FINAL REPORT

HDC PROJECT PC 25

NO_x POLLUTION IN GREENHOUSES USING BOILER FLUE-GASES FOR SUMMER CO_2 ENRICHMENT

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HRI LITTLEHAMPTON

NO_x POLLUTION IN GREENHOUSES USING BOILER FLUE-GASES FOR SUMMER CO_2 ENRICHMENT

Contract (No. PC25) for Horticultural Development Council

Final Report

Summary

* Ducting flue-gases into greenhouse atmospheres from centralized, gas-fired boilers has become an increasingly attractive technique for practising summer CO_2 enrichment on long-season crops of tomatoes and sweet peppers.

* The atmospheric concentrations of nitrogen oxides (generic term 'NO_x') such as nitric oxide (NO) and nitrogen dioxide (NO_2) were monitored for nine weeks from early August to mid October 1990) and for seven weeks (from early May to late June 1991) at Runcton (long-season tomatoes) and Angmering (long-season sweet peppers) nurseries of John Hall Nurseries Ltd and Van Heyningen Bros Ltd respectively.

* In general, the level of NO_x pollution rose and fell concomitantly with the rise and fall in the CO_2 concentration.

* The level of NO_x pollution was similar at both nurseries and varied directly from a mean value of 0.06 to 0.14 vpm when the greenhouse CO_2 concentration was maintained within 350-500 vpm, i.e. the normal range of CO_2 concentrations used for summer CO_2 enrichment of long-season crops of tomatoes and sweet peppers.

* Regression analysis was used to show that within the range 350-500 vpm CO_2, the NO_x level increased linearly by 0.000553 vpm and 0.000506 vpm for each vpm increase in mean CO_2 at the Runcton and Angmering nurseries respectively.

* The ratio of the concentrations of $NO:NO_2$ averaged 4.7:1 and 2.5:1 at the Runcton and Angmering nurseries respectively.

* The risks of injury to long-season crops of tomatoes and sweet peppers when flue-gases from gas-fired boilers are used for summer CO_2 enrichment are probably slight provided that the CO_2 concentration is kept within the recommended range of 350-500 vpm.

* Ventilation of greenhouses influences the levels of CO_2 and NO_x present in the atmosphere when boiler flue-gases are used for summer CO_2 enrichment. NO_x levels of 0.5 vpm and above were recorded at both the Runcton and Angmering nurseries on those occasions (usually dull weather) when low rates of ventilation contributed to a 4- to 5-fold increase in atmospheric CO_2 concentration. Levels of NO_x pollution above 0.5 vpm may be injurious to the foliage if the exposure is too prolonged in dull light.

Introduction

Plentiful supplies of natural gas have encouraged growers to use this premium fuel for greenhouse heating. Natural gas burns cleanly and CO_2 enrichment can be readily achieved by extracting a proportion of the combustion gases, diluting these with air and expelling the mixture into the greenhouse atmosphere through a ground-level network of inflated tubes. Holes are drilled every 0.2 m and the tubes are normally positioned along the midlines of every second or fourth row of plants. The use of flue-gases from centralized, gas-fired boilers for CO_2 enrichment is the preferred method in Holland and accounts for over 54 hectares (133 acres) of protected cropping in Britain.

Systems have recently been developed which allow the heat produced during combustion to be retained in hot-water, buffer tanks. This makes the technique especially attractive for summer CO_2 enrichment because the heat stored during the daytime can be pumped into the greenhouse at night without recourse to further use of the boiler. However, there is a risk that the presence of nitrogen oxides (generic term 'NO_x') such as nitric oxide (NO) and nitrogen dioxide (NO_2) in the flue-gases may adversely affect the productivity of sensitive crops like sweet peppers and tomatoes.

Measurements made in a large block of Venlo glass at a local tomato nursery near Littlehampton have shown that the NO_x levels frequently exceed 0.5 vpm for eight hours or more during winter when flue-gases are used for threefold CO_2 enrichment (*Grower*, February 8, 1990). At present, there is a dearth of information about the levels of NO_x pollution under conditions of summer CO_2 enrichment. Indeed, it is possible that growers may not realize the **full** potential of summer CO_2 with NO_x-sensitive crops like sweet peppers and tomatoes when using boiler flue-gases for enrichment purposes.The present studies were therefore commissioned to establish the NO_x levels present in greenhouse atmospheres when flue-gases from centralized, gas-fired boilers are used for summer CO_2 enrichment. For this purpose, the managements of John Hall Nurseries Ltd and Van Heyningen Bros Ltd generously made suitable glasshouse facilities available at their Runcton and Angmering nurseries respectively.

Materials and Methods

Measurements of NO_x pollution were made for nine weeks (from early August to mid October 1990) and for seven weeks (from early May to late June 1991) at the Runcton and Angmering nurseries respectively. State-of-the-art technology was used for growing the long-season crops of tomatoes (4.5 hectares) at Runcton and sweet peppers (5.3

hectares) at Angmering. Biological control agents were used at both locations for suppressing pests: this practice enabled the nurseries to use bees for improving the pollination of the crops.

At Runcton the hot-water boiler (Crone) could be fired by either mains gas or oil. The boiler with a rating of 12.67 TJ h^{-1} (equivalent to 12,000,000 Btu h^{-1} or 3,517 kWh) was equipped with a two-speed, fully-modulating burner (Vitotherm). A high, 'turn-down' ratio (10:1) allowed the burner to be used solely for CO_2 generation when there was little or no requirement to 'dump' heat into a large buffer tank (capacity *c.* 114 m^3 or 25,000 gallons) adjacent to the boiler house. Overall efficiency of the boiler was maximised by using a heat economizer/condensor (Crone). This device resulted in a lowering of the temperature of the flue-gases to about 65 °C prior to dilution with outside air and distribution inside the greenhouse. A 'trap' was used to collect the condensate from the economizer/condensor.

Arrangements at the Angmering nursery were broadly similar to those at Runcton. The mains gas/oil-fired boiler (Crone) with a rating of 29.54 TJ h^{-1} (equivalent to 28,000,000 Btu h^{-1} or 8,140 kWh) was equipped with a fully-modulating burner (Puripher). An economizer/condensor (Puripher) was again used to maximize the overall effiency of the boiler. The temperature of the undiluted flue-gases after heat recovery by the economizer/condensor was about 40 °C: this contrasts with a temperature of 125 °C for the flue-gases entering the device.

Boiler flue-gases were used during the daytime at both nurseries to minimize CO_2 depletion during spring and summer. Air for analysis of the atmospheric concentrations of CO_2 and noxious gases inside the glasshouses was sampled at a height of 0.5 m above the inflatable tubing used for distributing the diluted flue-gases. A 3 m length of 4 mm bore T.F.E. (impervious to nitrogen oxides) tubing was used for forwarding the air samples to the monitoring equipment.

CO_2 was monitored with an infra-red type of gas analyzer (Edinburgh Sensors 'Guardian II') accurate to within ± 15 vpm and insensitive to water vapour. A chemiluminescent type of nitrogen oxides analyzer (Meloy Labs Inc. Model 8840) was used to monitor nitric oxide (NO) and nitrogen dioxide (NO_2). The NO_x measurements were synchronized with those of CO_2 in order to determine whether there was a direct relationship between the concentrations of pollutant gases and the CO_2 level in the glasshouse atmosphere. Cylinders containing known concentrations of either NO in nitrogen or NO_2 in air were used to check the calibration of the NO_x analyzer. The test gas mixtures ('Specta Seal' grade supplied by the Special Gases Division of B.O.C. Ltd) were accurate to ± 5% and the minimum detectable concentration of each of the pollutant gases was 0.01 vpm. A portable data logger ('Delta Logger' supplied by Delta-T Devices Ltd) was used to collect data of three variables (viz. CO_2, NO and NO_2) from the two gas analyzers. The device was set to scan the inputs at 5 s intervals, store and record the integrals every 5 m. Connection of the logger to a PC aided collation, analysis and graphical presentation of the data.

Results

Runcton Nursery (Chichester)

Figure 1 typifies the results obtained when the flue-gases from a gas-fired boiler were used to provide CO_2 enrichment for a long-season tomato crop in early autumn. Concentrations of NO_x above ambient (normally less than 0.01 vpm for unpolluted areas such as the South Coast of England) provide a clear indication of when flue-gases were present in the greenhouse atmosphere.

Flue-gases were expelled daily into the greenhouse atmosphere from 5 a.m. until 5 p.m. In general, the level of NO_x pollution rose and fell concomitantly with the rise and fall in the CO_2 concentration. Cessation of CO_2 enrichment in the late afternoon resulted in the NO_x level declining to ambient by early evening on windy days (e.g. 9 and 10 October 1990) and during the night-time on calm days (e.g. 7 and 8 October 1990). The rate of decay of the NO_x pollution is strongly influenced by the rate of air exchange between the greenhouse and outside. Factors which promote air exchange are the degree of ventilator opening and the direction of speed of the wind. Regrettably, records of the ventilation are not available for the period of monitoring. However, the slowest rates of decay of the NO_x pollution were registered on the evenings of 7 and 8 October when the average wind velocities were 1.46 and 0.52 m s^{-1} respectively.

