Bio Factsheet

Number 25

Tackling Data Interpretation Questions II: Photosynthesis

1. Limiting Factors

The rate of photosynthesis is slowed down or **limited** by many factors. Photosynthesis involves hundreds of chemical reactions and the products of one reaction become the reagents for the next. The overall rate of photosynthesis can be slowed or limited by any one of these steps. In A Level photosynthesis questions, examiners tend to focus on just three of the main limiting factors: temperature, carbon dioxide concentration and light intensity. It is essential that you understand:

(a) How each of these may individually limit the rate of photosynthesis - (simple questions).

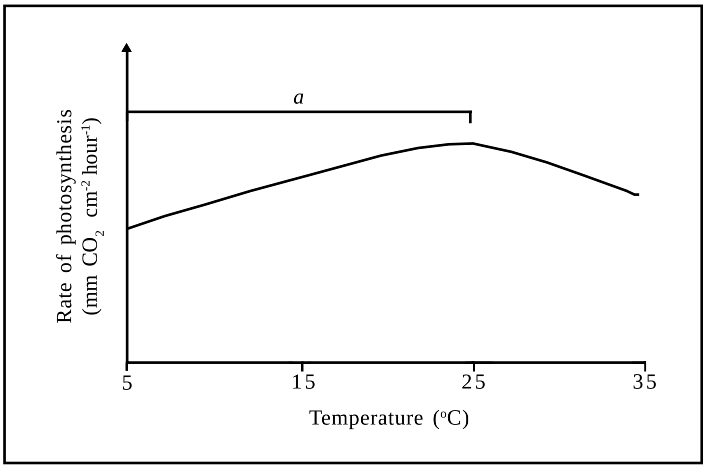
(b) How they may interact to limit the rate of photosynthesis - (trickier questions).

(a) Individual limiting factors

Temperature

Temperature affects the rate of enzyme activity. Generally, as long as temperatures do not lead to enzyme denaturation, as temperature increases so does enzyme activity, so we might expect the rate of photosynthesis to increase as well. However, it is important to remember that photosynthesis occurs in two distinct stages - the light dependent stage (LDS) and the light independent stage (LIS). The key point here is that the LDS in the thylakoids of the chloroplast is much less dependent upon enzyme activity than the LIS in the stroma. In other words, an increase in temperature speeds up the LIS much more than it speeds up the LDS. Thus, the supply of products from the LDS ($NADPH_2$ and ATP) will not be able to keep up with demand from the LIS. In other words, the overall rate of photosynthesis will become limited by the supply of $NADPH_2$/ATP. Fig 1 shows how the rate of photosynthesis of a field of wheat is influenced by temperature.

Fig 1. Effect of temperature on the rate of photosynthesis



Over part *a* of the graph i.e. between 5°C and 25°C, the rate of photosynthesis increases as temperature increases - we can therefore say that temperature is a *limiting factor.*

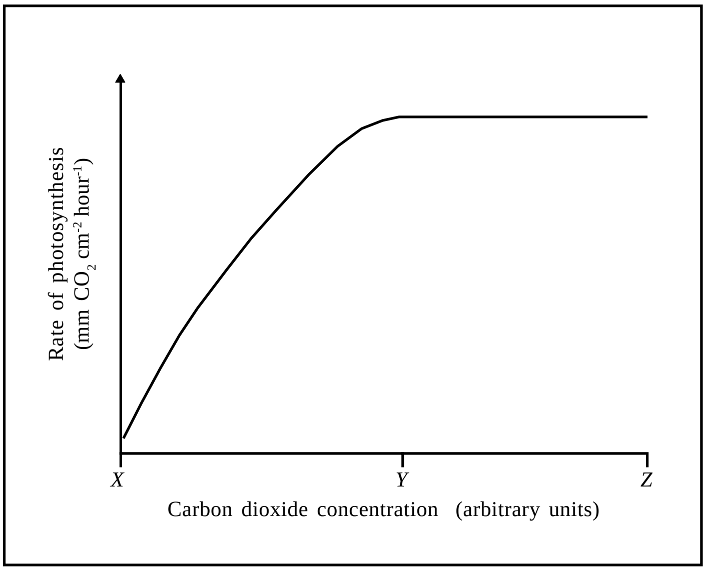
However, above 25°C, increasing temperature does not increase the rate of photosynthesis - so temperature is *not* a *limiting factor.*

