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Practical guidelines for CO_2 enrichment of greenhouse tomato crops

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Summary

Practical information on CO_2 enrichment for greenhouse tomatoes is presented that allows growers to obtain the most cost effect use of CO_2 produced by burning natural gas in boilers or CHP units. The optimum size of heat store is shown to be 20 m^3 per 1000 m^{-2} of greenhouse area and it is not strongly dependent on gas or tomato prices. When a heat store is not used, the benefits of using minimum heating pipe temperatures were determined and shown to increase grower income by £5-7 m^{-2} depending on gas price. Profiles of gas burn rates through average days of the summer months that maximise the cost-effective use of CO_2 are presented. These show that the highest burn rates occur near noon in early spring and late autumn, but are strongly biased towards the morning in summer. The profiles are not significantly affected by gas or tomato prices. In practice the constant rate at which gas should burnt in a boiler for CO_2 production, is approximately 30 m^3 per 1000 m^{-2} of greenhouse area.

Computer programs have been created for CO_2 derived from boilers and from CHP units. These enable users to identify the economically optimal values of gas burn rate, and CO_2 concentration for values of solar radiation, ventilator opening and wind speed provided by greenhouse environmental controllers. The programs also enable the gas burn rate to be determined that will fill a heat store by the end of the CO_2 enrichment period. These programs can be operated on a compatible personal computer operating an Excel® spreadsheet.

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Contents

Introduction

One of the objectives of greenhouse environmental control is to provide a greenhouse environment that enables profitable crop production. Controlling the environment incurs a cost, and a necessary step towards increasing profit is to maximise the margin between crop value and the cost of creating the environment. In the case of CO_2 enrichment which tomato growers now routinely use to increase photosynthesis and raise crop productivity, the factors that influence the economics of enrichment are the effects of CO_2 on crop production and crop value, and the amount of CO_2 used and its price.

The main sources of CO_2 are the flue gases of boilers burning natural gas and the exhaust gases of natural gas powered internal combustion engines that drive combined heat and power (CHP) units. Both systems produce heat and CO_2 at the same time, and as CO_2 is required during the day while heat is mainly needed at night, the heat produced is stored as hot water until required. As a consequence the amount of CO_2 that can be produced during a day is limited by the capacity of the heat store and the day time heat requirement of the greenhouse. This raises questions over the most economic size of heat store, how the CO_2 supply rate should vary through the day, and the maximum rate at which CO_2 should be generated. Carbon dioxide enrichment can also be controlled using a CO_2 controller to maintain the CO_2 concentration at a CO_2 set point. Information is then required on the how the concentration should be varied in relation to solar radiation, ventilator opening and wind speed in order to maximise the financial margin between crop value and gas cost.

This Guide provide such information to help growers make the best use of CO_2 enrichment. The information presented is based on research on the optimal control of CO_2 enrichment for greenhouse tomatoes commissioned by MAFF and undertaken at Silsoe Research Institute and Horticulture Research International.

2 Optimum size of heat store

When natural gas is burnt during the day to provide CO_2 for enrichment, the heat produced is often stored as hot water in a heat store. The capacity of the store places an upper limit on the amount of hot water that can be stored and thus on the amount of gas that can be burnt and consequently on the quantity of CO_2 produced during a day. Increasing the store capacity increases the amount of CO_2 that can be generated, however, the heat must be utilised before more can be stored.

The effect of heat store capacity on the financial margin of crop value minus gas cost is shown in Figures 2.1 and 2.2 for a range of natural gas and tomato prices.

The optimum capacity of the heat store is primarily determined by the heat requirement of the greenhouse and it is not influenced markedly by the prices of natural gas or tomatoes. Consequently changing the greenhouse heating temperature regime will affect the optimum size of store. The optimum size will be higher if the greenhouse heat consumption is increased and vice-versa. This information relates to a boiler and heat store, however, the same conclusions will apply to a CHP system.

The optimum size of heat store for the temperatures currently used in tomato production is 20 m^3 per 1000 m^2 of greenhouse area.