The events of two contrasting 24-hour periods from mid-night to mid-night are illustrated in Figures 2 and 3. Briefly, the results may be summarized:

8 October 1990 From mid-night until 7 a.m. the greenhouse CO_2 concentration climbed steadily as a result of the crop's respiration and the relatively still weather conditions (average windspeed 0.52 m s^{-1}). A 'peak' of *c.* 1,275 vpm CO_2 was recorded while the NO_x level declined gradually towards a level near that of ambient (i.e. 0.01 vpm or less). With increasing light (and presumably ventilation) the CO_2 level then fell to *c.* 400 vpm by 9 a.m. Thereafter, the level fluctuated between 300 and 500 vpm until 3 p.m. in the afternoon. Flue-gases were primarily released into the greenhouse atmosphere during this six hour period for the purposes of CO_2 enrichment. Clearly, the technique was successful in preventing CO_2 depletion though the presence of the NO_x (varying between 0.05 and 0.3 vpm) may have been potentially injurious. From 3 p.m. onwards both the CO_2 and NO_x levels rose rapidly to reach maxima of 1,475 vpm and 0.65 vpm respectively. Near to dusk the CO_2 level declined rapidly until an equilibrium was established between the amounts of CO_2 gained from the crop's respiration and those lost through ventilation and leakage. NO_x levels declined rapidly for a short period after dusk and then decayed slowly towards ambient throughout the remainder of the night.

10 October 1990. This day was characterized by average windspeed (2.23 m s^{-1}) and below average solar radiation receipt (6.50 MJ m^{-2}). Flue-gases were ducted into the greenhouse for 12 hours from 5 a.m. onwards. At the beginning and end of the day-time the CO_2 level was generally maintained at 1,000 vpm or above. NO_x levels were about 0.25 vpm at these times, though a maximum of *c.* 0.45 vpm was attained in the late afternoon at 5.30 p.m. During an eight hour period from 8 a.m. to 4 p.m. the CO_2 level

was kept at or just above ambient. Generally, NO_x levels varied between 0.02 and 0.08 vpm. A 'peak' value of 0.18 vpm was recorded at noon when the CO_2 level rose to just above 600 vpm.

Regression analysis was used to examine the relationship between the concentrations of NO_x and CO_2 present in the greenhouse atmosphere when flue-gases from a gas-fired boiler were used for summer CO_2 enrichment. A total of 246 datasets of NO_x/CO_2 concentrations (observed between 8 a.m. and 4 p.m. during an eight day period from 5 October 1990) were used in the analysis. The results show that, within the range 350-500 vpm CO_2, the NO_x level increased linearly by 0.000553 vpm for each vpm increase in mean CO_2 level (Figure 4). Also, the ratio of $NO:NO_2$ averaged 4.7:1 within the range 350-500 vpm CO_2.

West End Nurseries (Angmering)

Figure 5 typifies the results obtained when boiler flue-gases were used for enriching a long-season crop of sweet peppers in the late spring and early summer. In general, the level of NO_x pollution rose and fell concomitantly with the rise and fall in the CO_2 concentration. When flue-gas extraction ceased towards the end of the afternoon the NO_x level usually fell back to ambient (normally less than 0.01 vpm for unpolluted areas such as the South Coast of England).

The rise in the greenhouse CO_2 concentration which was observed on most days from early evening until about 3 a.m. was mainly due to the gains of CO_2 produced by the crop's dark respiration and evolved from the root-zone environment through microbial activity. At Angmering the boiler flue-gases were released into the greenhouse atmosphere from 3 a.m. onwards: this practice resulted in comparatively high levels of both CO_2 and NO_x being experienced by the crop until about 10 a.m. During the late mornings and early afternoons when the main aim was to keep the CO_2 level near ambient (normally 350 vpm) the NO_x level averaged about 0.06 vpm. However, in the mid- to late-afternoons, there were often periods when the greenhouse atmosphere became depleted of CO_2. Invariably, this was the result of the boiler being shut-down to conserve fuel at a time when the heat-storage tanks were at full capacity.

The events of two contrasting 24-hour periods from mid-night to mid-night are illustrated in Figures 6 and 7. Briefly, the results may be summarized:

10 May 1991 From mid-night the atmospheric CO_2 concentration rose steadily through the crop's dark respiration while the NO_x level remained constant at ambient. At 3.30 a.m. flue-gases were introduced into the greenhouse: this resulted in both the CO_2 and NO_x levels increasing rapidly until maxima of 1,200 vpm and 0.2 vpm were reached respectively at 5 a.m. From then onwards the CO_2 and NO_x levels declined until an equilibrium was established at about 6.45 a.m. This was maintained until flue-gas extraction from the boiler ceased shortly after 2 p.m. Thereafter the CO_2 level fell below ambient and there was significant depletion of the atmosphere for about 80% of the time until 7 p.m. In the absence of the flue-gases the NO_x level declined from *c.* 0.1 vpm at ambient CO_2 to 0.01 with depletion to *c.* 200 vpm CO_2.

17 May 1991 During the first five hours from mid-night the CO_2 and NO_x levels followed a similar pattern to that observed on 10 May. Maxima of 1,250 vpm CO_2 and 0.265 vpm NO_x were reached at about 4 a.m. Thereafter the CO_2 and NO_x levels declined but were maintained at significantly higher levels throughout both the morning and afternoon than on 10 May. Also, there was no evidence of CO_2 depletion and the NO_x level was correspondingly higher throughout the daytime than in the earlier example. The main reason for the difference in CO_2 and NO_x levels between the two days was that the weather was duller (5.64 MJ m^{-2} versus 24.19 MJ m^{-2}) on the 17 May. This resulted in less ventilation and a greater demand of heat from the boiler. Consequently, flue-gases were ducted into the greenhouse from 3 a.m. until 6 p.m. From then onwards the CO_2 concentration rose naturally with dark respiration and the NO_x level decayed slowly towards an ambient value *c.* 0.018 vpm.

A total of 2,457 datasets of NO_x/CO_2 concentrations observed between 8 a.m. and 4 p.m. were used in regression analysis to show that, within the range 350 - 500 vpm CO_2, the NO_x level increased linearly by 0.000506 vpm for each vpm increase in mean CO_2 level (Figure 8). This result is similar to that obtained at Runcton and not very different from that obtained previously in a large commercial block of Venlo glasshouses at a Littlehampton nursery when residual flue-gases from a gas-fired boiler were used to provide a three-fold level of CO_2 enrichment (*Grower*, February 8, 1990). In this case the NO_x level increased by 0.000632 vpm for each vpm increase in mean CO_2 level.

The ratio of $NO:NO_2$ averaged 2.5:1 within the range 350-500 vpm CO_2, i.e. the normal range of CO_2 concentrations for summer CO_2 enrichment of a long-season crop of sweet peppers. For comparison, the ratio of $NO:NO_2$ approaches unity in unpolluted air at rural sites free from any sources of NO_x. However, when conventional burners are used for CO_2 production and warm-air heating the ratio of $NO:NO_2$ is inevitably biased in favour of NO, i.e. the first-formed oxide which arises in the burner flame from the heat-promoted combination of atmosphere nitrogen and oxygen.

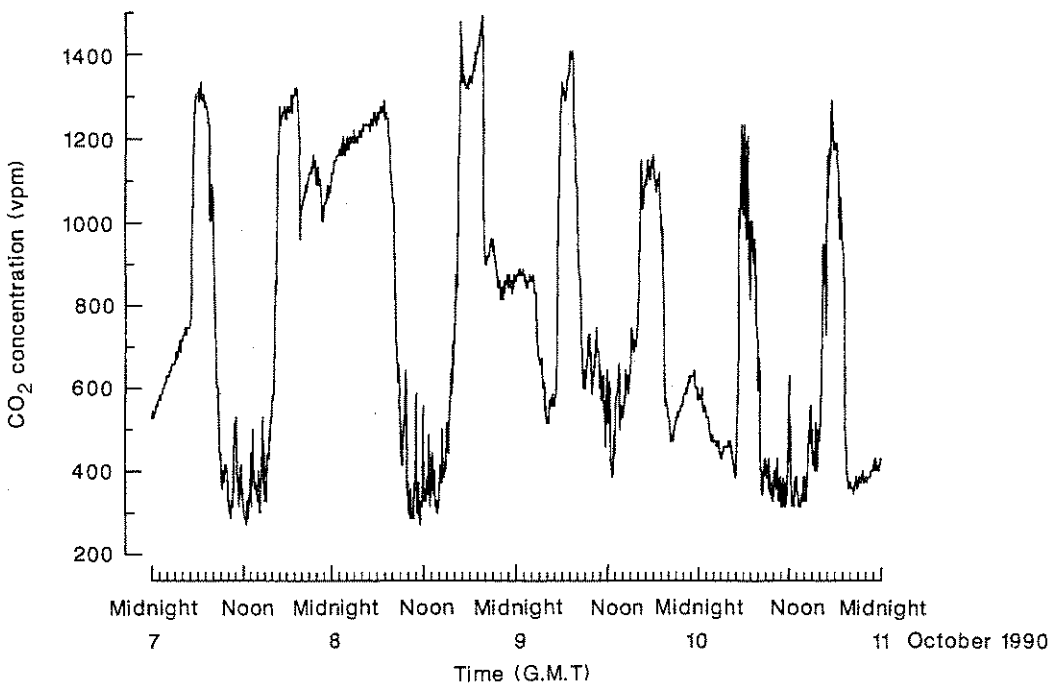
Discussion

The level of NO_x pollution was similar at both nurseries and varied directly from a mean value of 0.06 to 0.14 vpm when the greenhouse CO_2 concentration was maintained within 350-500 vpm, i.e. the normal range of CO_2 concentrations used for summer CO_2 enrichment of long-season crops of tomatoes and sweet peppers. Regrettably, very little is known about the long-term exposure of tomato and sweet pepper crops to low levels of NO_x pollution. In this investigation there was no direct evidence of phytotoxicity though the more subtle forms of injury (e.g. reduced photosynthesis, slower growth and lower yield) are impossible to diagnose without recourse to experimentation.

