

Energy-conscious CO₂ enrichment

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In the warmer months of the year, less energy is used for heating but more can be used for CO₂ enrichment. This is the case when CO₂ is generated by burning fuel such as natural gas, especially if a heat buffer is used. The combination of a gas-fired boiler and a heat buffer uses more energy than a gas-fired boiler alone. This indicates that gas is burned for CO₂ enrichment. If energy use becomes an issue, it is worthwhile to critically review the CO₂ enrichment strategy.

CO₂ from fuels

Combustion of 1 m³ of natural gas produces 39 MegaJoule of heat and 2 kg of CO₂. In other words, the CO₂ production from natural gas is about 2 kg CO₂ per m³ gas, or nearly 53 kg CO₂ per GigaJoule gas. The CO₂ production from some other fuels is shown in Table 1. In most situations, either the heat or the CO₂ is needed, and rarely both are needed at the same time, at least not in equivalent amounts. A heat buffer helps to partly overcome this dilemma. The table can be used for calculations on CO₂ enrichment and heat storage.

CO₂ enrichment in light only

CO₂ speeds up the photosynthesis, which requires light as the energy source. Hence CO₂ enrichment in darkness is absolutely useless. Photosynthesis is higher at higher light levels, so CO₂ enrichment is more beneficial in better light conditions. For example, if the CO₂ concentration is elevated to 900 ppm in the early morning hours, the crop will grow about 30% faster in these hours. If 900 ppm could be maintained around midday, the growth would be 30% higher in those hours. Due to the higher light level, the effect of midday CO₂ enrichment is larger than of early morning CO₂ enrichment. But it is quite impossible to reach high CO₂ levels at midday when vents are wide open. Hence CO₂ is often supplied in the early morning and late evening. Late evening enrichment is less effective because plants are saturated after a long day of photosynthesis. If possible, it would be good to supply some CO₂ during the lightest hours of the day, so during midday. The aim is not to aim for a high level, but to give a little bit extra CO₂.

Avoiding CO₂ depletion

The normal CO₂ concentration in the outside air is about 360 ppm. The CO₂ concentration in a greenhouse can be lower than outside because the plants absorb CO₂. The lower-than-outside CO₂ concentration is called CO₂ depletion. It happens especially in cold weather, when venting is minimal and when there is enough light to trigger photosynthesis. In extreme cases the CO₂ level in the greenhouse can drop below 200 ppm. If the windows are cracked open, some fresh air with CO₂ will continuously flow in, and the CO₂ concentration will stabilise at for instance 300 ppm, which is still CO₂ depletion. The number-one goal of CO₂ enrichment is avoiding CO₂ depletion. This can be achieved by a low CO₂ supply rate, e.g. 2 gram/m²/hour only (equivalent to 5 m³ gas/ha/hour, or 0.2 GJ/ha/h). When the vents are closed or cracked, the grower will aim for a CO₂ level above ambient. In that case the 'standard' CO₂ supply rate of 5 g/m²/h will be sufficient (see below).

CO₂ curve

The main principle is how plants respond to CO₂ (see Figure 1). At the natural ambient CO₂ concentration (around 360 ppm) the growth rate is 'normal' or 100%. CO₂ levels below the outside concentration hamper photosynthesis and growth, so the percentage is below 100%. Above ambient CO₂ level, the photosynthesis and hence the growth rate increases considerably, up to 125-140%. However, the positive effect tapers off if the CO₂ level gets above 1000 ppm. There is not much extra growth at 1500 compared to 1000 ppm. It is certainly not enough to warrant high costs and high risks. The CO₂ curve can be used to estimate the yield increase due to CO₂ enrichment. If CO₂ is supplied during a part of the day only, the yield increase is proportionally less. For instance full-time enrichment to 1000 ppm may give 32 % growth boost. Enrichment for only 3 out of 12 hours will boost the growth by 8% (or less if enrichment took place in the early morning only and not in the lightest hours of the day).

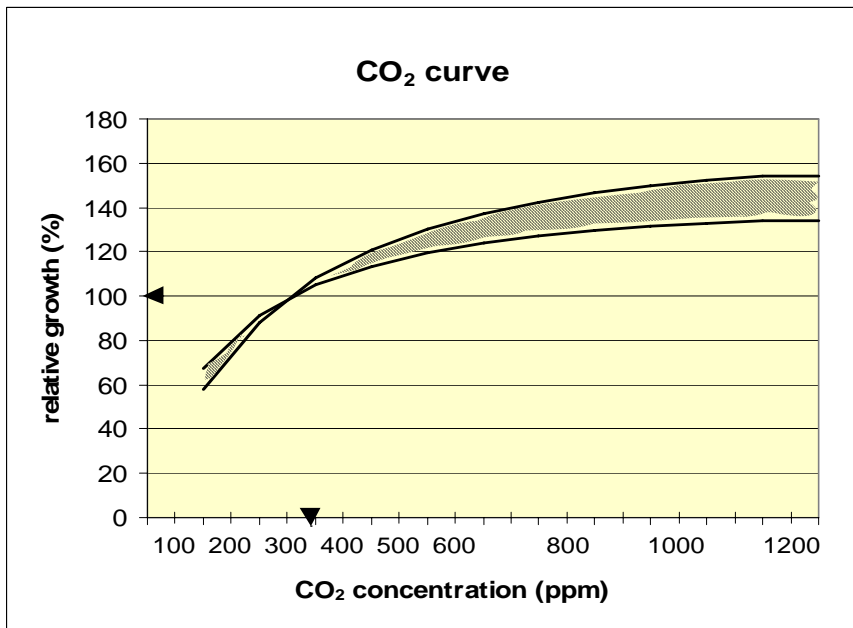


Figure 1: *CO₂ curve: relative growth (in %) versus CO₂ concentration (ppm)*

Maximum of 1000 ppm CO₂

It is not recommended to increase the CO₂ concentration beyond 1000 ppm, also not when plenty of CO₂ is available while gas is burned for heating. Plants gradually close the stomata (the pores in the leaves) when the CO₂ level increases. At 1000 ppm the closure is significant, which markedly reduces the transpiration and hence the uptake of nutrients.