In this example, the rate of photosynthesis begins to fall above a temperature of 25°C. This is not because enzymes are becoming denatured, but because the increase in temperature is simultaneously increasing the rate of respiration. Generally speaking, respiration is more temperature dependent than photosynthesis (consider that all stages of respiration - glycolysis, Kreb's cycle and the electron transfer chain - are dependent upon enzymes whereas only one of the two stages of photosynthesis is heavily influenced by temperature) so above 25°C, the **net** uptake of carbon dioxide is actually decreasing.

Carbon dioxide concentration

During photosynthesis, carbon dioxide is fixed i.e. combined with hydrogen to form carbohydrates. Since carbon dioxide makes up only 0.035% of normal air, it is very often the limiting factor in photosynthesis. The effect of carbon dioxide on the rate of photosynthesis is shown in Fig 2.

Fig 2. Effect of carbon dioxide on the rate of photosynthesis

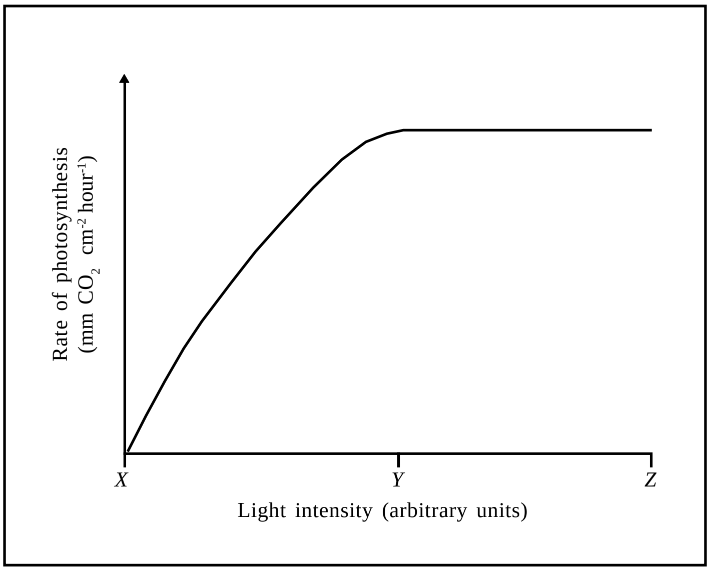


Between *X* and *Y* as carbon dioxide concentration increases, so too does the rate of photosynthesis. We can therefore say that carbon dioxide is a *limiting factor.*

Between *Y* and *Z* as carbon dioxide concentration increases the rate of photosynthesis remains constant. Therefore carbon dioxide is *not* a *limiting factor.*

Light intensity
Light is essential for the excitation of electrons and for photolysis (which both occur in the LDS in the thylakoids). As light intensity increases so too does the rate of cyclic and non-cyclic photophosphorylation, hence $NADPH_2$ and ATP production also increase. These two products pass from the thylakoids into the stroma and are used up in the LIS. The effect of light intensity on the rate of photosynthesis is shown in Fig 3.