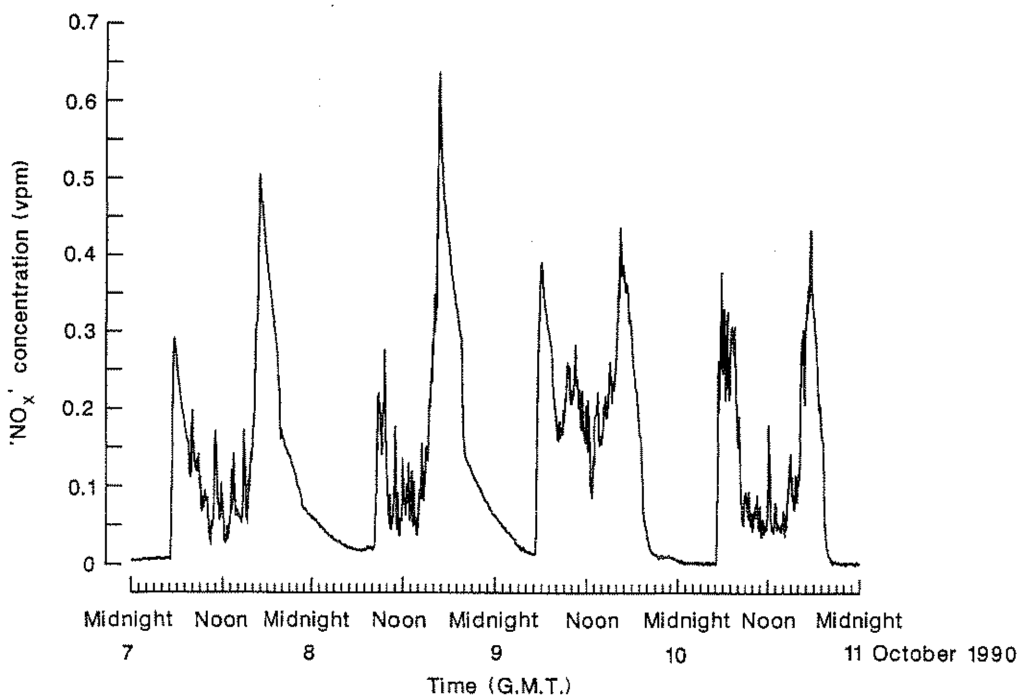
Researchers in both England and The Netherlands have demonstrated that 'invisible injury' can occur on tomato and sweet pepper crops. However, the levels of NO_x used in the various experiments with these crops were considerably higher than those recorded at either the Runcton or Angmering nurseries when flue-gases were used to maintain the CO_2 concentration within a range of 350-500 vpm. Also, with the tomato, there is evidence of a marked cultivaral sensitivity to NO_x pollution. It seems that some of the older cultivars like the English-bred Moneymaker are ultra-sensitive whereas the Dutch-bred Sonato and Eurocross BB appear to show tolerance. However, the sensitivity/tolerance of modern cultivars to NO_x pollution is unknown.

Environmental factors which help to alleviate the effects of NO_x pollution on crops include bright light, high temperature and CO_2 enrichment. The risks of injury to long-season crops of tomatoes and sweet peppers when flue-gases are used for summer CO_2 enrichment are therefore probably slight provided that the CO_2 concentration is kept within the recommended range of 350-500 vpm. Higher levels of daytime CO_2 enrichment with flue-gases will result in increased NO_x pollution and greater risks of injury to crops. Indeed, levels of NO_x pollution above 0.5 vpm may cause visible damage to the foliage if the exposure is extended beyond a day or two in dull light.

Grateful acknowledgement is given to the managements and staffs of John Hall Nurseries Ltd and Van Heyningen Bros Ltd for their co-operation throughout the project.

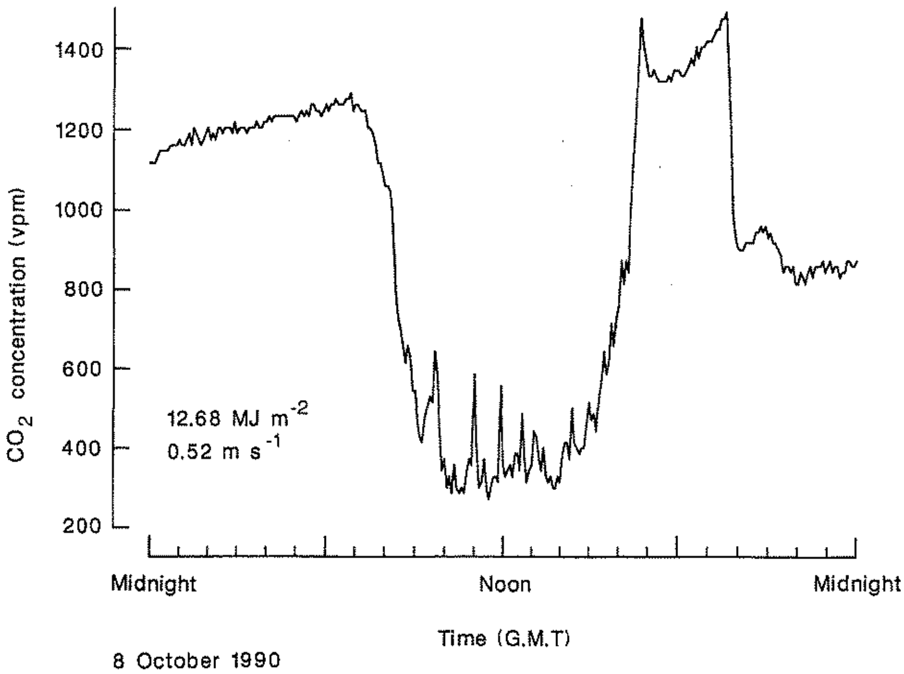


CO_2 concentration in a glasshouse using boiler flue-gases for CO_2 enrichment of a long-season tomato crop in early autumn.



'NO_x' concentration in a glasshouse using boiler flue-gases for CO_2 enrichment of a long-season tomato crop in early autumn.

FIGURE 1



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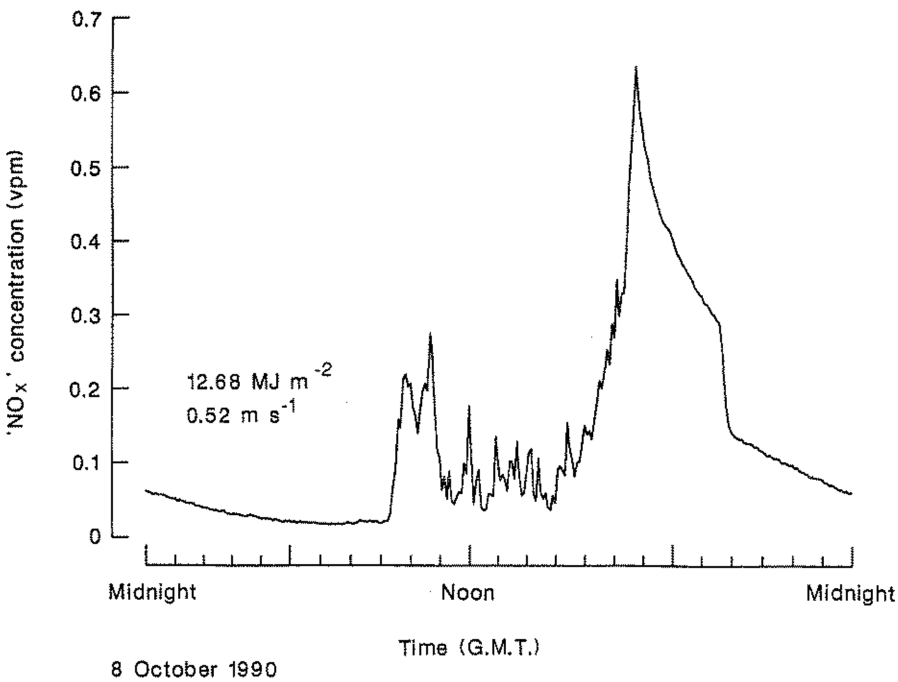

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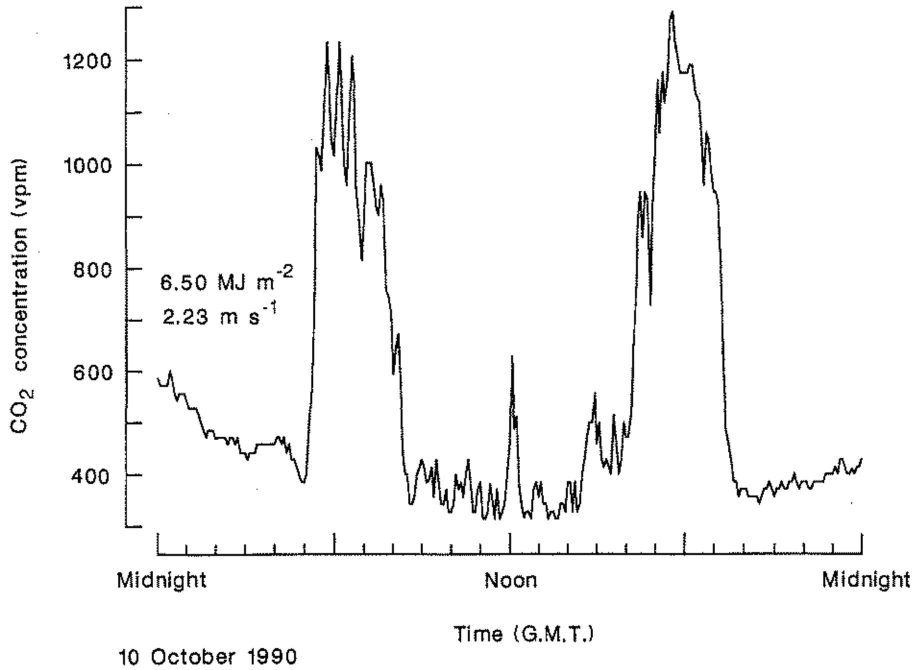
FIGURE 2



