AGRICULTURAL AND FOOD SCIENCE IN FINLAND

Vol. 5 (1996): 25–47.

Arrangement of experiments for simulating the effects of elevated temperatures and elevated CO_2 levels on field-sown crops in Finland

Kaija Hakala, Timo Mela and Heikki Laurila
Agricultural Research Centre of Finland, Institute of Crop and Soil Science, SF-31600 Jokioinen, Finland
Timo Kaukoranta
Agricultural Research Centre of Finland, Institute of Plant Protection

The experimental plants: spring wheat, winter wheat, spring barley, meadow fescue, potato, strawberry and black currant were sown or planted directly in the field, part of which was covered by an automatically controlled greenhouse to elevate the temperature by 3°C. The temperature of the other part of the field (open field) was not elevated, but the field was covered with the same plastic film as the greenhouse to achieve radiation and rainfall conditions comparable to those in the greenhouse. To elevate the CO_2 concentrations, four open top chambers (OTC) were built for the greenhouse, and four for the open field. Two of these, both in the greenhouse and in the open field, were supplied with pure CO_2 to elevate their CO_2 level to 700 ppm. The temperatures inside the greenhouse followed accurately the desired level. The relative humidity was somewhat higher in the greenhouse and in the OTC:s than in the open field, especially after the modifications in the ventilation of the greenhouse and in the OTC:s in 1994. Because the OTC:s were large (3 m in diameter), the temperatures inside them differed very little from the surrounding air temperature. The short-term variation in the CO_2 concentrations in the OTC:s with elevated CO_2 was, however, quite high. The control of the CO_2 concentrations improved each year from 1992 to 1994, as the CO_2 supplying system was modified. The effects of the experimental conditions on plant growth and phenology are discussed.

Key words: climate change, carbon dioxide, open top chamber (OTC), crop plants, horticultural plants

Introduction

According to current predictions, atmospheric concentrations of carbon dioxide (CO_2) will rise, and the climate will become warmer in the future (Houghton et al. 1992). Increased CO_2 concentration is expected to increase the photosynthetic capacity of C_3 plants (Bowes 1991, Lawlor and Mitchell 1991) and lead to higher productivity (Lawlor and Mitchell 1991). Higher growing season temperatures may also enhance crop growth, mainly through the lengthening of the growing season; especially in the spring when light intensity is high but temperatures are too low for crop growth in the present

Manuscript received December 1995

Fig. 1. The greenhouse built on the experimental field in order to elevate the temperatures continuously by 3°C, and the adjacent open field, covered with the same material as the greenhouse.

climate. However, the rate of development of cereals like wheat and barley is strongly related to temperature. In conditions of high temperatures and long days, the development of cereal crops may proceed excessively fast, resulting in a smaller volume of assimilating biomass, a shorter grain filling time and subsequently, lower yields than would be possible at lower temperatures (Mela et al. 1994). Warming of climate can also be assumed to increase damage caused by pests and pathogens at northern latitudes where their development and reproduction rates are currently limited by low temperatures (Mela et al. 1994).

The present investigation was undertaken in order to evaluate, through direct experimentation, the possible impact of climatic changes on the growth and yield of the cereal crops spring barley, winter wheat and spring wheat; potato; a grass crop, meadow fescue and two horticultural plants, strawberry and black currant. Although many experiments have been conducted to study the effects of temperature and CO_2 on individual crop plants, few investigations have been made of crop stands, especially those under long photoperiod conditions experienced during the growing season at high latitudes. The experimental conditions were maintained as close to natural field conditions as possible: the experimental plants were sown directly in the field, at normal sward density. Optimal fertilization and irrigation were applied so that soil moisture and nutrients would not limit growth. Pests and diseases were controlled in all the treatments.

To elevate the temperatures and the CO_2 levels, but without the resources to conduct "free air" CO_2 enrichment (FACE) experiments (e.g., see Drake et al., 1985), an artificial system (greenhouse and open top chambers, OTC:s) was constructed inside of which the experimental plants were grown. This paper describes the arrangement of the experiment and evaluates the level of environmental control achieved.

Vol. 5 (1996): 25–47.

Material and methods

Arrangement of the experimental conditions

Elevated temperatures

In order to maintain the experimental temperatures at a constant 3°C higher than ambient temperatures, a greenhouse (20 m x 30 m) was built over an experimental field at Jokioinen, Finland (60°49'N, 23°30'E). The greenhouse was built with white, pressure-impregnated, laminated wood arches in an east-west direction. The shape of the greenhouse was the pointed arch type (Fig. 1) with continuous ridge ventilation. A standard ethyl vinyl acetate (EVA) antifog film (light transmission 60 % at PAR (400–700 nm) wavelengths, 0 % at wavelengths under 360 nm) was used as the covering material. Air temperatures were regulated by an automatic intelligent controller system, ITU computer HS -outstation (Itumic OY, Jyväskylä, Finland), which was installed inside the greenhouse. This operated by opening and closing the overhead hatches on the roof of the greenhouse, or by heating the greenhouse with heater fans. In 1992–1993, in order to achieve better air circulation inside the greenhouse in warm and sunny periods during the growing season, the greenhouse was also ventilated through openings running along its longitudinal sides at the height of 1–1.5 m. However, this type of ventilation was found to decrease daytime temperatures at the edges of the greenhouse by about 0–1 °C, depending on the distance from the openings, and in 1994–1995 an extra fan (type RP, 8.1 kW, OY Wikström AB, Loviisa, Finland) was installed in the centre of the greenhouse to mix the air, while the openings at the sides of the greenhouse were kept closed.

The experimental field outside the greenhouse, at ambient temperature, was covered at the height of 3–4 m with the same plastic film that was used in the construction of the greenhouse, so as to achieve radiation and rainfall conditions comparable to those in the greenhouse. Temperature and humidity were measured in the greenhouse and in the open field with Itumic ventilated psychrometers with Pt 100 sensors (Itumic OY, Jyväskylä, Finland) during all of the experimental years (1992–1995) and inside the OTC:s in 1993–1995. The measurements in the open field were made under the plastic film covering the field. The temperature measurements conducted in 1992 inside the OTC:s (Hakala et al. 1993) were later found to be incorrect, because the radiation shields of unventilated thermometers used in the OTC:s in 1992 could not entirely prevent the thermometers from being warmed by radiation. Temperature and humidity recordings were taken every 4 minutes and then transferred to a master unit, from which data files could be obtained, and information processed on a personal computer.

Elevated CO_2 levels

For the experiments on elevated CO_2 concentrations, OTC:s were constructed according to the basic design described by Ashenden et al. (1992). Their design was modified greatly, however, to meet our demands. The OTC:s were cylindrical in shape with a diameter of 3 m and a height of 2 m. They were constructed from colourless corrugated acrylate sheets (Vetricell, ER, photosynthetically active radiation (PAR) transmission 90 %) bolted together on an aluminium frame. The thickness of the sheets was 1.5 mm, corrugation depth 18 mm and corrugation width 76 mm. One side of one sheet was left unbolted, which served as a door for entering the chamber. An overhead frustrum covered the upper end of the chamber; it was 35 cm wide and constructed from 1.0 mm thick polymethyl meta-acrylate sheets. Eight chambers were constructed, providing two independent replicates for each CO_2 x temperature treatment. Both wheat and meadow fescue were grown in each chamber, so that the meadow fescue occupied the southern side and the wheat, the northern side of the chamber. In this way, the meadow fescue canopy, which was cut from time to time, was not shaded by the wheat canopy.

The CO_2 gas was supplied to the chambers from a set of gas cylinders by vapour withdrawal, with each cylinder containing 28–30 kg of pure CO_2 gas (Woikoski OY in 1992 and AGA OY in 1993–1995, Finland). There were 12 cylinders together in a set, from which the gas was released through a heating device and a two stage pressure regulator, into rubber tubing of 12 mm in diameter, which led to a delivery stand inside the greenhouse. This main flow was divided into 8 minor flows, stopped with separate main valves. From this point, the gas was passed through solenoid valves regulated by an automatic measuring-dosing feedback-system (Itumic OY, Jyväskylä, Finland).

The feedback system functioned by sampling and analysing the air from two points in each chamber with elevated CO_2, both in the greenhouse and in the outside field. Depending on the analysis, the solenoid valves between the influx and outflux tubing were either opened or closed in order to adjust the CO_2 levels in the chambers with elevated CO_2, to the target CO_2 concentration, 700 ppm. Two separate sets of CO_2 dosings were applied for each chamber with elevated CO_2, functioning independently according to the two analysing systems in each chamber. As the system was originally planned to meet the needs of large greenhouse departments, it was unsatisfactory for chambers as small as our OTC:s. Therefore, in 1993 only one analysing-dosing-set of the CO_2-enriched chambers was set to operate automatically, while the other channel was open all day, and shut off only for the night. In 1994–1995, the automatic function of the CO_2 dosing system was shut off totally, and the CO_2 levels were operated manually, by adjusting the CO_2 flow rates according to the levels in the chambers. The air of the chambers with ambient CO_2 and over open air plots was analysed, but no CO_2 adjustment was applied.

From the solenoid valves, the CO_2 gas was delivered to the chambers individually, through separate flow meters and rubber tubing of 7 mm in diameter. Inside the chambers, the rubber tubing was perforated and criss-crossed over the plant canopy, in order to make the gas flow even. Overhead fans were attached to each chamber to mix the CO_2 gas with the chamber air, and also in an attempt to prevent the temperature in the chamber from rising above that outside the chamber. In 1994–1995, the fans were connected to a perforated plastic tunnel system, in which CO_2 from one of the separate dosing sets was introduced together with air from the overhead fans, while the other CO_2 dosing set was still connected to the perforated rubber tubing. In the ambient CO_2 chambers, a similar ventilation system was arranged, but with no CO_2 added. The tunnel was a standard greenhouse ventilation tunnel comprised of a thin plastic tube 24 cm in diameter. This configuration was built in order to achieve more uniform CO_2 levels and airflow inside the chambers.

The CO_2 source (the perforated rubber tubing or the plastic tunnel) was placed above, rather than within, the plant canopy in order to avoid the problem of CO_2 depletion due to plant uptake in the canopy during photosynthesis. The standard measurements of ambient atmospheric CO_2 concentrations were made in free air, between the CO_2 source and the plants. It is known that concentrations within a plant canopy can be significantly lower than these.

In 1993–1994, the CO_2 concentrations were sampled every 5–8 minutes by one of the two measuring channels in an OTC while in 1992, the sampling interval in each chamber was about 12 minutes. CO_2 measurements were transferred to a master unit for storage and analysis.

Experimental plots

Before the onset of the experiments, the heavy clay soil of the experimental area was mixed with peat containing 35 % sand. The peat-sand mixture was limed, but not fertilized and was added in the proportion of 0.1 m^3 of the mixture /m^2 of soil. In the autumn of 1993, this soil was replaced by sandy loam soil brought to the experimental field from another field in Jokioinen. The nutrient levels of the soil were tested before the sowings, and nutrients were added according to the test results, so that the nitrogen level of the soil

Vol. 5 (1996): 25–47.

would be approximately 120 kg/ha and the other nutrients would not limit growth.

