Limiting factors in photosynthesis – carbon dioxide

In a previous issue of this Bulletin [1] we described how the effect of light intensity on the rate of photosynthesis could be measured using a variety of different methods. We finished that previous article by suggesting that the use of carbon dioxide probes would, in principle, allow the measurement of the rate of photosynthesis with varying carbon dioxide concentrations present. In this article we present results from such experiments.

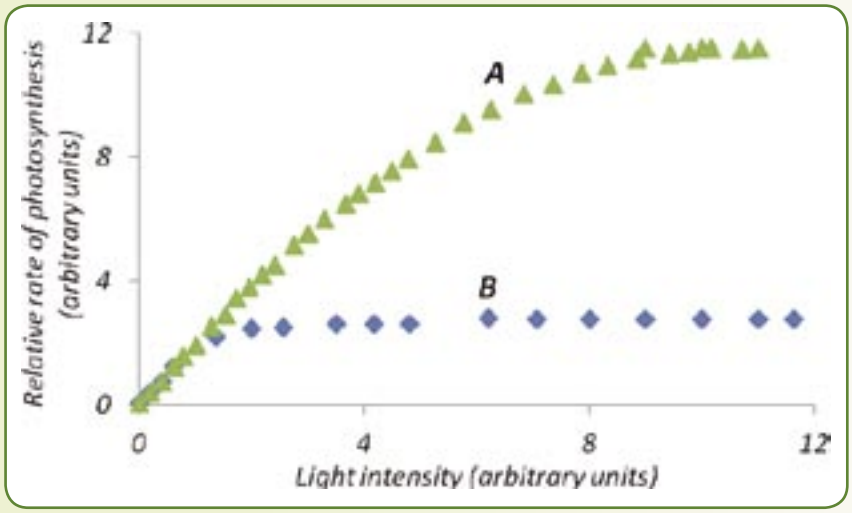

Figure 1 *- Effect of external factors on the rate of photosynthesis in Chlorella (plot adapted from [2]).*
A) Effect of light intensity at 25°C, 0.04% CO_2.
B) Effect of light intensity at 25°C, 0.01% CO_2.

A number of factors are known to affect photosynthetic rates in plants. Classically the variation of factors is as shown in Figure 1 [2].

The interpretation [2] of the plots in Figure 1 can be summarised as:

- At low light intensities the rate of photosynthesis increases linearly as a function of light intensity.
- At higher light intensities the rate of photosynthesis is limited by the available CO_2 concentration (Curve B).

The implication is that if we remove the effect of all other variables (temperature, chlorophyll concentration and light intensity) then we should be able to show experimentally that the rate of photosynthesis will be increased if we increase carbon dioxide concentration (assuming the light intensity is sufficiently high).

In previous articles on this topic [1, 3] we have described how carbon dioxide probes can be used experimentally in the classroom. We noted a number of advantages of such probes including the observations that:

- a wide range of different plant materials can be investigated;
- photosynthesis rates can be investigated in 'real situations' e.g. in the field;
- the readings of carbon dioxide concentration are direct and available in 'real time'.

Experimental set-up

The experimental set-up has been described previously [3] and is shown in Figure 2. A tissue culture flask filled with water (to act as a heat sink) is placed in front of the experimental chamber into which the CO_2 sensor is placed.

The light source is a small desk lamp although a range of lamps could be used.

- Leaves from a basil plant (approximately 2.5 g of material [*ca.* 12 leaves]) were placed in a chamber wrapped in aluminium foil to exclude light. Under these conditions carbon dioxide levels rises as respiration takes place in the leaves.
- Data was collected for about 10 min until the concentration of carbon dioxide present increased from its starting level of *ca.* 380 ppm to approximately 580 ppm.

Figure 2 *- Experimental set-up for measuring respiration and photosynthesis rates in plants.*

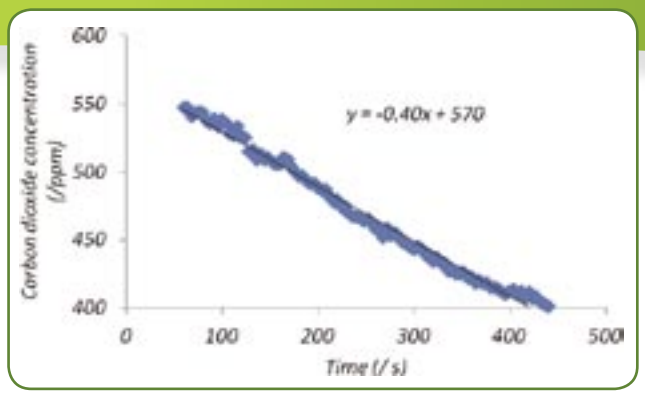

Figure 3 *- The rate of photosynthesis in basil leaves. Data were obtained using a Vernier VR105512 probe. Starting carbon dioxide concentration was measured to be 580 ppm.*