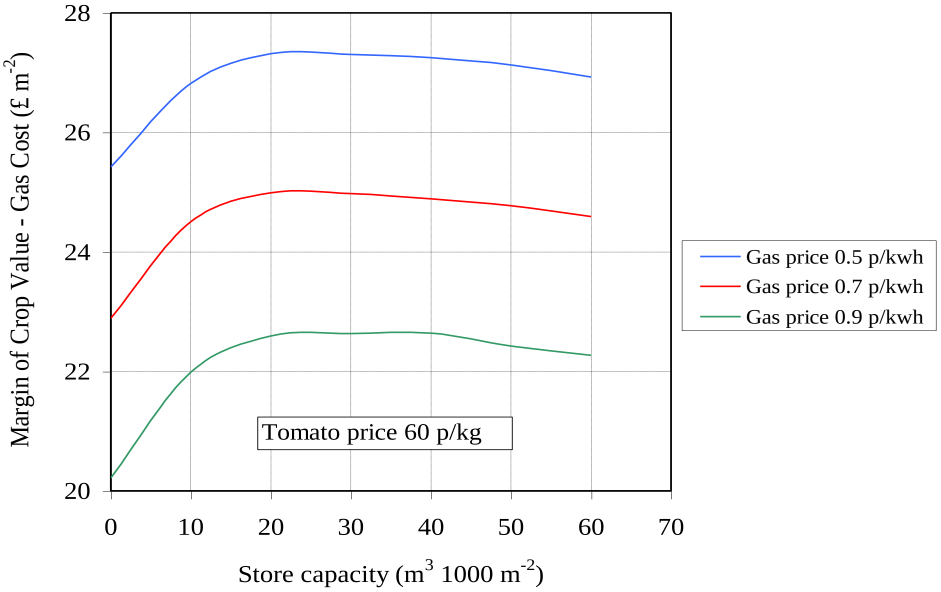

Fig 2.1 Optimum size of heat store - influence of natural gas price

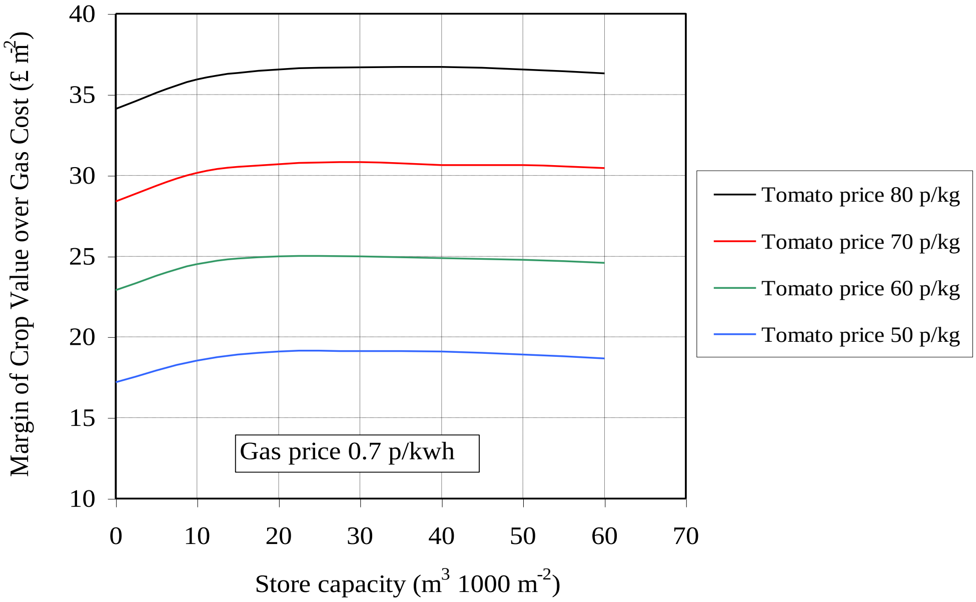

Fig 2.2 Optimum size of heat store - influence of tomato price

3 Effect of minimum heating pipe temperature on CO_2 economy

When a heat store is not used, CO_2 can be produced during the day in summer by operating the boiler and maintaining a minimum pipe temperature to dissipate the heat generated. The effect of a minimum pipe temperature on the economics of CO_2 enrichment is shown in Fig3.1.

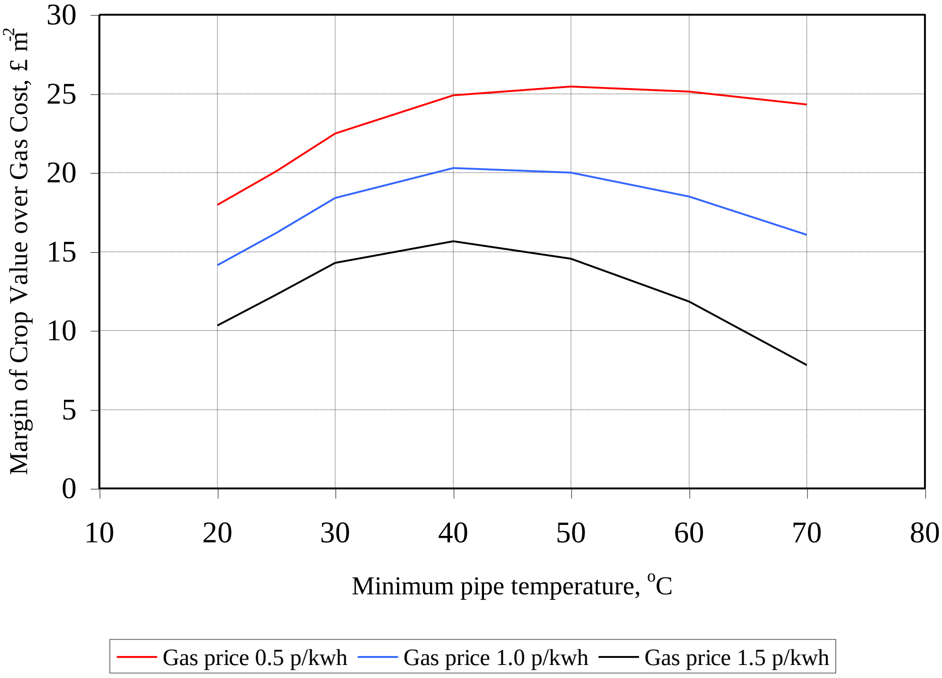

Fig 3.1 Boiler generated CO_2 - influence of minimum pipe temperature

Increasing the pipe temperature enables more CO_2 to be produced, but also increases the heat dissipated in the greenhouse which increases the ventilation requirement. At high pipe temperatures the cost of the additional gas burnt exceeds the value of the increased crop produced because of the high CO_2 loss by ventilation.

The influence on CO_2 economy is only one of the factors that should be considered when selecting a minimum heating pipe temperature. Other factors which are influenced by minimum pipe temperature include disease suppression, stimulation of plant transpiration, maintaining plant and fruit temperatures, creating air movement and providing a more buoyant atmosphere.

4. Optimal daily natural gas burn profile for CO_2 enrichment

4.1 Optimal values from April to September

The optimal rate of CO_2 supply to a greenhouse for enrichment represents an economic balance between the marginal increase in crop value from the higher CO_2 concentration and the marginal increase in the CO_2 production cost. Crop value is related strongly to solar radiation, while CO_2 cost is strongly linked to greenhouse ventilation rate.

The variation of the economically optimum rate of burning natural gas in a boiler to produce CO_2 through an average day for the months April to September is shown in Figures 4.1 to 4.6.

These optimal gas burn rate values were determined for the following conditions:

Gas price	0.75 p kwh^{-1}
Tomato price	60 p kg^{-1}
Maximum rate of gas burning	40 m^3 h^{-1} 1000 m^{-2}
Heat store capacity	20 m^3 1000 m^{-2}
Minimum pipe temperature	40 ^{o}C

In general the optimum gas burn rate and the optimum CO_2 concentration are highest in the morning and reduce through the afternoon. This is a result of the higher ventilation rates in the afternoons compared to the mornings.

These calculations were made in a way that ensured the heat store became full when the gas burn rate reached zero at the end of the day period. In practice this is not always achieved and reductions in the burn rate become necessary when the heat store is nearing full capacity. Ensuring that these take place as late as possible during the afternoon will give the highest economic benefit.

A control strategy for boilers used for CO_2 production in which the gas burn rate is adjusted can be determined from Figures 4.1 to 4.6. The aim should be to select the times of change and the burn rate settings to match the optimal burn rate.