At elevated temperatures, inside the greenhouse, the experimental plots for the spring-sown cereals and the grass crop were sown at normal sowing density shortly after the thermal growing season had started (i.e. when the temperatures were expected to stay constantly above 5 °C). According to this principle, in 1992–1995 the growing season started inside the greenhouse 25 April, 22 April, 19 April and 15 April, respectively. In the open field (ambient temperatures) the thermal growing season started 27 April, 22 April, 22 April and 20 April. In the open field there was a delay in the sowing because, while the temperatures rose rapidly at the onset of the growing season, the cold weather before the beginning of the growing season did not allow the soil to dry enough for sowing. The sowing dates were thus 14 May, 10 May, 9 May and 10 May from 1992 to 1995. Potato was planted in the outside field at the beginning of June to avoid late spring frosts and inside the greenhouse about 3 weeks earlier.

Crops and treatments

The spring wheat (*Triticum aestivum* L. var. "Polkka") and the grass crop, meadow fescue (*Festuca pratensis* Hudson var. "Kalevi") were grown in the following four treatments: a) ambient air temperature and ambient CO_2 concentration; b) increased temperature (3°C above ambient) and ambient CO_2; c) ambient temperature and elevated CO_2 (700 ppm), and d) increased temperature and elevated CO_2. In an effort to estimate the chamber effect, the phenology, growth and yield of the experimental plants inside the chambers were compared to those of the plants growing on the adjacent plots with no chamber (open air plots).

The other cereal crops, spring barley (*Hordeum vulgare* L. emend. Bowden, var. "Kymppi", Finland, and var. "Golf", Sweden) and winter wheat (*Triticum aestivum* L., var. Aura, Finland and var. Orestis, Germany), and potato (*Solanum tuberosum* L. var. "Pito", Finland and var. "Bintje", the Netherlands) were also grown at elevated temperatures and at ambient temperatures to measure growth reduction caused by pathogens, but no experiments with CO_2 were conducted. The growth, yield, phenology and occurrence of pests on the horticultural plants black currant (*Ribes nigrum* L., var. "Öjebyn", Sweden and var. "Ben Tirran", Scotland) and strawberry (*Fragaria* x *ananassa* Duch., var. "Ostara", the Netherlands, var. "Senga Sengana", Germany and var. "Bogota", Germany) were observed at elevated and at ambient temperatures.

Results and discussion

Temperatures

Daily mean temperatures in the greenhouse and in the open field (both in the OTC:s and in free air) during the period 22 July – 10 September in 1993 and 1994 are presented in Figure 2. The reason for choosing this period, is that the measurements of the temperatures were available in all the treatments, for both years, which makes comparisons between the different ventilation systems in the OTC:s possible. The results for 1995 are not shown here because the ventilation system of the greenhouse and in the OTC:s remained the same in 1995 as in 1994.

In the diagrams in Fig. 2, it can be seen that the greenhouse temperatures were constantly higher than the ambient temperatures. The temperature difference between the greenhouse and the open field was on average 3.2 °C (± 0.1 °C, range 2–4.4 °C) in 1993 and 3.0 °C (± 0.0 °C, range 2.2–3.4 °C) in 1994 during the period 22 July – 10 September. Temperatures within the OTC:s closely tracted those of the surrounding air in both 1993 and 1994. In 1993, the daily mean temperatures in the OTC:s during the period 22 July – 10 September were on average

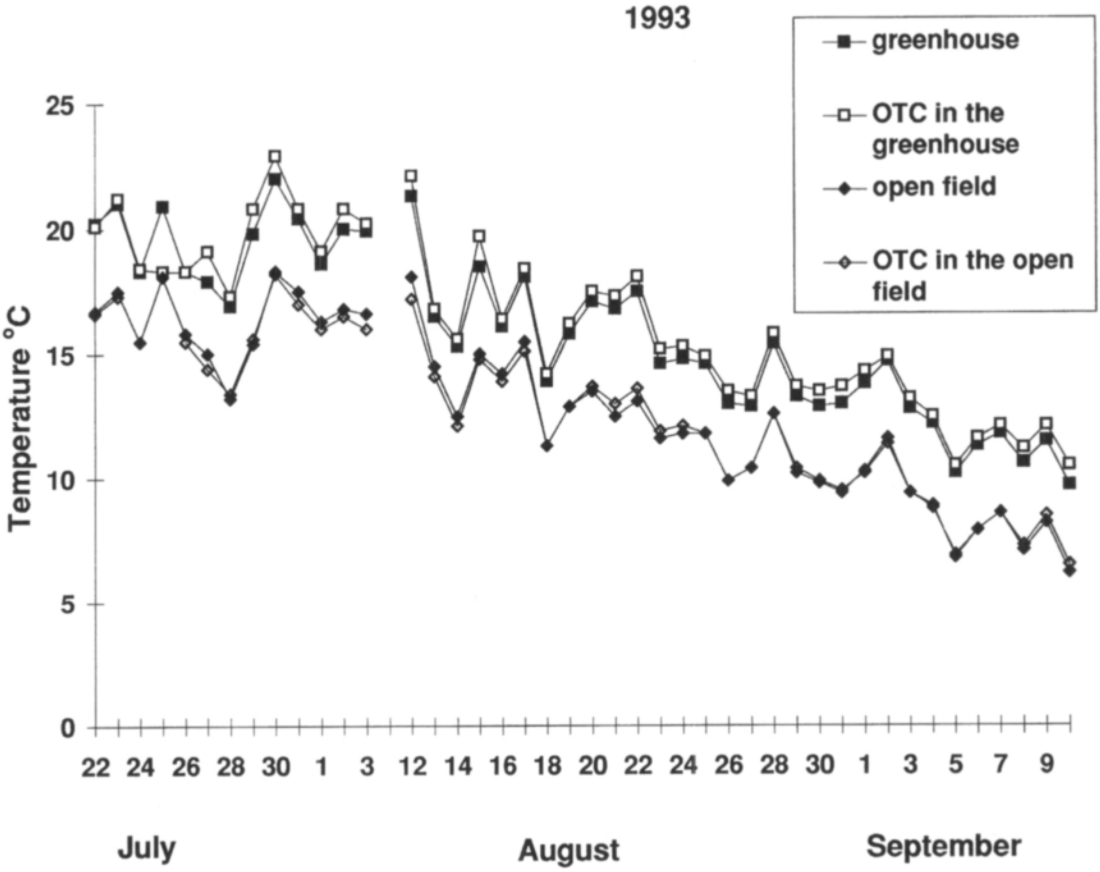


Fig. 2A. The ambient daily mean temperatures and the daily mean temperatures inside the open top chambers in the greenhouse and in the open field from 22nd July to 10th September in 1993.

0.4 °C (± 0.1 °C, range +1.2– –2.6) higher than the surrounding air inside the greenhouse and in 1994 the OTC temperatures were on average 0.5 °C (± 0.1, range +1.3– –1.3 °C) higher than the greenhouse temperatures. The difference in the OTC and the greenhouse temperature was approximately the same (within ± 0.1 °C) both during day (from 9–19) and night (from 19–9). In the open field, the OTC temperatures were approximately the same as the surrounding air in 1993 (within ± 0.05 °C, range +0.5– –0.9 °C) and 0.2 °C (± 0.1 °C, range +0.6– –1.6) lower than the surrounding air in 1994. The difference in temperature between the OTC:s and the open field was approximately the same during night and day in 1993; while in 1994, the temperatures were 0.4 °C lower in the OTC:s during the day, and the same as the open field temperatures dur-

Vol. 5 (1996): 25–47.

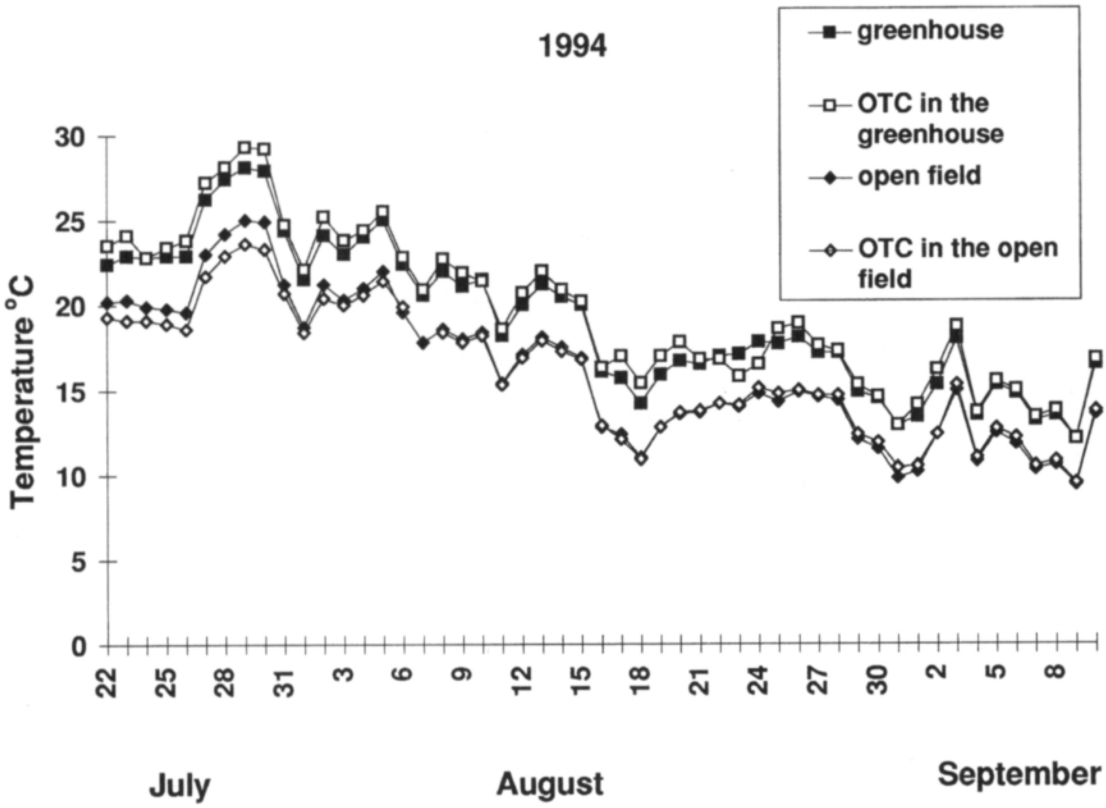


Fig. 2B. The ambient daily mean temperatures and the daily mean temperatures inside the open top chambers in the greenhouse and in the open field from 22nd July to 10th September in 1994.

ing the night. In Fig. 3 it can be seen that the ventilation system installed inside the OTC:s in 1994 was quite efficient in keeping the OTC temperatures at the level of the surrounding air in the greenhouse for both sunny and cloudy days (Figs. 3 B and 3 D). In 1993, the daytime chamber temperatures inside the greenhouse were 1–3 °C higher than the surrounding air temperatures on sunny days and about 0.5 °C higher on cloudy days (Figs. 3A and 3 C). In 1993, the chamber temperatures in the open field were more or less the same as the ambient surrounding temperatures both on sunny and cloudy days (Figs. 3 A and 3 C); while in 1994 the new ventilation system resulted in the daytime temperatures inside the OTC:s in the open field being about 1 °C lower than the ambient temperatures (Figs. 3 B and 3 D). The reason for the chamber