Fig 3. Effect of light intensity on the rate of photosynthesis

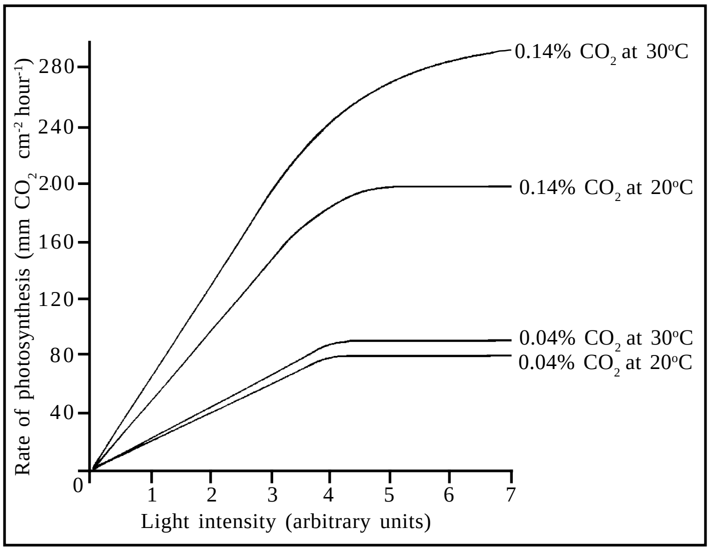


Between *X* and *Y*, as light intensity increases, so too does the rate of photosynthesis. We can therefore say light intensity is a *limiting factor.*

Between *Y* and *Z*, as light intensity increases, the rate of photosynthesis remains constant. Therefore light intensity is *not* a *limiting factor.*

(b) Interacting limiting factors
Very often candidates will be faced with the sort of data shown in Fig 4.

Fig 4. The effect of light intensity on rate of photosynthesis



The graph combines all three of the main limiting factors; light intensity, carbon dioxide concentration and temperature. A typical question would ask candidates to summarise the information shown.

> ***Exam Hint*** *When asked to summarise, interpret or comment upon graphs which have more than two variables, the key is:*
> 1. *To be systematic and say something meaningful about each point of the graph.*
> 2. *Avoid just describing the graph if the question asks for interpretation or comment.*

Consider light intensity; as light intensity increases from 1-4 units the rate of photosynthesis also increases. At low light intensity, light intensity is a *limiting factor.*

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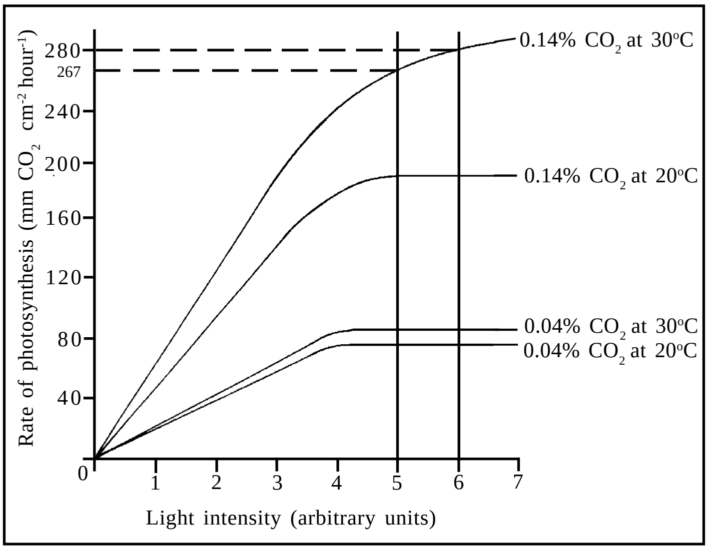
Now, focus in on what happens when light intensity increases from 5-6 units (draw a ruler line straight up from the bottom (*x*) axis at 5 and 6 units).

Fig 5.



Ask yourself: what effect does increasing the light intensity from 5 to 6 units have on the rate of photosynthesis under the four conditions shown?

Start with the top line (0.14 % CO_2 & 30°C)
The rate of photosynthesis at light intensity 5 units = 267
The rate of photosynthesis at light intensity 6 units = 280
Thus, the percentage increase in photosynthesis =

$$\frac{280-267}{267} \times 100 = 4.9\%$$

So, at high carbon dioxide concentrations and high temperatures, light intensity is still a *limiting factor* - because increasing it increased the rate of photosynthesis.