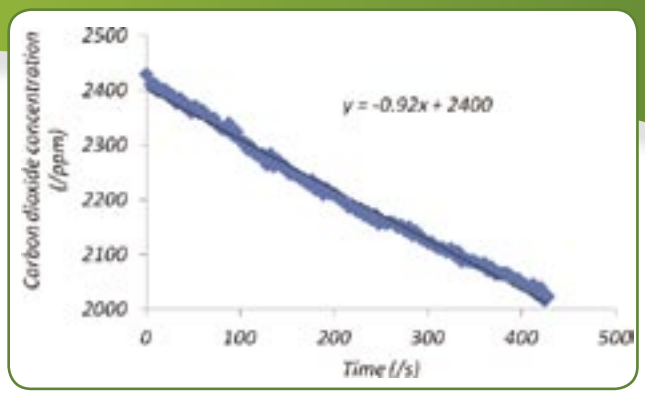

Figure 4 *- The rate of photosynthesis in basil leaves. Data were obtained using a Vernier VR105512 probe. Starting carbon dioxide concentration was measured to be approximately 2400 ppm.*

- The aluminium foil was removed and the lamp switched on and the system allowed to equilibrate (approximately 1 minute).
- Data was collected for a period of approximately 6 minutes (Figure 3) during which time the carbon dioxide concentration fell from *ca.* 550 ppm to *ca.* 400 ppm.

As shown in Figure 3, over the time of observation there is a reasonably linear fall in carbon dioxide concentration allowing the rate of fall to be estimated as -0.4 ppm s^{-1}.

It is possible to repeat the experiment with different starting carbon dioxide concentrations. In order to do this we filled a syringe (5 cm^3) with pure carbon dioxide (in our case this was taken from a cylinder which we had available but there is no reason why carbon dioxide could not be generated chemically - for example using marble chips and dilute acid). Taking care not disturb the experimental set-up shown in Figure 3 we added carbon dioxide from the syringe to the bottle containing the basil leaves. We used a separate syringe to mix the contents and allowed a period of equilibration (1-2 minutes) with the lamp switched off. The lamp was switched on and data on the carbon dioxide concentration recorded (Figure 4). Note the approximately 4-fold increase in starting carbon dioxide concentration compared to the data shown in Figure 3.

Data was collected over a period of some 7 minutes and an estimate of the rate of fall in carbon dioxide concentration (-0.92 ppm s^{-1}) obtained.

Comparing the slopes from Figures 3 and 4 we can conclude that at elevated starting levels of carbon dioxide concentration the rate of photosynthesis is increased; clearly the experiment could be repeated at a variety of different starting carbon dioxide concentrations. In our judgment, the system described above would support those areas of both Higher and Advanced Higher Biology [4, 5] where learners are invited to carry out investigations on limiting factors which affect the rate of photosynthesis. Clearly a carbon dioxide probe set-up would be required in order to do such experiments and the cost of these may be prohibitive for some school departments. Don't forget though that SSERC has a number of probes which can be borrowed!

We have opted to include lines of best fit to the data in Figures 3 and 4. Although we recognise that whilst a reasonable fit is obtained (the R^2 value for the data in Figure 4 is 0.99) a linear plot is somewhat misleading since, as is implied in Figure 1, the rate of photosynthesis is related to the CO_2 concentration present and as this is reduced the rate will fall. Given sufficient time of observation plots such as those in Figures 3 and 4 will appear curved. However, measuring the initial rates allows comparisons between different data sets to be made.

Curriculum links

CfE Higher in Biology [4] - *Sustainability and Interdependence* - learners might *'Carry out experimental investigations on limiting factors in photosynthesis'*.

CfE Advanced Higher in Biology [5]
- *Investigative Biology-2*. Experimentation (c) Experimental design - Design and carry out a simple laboratory true experiment where confounding variables are tightly controlled.

References

[1] Limiting factors in photosynthesis. SSERC Bulletin (2014), **246**, 2-6.
[2] Hall, D.O. and Rao, K.K. (1999) Photosynthesis, 6th Edition, Cambridge University Press, pp. 24-26.
[3] Measuring gaseous carbon dioxide. SSERC Bulletin (2012), **238**, 5-7.
[4] SQA (2012) Higher Biology Course Support Notes - can be downloaded at www.sqa.org.uk/files_ccc/CfE_CourseUnitSupportNotes_Higher_Sciences_Biology.pdf (accessed July 11th 2014).
[5] SQA (2012) Advanced Higher Biology Course Support Notes - can be downloaded at www.sqa.org.uk/files_ccc/AHCUSNBiology.pdf (accessed July 11th 2014).