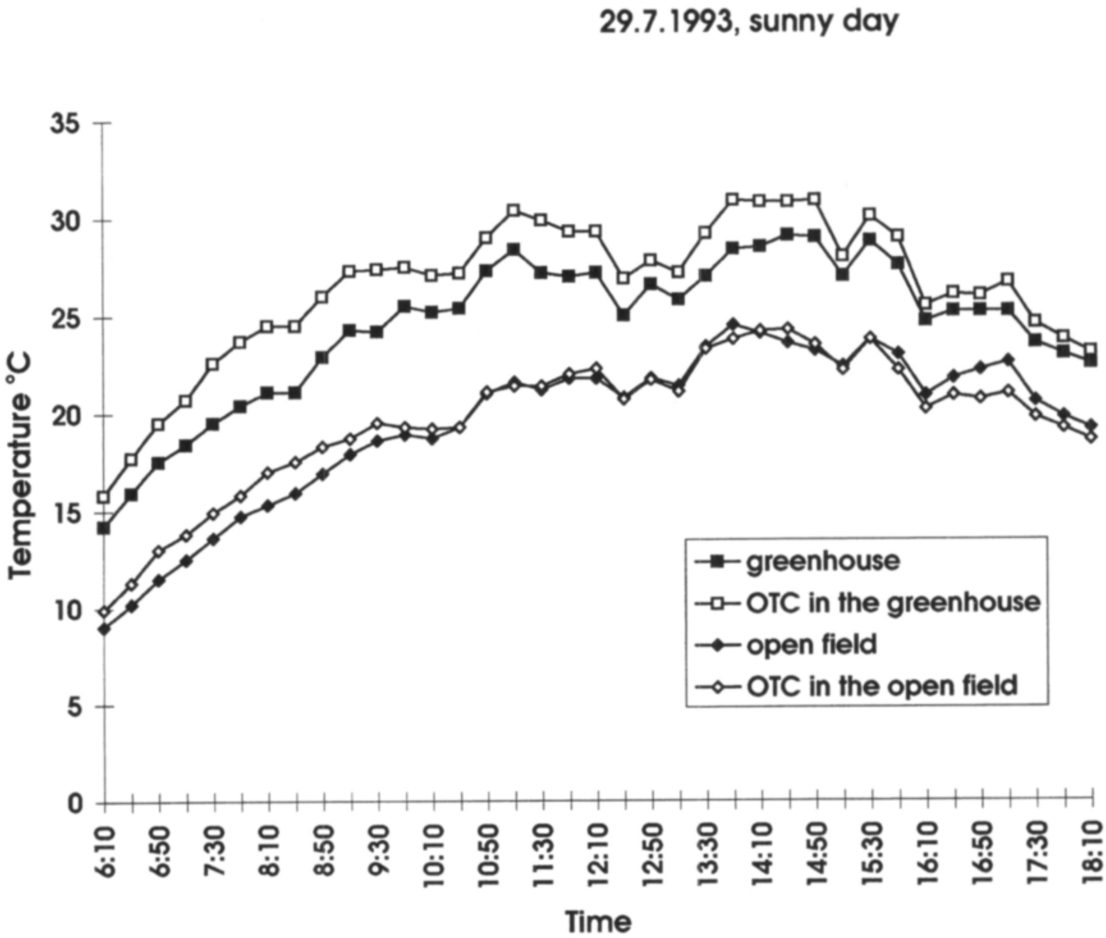


Fig. 3A. Temperatures in the greenhouse and in the open field and inside the open top chambers in the greenhouse and in the open field during a sunny day in 1993 (21.49 MJ/m²/day).

temperatures being lower than ambient temperatures could be that, in the open field, the fans inside the OTC:s provided higher rates of air-mixing than in the surrounding area, as the air in the open field was not mixed with fans, although it was covered with plastic film.

1–2 °C increases in daytime temperatures and 0.2–1°C increases in nighttime temperatures inside the OTC:s have been reported earlier (Heagle 1989; Ashenden et al. 1992). The daily mean temperatures in the OTC:s in our experiments differed very little from the surrounding temperatures, possibly because of the large size and the truly open structure of the OTC:s. However, in 1992–1993 the phenological development of wheat inside the OTC:s was 1–3 days ahead of the open air plots in the greenhouse and in the open field. In 1994, both in the greenhouse and

Vol. 5 (1996): 25–47.

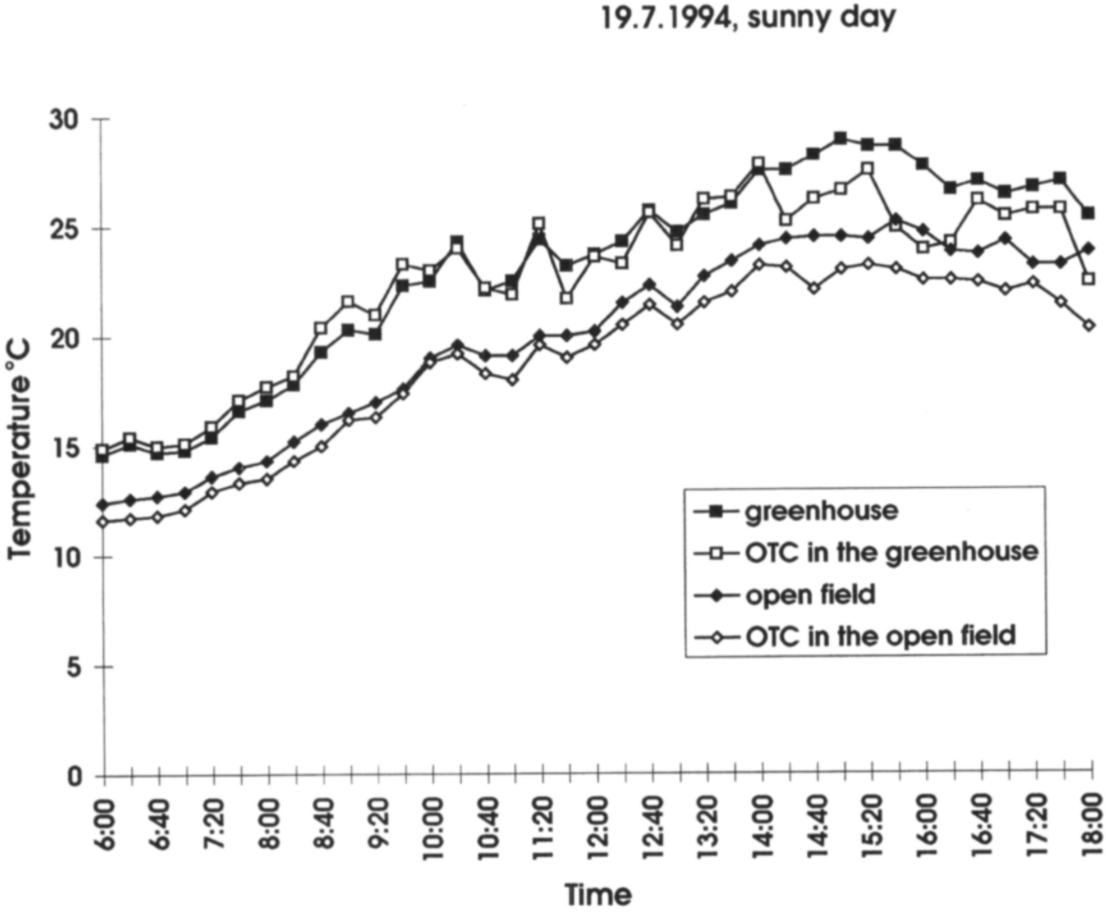


Fig. 3B. Temperatures in the greenhouse and in the open field and inside the open top chambers in the greenhouse and in the open field during a sunny day in 1994 (21.56 MJ/m^2/day).

in the open field, and in 1995 in the greenhouse, the phenological development of wheat proceeded at the same speed in the open air plots and in the OTC:s. In 1995, in the open field, the corresponding phenological stages were recorded 2–5 days earlier in the OTC:s than on the open air plots. The higher rate of development in the OTC:s may have been caused by the slightly higher OTC temperatures in 1992 and 1993. The delay in the development in the open air plots in the open field in 1995 compared to the development in the OTC:s cannot be explained by higher OTC temperatures because the OTC temperatures should have been lower than the ambient in the open field in 1995.

As air temperatures increased steadily during April–July and the crops were sown approximately three weeks earlier in the greenhouse

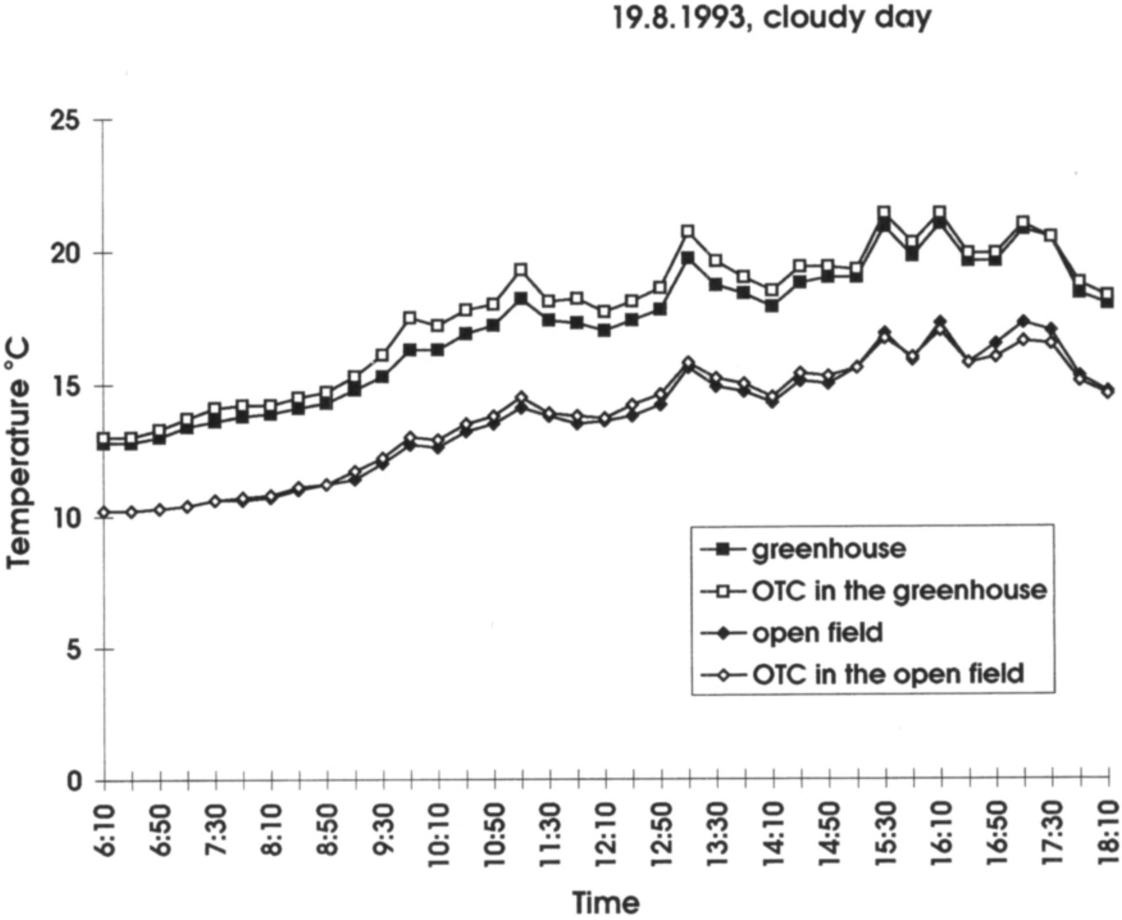


Fig. 3C. Temperatures in the greenhouse and in the open field and inside the open top chambers in the greenhouse and in the open field during a cloudy day in 1993 (10.16 MJ/m^2/day).

than in the open field, the temperatures experienced by the crops at comparable development stages were not necessarily higher in the elevated temperature treatment than in the ambient temperature treatment.