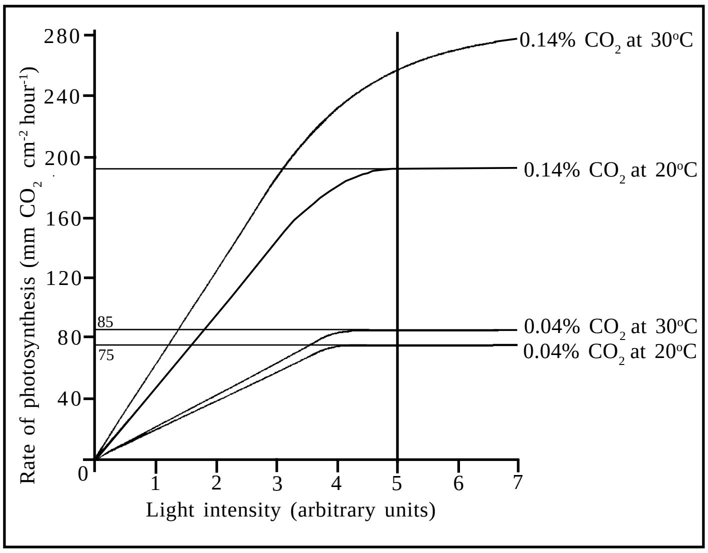
Now consider the bottom line (0.04% CO_2 & 20°C)
The rate of photosynthesis at light intensity 5 units = 75
The rate of photosynthesis at light intensity 6 units = 75

Thus, increasing light intensity has no effect on the rate of photosynthesis. In other words, at low carbon dioxide concentrations and low temperatures, light intensity is *not* a *limiting factor* (because increasing it does not increase the rate of photosynthesis).

So, if light intensity is not a limiting factor at low carbon dioxide concentrations and low temperatures, what is? Clearly, it could be carbon dioxide concentration or temperature or both.

Consider the situation (0.04% CO_2 & 20°C) (Fig 6.)

Fig 6.



The rate of photosynthesis at light intensity 5 units = 75

If the light intensity is kept at 5 units and the carbon dioxide is kept at 0.04% consider what happens when the temperature is increased by 10°C (0.04% CO_2 & 30°C)
The rate of photosynthesis = 85.
The rate of photosynthesis has therefore increased by 10 units - not much.

Now consider what happens if, still at light intensity = 5 units, the carbon dioxide concentration is increased and temperature is kept constant (0.14% CO_2 & 20°C)
The rate of photosynthesis = 192 i.e. it has more than doubled!

So, to summarise, at light intensity = 5 units, increasing the carbon dioxide concentration has a greater effect on the rate of photosynthesis than increasing the temperature - in other words at light intensity = 5 units, carbon dioxide concentration is the main limiting factor.

Note however, that increasing the temperature did have a small effect - so it was *a* limiting factor but it was not *as* limiting as carbon dioxide. In this situation, we say that the *overall* limiting factor was the carbon dioxide concentration.

Typical exam questions
Once examiners have asked you to wrestle with the interpretation of such graphs, they often turn to applications of this topic. There are two favourite areas:

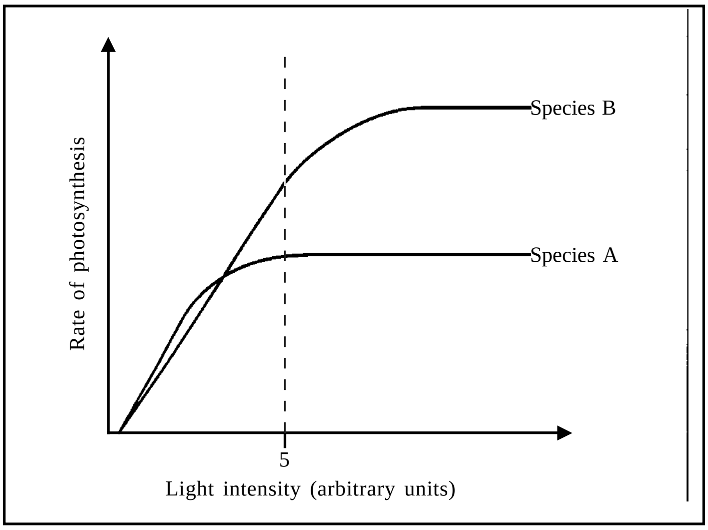
1. Technical aspects - e.g. How, in practical terms can carbon dioxide concentrations be increased in a greenhouse?
Use an oil burner which will release carbon dioxide and increase temperature.