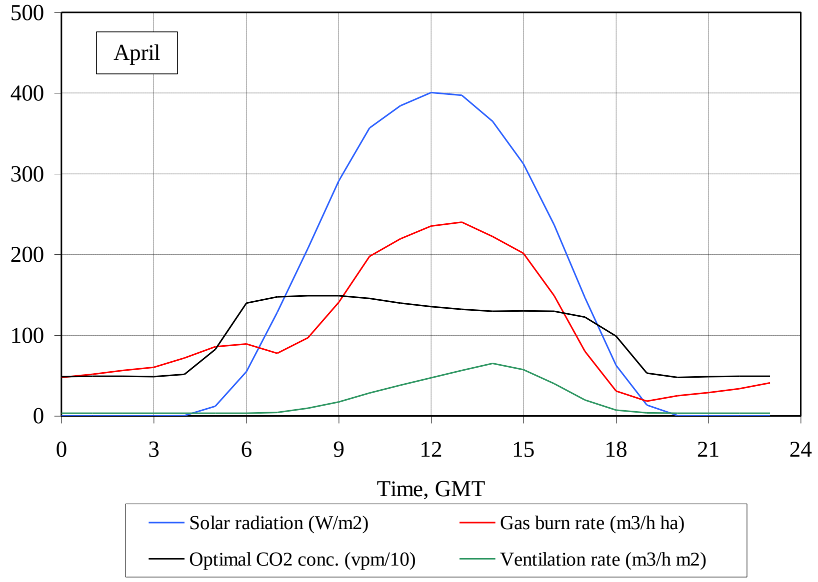

Fig. 4.1 Optimal CO_2 concentration and gas burn rate during April

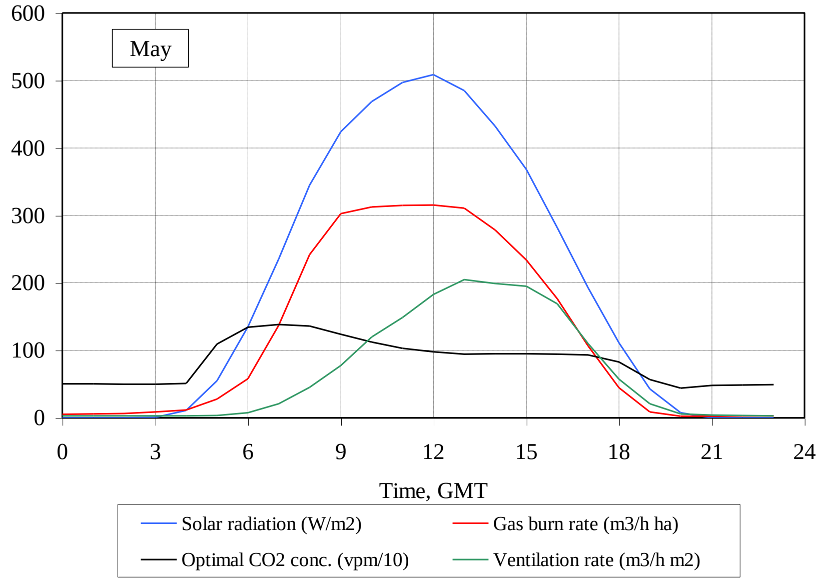

Fig 4.2 Optimal CO_2 concentration and gas burn rate during May

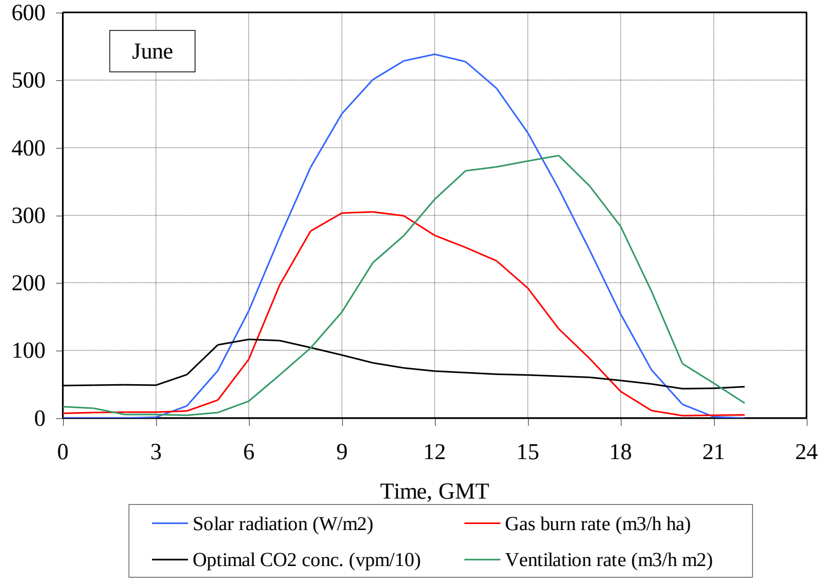

Fig 4.3 Optimal CO_2 concentration and gas burn rate during June

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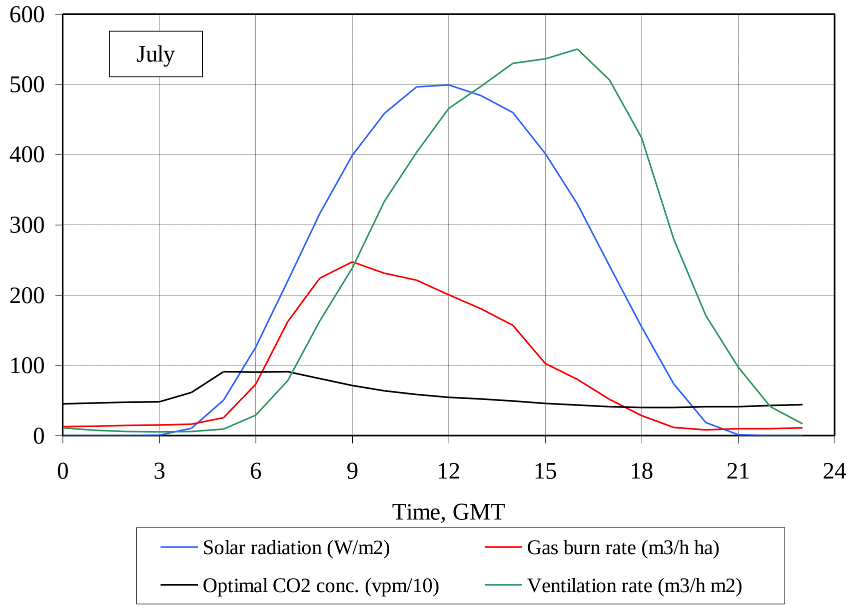