The beginning of the growing season for spring-sown crops was mostly cooler in the greenhouse than in the open field (Fig. 4). The effective temperature sum (ETS), base temperature 5 °C, accumulated faster in the open field during the first 12–15 days after sowing (DAS) in 1992 and in 1993, after which the accumulation rate of ETS became higher in the greenhouse (Fig. 4A and 4B). The ETS in the greenhouse exceeded that of the open field 39 DAS in 1992 and 29 DAS in 1993. In 1994 the accumulation rates of ETS in the greenhouse and in the open field were more or less the same dur-

Vol. 5 (1996): 25–47.

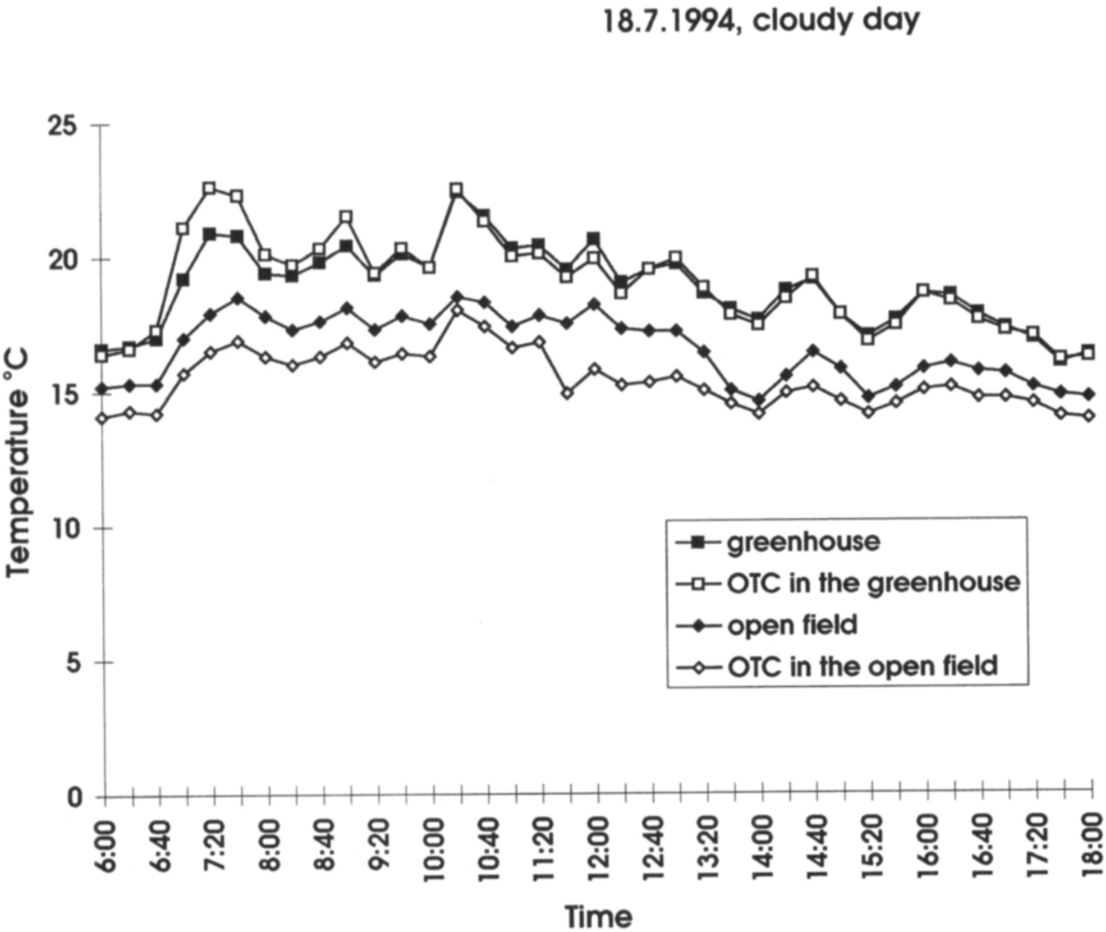


Fig. 3D. Temperatures in the greenhouse and in the open field and inside the open top chambers in the greenhouse and in the open field during a cloudy day in 1994 (10.33 $MJ/m^2/day$).

ing the growing season (Fig. 4C). In 1995 ETS in both the greenhouse and in the open field accumulated similarly during 20 DAS, then the accumulation of ETS was significantly slower in the greenhouse until 40 DAS and again faster towards the end of season (Fig. 4D). Because of the slow accumulation of ETS in the greenhouse, it did not exceed that in the open field until 65 DAS. The phenological stages of spring wheat grown in the open air plots are marked on the ETS diagrams in Fig. 4. The ETS for anthesis and yellow ripening was more or less the same, both at ambient, and at elevated temperatures in 1992–1994. In 1995 the ETS for anthesis was 140 degree-days and for yellow ripening 148 degree-days higher in ambient than in elevated temperatures (Fig. 4 D). The reason for this may be that the response of development rate to tem-

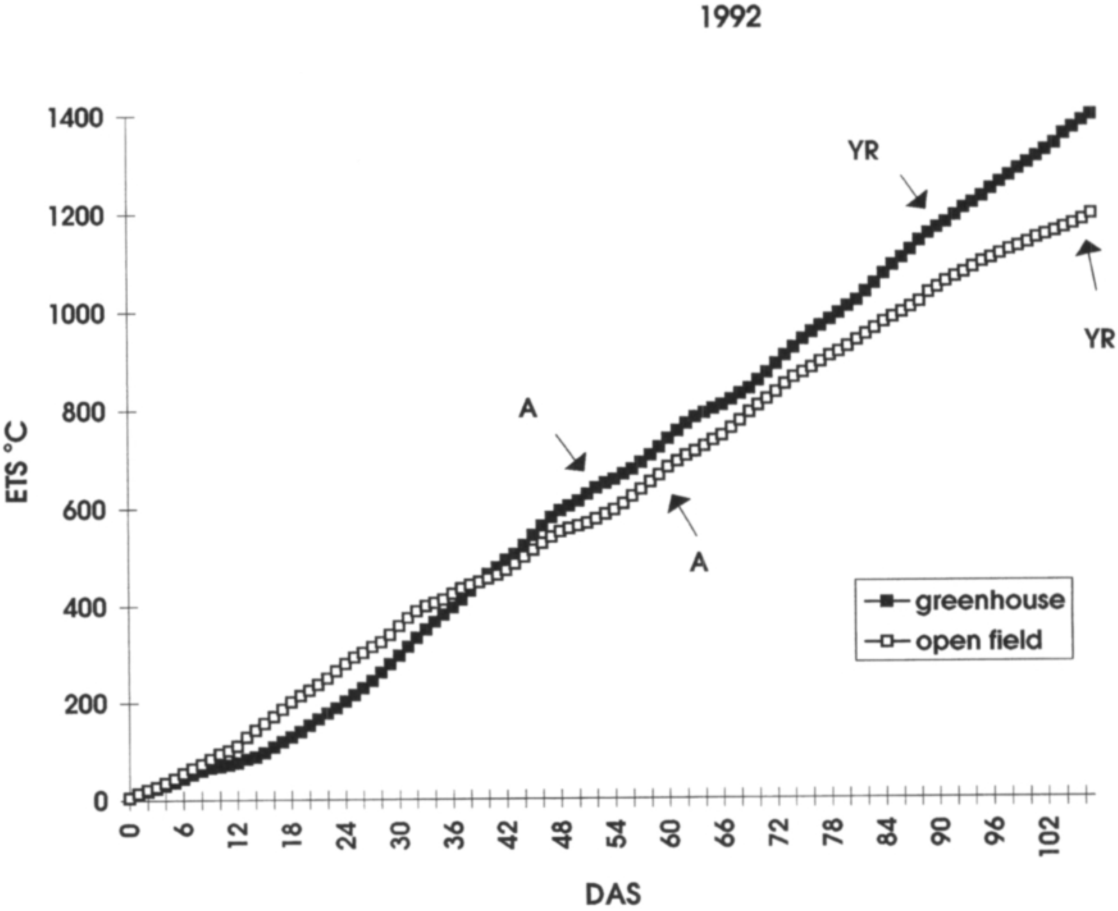


Fig. 4A. Effective temperature sum (ETS) vs. days after sowing (DAS) of spring cereals at elevated temperatures (greenhouse) and at ambient temperatures (open field) in 1992. The phenological stages of spring wheat "Polkka" are marked on the ETS curves: A = anthesis, YR = yellow ripening. The sowing dates inside the greenhouse and in the open field were, respectively, 29th April and 14th May in 1992.

perature may not have been linear, as the temperature peaked in the greenhouse 40–47 DAS and remained high (daily mean temperature about 20 °C) until heading (56 DAS) and anthesis (58 DAS). In the open field again, the high temperature period experienced by the crops in the greenhouse after 40 DAS, occurred at 18 DAS, and it was not as pronounced, while the temperatures were then 3 °C lower in the open field than in the greenhouse.

Relative humidity

The relative humidity (RH) of air was almost the same in the greenhouse as in the open field and the RH in the OTC:s was approximately the same as the RH of the surrounding air both in the

Vol. 5 (1996): 25–47.