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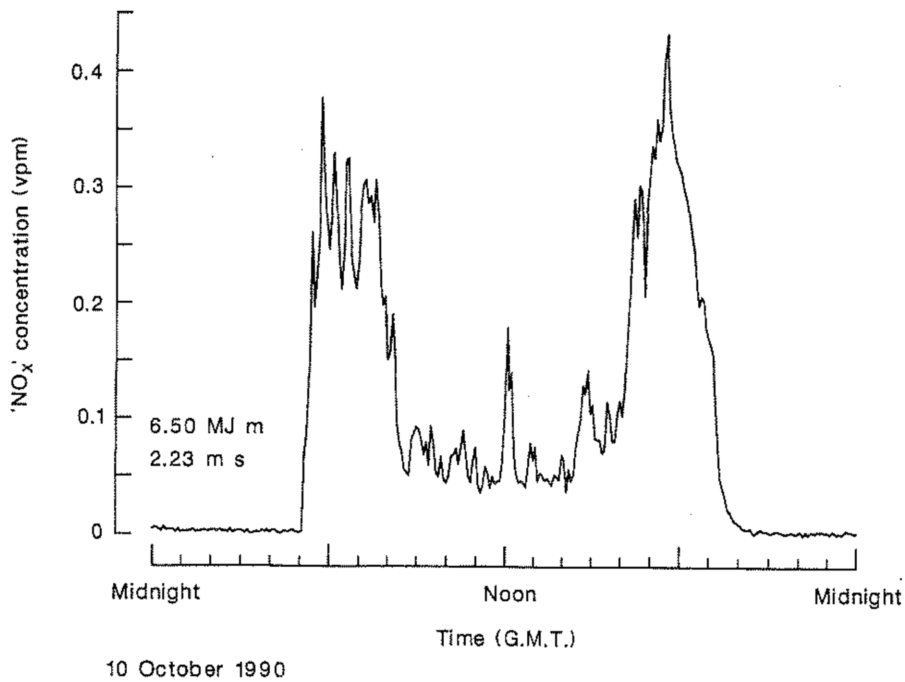

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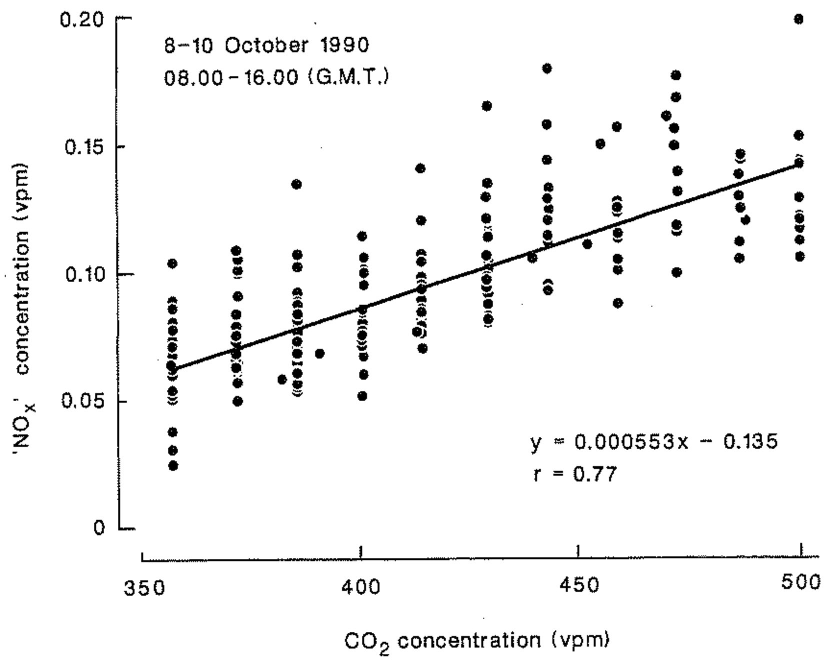
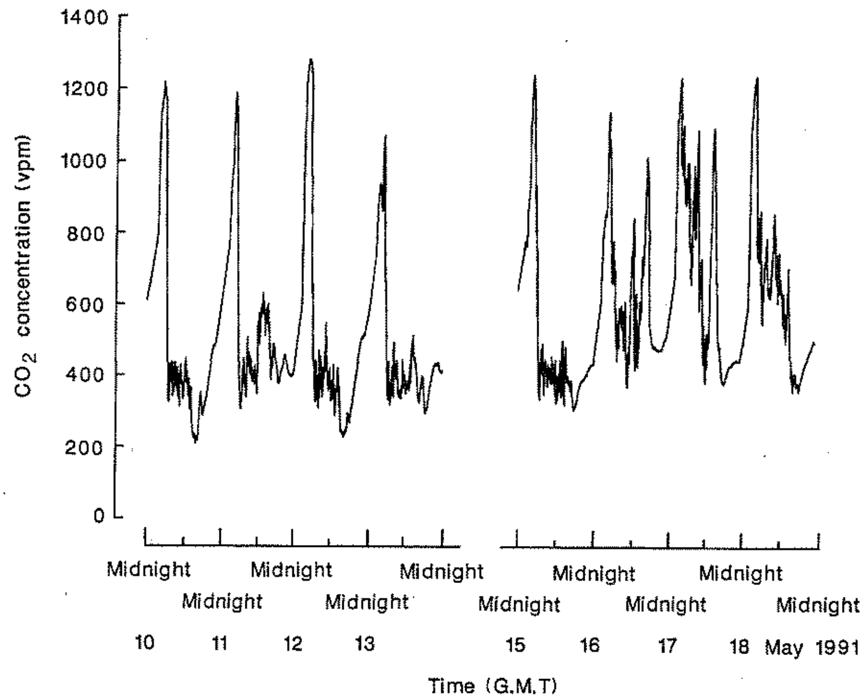
FIGURE 3



'NO_x' pollution in a glasshouse using boiler flue-gases for summer CO_2 enrichment of a long-season tomato crop in early autumn: relationship between 'NO_x' and CO_2 within the range 350-500 vpm CO_2.

FIGURE 4



CO_2 concentration in a glasshouse using boiler flue-gases for CO_2 enrichment of a long-season crop of sweet peppers in late spring.

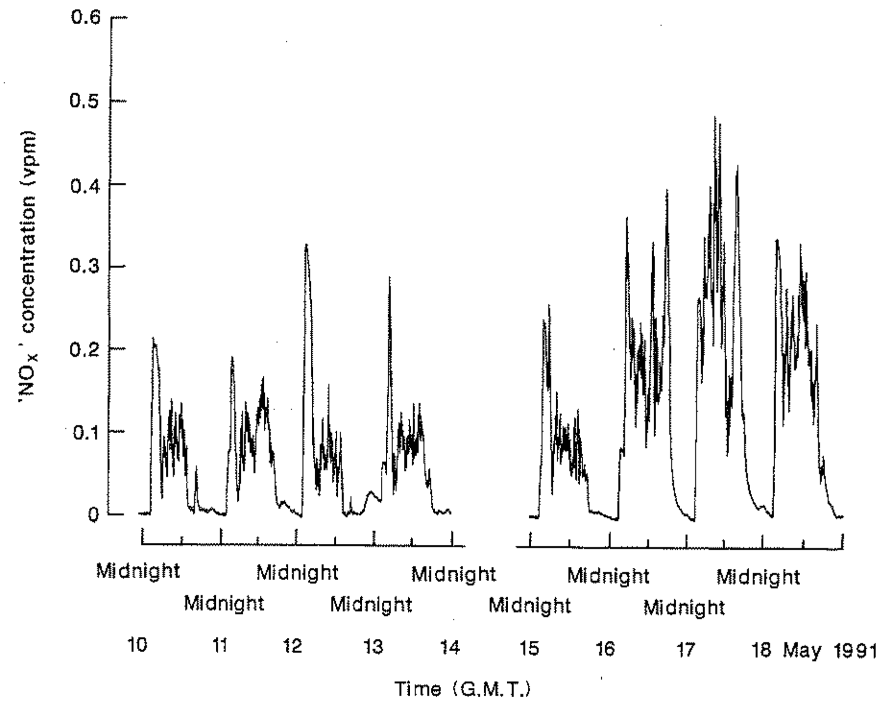


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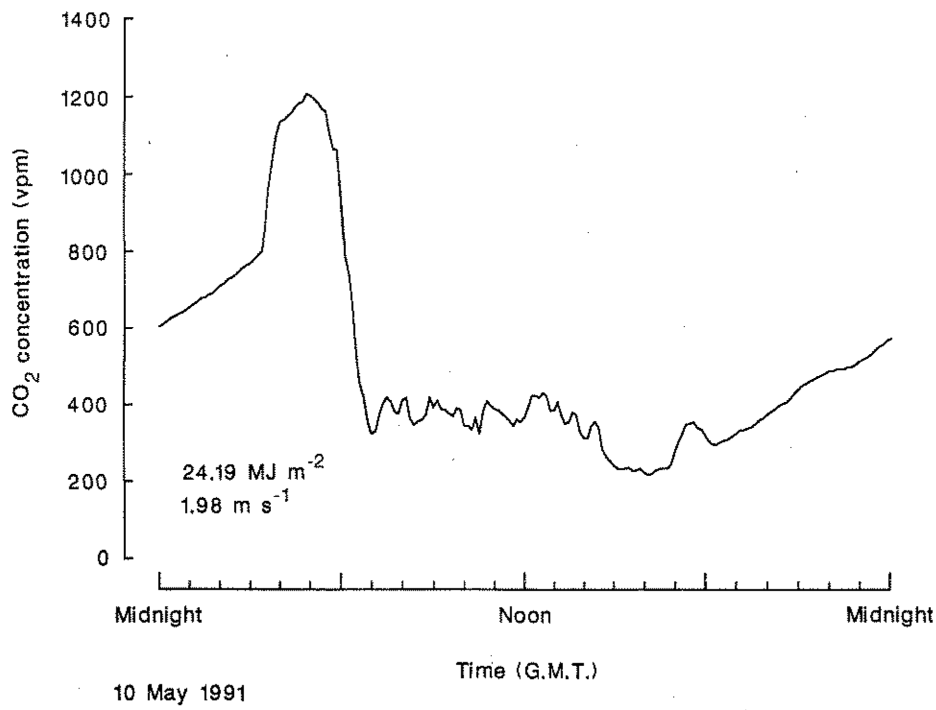
FIGURE 5



