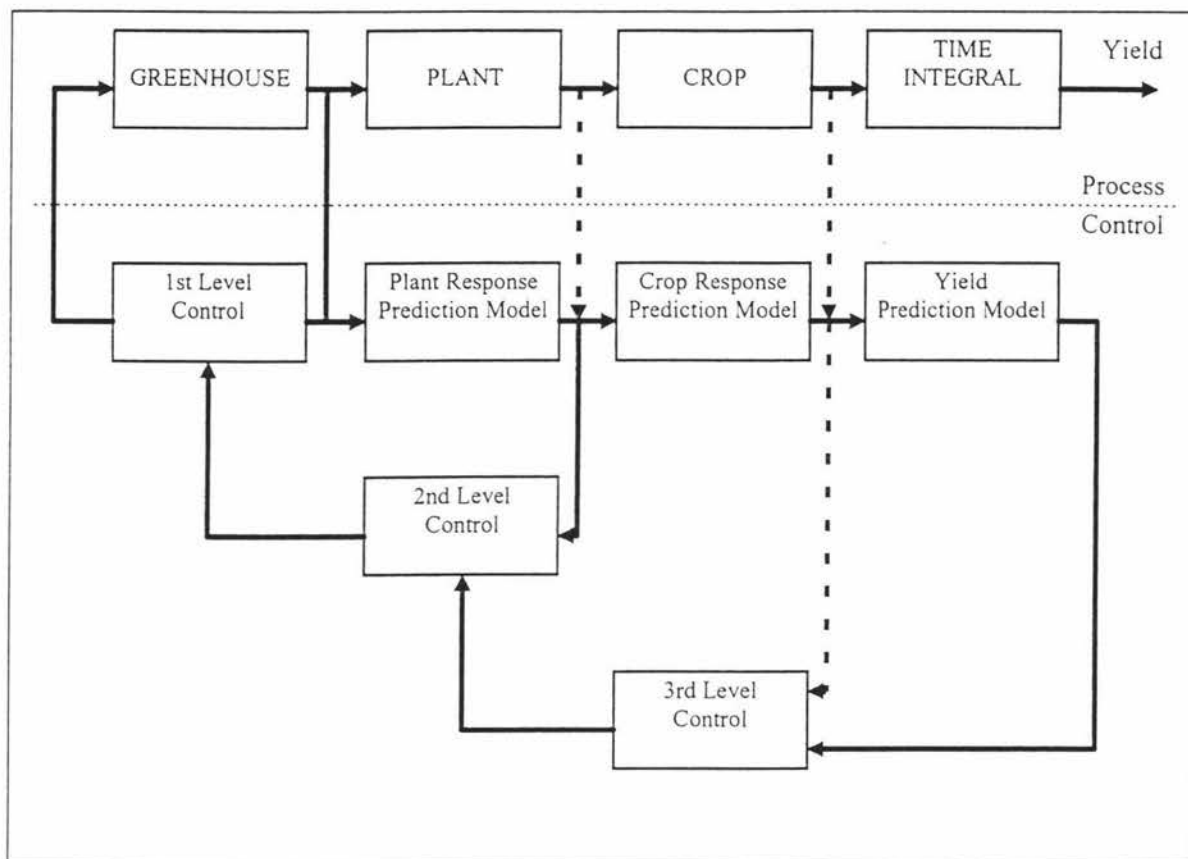


Figure 1.1 Hierarchical model of crop growth (Udink ten Cate, 1983).

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 $350 \mu\text{l.l}^{-1}$ (e.g. 600-1000 $\mu\text{l.l}^{-1}$).

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.