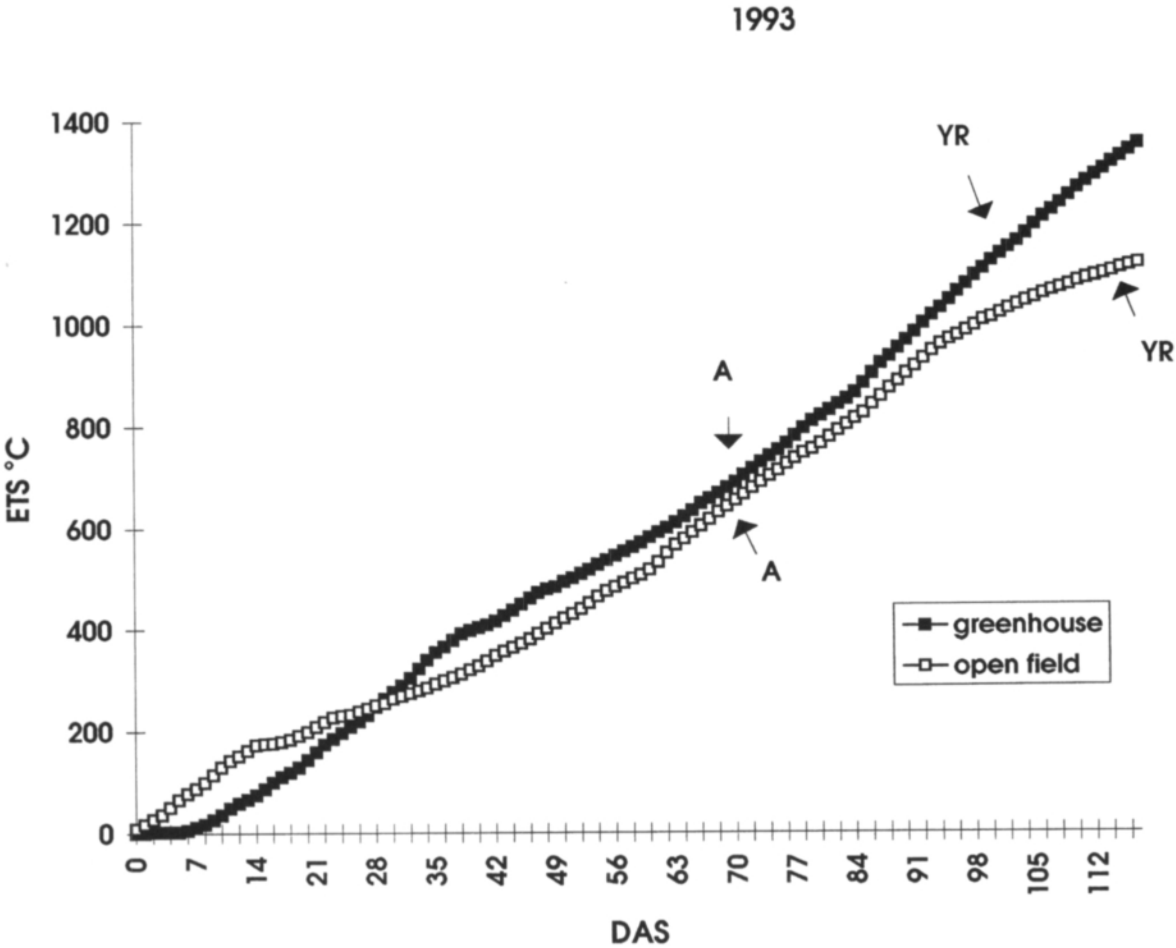


Fig. 4B. Effective temperature sum (ETS) vs. days after sowing (DAS) of spring cereals at elevated temperatures (greenhouse) and at ambient temperatures (open field) in 1993. The phenological stages of spring wheat "Polkka" are marked on the ETS curves: A = anthesis, YR = yellow ripening. The sowing dates inside the greenhouse and in the open field were, respectively, 16th April and 10th May in 1993.

greenhouse and in the open field in 1993. However, on a sunny day the RH of the OTC air inside the greenhouse was on average 5 % higher than the surrounding air (Figs. 5A and 5C). Slight increases (5 % or less) in the RH in the OTC:s have been reported earlier (Heagle 1989, Ashenden et al. 1992). In 1994, the RH in the greenhouse was 17–19 % higher than in the ambient air, and 7–10 % higher in the OTC:s than in the surrounding air both on sunny and cloudy days (Figs. 5B and 5D). The higher RH inside the greenhouse compared to the open field in 1994 was probably caused mainly by the permanent closure of the side openings of the greenhouse in 1994, when an extra fan was installed to mix the greenhouse air and to replace the ventilation through the side openings. The larger volume of perennial plants, which had been growing from

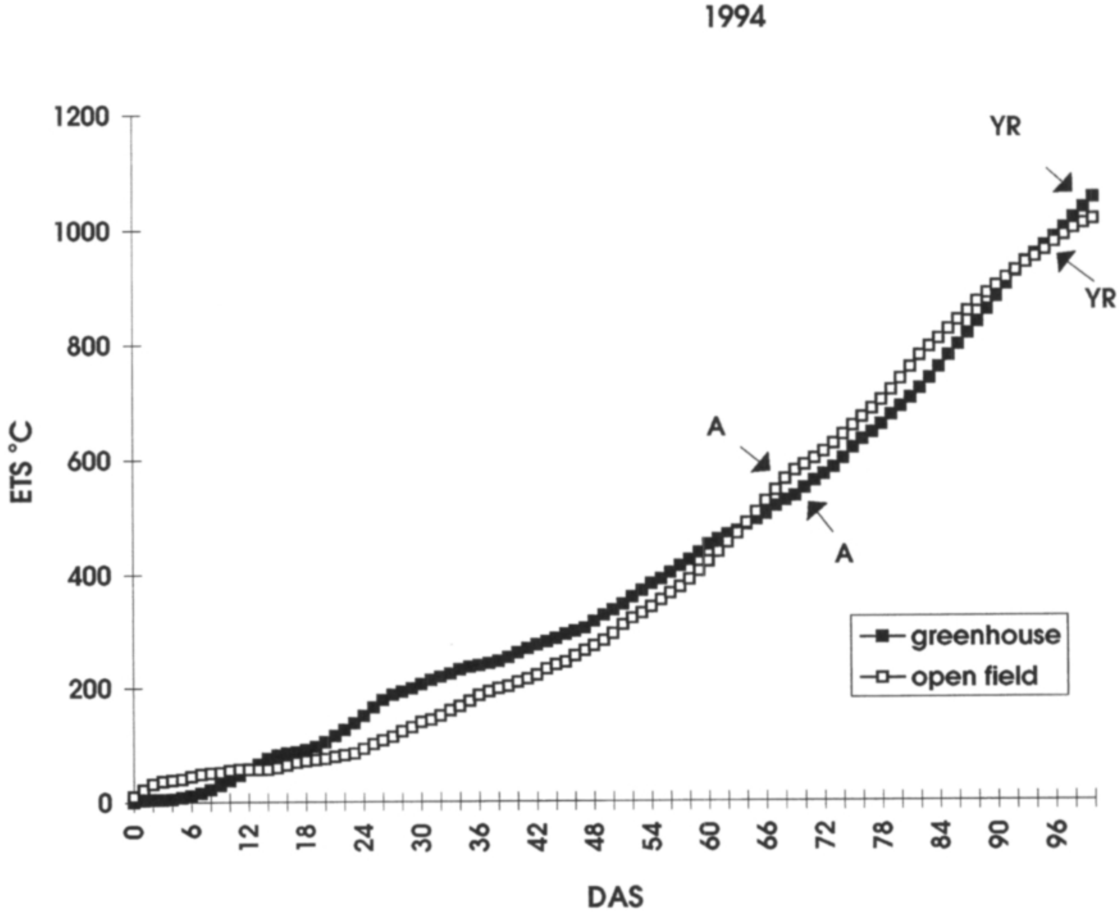


Fig. 4C. Effective temperature sum (ETS) vs. days after sowing (DAS) of spring cereals at elevated temperatures (greenhouse) and at ambient temperatures (open field) in 1994. The phenological stages of spring wheat "Polkka" are marked on the ETS curves: A = anthesis, YR = yellow ripening. The sowing dates inside the greenhouse and in the open field were, respectively, 15th April and 9th May in 1994.

the year 1992, may have also contributed to the higher humidities inside the greenhouse. The temperature differences between the OTC:s and the surrounding air in 1994 and 1993 may partly explain why the difference between the RH inside the OTC:s and in the surrounding air was greater in 1994 than in 1993. In 1994 the temperatures inside the OTC:s were lower than ambient temperatures in the open field, and inside the greenhouse the temperatures in the OTC:s were lower in 1994 than in 1993 during the daytime (Fig. 3).

The higher RH in the OTC:s and in the greenhouse could have given the plants a competitive advantage compared with those in the open field. At a higher RH, plants are able to maintain a higher stomatal conductance, resulting in better penetration of CO_2 into the leaves and thus, high-

Vol. 5 (1996): 25–47.