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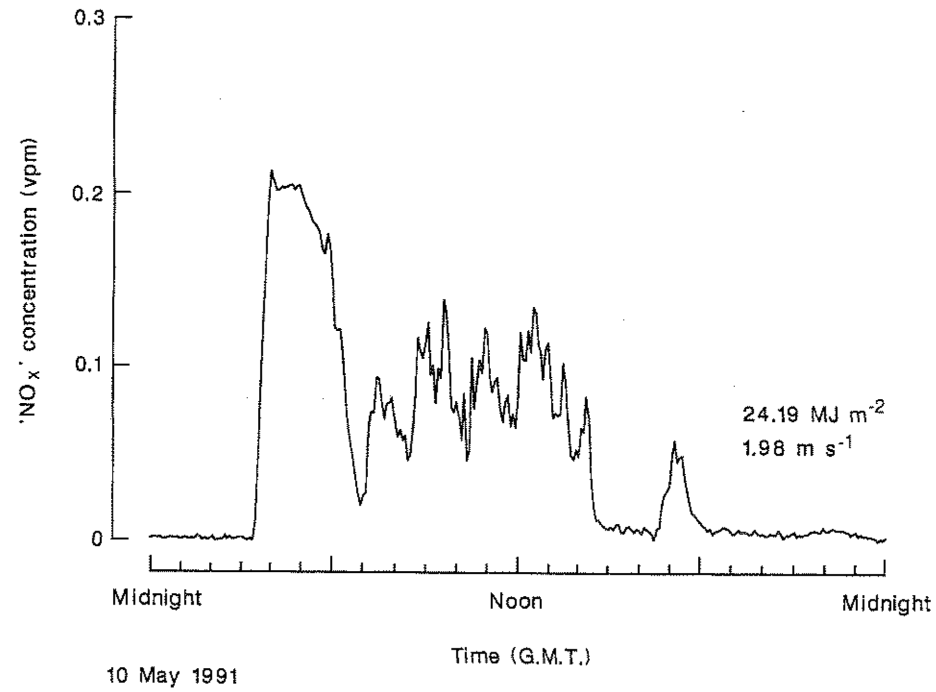

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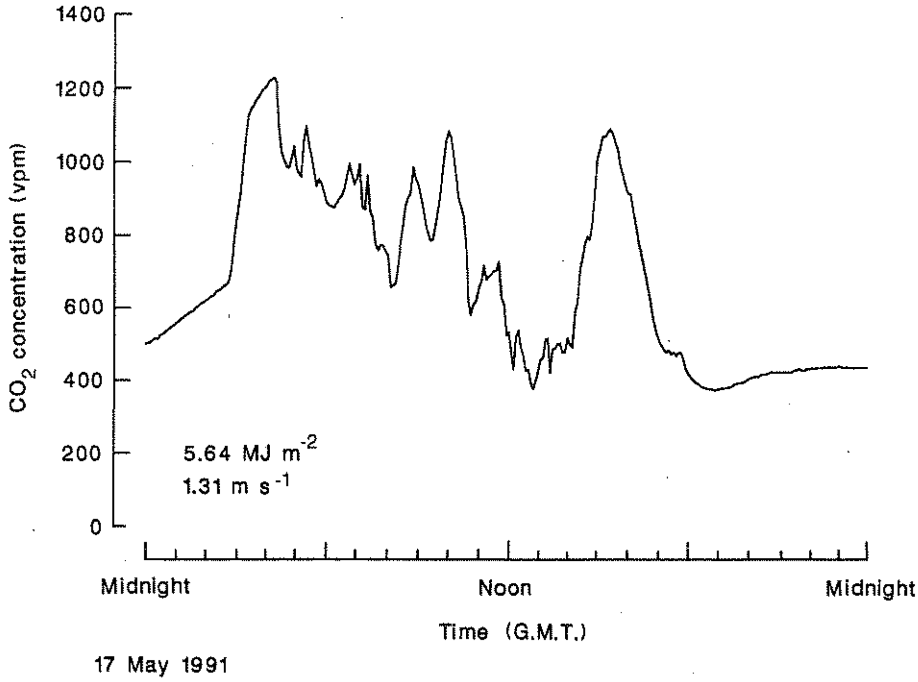
FIGURE 6



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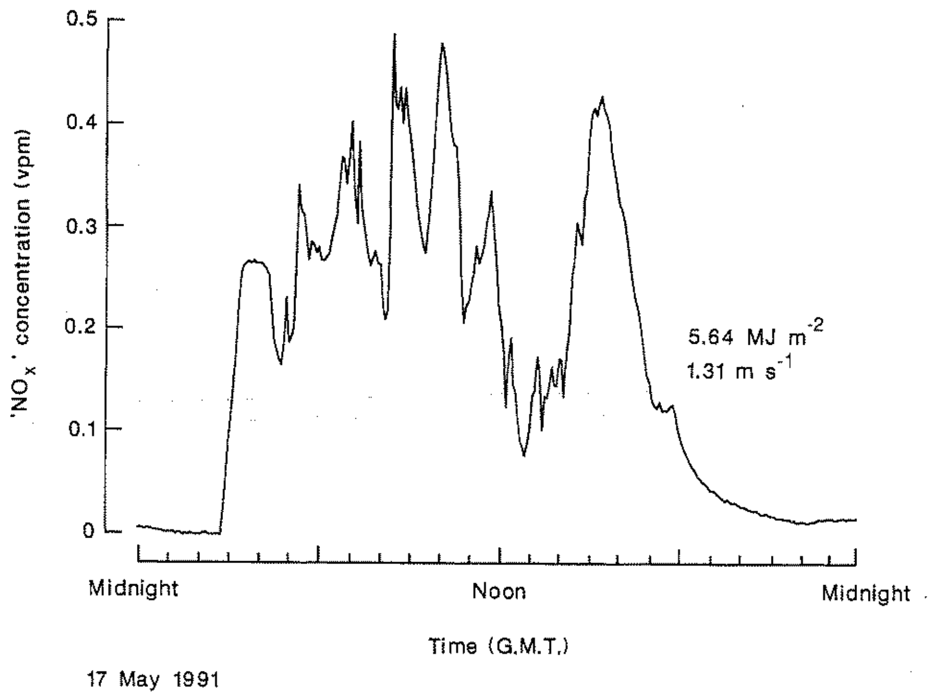

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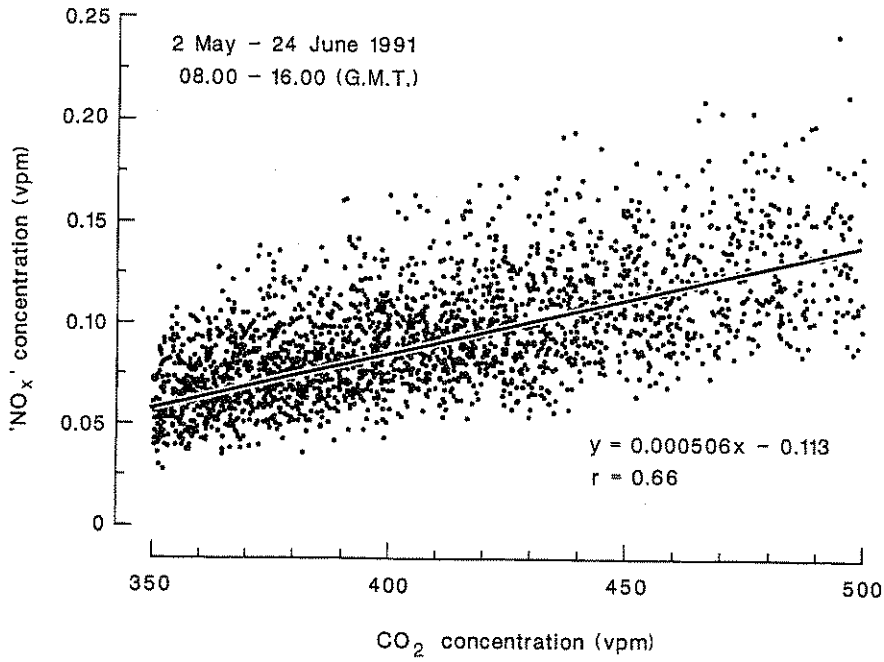
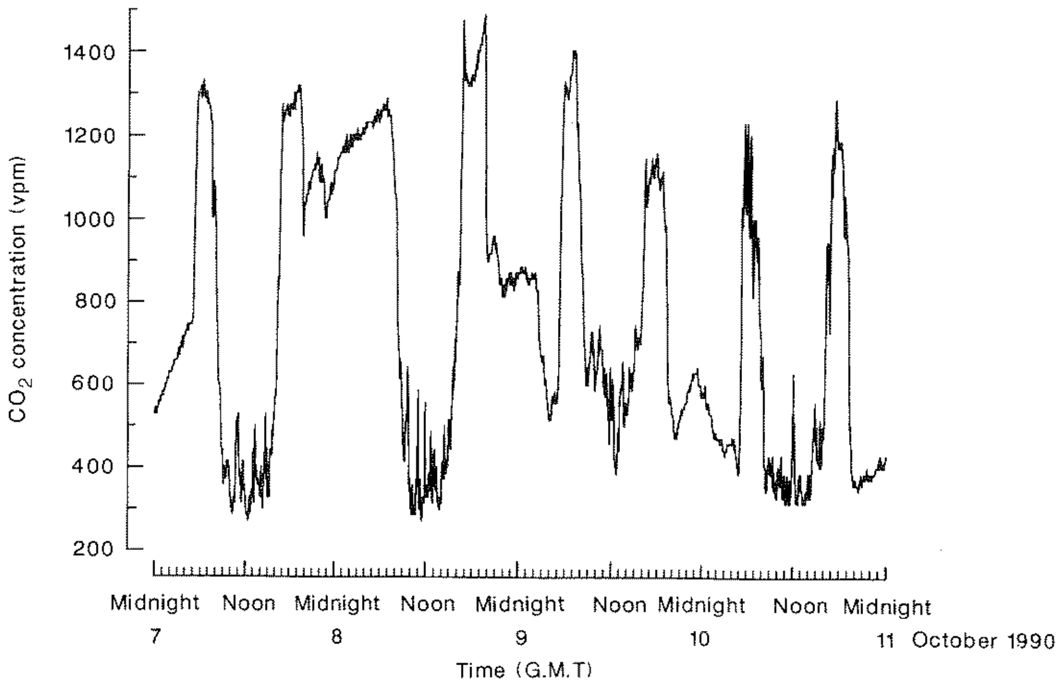
FIGURE 7