Fig 4.4 Optimal CO_2 concentration and gas burn rate during July

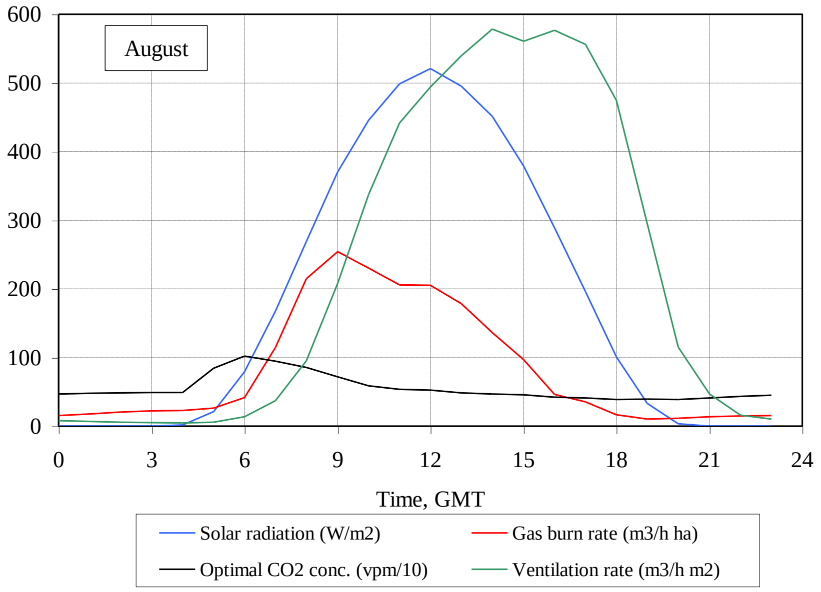

Fig 4.5 Optimal CO_2 concentration and gas burn rate during August

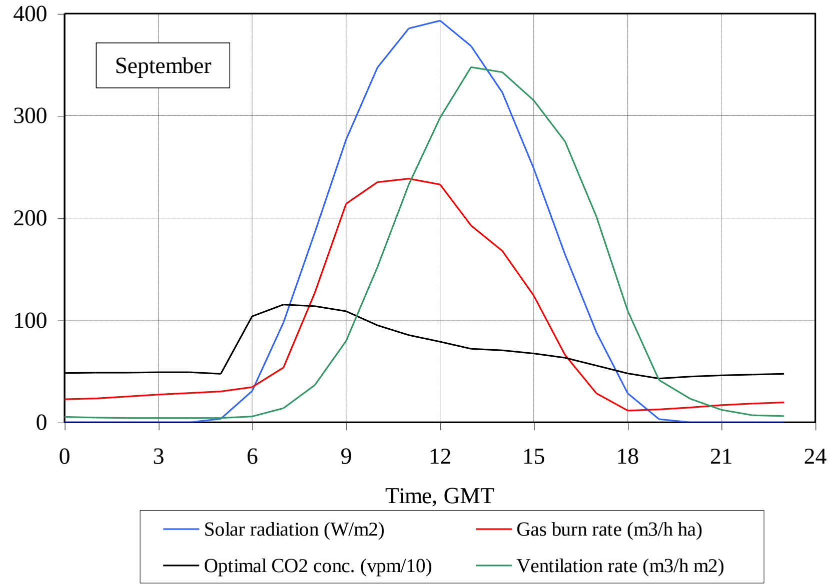

Fig 4.6 Optimal CO_2 concentration and gas burn rate during September

4.2 Influence of gas and tomato prices

The optimal rates of gas burning are influenced by gas price and by the value of the tomato crop.

The effect of gas price is shown in Figure 4.7 which was obtained using weather data for June 1972. As the price is increased the optimal burn rate decreases. However, the biggest effect is apparent in the afternoon, when ventilation is highest. Therefore a consequence of an increase in gas price is that increased emphasis should be placed on morning enrichment.

The effect of tomato price is shown in Figure 4.8. The result is the converse of that for an increase in gas price, increasing tomato prices would justify greater use of CO_2. The effect in this case is to justify increased enrichment during the afternoon.

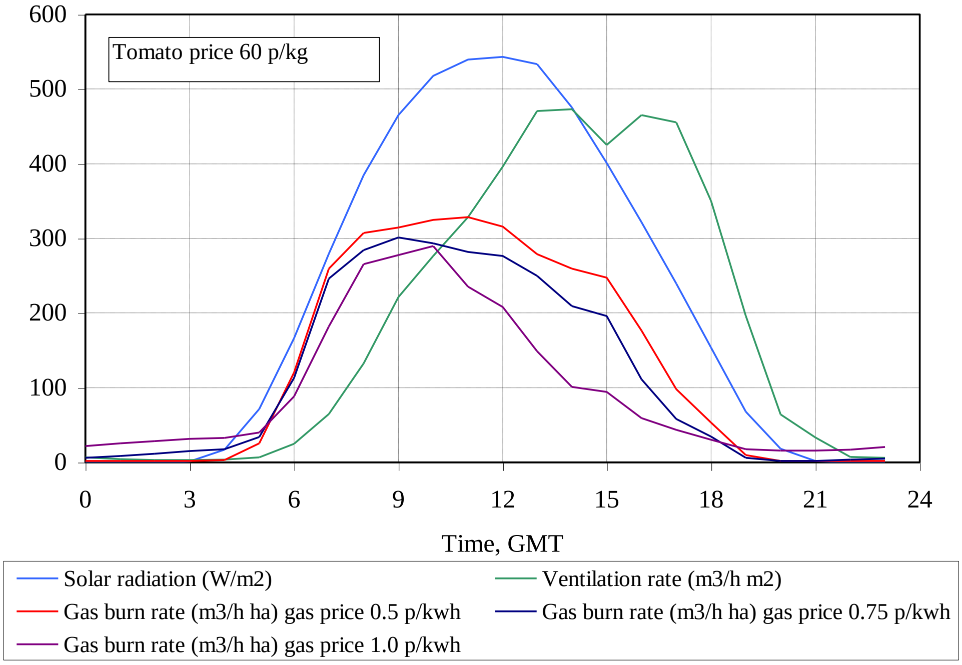

Fig. 4.7 Influence of gas price on optimal gas burn rate in a boiler (June 1972)