Another risk is that flue gases usually contain small amounts of harmful gases. The more CO₂ is supplied, the more harmful gases are introduced too. Both the pores closure and the harmful gas accumulation are reasons for switching off the CO₂ supply if a maximum CO₂ level of 900 or 1000 ppm is reached.

Economic optimum

Ideally, a grower would aim for the CO₂ concentration that is optimal for plant growth, e.g. 1000 ppm. Maintaining 1000 ppm is often too expensive due to venting. Only if the produce prices is extremely high, it might be feasible to maintain a high CO₂ level all the time. So what CO₂ level is economically optimal?

Computer programs had been developed that made on-line calculations to determine the economic optimum. The programs compared the costs of enrichment (based on the amount of CO₂ needed and the CO₂ price) and the benefits (based on extra yield and produce price). The programs were not very accurate yet. Moreover, the extra yield always comes some weeks later, and the future price of the produce was often unknown. Since the produce price is of critical importance, the calculated optimum level was very uncertain. The idea of economic optimisation was good, but is not really used in practice yet.

Maximum use of heat buffer

Modern control programs for CO₂ enrichment aim to maximise the use of the heat buffer. This is based on the assumption that CO₂ enrichment is profitable, and that all heat storage capacity must be utilised for CO₂ generation. The heat storage is filled during the day and emptied overnight to allow CO₂ enrichment the next day. Modern programmes use predictions of the local weather to decide how to spread the heat buffering capacity and CO₂ enrichment capacity over the day. It is up to the grower to decide if the CO₂ enrichment should continue until the buffer is filled at maximum capacity, or if CO₂ should be limited when there is a limited amount of heat required at night.

'Standard' CO₂ supply rate

In the early days of CO₂ enrichment, the rate of CO₂ supply was 5 g/m²/h. This is equivalent to 25 m³ gas/ha/hour, or nearly 1 GJ/ha/h. This is still a useable standard. With vents closed, it can bring the CO₂ concentration up to about 900 ppm. With the vents cracked open it may keep the CO₂ at 400 or 450 ppm. (The actual CO₂ level achieved depends on wind speed, light level, vent opening). The advantage of the 'standard' supply rate is that it is very safe: it cannot cause extremely high levels of CO₂ or harmful gases, and will keep the costs within limits.

Controlled supply rate

CO₂ enrichment strategies can have a setting for minimum and maximum supply rate. (Although the supply rate cannot always be controlled as desired, because it is related to burner speed, fan speed etc.). The minimum supply rate can be set at 5 g/m²/h for avoiding depletion and for reaching 900 ppm with vents closed. The maximum supply rate can be set at for instance 10 or 15 g/m²/h. The supply rate can be converted to total CO₂ input. For instance, if the supply is set at 5 g/m²/h, the use on a summer's day (12 hours) will be not more than 60 g/m²/d. Over the warmer season (200 days) the CO₂ use will be 12 kg/m²/season. This is equivalent to 6 m³ natural gas or 0.23 GJ natural gas per m², or 60,000 m³ or 2300 GigaJoule natural gas per hectare over the warmer season. At low CO₂ supply rates, the major part of the heat produced will be used for heating at night. When the nights are warm, some heat may be wasted, because it is not needed for heating.

Review

The figures from the table can be used to calculate the CO₂ input and heat production. Other calculations can be made to find how much of the heat is needed for heating at night. The difference is the amount of gas is burned just for CO₂ enrichment. The CO₂ curve can be used to estimate the benefits of CO₂ enrichment. Such calculations may help to review CO₂ supply and energy consumption.

Summary

Calculations of CO₂ supply and estimated yield increase can be done to review CO₂ enrichment. The benefits of CO₂ enrichment should outweigh the costs. CO₂ enrichment should never go beyond 1000 ppm. Plants in a sensitive stage (young plants, stressed plants, sensitive species) should not be exposed to more than 700 ppm CO₂. Moderate CO₂ enrichment is sometimes more economic than excessive enrichment. High CO₂ levels reduce transpiration, hold the risk of accumulation of harmful gases, and waste energy. CO₂ enrichment at night is not useful at all, because there is no photosynthesis at night.

Table 1. Energy content and CO₂ production of some fuels.

	energy content (gross calorific value)	CO₂ production per amount of fuel	kg CO₂ per GigaJoule
Natural gas (Maui)	39 MJ/m ³ or 3.6 MJ/kWh	2.05 kg CO ₂ per m ³ gas	52.6
Propane	50.4 MJ/kg	3.00 kg CO ₂ per kg propane	59.6
Butane	49.5 MJ/kg	3.04 kg CO ₂ per kg butane	61.4
LPG	50 MJ/kg 26.5 MJ/litre	3.02 kg CO ₂ per kg LPG 1.60 kg CO ₂ per litre LPG	60.4