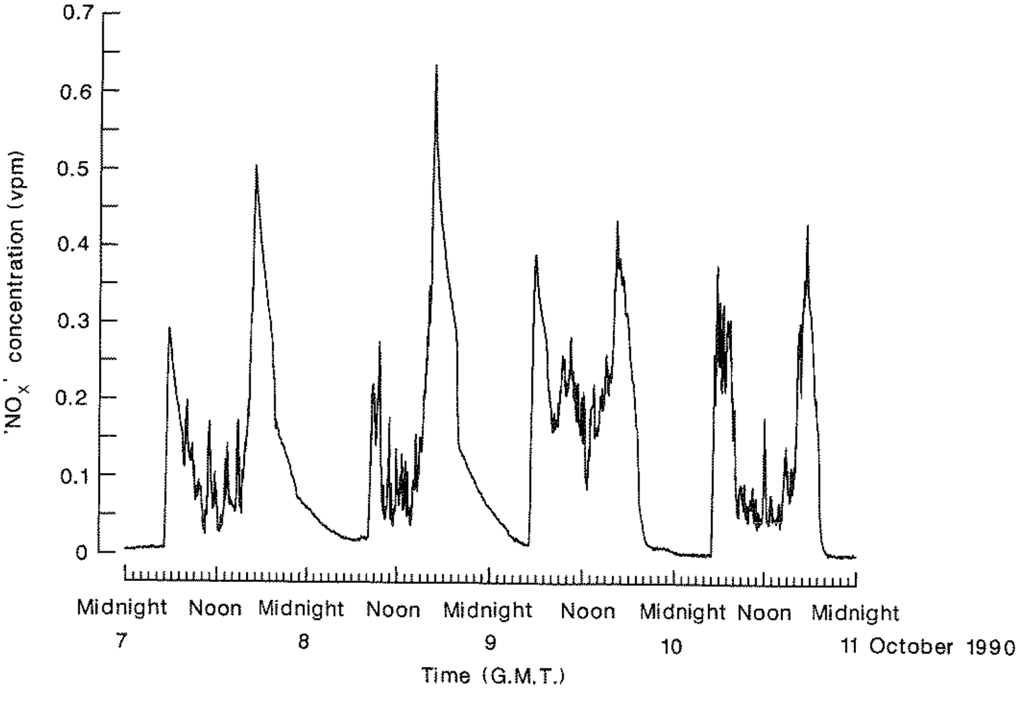


'NO_x' pollution in a glasshouse using boiler flue-gases for summer CO_2 enrichment of a long-season crop of sweet peppers in late spring: relationship between 'NO_x' and CO_2 within the range 350-500 vpm CO_2.

FIGURE 8



CO_2 concentration in a glasshouse using boiler flue-gases for CO_2 enrichment of a long-season tomato crop in early autumn.



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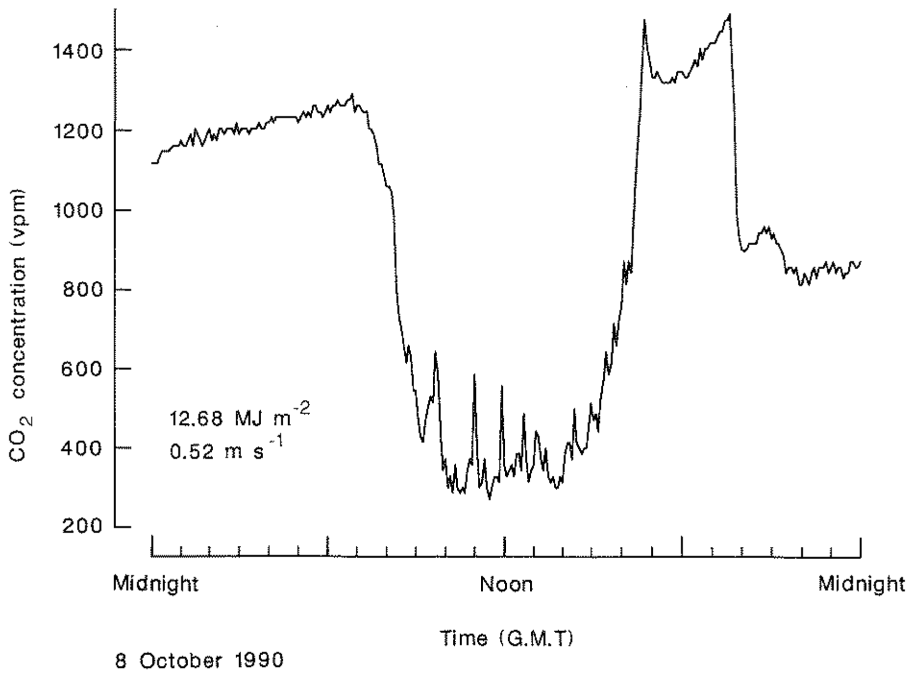

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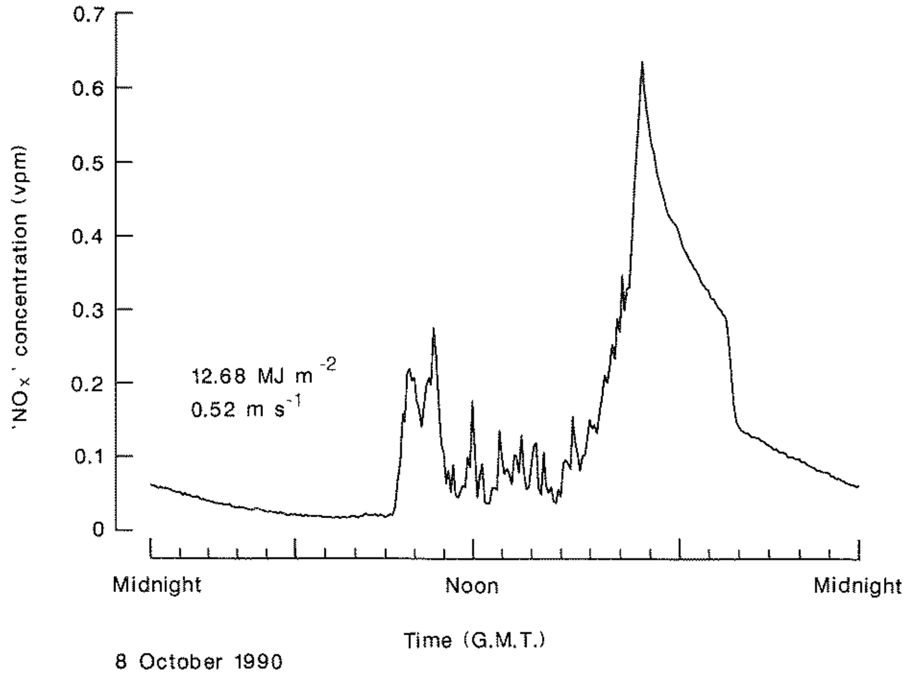

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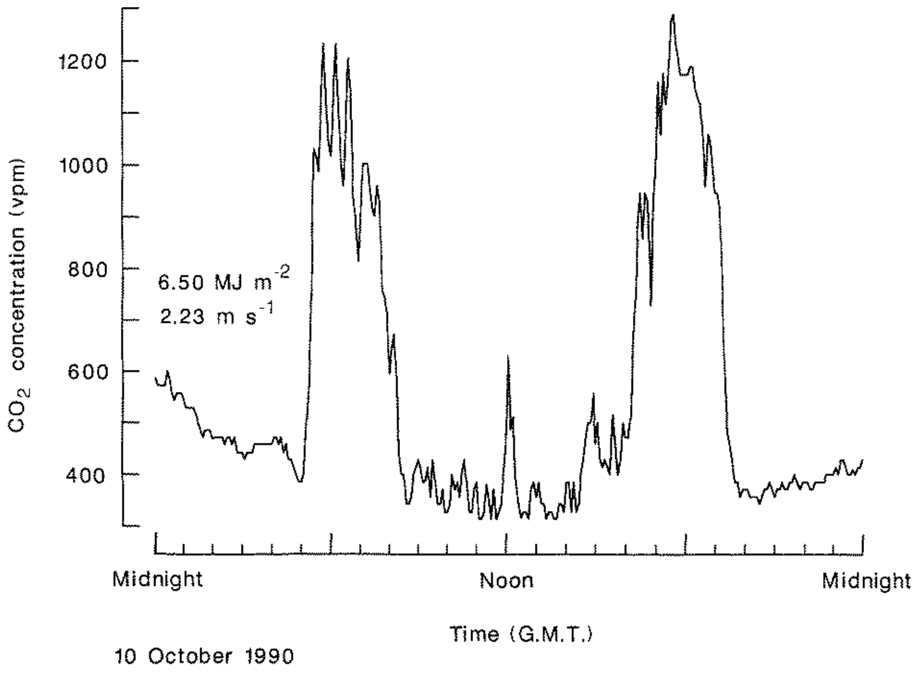
FIGURE 2