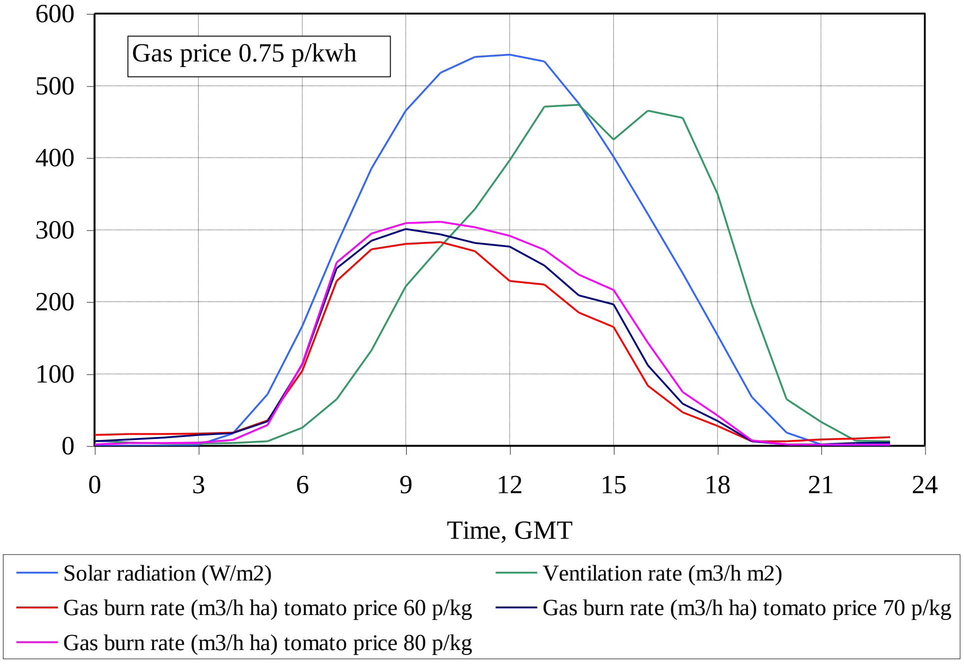

Fig. 4.8 Influence of tomato price on optimal gas burn rate in a boiler (June 1972)

4.3 Rate of natural gas burning for CO_2 production

In summer, when greenhouse ventilators are open, the CO_2 concentration in the greenhouse depends on the rate of CO_2 supply and the rate of loss through the ventilators. Increasing the rate of CO_2 supply will result in higher concentrations and thus increase crop yield, however, this will also increase the CO_2 lost by ventilation.

The influence of the rate at which natural gas can be burnt in a boiler to provide CO_2 is shown in Figure 4.9.

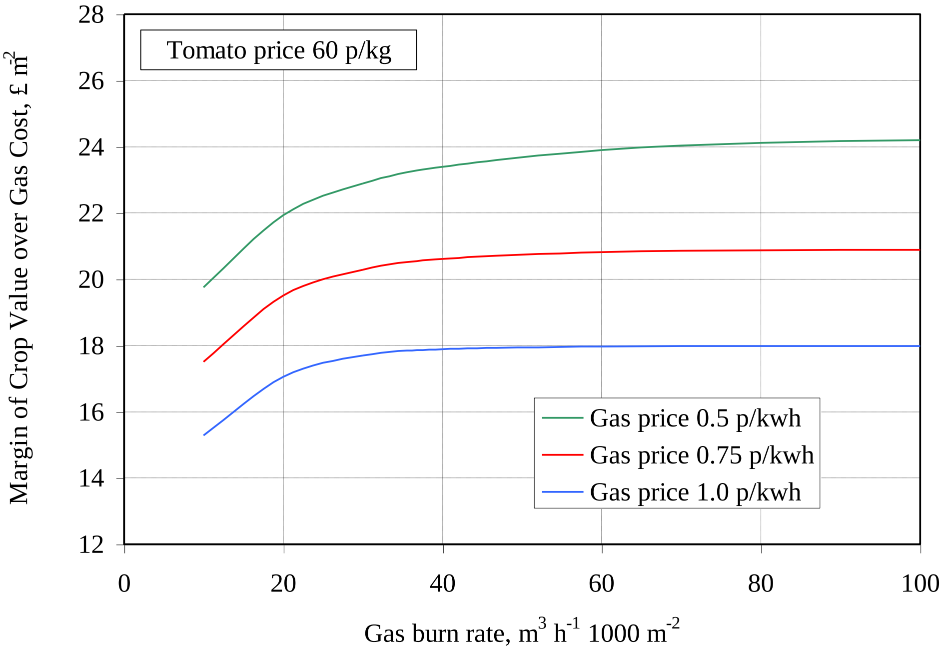

Fig 4.9 Influence of gas burn rate in a boiler on CO_2 economy

The highest rate of gas burning when averaged over a month (May) is approximately 32 m^3 h^{-1} 1000 m^{-2}. Compared to this value, the additional economic benefit of using higher gas burn rates is £1 m^{-2} at a gas price of 0.5 p kwh^{-1} and £0.5 m^{-2} for a gas price of 1 p kwh^{-1}.

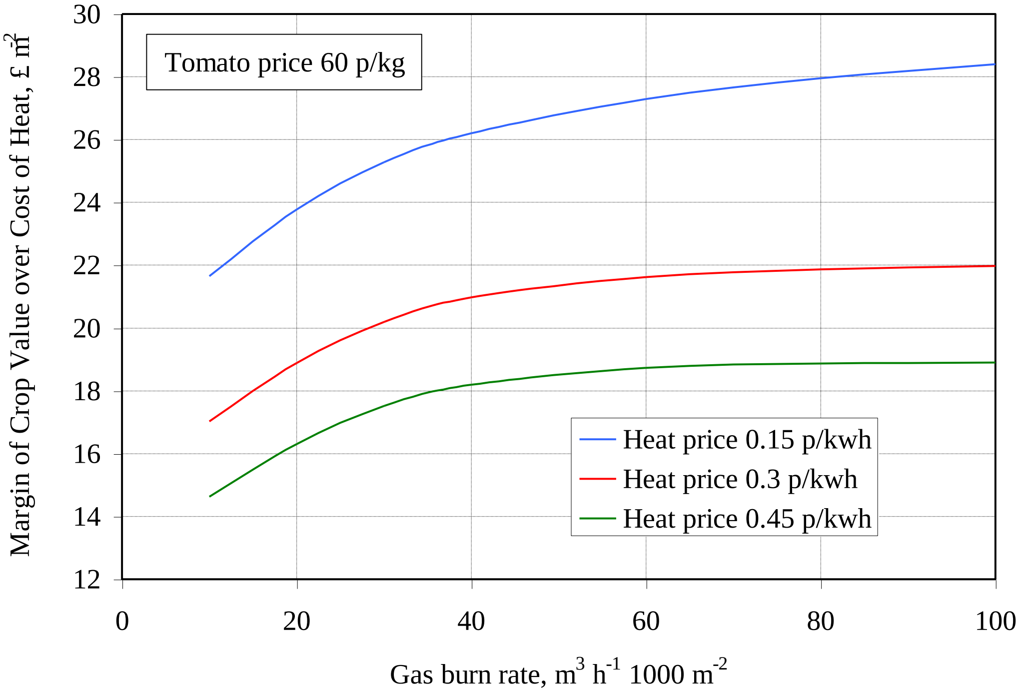

Fig 4.10 Influence of gas burn rate in a CHP unit on CO_2 economy

It should be noted that these burn rates were calculated on the basis that the CO_2 production rate could be modulated between zero and maximum output to give maximum economic performance. This is not possible at present in commercial horticulture, however, it could be implemented by the optimal CO_2 controller developed at the Silsoe Research Institute.