2. Economic aspects - e.g. By how much would it be economically sensible to increase carbon dioxide concentrations in a greenhouse?
Increasing carbon dioxide concentrations in a greenhouse will increase the rate of photosynthesis - especially if light intensity is high i.e. not limiting. More photosynthesis means more growth (for example, more or bigger tomatoes), hence more income. The extra increase in income however must be set against the cost of burning the oil. If the extra profit from the tomatoes is greater than the extra cost of the oil, then it is worth doing.

2. Light and shade plants

Some plants are adapted for life in shady conditions (Fig 7).

Fig 7. Effect of light intensity on the rate of photosynthesis of two species of plant



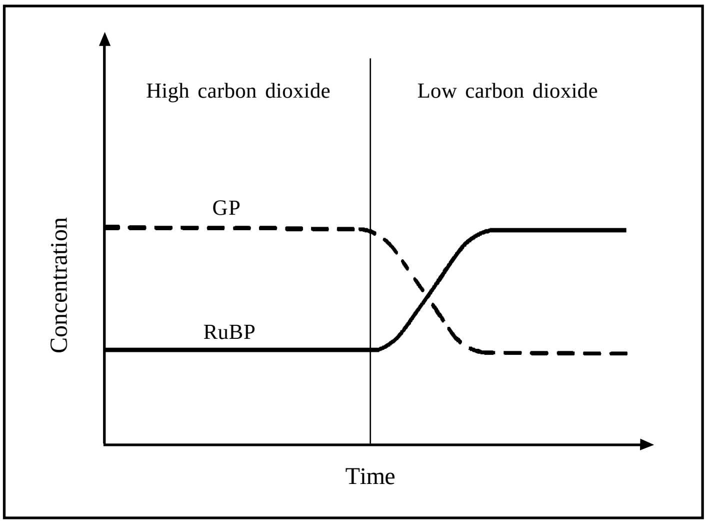
At light intensity = 5 units, species A has reached its maximum rate of photosynthesis. As light intensity increases above 5 units, the rate of photosynthesis of species B continues to increase, indicating that it normally experiences these light intensities i.e. it lives in sunnier conditions than species A.

Plants or parts of plants which are adapted to living in shady conditions often have leaves which are adapted to take advantage of very low light levels. Typically, **shade leaves** are bigger and thinner than sun leaves and have fewer but bigger chloroplasts which contain more grana. Such leaves have greater concentrations of chlorophyll and therefore appear very dark green. The cuticle of shade leaves is often very thin and epidermal cells may contain chloroplasts. All of these adaptations enable shade leaves to absorb small amounts of light effectively.

3. The light independent stage

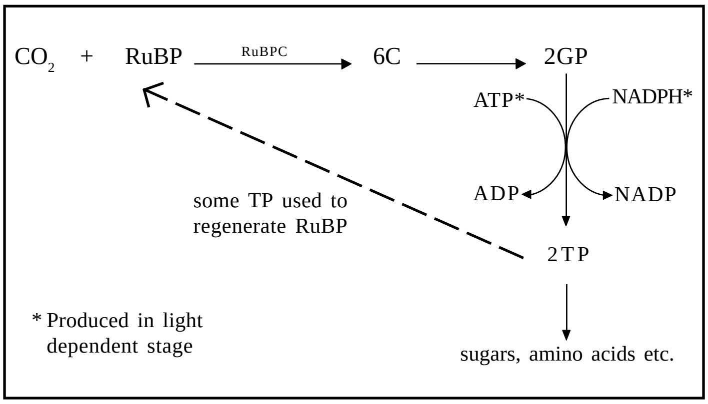
Occasionally, the concentration of some of the intermediate products of the light independent stage are shown in a graph (Fig 8).

Fig 8. RuBP/GP under different light/CO_2 conditions



Such graphs may appear terrifying, simply because you have never seen them before. The secret is to keep calm and write down what you know of the biochemistry of the light independent stage (see Factsheet 2 - The Essential guide to photosynthesis). This is summarised in Fig 9.