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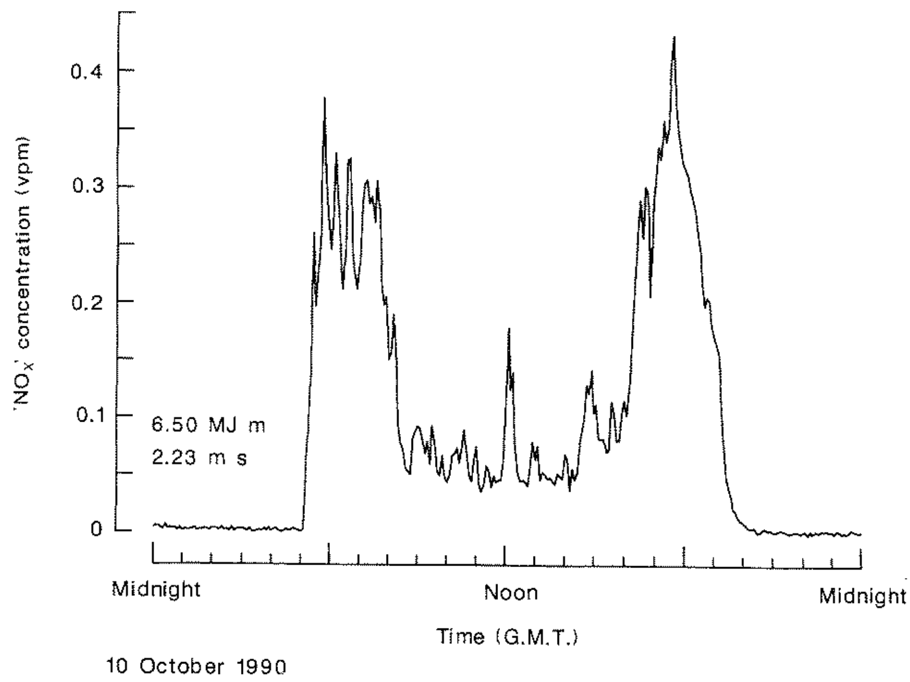

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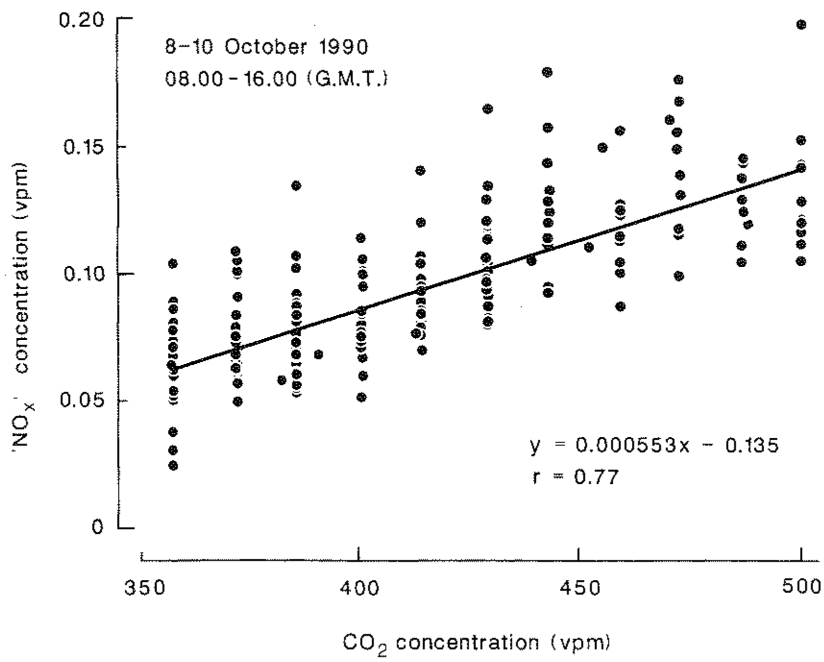
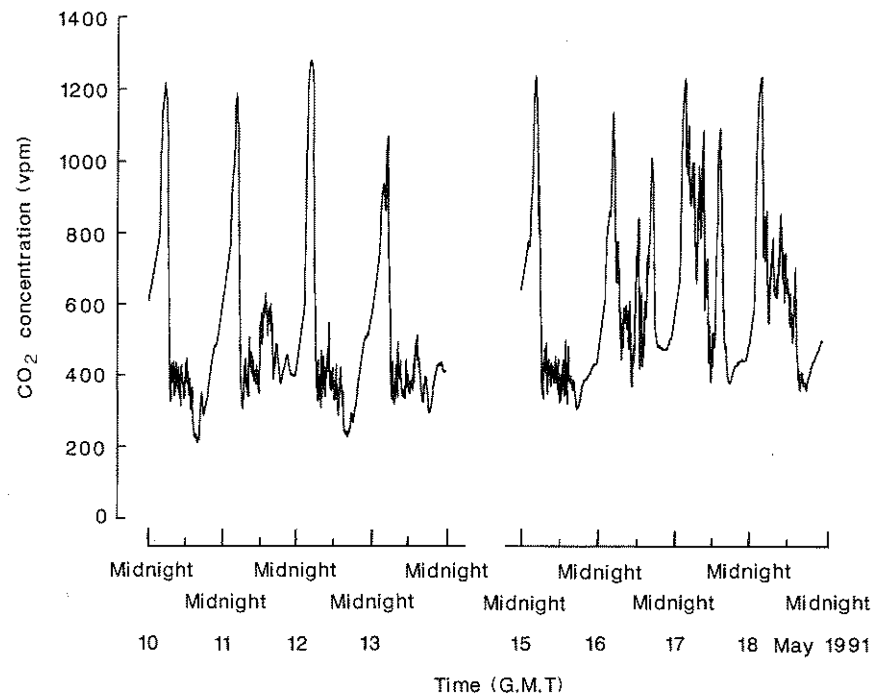
FIGURE 3



'NO_x' pollution in a glasshouse using boiler flue-gases for summer CO_2 enrichment of a long-season tomato crop in early autumn: relationship between 'NO_x' and CO_2 within the range 350-500 vpm CO_2.

FIGURE 4



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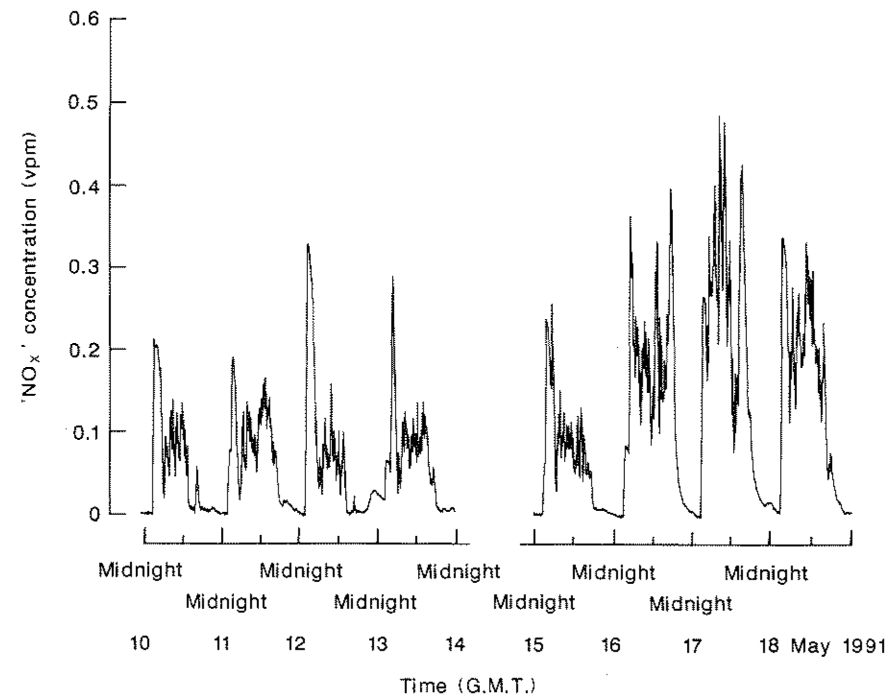
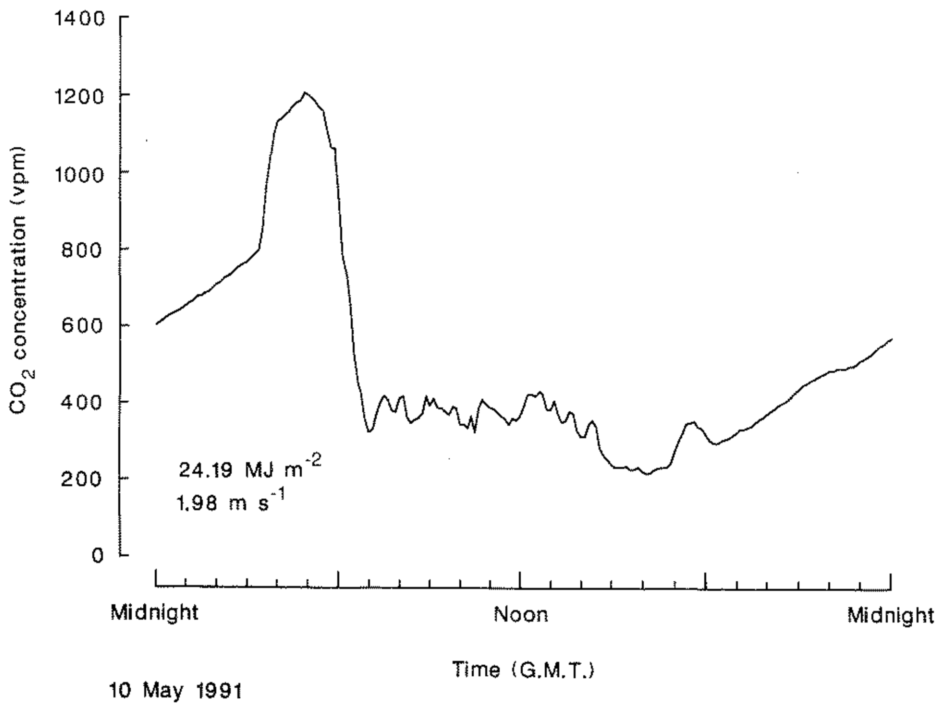
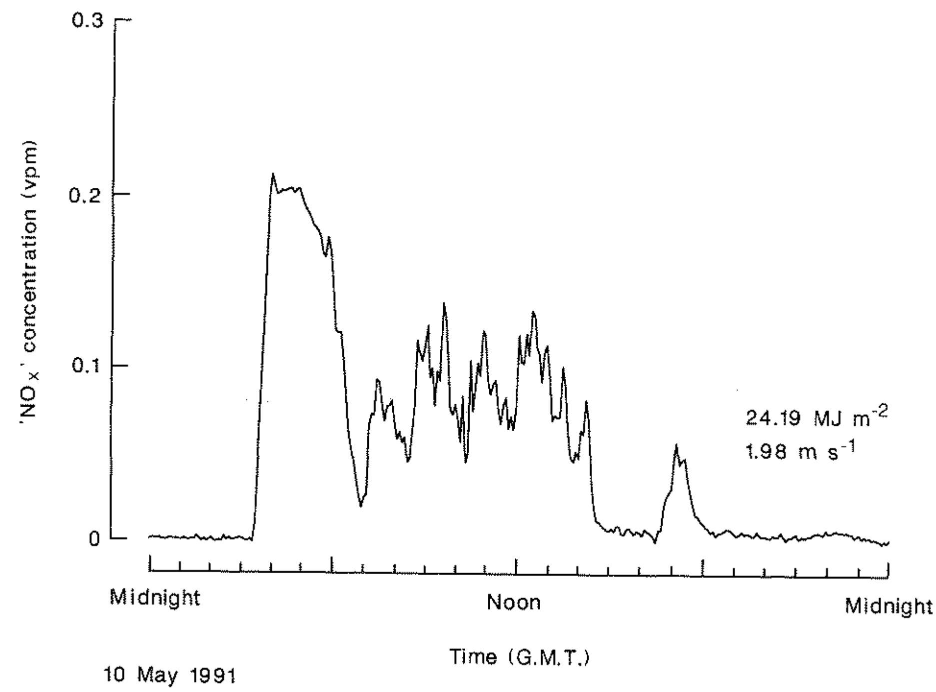