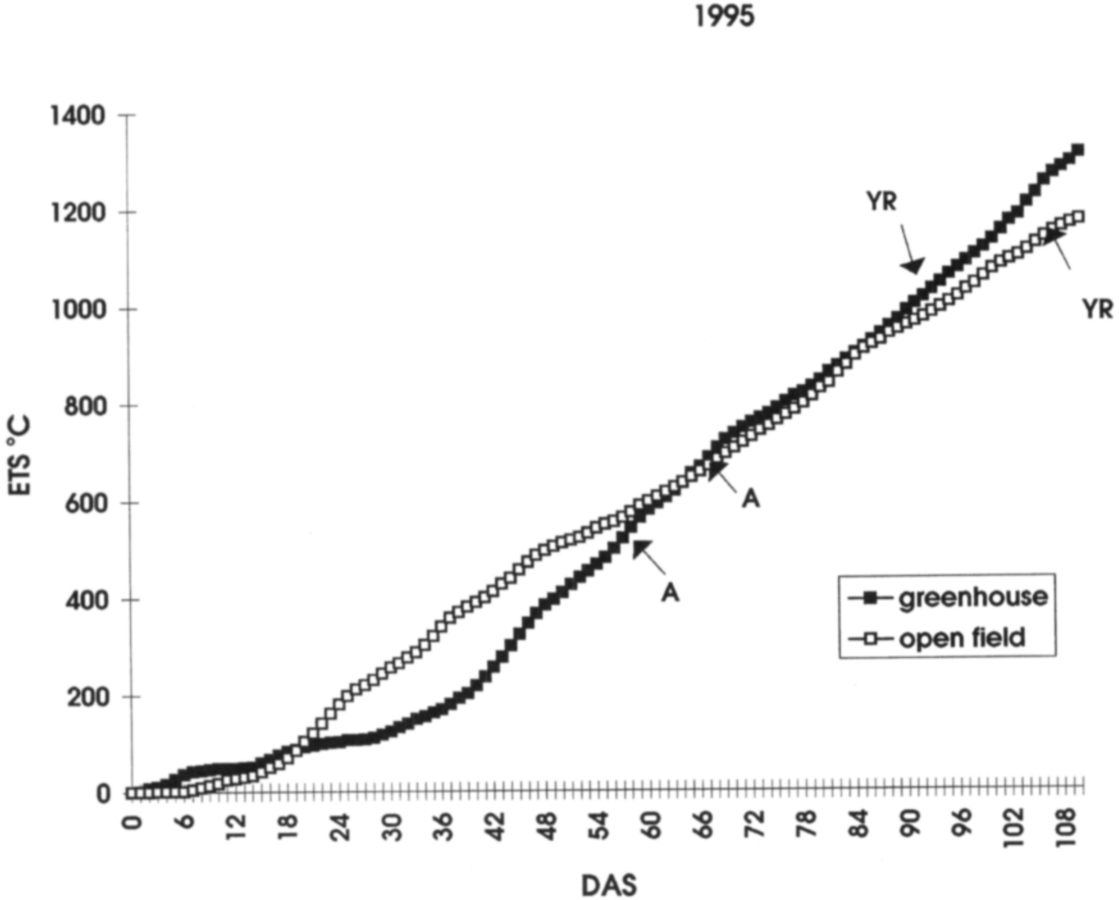


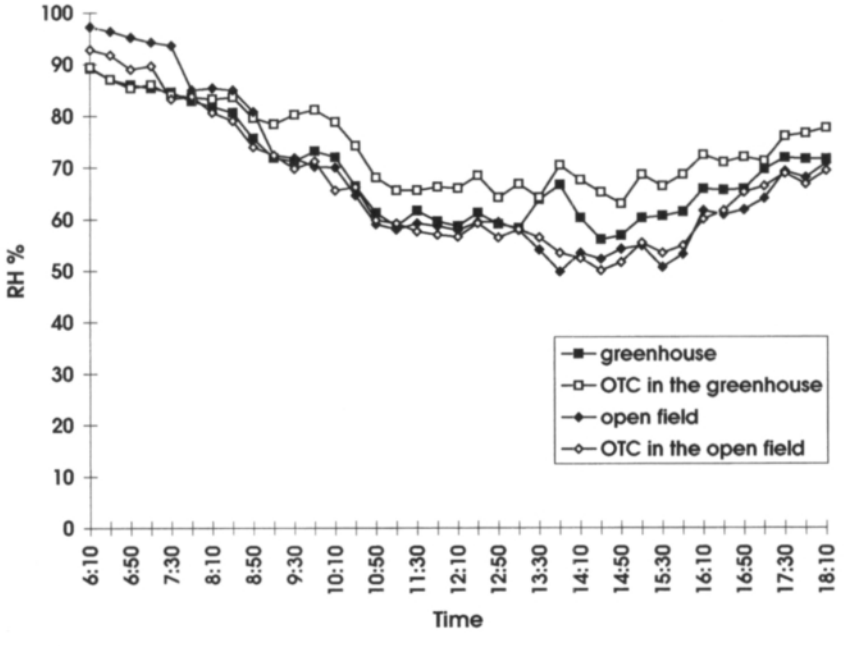
Fig. 4D. Effective temperature sum (ETS) vs. days after sowing (DAS) of spring cereals at elevated temperatures (greenhouse) and at ambient temperatures (open field) in 1995. The phenological stages of spring wheat "Polkka" are marked on the ETS curves: A = anthesis, YR = yellow ripening. The sowing dates inside the greenhouse and in the open field were, respectively, 18th April and 10th May in 1995.

er assimilation rates (Collatz et al. 1991). The comparison of plant growth between the greenhouse and the open field is thus complicated, especially after the increase in the RH of the greenhouse after 1994. However, both inside the greenhouse and in the open field, the comparison of plant growth between the CO_2 enriched OTC:s and the OTC:s with ambient CO_2 can be made reliably, as the ventilation systems in the OTC:s were identical, and thus the RH levels in the OTC:s should have been identical.

Increases in temperature and the RH, decreases in light intensity and changes in wind velocity and boundary layer resistance of the plants caused by an OTC have sometimes been found to affect plant growth and biomass yield inside the chambers (Heagle 1989). The effects have, however, been quite small and they vary accord-

5 A

29.7.1993, sunny day



5 B

19.7.1994, sunny day

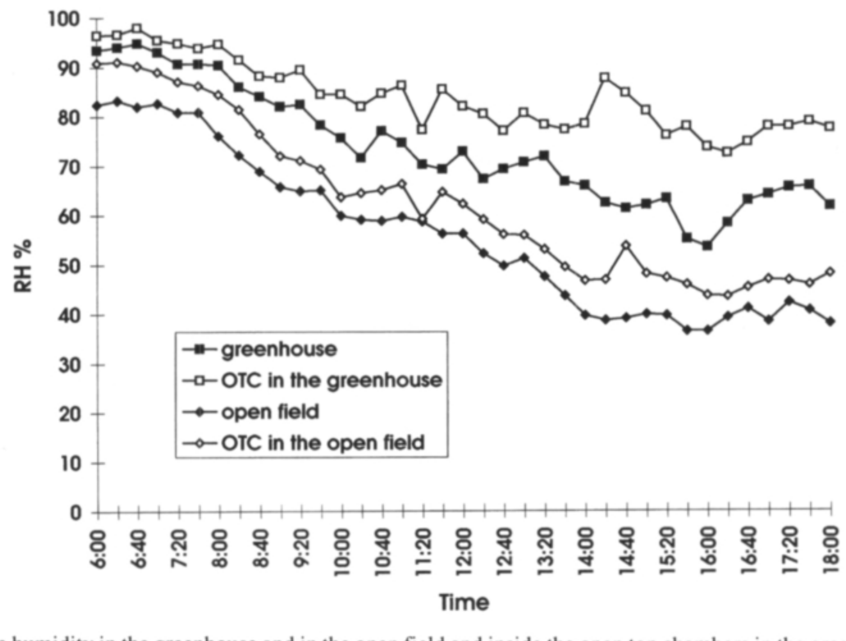
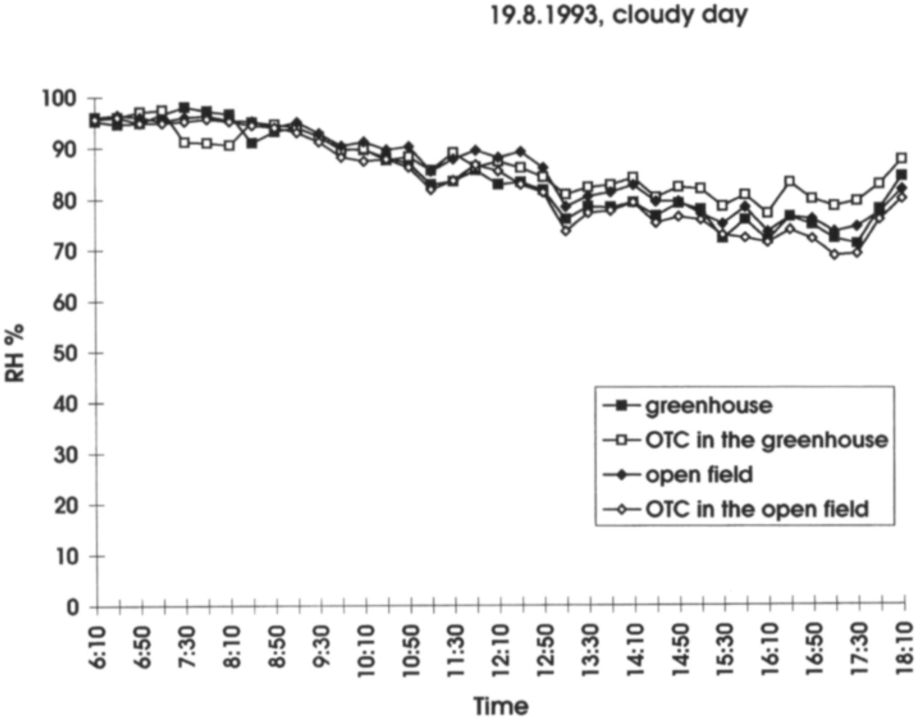


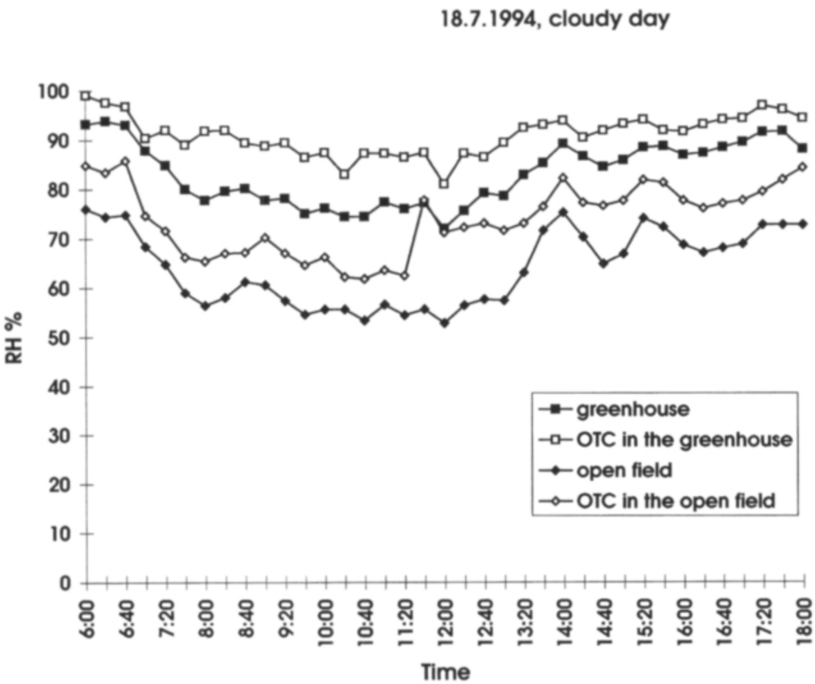
Fig. 5. Relative humidity in the greenhouse and in the open field and inside the open top chambers in the greenhouse and in the open field during a sunny day in A) 1993 (21.49 MJ/m^2/day) and B) 1994 (21.56 MJ/m^2/day) and during a cloudy day in C) 1993 (10.16 MJ/m^2/day) and D) 1994 (10.33 MJ/m^2/day).

Vol. 5 (1996): 25–47.

5 C



5 D



ing to the plant species, plant cultivar, growing season and cultivation site (Heagle 1989). In our experiments, the biomass of meadow fescue was on average (over the years 1992–1995) 2 % higher (varying from 13 % lower to 15 % higher) in the OTC than in open air plots in the greenhouse and 20 % higher (9–37 % higher) in the OTC in the open field. The yield of wheat was on average 15 % higher and the biomass 7 % higher inside the OTC than in open air plots in the open field, while in the greenhouse both the yield and biomass of wheat were 13 % lower in the OTC than in open air plots.

Even though the levels of radiation were about 40 % lower under the plastic film covering both the greenhouse and the open field, the yield of meadow fescue "Kalevi" on the open air plots was 30 % higher in the open field and 70–170 % higher in the greenhouse as compared to the 8 year average yield of the same variety in the official variety tests over a comparable area in Finland. The yield of the spring wheat "Polkka" in the open air plots was 40–50 % higher in the open field and 20–60 % higher in the greenhouse than the 8 year average yield of the same variety in the official variety tests.

CO_2 levels

The average CO_2 concentrations in Table 1 were computed over the two CO_2-enriched chambers, referred to with numbers 1 and 2 inside the greenhouse, and 3 and 4 in the open field. First, hourly mean values were calculated from the concentration samples drawn every 5–12 minutes. Then, the average concentrations were computed from the hourly values (6 a.m. to 6 p.m.) over periods varying from almost 5 months (1993, elevated temperatures) to 2.5 months (in 1994) (the exact periods are listed in the legend of Table 1), which means that the figures in Table 1 are computed from 147–76 hourly observations. The variation of the CO_2 concentrations in the individual OTC:s is expressed as the standard error of the mean. The concentrations in each chamber are the means of two measuring channels. The data for the year 1995 is not presented, because the CO_2 dosing system was the same as in 1994.