5. The CO_2 Optimiser Program for estimating optimal CO_2 conditions

The information in the preceding section enables CO_2 enrichment to be implemented at near optimal conditions averaged over a month period. Variations between individual days cannot be taken into account, i.e. a day with low solar radiation will have the same CO_2 supply as one with high radiation. The CO_2 Optimiser Program enables a number of parameters related to the economically optimum use of CO_2 concentration to be estimated. The Program enables their dependence on solar radiation, wind speed and ventilator opening, and the cost of natural gas and tomato price to be taken into account.

The following information is required by the program:

Basic values for the greenhouse:

Area (plan area of house)	m^2
Roof angle (usually in the range 20-26)	degrees
Total area of ventilators (measured in the plane of the roof slopes)	m^2
Length of an individual ventilator	m
Depth (width) of individual ventilator	m
Maximum angle of ventilator opening (typically 44 for a Venlo)	degrees

Basic values for the heat store:

*Volume of heat store	m^3 per 1000 m^2 greenhouse
*Maximum temperature of heat store	^oC

Prices:

Gas price (heat price for CHP systems)	pence per kwh
Tomato price	pence per kg

Environmental variables:

Solar radiation	W m^{-2}
Leeward ventilator opening	%
Windward ventilator opening	%
Wind speed	m s^{-1}
Internal temperature	^oC
External temperature	^oC
*Current heat store temperature	^oC
*Time remaining for CO_2 enrichment	hours

Based on the values provided for the above quantities, the program estimates the following:

Optimum CO_2 concentration (${}^{+}$100 vpm)	v.p.m., i.e.volumes per million
Optimal gas burn rate (${}^{+}$2 m^3 / hour 1000 m^2)	m^3 / hour 1000 m^2
Financial margin creation rate i.e. the rate at which the monetary value of the crop less the expenditure on natural gas (or heat from CHP units) is increasing (${}^{+}$0.4 £ / hour 1000 m^2)	£ / hour 1000 m^2
The rate at which gas should be burnt from now until the end of the CO_2 enrichment period so the heat store is then full (${}^{+}$0.5 m^3 / hour 1000 m^2)	m^3 / hour 1000 m^2

Values marked * are only used to estimate the rate at which gas should be burnt to fill the heat store at the end of the enrichment period. They have no influence on any other values.

Values marked ${}^{+}$ represent the level of uncertainty in the estimated values.

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5.1 Operating CO_2 Optimiser

5.1.1 Installation

Copy the CO_2 Optimiser program into the required directory.

5.1.2 Operation

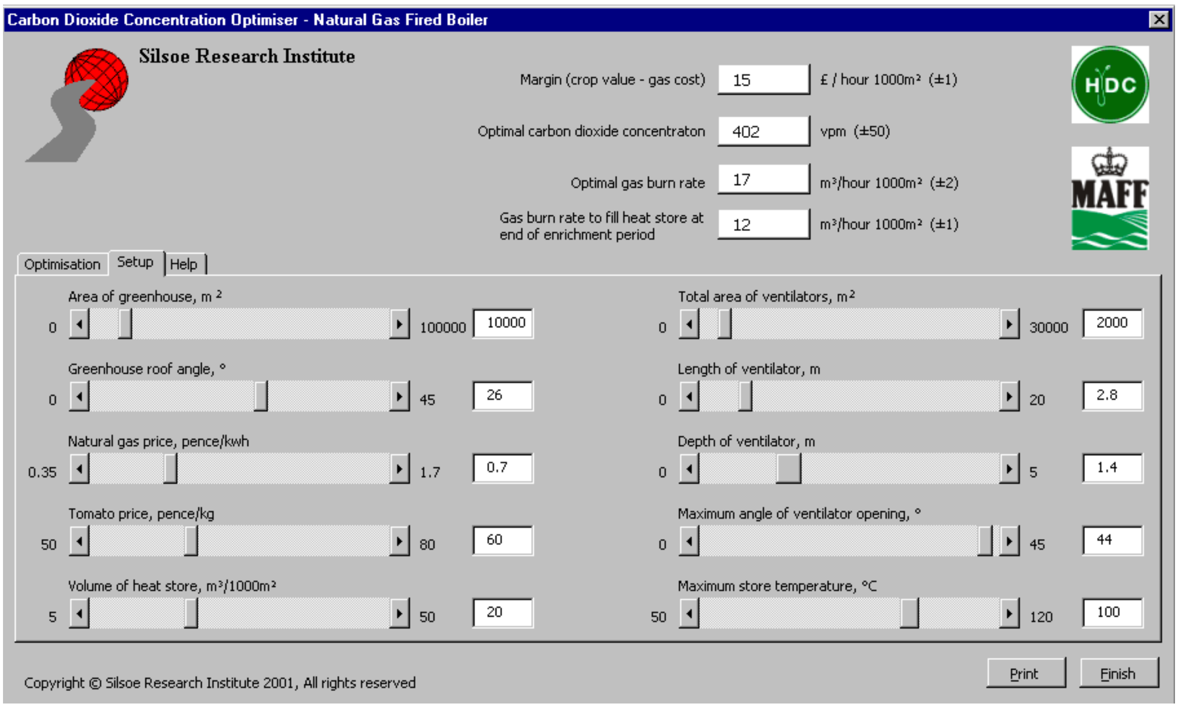
Open either Microsoft Excel of Windows Explorer.

Find the directory containing the CO_2 Optimiser program.

Double click on the CO_2 Optimiser filename.

Double click on the “Enable Macros” button when displayed

Use the tab to select the **Setup** screen (Fig. 5.1) and adjust the values displayed on lower part of the screen by dragging the sliders or clicking on the buttons at the end of the slider boxes.