'NO_x' concentration in a glasshouse using boiler flue-gases for CO_2 enrichment of a long-season crop of sweet peppers in late spring.

FIGURE 5

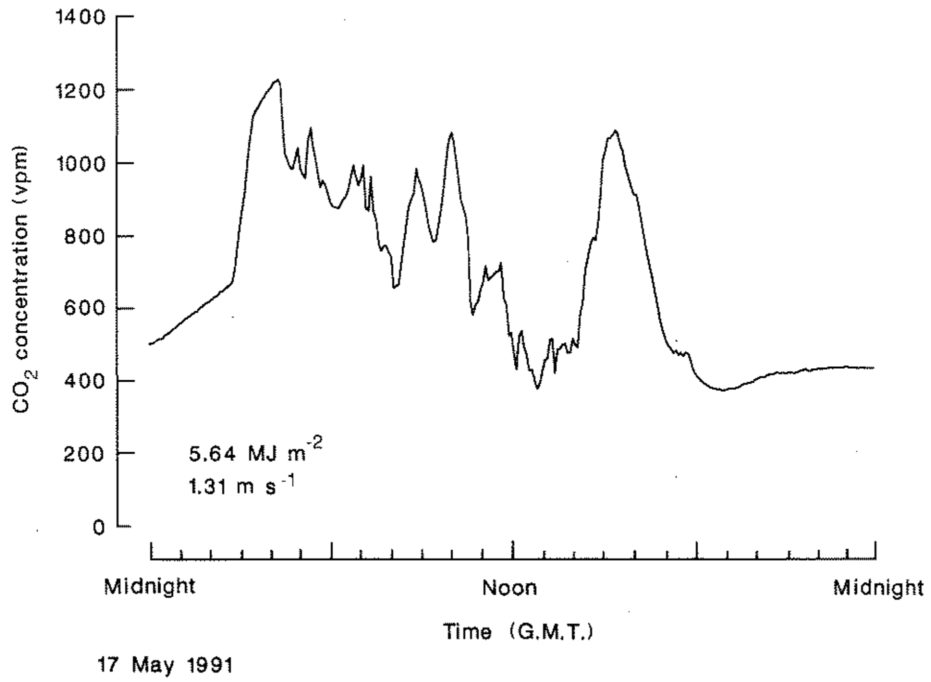


CO_2 concentration in a glasshouse using boiler flue-gases for CO_2 enrichment of a long-season crop of sweet peppers in late spring.

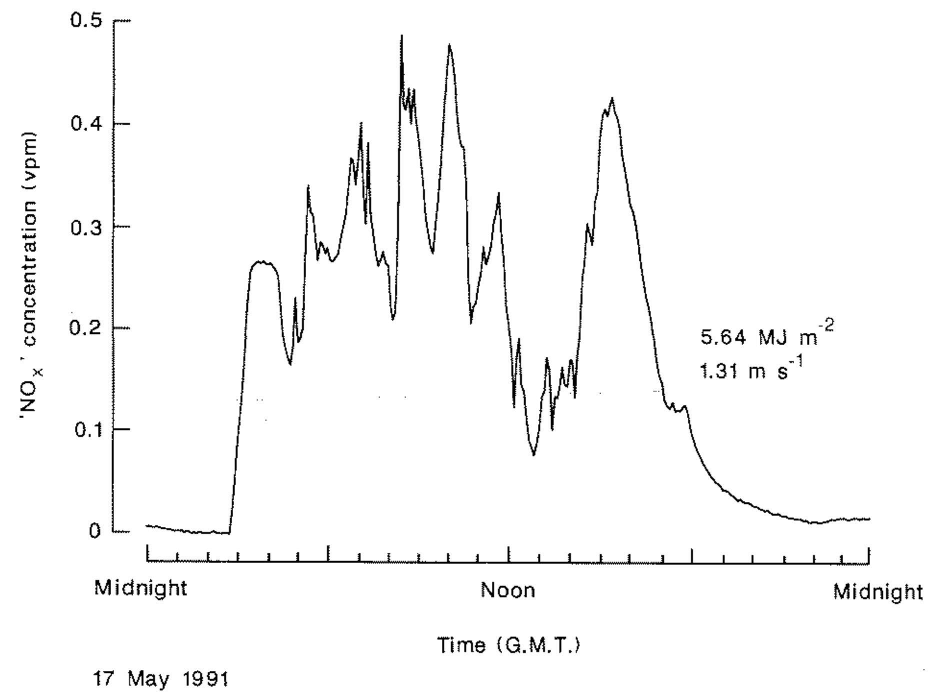


'NO_x' concentration in a glasshouse using boiler flue-gases for CO_2 enrichment of a long-season crop of sweet peppers in late spring.

FIGURE 6

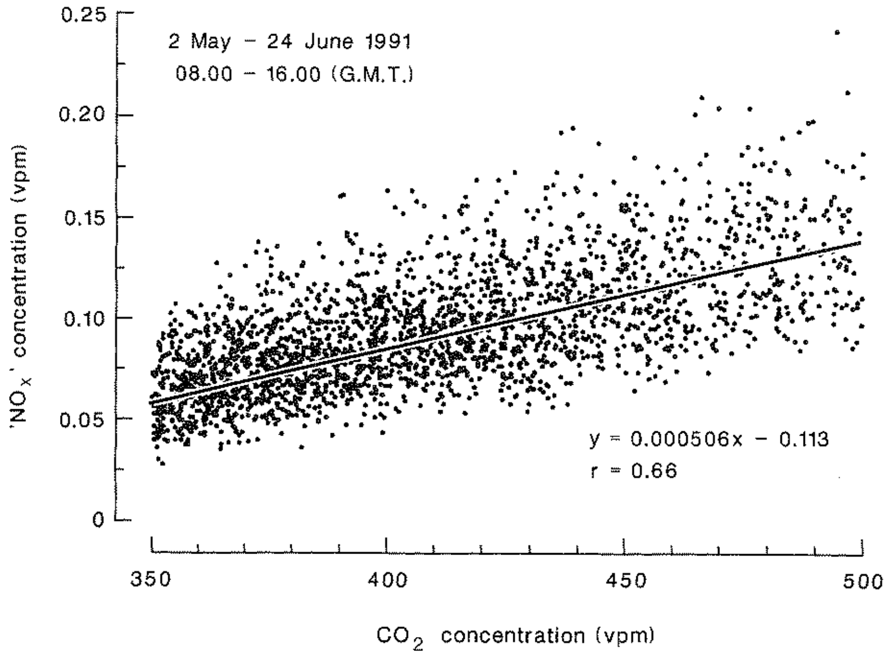


CO_2 concentration in a glasshouse using boiler flue-gases for CO_2 enrichment of a long-season crop of sweet peppers in late spring.



'NO_x' concentration in a glasshouse using boiler flue-gases for CO_2 enrichment of a long-season crop of sweet peppers in late spring.

FIGURE 7



'NO_x' pollution in a glasshouse using boiler flue-gases for summer CO_2 enrichment of a long-season crop of sweet peppers in late spring: relationship between 'NO_x' and CO_2 within the range 350-500 vpm CO_2.

FIGURE 8