It can be seen in Table 1 that the control of CO_2 levels inside the chambers improved from year to year as the system was modified. The best results were achieved with the system introduced in 1994, in which CO_2-enriched air was delivered through the plastic tunnel. As CO_2 levels were substantially higher during the night, only the hours with levels of light intensity high enough to support photosynthesis throughout the growing season are listed here. The nighttime accumulation of CO_2 in the chambers was greater inside the greenhouse than in the outside field. This is partly due to crop and soil respiration. The CO_2 released could not escape from the greenhouse, as the hatches were usually closed at night to maintain the desired temperature levels.

The daytime variations of the CO_2 levels in the CO_2-enriched chambers, both inside the greenhouse and in the open field in 1993 and 1994, are presented in Fig. 6. The variation in the CO_2 levels in the OTC:s in 1992 has been presented earlier (Hakala et al. 1993). The mean daytime CO_2 levels recorded from one measuring point in one chamber ranged from 600–800 ppm and 650–1000 ppm inside the greenhouse and from 550–650 ppm and 600–700 ppm in the open field in 1993 and 1994, respectively. The variation in the CO_2 levels was larger inside the greenhouse than in the open field in both 1993 and 1994. In 1993 the variation was smaller than in 1994, when the CO_2 levels were higher (Fig. 6). The larger variation of the CO_2 levels inside the greenhouse in 1992 compared to 1993 is explained by the different method of measurement used in 1992 which resulted in a longer time lag (12 minutes) of measuring the CO_2 levels in the individual chambers. This emphasises the problems of feedback systems with long time delays. In addition to the long time delay, both dosing channels were operated automatically in 1992, which led to unsatisfactorily low CO_2 levels.

The CO_2 levels in the chambers not fed with CO_2, both inside the greenhouse and in the open

Vol. 5 (1996): 25–47.

Table 1. Mean CO_2 levels in the CO_2-enriched open top chambers during the day inside the greenhouse (OTC 1 and 2) and in the open field (OTC 3 and 4), and the difference of the mean CO_2 levels (SEM) between the replicate OTC:s in 1992, 1993 and 1994. The hourly CO_2 level values are means of the values during 14th May – 22nd September in 1992, 21st April – 14th September in the greenhouse and 1st June – 14th September in the open field in 1993 and 1st July – 14th September in 1994.

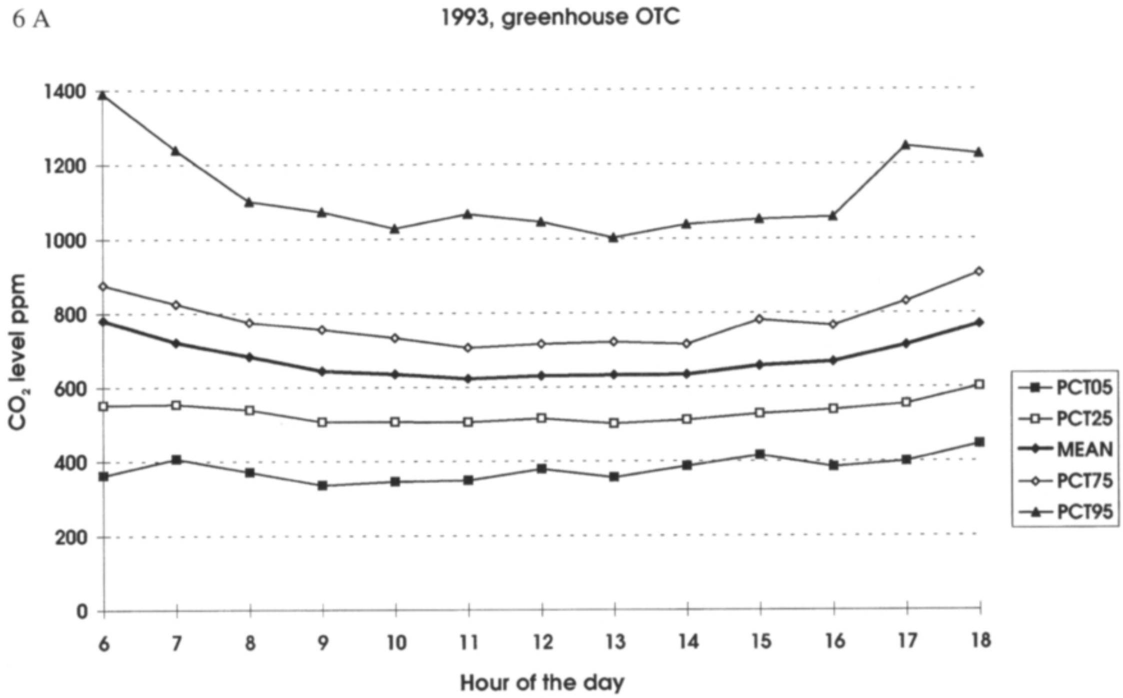
	1992, elevated T		1992, ambient T		1993, elevated T		1993, ambient T		1994, elevated T		1994, ambient T	
Time of day	MEAN OTC 1,2	SEM OTC 1,2	MEAN OTC 3,4	SEM OTC 3,4	MEAN OTC 1,2	SEM OTC 1,2	MEAN OTC 3,4	SEM OTC 3,4	MEAN OTC 1,2	SEM OTC 1,2	MEAN OTC 3,4	SEM OTC 3,4
6	734	48	569	14	702	27	613	26	1044	11	780	75
7	709	63	531	15	657	25	593	27	982	12	821	88
8	685	71	508	16	619	26	567	25	911	24	798	101
9	643	65	483	16	587	25	538	21	803	13	747	109
10	628	69	471	16	578	27	533	20	735	18	697	94
11	618	69	471	15	575	26	528	18	692	18	669	99
12	614	59	480	14	581	26	528	20	669	12	653	80
13	620	63	482	15	587	25	542	20	679	17	648	80
14	625	59	487	15	587	25	545	21	701	19	668	84
15	647	69	497	16	602	27	543	23	721	19	642	67
16	665	66	505	16	610	29	545	23	747	21	662	74
17	701	68	527	21	648	33	569	27	809	22	689	81
18	742	61	555	20	692	34	602	30	867	12	714	76

field, also fluctuated diurnally, being highest during the night and lowest during the day. The mean daytime CO_2 concentrations were approximately the same both in the OTC:s with ambient CO_2 and over open air plots, i.e. 380–400 ppm in the greenhouse and about 350 ppm in the open field.

In previous investigations with large OTC:s, the daily mean CO_2 values inside the chambers were within 9 % of the desired value (Drake et al. 1985). The variation of the mean CO_2 values was smaller (less than 6 %), when the chambers were smaller (diameter 1.28 m and 1 m high) and partially covered (average of three chambers over a 24 h period, Ashenden et al. 1992) or as big as the chambers in our experiment, but partially covered (average daily CO_2 levels over a period from May to August, Fig. 4 in Weigel et al. 1992). In the present study, in an effort to keep the conditions as close to natural as possible, the OTC:s were large, and there were no extra covers other than the frustrum on top of the OTC:s to control the CO_2 levels.

Conclusion

The elevation of the temperature succeeded well with respect to the temperature difference between the greenhouse and the open field, and could be controlled quite accurately. The control of the temperatures required the construction of an artificial system, the greenhouse, inside which conditions were not fully comparable with the natural (i.e. field) environment. The major differences compared to natural conditions were 1) the light intensity, which was cut by 40 % at the PAR wavelenght (400–700 nm) region and totally at the UV-B region 2) the RH which was on average 17–19 % higher inside the greenhouse than in the open field during the daytime, particularly after the modification of the greenhouse ventilation system in 1994 (ventilation through the side openings was stopped and the air was mixed with a fan) and 3) wind velocity. The differences in wind velocity between the greenhouse and the open field were not studied, 6 A



6 B

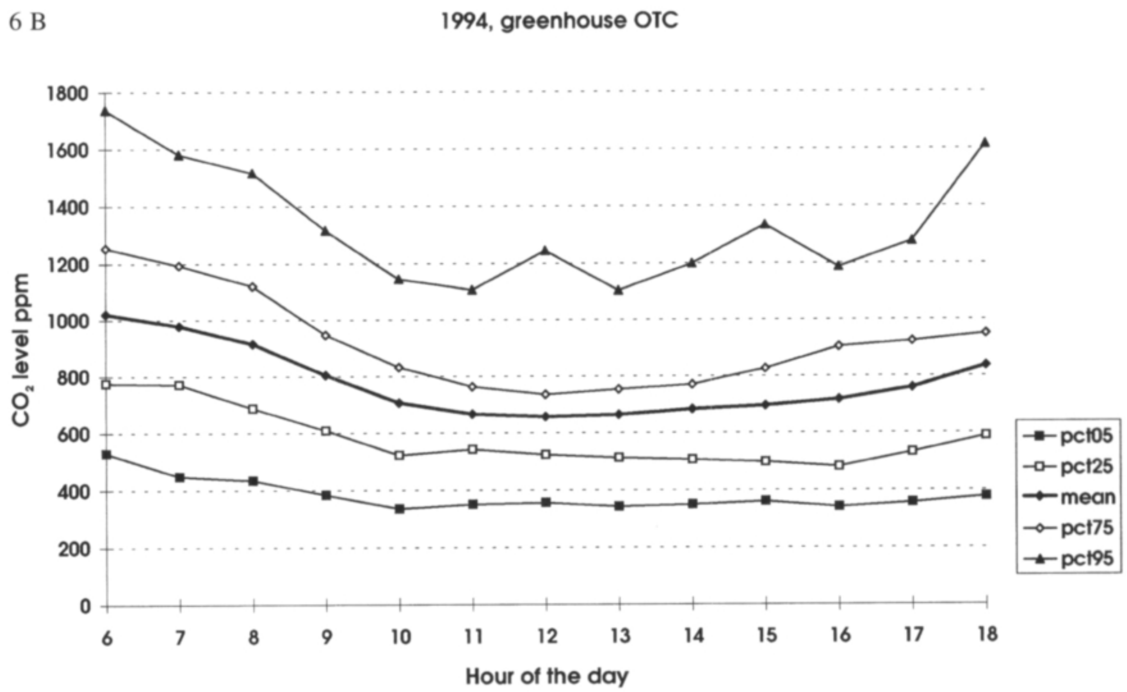
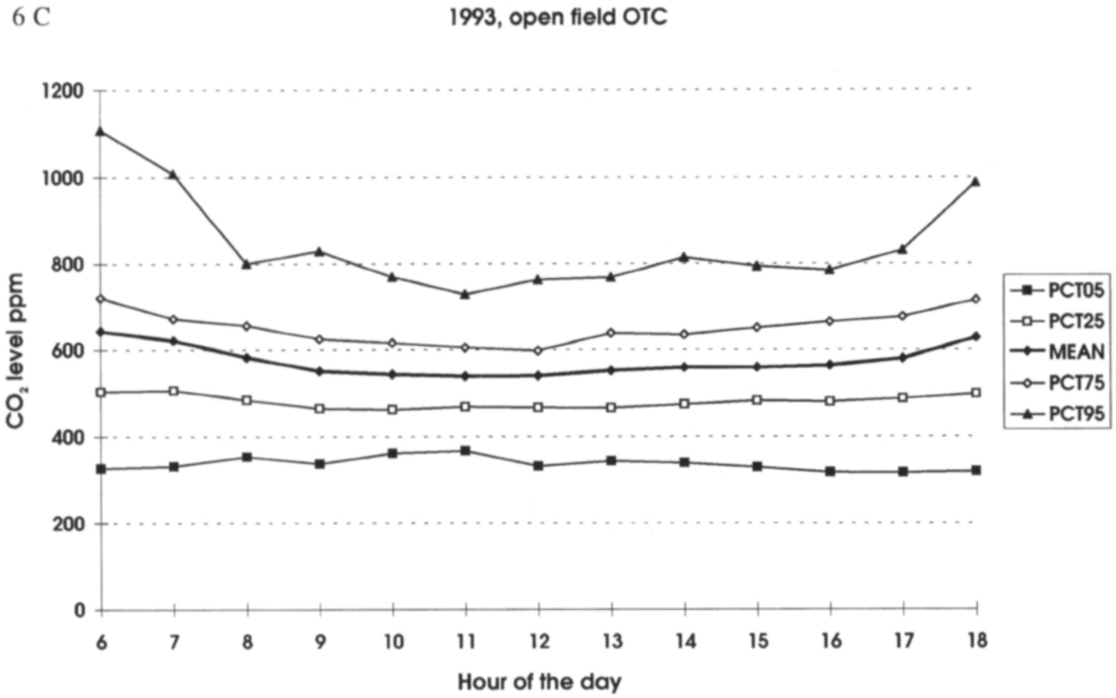