Carbon Dioxide Concentration Optimiser - Natural Gas Fired Boiler

Margin (crop value - gas cost) 15 £ / hour $1000m^2$ (±1)

Optimal carbon dioxide concentraton 402 vpm (±50)

Optimal gas burn rate 17 m^3/hour $1000m^2$ (±2)

Gas burn rate to fill heat store at end of enrichment period 12 m^3/hour $1000m^2$ (±1)

Area of greenhouse, m^2 0 100000 10000

Greenhouse roof angle, ° 0 45 26

Natural gas price, pence/kwh 0.35 1.7 0.7

Tomato price, pence/kg 50 80 60

Volume of heat store, $m^3/1000m^2$ 5 50 20

Total area of ventilators, m^2 0 30000 2000

Length of ventilator, m 0 20 2.8

Depth of ventilator, m 0 5 1.4

Maximum angle of ventilator opening, ° 0 45 44

Maximum store temperature, °C 50 120 100

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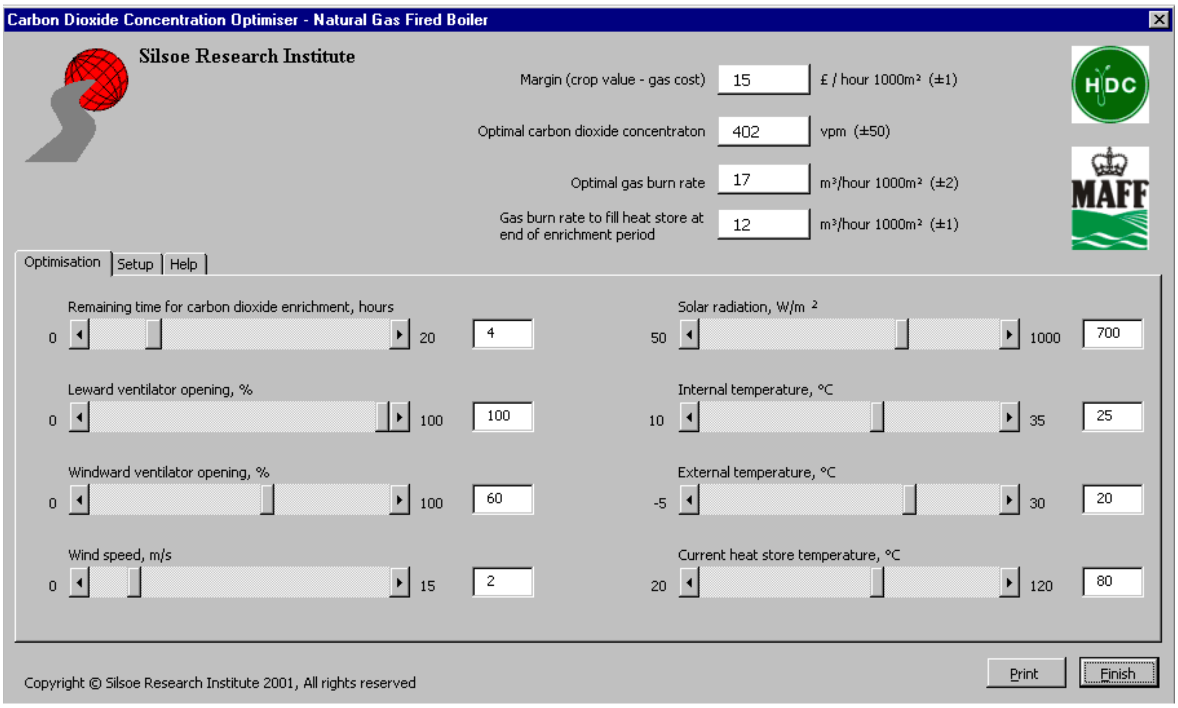
Fig. 5.1 Display when Setup tab selected

Use the tab to select the **Optimisation** (Fig. 2) screen and adjust the values displayed on lower part of the screen by dragging the sliders or clicking on the buttons at the end of the slider boxes.



Margin (crop value - gas cost) 15 £ / hour 1000m² (±1)

Optimal carbon dioxide concentraton 402 vpm (±50)

Optimal gas burn rate 17 m³/hour 1000m² (±2)

Gas burn rate to fill heat store at end of enrichment period 12 m³/hour 1000m² (±1)

Remaining time for carbon dioxide enrichment, hours	0	20	4
Leward ventilator opening, %	0	100	100
Windward ventilator opening, %	0	100	60
Wind speed, m/s	0	15	2
Solar radiation, W/m 2	50	1000	700
Internal temperature, °C	10	35	25
External temperature, °C	-5	30	20
Current heat store temperature, °C	20	120	80

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Fig. 5.2 Display when optimisation tab selected

The estimated values are displayed on the upper part of both the **Setup** and **Optimisation** screens.

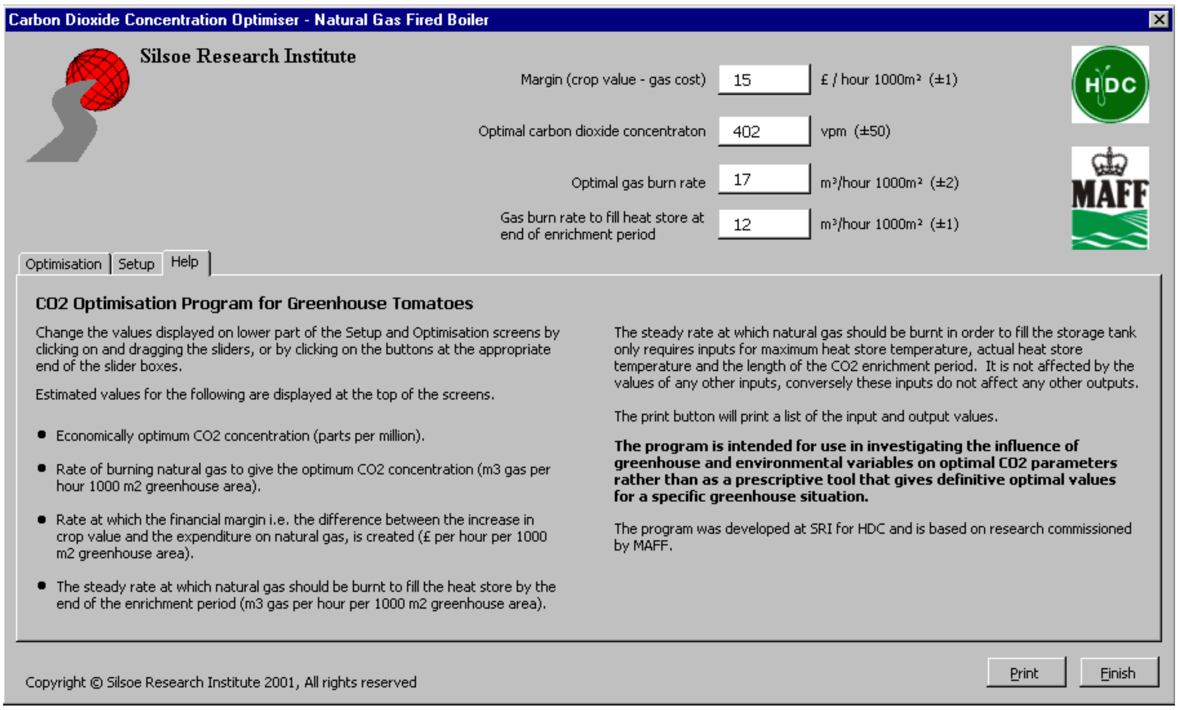
The values can be changed in any order on the **Setup** and **Optimisation** screens.