Fig 9. The light independent stage



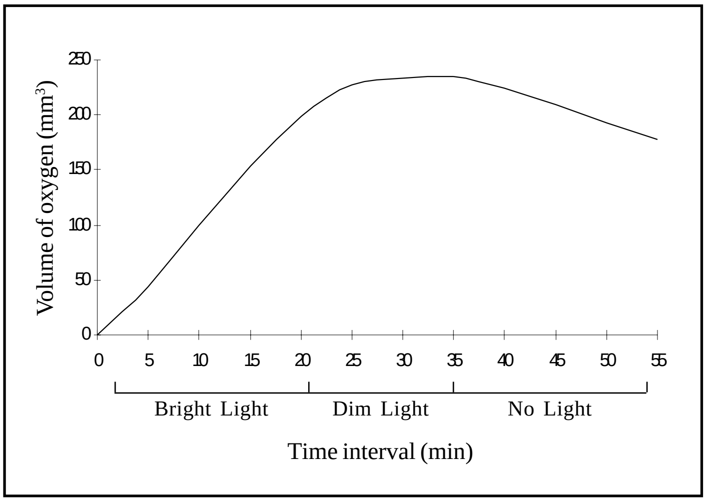
When carbon dioxide concentrations are high, the reaction will proceed rapidly i.e. RuBP will be used up and a lot of GP will be produced. This explains why the concentration of the GP is high and the concentration of RuBP is low on the left hand side of Fig 8. When carbon dioxide concentration is low, less GP can be produced so the line on the right hand side of Fig 8 falls. Less RuBP is used to fix the carbon dioxide so its concentration increases.

Some enzyme inhibitors such as cadmium chloride inhibit the regeneration of RuBP from TP. Consequently, biochemical analysis of chloroplasts treated with this substance reveals very high concentrations of TP and lower than usual levels of RuBP.

4. Photosynthesis and respiration.

Candidates are often asked to interpret data collected from investigations involving aquatic plants or leaf discs in $NaHCO_3$ solutions. Often, the investigation involves measuring the volume of oxygen which is taken up or released from the plants or leaf discs when an environmental factor such as light intensity is altered. Fig 10 shows the results of such an experiment.

Fig 10. Effect of light intensity on the volume of oxygen taken up



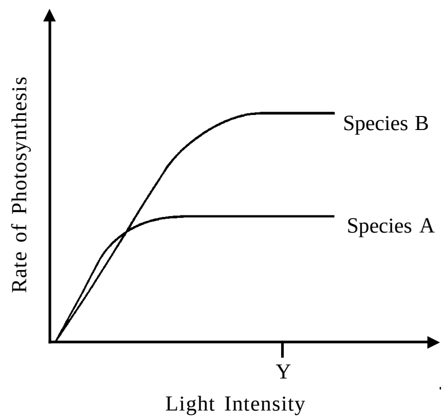
Although the data may look daunting, the biological principles are usually very simple. Remember: oxygen is released in photosynthesis and used up in respiration. Plants photosynthesise (release oxygen) only in the light but they respire (use up oxygen) every second of the day and night.

- In bright light (0-20mins), the rate of photosynthesis is greater than the rate of respiration so the **net effect** (overall effect) is that a lot of oxygen is released.
- In dim light (20-35mins), the rate of photosynthesis may just exceed the rate of respiration so the net effect is that a small amount of oxygen is released - the curve is less steep.
- In the dark, no photosynthesis occurs, no oxygen is released but oxygen is used up for respiration so the net effect is that the volume of oxygen in the atmosphere will decrease.

***Exam Hint** - Investigations often involve plants being subjected to changing light conditions e.g. dark to bright to dim to dark. Marks are often awarded for commenting that the initial readings in very bright light, dim light or darkness are inaccurate because the plant is adapting or because, for example, in the first minute of darkness some residual oxygen will be left behind.*

Practice Questions

1. The graph shows the effect of light intensity on the rates of photosynthesis of plant saplings growing in a woodland. One species normally grows in direct sunlight, the other species normally grows in shaded conditions.



