Have you ever rewritten an article? Dr. H. Z. Enoch from the Agricultural Research Organization, Bet-Dagan, Israel, kindly corrected, rewrote and expanded this article recently published in the January Newsletter (#83). The new text is as follows:

CARBON DIOXIDE USE IN COLD GREENHOUSES

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Should carbon dioxide (CO_2) enrichment of greenhouse atmospheres be continued when temperatures are lowered? Yes!

When severe cold weather occurs, some growers have lowered temperatures to conserve fuel knowing full well that growth will slow down. They then reason that the crops will not benefit from CO_2 enrichment so why spend the money for gas. Neither plant physiologists nor greenhouse engineers can agree with this.

From an engineering viewpoint, CO_2 does not cost anything. The heat from the gas burned and accumulation of solar energy at the higher day temperatures practiced with CO_2 enriched atmospheres reduce fuel consumption sufficiently to pay for the propane or natural gas used to produce the CO_2. This is detailed in the Connecticut Greenhouse Newsletter 77: 18-19, January, 1977. It has been calculated (Enoch, 1978) that a CO_2 enrichment of 1000 ppm gives a mean temperature increase of 2.4^{o}C (4.5^{o}F) under U.K. Glasshouse conditions.

From a physiologist's viewpoint, plants may be considered as efficient users of CO_2 also at low temperatures and therefore do respond to atmospheric CO_2 enrichment. The following paragraphs treat several arguments substantiating why CO_2 should be used even when temperatures are below normal.

The process of photosynthesis is somewhat insensitive to low temperature. In greenhouse crops the limiting factor in photosynthesis is most frequently light or carbon dioxide (CO_2) in correlation with the temperature. Greenhouse crops are generally grown at the maximum temperature possible that is commensurate with the food (photosynthate) available in their tissues for an acceptable quality and rate of growth. Lower temperatures generally improve quality but delay production.

Hurd and Enoch (1976) have found that the rate of net photosynthesis and transpiration during the day is not influenced in carnations by the temperature of the preceeding night. The effect of CO_2 enrichment on net photosynthesis of carnations seem to be equally worthwhile at all temperatures between 5 and 30^{o}C (see Figure 6, Enoch & Hurd, 1977). Only at the highest light intensity (equivalent to summer midday radiation conditions) and leaf temperature below 12^{o}C did CO_2 enrichment appear to be ineffective in increasing net photosynthesis.

The benefit of CO_2 enrichment on net photosynthesis at all combinations of light, CO_2 and temperature can be calculated from the equation (see p. 383, Enoch 1977) which gives F net photosynthesis (in mg CO_2 10^{-1} dm^{-2} h^{-1}) as a function of (i) light (in Wm^{-2} photosynthetic action radiation), (c) CO_2 concentration (ppm on volume basis) and (t) leaf temperature (in ^{o}C).

$$F = 0.3116\, i^{0.789} c^{0.241} t^{0.167} - [5.673 + 5.182\, \ln(i)]\, 2^{(t-20)/10}$$

In order to obtain a numerical expression for the benefit of CO_2 enrichment at a given light and temperature regime, insert 2 values for c--one the normal CO_2 concentration of air (=330 ppm) and the other the elevated level, for instance 1500 or 2000 ppm. The calculations can be made on a relatively simple pocket calculator.

Plant growth may be reduced by many factors such as water stress, lack of photosynthate and temperature. Water stress often occurs when roots (and soil) are cold. Lack of photosynthate may be attributed to inadequate translocation, low light and/or insufficient CO_2. It is not possible to eliminate CO_2 as a limiting factor through enrichment of the greenhouse atmosphere to 1000-1500 ppm. At all light intensities additional CO_2 will increase photosynthesis.

It may be argued that when temperatures are low the slow growth rate will place less demand on atmospheric CO_2 supplies and that CO_2 will not be as limiting. This is confounded by another plant response, stomatal closure at reduced temperatures which would reduce CO_2 diffusion into the stomates. Early in the morning the CO_2 in the leaf from nighttime respiration will be sufficient for a few minutes only, whereupon it could be rapidly depleted. Increased levels in the atmosphere would thus be necessary to permit adequate diffusion of CO_2 through the partially closed stomatal apertures.

An opposing factor is the solubility of CO_2 (and oxygen) in plant tissue at low temperatures. Solubility is inversely related to temperature. A leaf will probably contain more CO_2 when night temperatures are decreased (Leopold and Kriedemann, 1975)*. One might argue that CO_2 injection may be delayed in the morning following cold nights. This may not even be valid on a dark day. When light is available, the CO_2 in the tissues is rapidly depleted and the stomatal apertures open sufficiently to allow CO_2 diffusion into the leaf. However, low air temperature and cold soil induced water stress combine to suppress stomatal opening and these conditions should be avoided.

The literature discloses some references that may be appropriate for CO_2 enrichment at

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* Insignificant for daytime CO_2 uptake.

low growing temperatures. Strawberries and cucumber plants were grown at ambient (300-330 ppm) and elevated levels of CO_2 such as 900, 1500 and 3000 ppm during winter in unheated greenhouses in Israel (Enoch, Aylski, and Spigelman, 1976). Strawberries yielded 31, 43 and 51% more than control in response to a 3, 5 and 10-fold CO_2 enrichment, respectively. Cucumber plants doubled their early yield and gave 26.3 percent more over the whole season in unheated greenhouses. It thus appears that CO_2 enrichment also can give increased growth and yield in unheated greenhouses.

Though CO_2 enrichment may increase photosynthesis and yield (Koths, 1965; Koths and Adzima, 1967) at most environmental conditions, small Co_2 additions (below say 1000 ppm) may be uneconomical (see Figure 2, Enoch et al., 1973). Unfortunately, the references on actual growth in CO_2 enriched greenhouse atmospheres stress increasing daytime temperatures. Perhaps some reader can supply further information.

In summary, if the temperature is maintained below that generally considered optimal for crop growth, photosynthate should accumulate faster when the atmosphere is enriched by CO_2. Quality should improve, and growth should increase.

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