Use the **Help** tab to obtain explanations (Fig 5.3).

The **Print** button will print a list of the input and output values.

The **Finish** or **X** buttons will save the program with the current values and close the Excel spreadsheet.

The program is intended for use in investigating the influence of greenhouse and environmental variables on optimal CO_2 parameters rather than as a prescriptive tool that gives definitive optimal values for a specific greenhouse situation.



Margin (crop value - gas cost) 15 £ / hour 1000m² (±1)

Optimal carbon dioxide concentraton 402 vpm (±50)

Optimal gas burn rate 17 m³/hour 1000m² (±2)

Gas burn rate to fill heat store at end of enrichment period 12 m³/hour 1000m² (±1)

CO2 Optimisation Program for Greenhouse Tomatoes

Change the values displayed on lower part of the Setup and Optimisation screens by clicking on and dragging the sliders, or by clicking on the buttons at the appropriate end of the slider boxes.

Estimated values for the following are displayed at the top of the screens.

- Economically optimum CO2 concentration (parts per million).
- Rate of burning natural gas to give the optimum CO2 concentration (m3 gas per hour 1000 m2 greenhouse area).
- Rate at which the financial margin i.e. the difference between the increase in crop value and the expenditure on natural gas, is created (£ per hour per 1000 m2 greenhouse area).
- The steady rate at which natural gas should be burnt to fill the heat store by the end of the enrichment period (m3 gas per hour per 1000 m2 greenhouse area).

The steady rate at which natural gas should be burnt in order to fill the storage tank only requires inputs for maximum heat store temperature, actual heat store temperature and the length of the CO2 enrichment period. It is not affected by the values of any other inputs, conversely these inputs do not affect any other outputs.

The print button will print a list of the input and output values.

The program is intended for use in investigating the influence of greenhouse and environmental variables on optimal CO2 parameters rather than as a prescriptive tool that gives definitive optimal values for a specific greenhouse situation.

The program was developed at SRI for HDC and is based on research commissioned by MAFF.

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Fig 5.3 Display when Help tab selected.

6. Values of parameters used in the analysis

The following values have been used in calculating the results presented except in Sections 2 and 3 where the influences of heat store size and minimum heating pipe temperature on the economy of CO_2 enrichment were determined.

Leaf area index of the crop	3.6
Minimum heating pipe temperature	40 °C
Boiler thermal efficiency	85 %
CHP system thermal efficiency	42.5%
Calorific value of natural gas	38.3 MJ m^{-3}
CO_2 production	1.72 kg per m^{-3} natural gas burnt
Cost of heat store (includes electricity for pumps and depreciation)	28 p m^{-2} per year

Meteorological data - air temperature, solar radiation and wind speeds recorded at RAF Cardington, Bedforshire 1972 - 1975.

7 Method of analysis

7.1 Introduction

The optimal CO_2 set point depends on several influences: the effect of CO_2 on the photosynthetic assimilation rate, the partitioning to fruit and to vegetative structure, the distribution of photosynthate in subsequent harvests, and the price of fruit at those harvests, as well as the amount of CO_2 used, the greenhouse ventilation rate and the price of the CO_2. The effects of these individual factors were described by mathematical models that were combined to produce a calculation procedure to determine the optimum CO_2 concentration (Aikman 1996).

Physiological models used were used to estimate canopy photosynthesis, photosynthate partitioning to tomato fruit and fruit growth from anthesis to harvest. Physical models were used to estimate glasshouse air temperature, the heat requirement and air exchange rates from leakage and ventilation.

The optimisation is based on maximising the financial margin between the crop value and the cost of the CO_2. As CO_2 is commonly obtained from the flue gases of boilers burning natural gas which are also used for heating, the gas cost includes the gas used for both heating and CO_2 enrichment.

7.2 Physiological models

The canopy photosyntheis model used is that of Acock *et al*. (1978) as modified by Nederhoff (1994). The relationship between photosynthate production and the harvested fruit was determined by assuming that photosynthate was distributed between fruits of different ages according to their demands which are proportional to their potential growth rates (Aikman 1996). The distribution of photosynthate over subsequent harvests was determined using a tomato growth rate model, driven by greenhouse temperature, and the relative growth rates of the fruits. The market price of fruit was expressed as the value per kg of the carbon in the fruit allowing for the water content (*circa* 94 %) and ratio of carbon to dry matter (*circa* 30 %). The model of tomato fruit price was combined with a model of the distribution of delay between photosynthesis and harvest to give a weighted average of the anticipated value per kg of carbon assimilated (Aikman 1996).

7.3 Physical models

The greenhouse energy balance model used to estimate greenhouse temperature was that of Fernandez and Bailey (1993) which was extended to include the heat supplied by the heating pipes. The ventilation model was derived from measurements made in a 38,700 m^2 Venlo glasshouse containing tomatoes at the Braydon Farm site of Cantelo Nurseries Ltd (Bailey 1999). The leakage model was developed by Fernandez and Bailey (1993).

7.4 Net income model

The net income was calculated as the difference between the anticipated value of fruit and the running costs corresponding to CO_2 and heating. An allowance of 28 p m^{-2} of greenhouse, was made for the depreciation and operating costs of the heat store.

7.5 Optimisation procedure

The models were used with an optimisation procedure to obtain the optimal CO_2 concentrations and natural gas combustion rates over one hour periods throughout the year, using weather data recorded at RAF Cardington, Bedfordshire for 1972 to 1975. Full details of the models used and the calculation procedure are given in Chalabi *et al*. (2001a) and Chalabi *et al*. (2001b).

Acknowledgements

The program was developed at SRI for HDC It is based on research on the optimal control of CO_2 enrichment for greenhouse tomatoes commissioned by MAFF and undertaken at Silsoe Research Institute and Horticulture Research International.

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