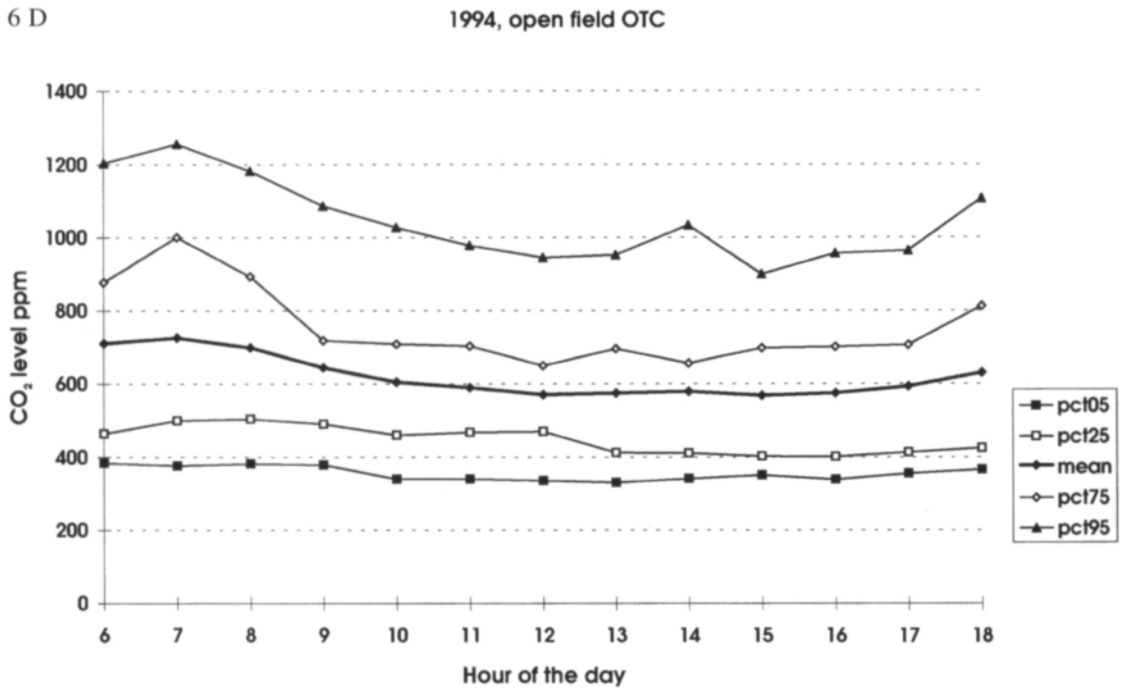
Fig. 6. Mean CO_2 levels during the day and the 0.05, 0.25, 0.75 and 0.95 percentiles of the observations in the greenhouse in A) 1993 and B) 1994 and in the open field in C) 1993 and D) 1994. The means and the percentiles were calculated from the hourly means of the observations during the periods 21st April – 14th September in the greenhouse and 1st June – 14th September in the open field in 1993 and 1st July – 14th September in 1994.

Vol. 5 (1996): 25–47.

6 C



6 D



but wind velocity is expected to be higher in the open field than inside the greenhouse. The temperature control plots that were sown on the adjacent field and covered with the same plastic as the greenhouse were protected from rainfall and received approximately the same amount of incident light as those inside the greenhouse. However, the RH and wind conditions in the open field remained different from the conditions in the greenhouse.

The OTC:s built for the CO_2 experiments had little effect on the temperatures, but the RH in the chambers was 7–10 % higher than in the surrounding air after the new ventilation system was installed in 1994. This system passed both CO_2 and air into the chamber through a perforated ventilation tunnel. In 1993, the RH in the OTC:s was more or less the same as in the surrounding air except in the greenhouse on sunny days, when the RH was about 5 % higher in the OTC:s. In 1992, the first year of experimentation, the CO_2 levels in the CO_2-enriched OTC:s were quite satisfactory inside the greenhouse, but in the open field the CO_2 concentrations could not be kept at a high enough level. The control over the CO_2 levels in the CO_2-enriched OTC:s improved in 1993 and still further in 1994, when the new ventilation system was installed in the OTC:s. The variation in the CO_2 levels could not be removed even with this new system. In spite of the variation, the CO_2 levels in the CO_2-enriched OTC:s were near the target of 700 ppm most of the time during the years 1993–1994 both in the open field and inside the greenhouse.

Acknowledgements: This work is a part of the Finnish Research Program for Climate Change (SILMU) and it was supported partly by the Academy of Finland. The skillfull technical assistance of Mr. Jari Poikulainen and Mr. Juha Naatula is gratefully acknowledged.

References

Ashenden, T.W., Baxter, R. & Rafarel, C.R. 1992. An inexpensive system for exposing plants in the field to elevated concentrations of CO_2. Plant, Cell and Environment 15: 365–372.

Bowes, G. 1991. Growth at elevated CO_2: photosynthetic responses mediated through Rubisco. Plant, Cell and Environment 14: 795–806.

Collatz, G.J., Ball, J.T., Grivet, C. & Berry, J.A. 1991. Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: a model that includes a laminar boundary layer. Agricultural and Forest Meteorology 54: 107–136.

Drake, B.G., Rogers, H.H. & Allen, L.H., Jr. 1985. Methods of exposing plants to elevated carbon dioxide. In: Strain, B.R. & Cure, J.D (eds.). Direct Effects of Increasing Carbon Dioxide on Vegetation. US Dept. of Energy, Office of Energy Research, Washington, USA. p. 11–31.

Hakala, K., Kaukoranta, T., Laurila, H., Mela, T. & Poikulainen, J. 1993. Preliminary report on open top chamber experiments with field-sown wheat and meadow fescue: experiments with elevated CO_2 levels and elevated (+3 °C) temperatures. In: Jäger, H. J., Unsworth, M., De Temmerman, L. & Mathy, P. (eds.). Effects of Air Pollution on Agricultural Crops in Europe. Air Pollution Research Report 46, Commission of the European Communities, Brussels. p. 531–549.

Heagle, A.S. 1989. Ozone and crop yield. Annual Review of Phytopathology 27: 397–423.

Houghton, J.T., Callander, B.A. & Varney, S.K. (eds.) 1992. Climate Change 1992: The supplementary report to the IPCC Scientific Assessment. Cambridge University Press, Cambridge. 200 p.

Lawlor, D.W. & Mitchell, R.A.C. 1991. The effects of increasing CO_2 on crop photosynthesis and productivity: a review of field studies. Plant, Cell and Environment 14: 807–818.

Mela, T., Carter, T., Hakala, K., Hannukkala, A., Hannukkala, A., Kaukoranta, T., Laurila, H., Saarikko, R., Tahvonen, R., Tiilikkala, K. &Tuovinen, T. 1994. The effects of climatic change on crop production. In: Kanninen, M. & Anttila, P. (eds.).The Finnish research programme on climatic change. Second Progress report. Publications of the Academy of Finland 1/94. Painatuskeskus OY, Helsinki. p. 233–243.

Weigel, H.-J., Mejer, G.-J. & Jäger, H.-J. 1992. Auswirkungen von Klimaänderungen auf die Landwirtschaft: Open-top Kammern zur Untersuchung von Langzeitwirkungen erhöhter CO_2- Konzentrationen auf landwirtschaftliche Pflanzen. Angew. Bot. 66: 135–142.

Vol. 5 (1996): 25–47.

SELOSTUS

Koejärjestelyt kohonneen lämpötilan ja CO_2-tason vaikutusten simuloimiseksi peltokasveilla Suomessa

Kaija Hakala, Timo Kaukoranta, Timo Mela ja Heikki Laurila
Maatalouden tutkimuskeskus

Vuosina 1992–1995 tehdyssä tutkimuksessa pyrittiin rakentamaan koejärjestelyt, joiden avulla saataisiin selvitettyä kohonneen lämpötilan ja CO_2-pitoisuuden vaikutuksia peltokasveihin. Koe aloitettiin kylvämällä tai istuttamalla kevätvehnää, syysvehnää, ohraa, nurminataa, perunaa, mansikkaa ja mustaherukkaa peltoon, jonka toinen osa oli peitetty automaattisesti säädellyllä kasvihuoneella, jotta sen lämpötila saataisiin kohoamaan kolme astetta ulkolämpötilaa korkeammaksi. Lämpötilaa ei kohotettu pellon toisessa osassa, mutta se katettiin samanlaisella muovikalvolla kuin kasvihuone, jotta säteilytasot ja sateen määrä olisivat vertailukelpoiset pellon molemmissa osissa. Sekä avoimelle pellolle että kasvihuoneeseen rakennettiin neljä päältä avointa kammiota, joiden halkaisija oli kolme metriä. Kahteen kammioon kasvihuoneessa ja avoimella pellolla johdettiin puhdasta CO_2-kaasua, jotta CO_2-pitoisuus saataisiin nostettua arvoon 700 ppm. Kasvihuoneen lämpötila pysyi melko tarkasti toivotut kolme astetta ulkolämpötilaa korkeampana. Suhteellinen kosteus oli kasvihuoneessa ja kammioissa hiukan suurempi kuin avoimella pellolla etenkin sen jälkeen, kun kasvihuoneen ja kammioiden tuuletusta muutettiin vuonna 1994. Kammioiden suuren koon takia niiden lämpötila ei juuri poikennut ulkoilman lämpötiloista, mutta CO_2-pitoisuudet vaihtelivat melko paljon niissä kammioissa, joissa pitoisuutta oli kohotettu. CO_2-tasojen säätö parani, kun kaasua annostelevaa systeemiä kehitettiin vuosina 1992–1994. Koejärjestelyn vaikutuksia kasvien kasvuun ja fenologiaan havainnoitiin koko tutkimuksen ajan.