(a) Suggest which species normally grows in shaded conditions. Explain your answer. (2 marks)

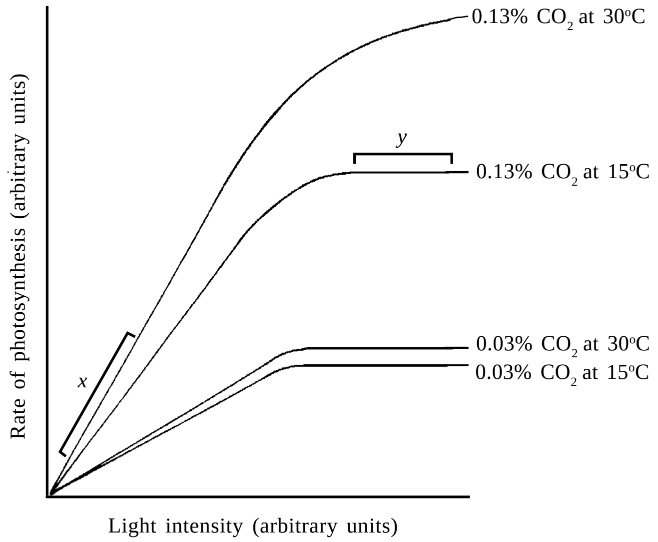
(b) Suggest which factor is limiting the rate of photosynthesis of species A at light intensity Y. (1 mark)

(c) The light compensation point is defined as ‘the light intensity at which the amount of carbon dioxide absorbed in photosynthesis equals that released in respiration. The light compensation point for three woodland species is shown in the table below. The average light compensation point for plants in this woodland is 1150 lux.

Species	Light compensation point (lux)
A	2000
B	350
C	900

State and explain which of these three species:
(i) normally grows in bright sunlight (2 marks)
(ii) has leaves with the highest chlorophyll content (2 marks)

2. The graph below shows some of the effects of light intensity, carbon dioxide, and temperature on the rate of photosynthesis.



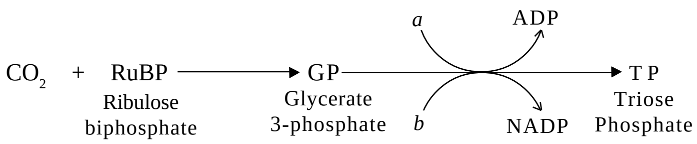
(a) Suggest what factor is limiting the rate of photosynthesis at:

(i) *x* (2 marks)

(ii) *y* (2 marks)

(b) Suggest why, on hot bright summer days, commercial greenhouses may use fans to cool the greenhouses. (2 marks)

3. The diagram below shows some of the steps in the light independent stage of photosynthesis.



(a) Identify substances *a* and *b* produced in the light dependent stage of photosynthesis. (2 marks)

(b) Suggest explanations for the following observations:

(i) At dusk, the concentration of glycerate-3-phosphate in chloroplast stroma begins to increase rapidly. (3 marks)

(ii) During the night, the level of glycerate-3-phosphate eventually levels off. (2 marks)

Answers

Semicolons indicate marking points.

1. (a) Species A;
curve is steeper at lower light intensity;
reaches a maximum at lower intensities;

(b) Carbon dioxide concentration;
temperature;

(c) (i) A;
At very high light intensities (e.g. 1999 lux) the rate of photosynthesis is greater than the rate of respiration.
(ii) B;
Shade plant with highest chlorophyll content;
and lowest compensation point;

2. (a) (i) Light intensity;
As light intensity increases, the rate of photosynthesis increases;

(ii) Temperature;
As temperature increases the rate of photosynthesis increases;

(b) At high temperatures the rate of respiration is greater than the rate of photosynthesis/net photosynthesis decreases;
less sugar available for growth/dry production decreases;

3. (a) *a* = ATP;
b = NADPH/$NADPH_2$.

(b) (i) Carbon dioxide + RuBP reaction continues/does not need light;
GP cannot be converted to TP;
because ATP is needed;
ATP only produced in light;

(ii) Less TP produced;
therefore less TP available to regenerate RuBP;
therefore rate of reaction of carbon dioxide and RuBP decreases;

Acknowledgements;
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