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Light interception and utilisation

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Light interception and utilisation

Abstract

Initial steps of photosynthesis involve interception and absorption of photons by photosynthetic organs; subsequent steps are involved with utilisation or dissipation of quantum energy so derived. Interception of light varies according to size, angle, orientation and surface features of the photosynthetic organ(s) and is also influenced by changes in the arrangement of photosynthetic tissue within those organs.

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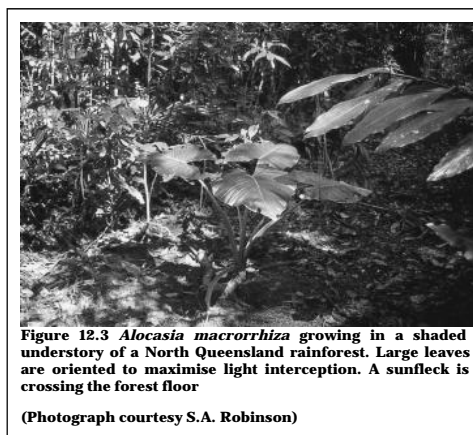
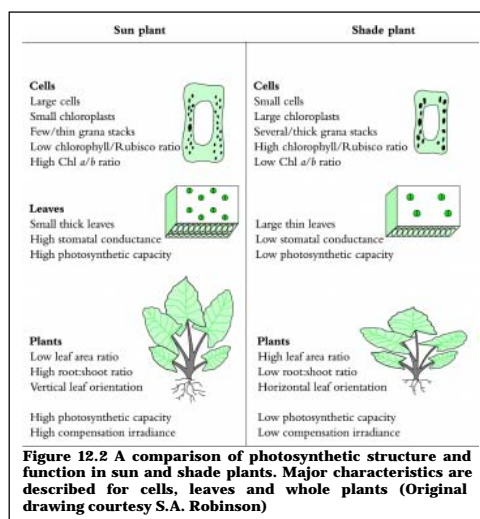
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Plants in Action

ADAPTATION IN NATURE, Edition 1 PERFORMANCE IN CULTIVATION

12.1.1 Light interception and utilisation

Initial steps of photosynthesis involve interception and absorption of photons by photosynthetic organs; subsequent steps are involved with utilisation or dissipation of quantum energy so derived. Interception of light varies according to size, angle, orientation and surface features of the photosynthetic organ(s) and is also influenced by changes in the arrangement of photosynthetic tissue within those organs.



Shade plants can increase their interception of light by producing larger leaves. Some of the largest leaves are produced by plants found in rainforest understoreys (Figure 12.3). Leaf size can even change within an individual plant, smaller leaves being produced near the top where irradiance is highest, and larger leaves towards the interior and base where light levels are lower. Another way to change light interception is by changing leaf angle and/or orientation. Vertical arrangements enhance interception of light at low sun angles during early morning or late afternoon, and reduce interception at solar noon when radiation levels are highest. Leaves that are displayed horizontally will intercept light all day long, but especially around midday. Accordingly, leaves in a rainforest tend to be vertical in emergent crowns and horizontal in the understorey. Similarly, pendulant leaves of many Australian trees such as eucalypts that typically occur in high light environments represent an adaptation that helps avoid excess midday radiation.

Many plants can change their leaf angles and orientation in response to a change in light. Some do this to increase interception while others do it to avoid high light. A good example of optimising light interception through leaf movement is given by *Oxalis oregana*, an understorey herb of red-wood forests in western USA (Figure 12.4). This plant is able to track sunlight on dull days, but can change leaf angle from horizontal to

BOOK NAVIGATION

TITLE PAGE

DEDICATION

CONTENTS PAGE

PREFACE

EDITING, AUTHORSHIP
AND
ACKNOWLEDGEMENTSPART I - PERSPECTIVES
ON PLANT SCIENCEPART II - PROCESSES
AND RESOURCES FOR
GROWTHPART III - COORDINATION
OF GROWTH AND
REPRODUCTIONPART IV -
ECOPHYSIOLOGY IN
NATURAL AND
MANAGED
COMMUNITIESChapter 12 - Sunlight: an all
pervasive source of energy

Introduction

12.1 Photosynthesis in sun
and shade12.1.1 Light interception
and utilisation12.1.2 Photoinhibition
and photoprotectionFEATURE ESSAY 12.1
Perspectives on
photoinhibition12.1.3 Sun/shade
acclimation and rainforest
gapsCASE STUDY 12.1
Interaction of light and
nutrients on rainforest
seedlings

12.1.4 Sunflecks

12.2 Ultraviolet radiation

12.3 Agricultural production

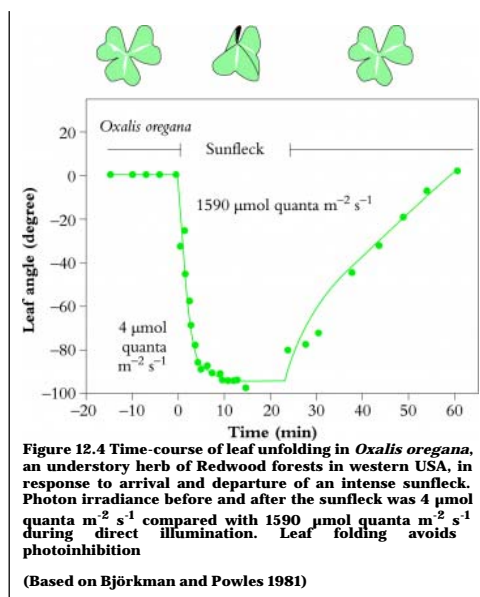
12.4 Forest production

12.5 Horticultural production

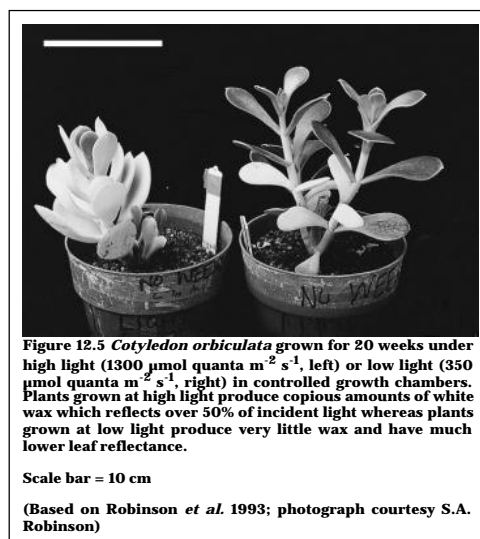
12.6 Concluding remarks

Further reading

Chapter 13 - Carbon dioxide:
a universal substrateChapter 14 - Temperature: a
driving variable for plant
growth and developmentChapter 15 - Water: a limiting
factor



vertical in only 6 min if exposed to full sunlight (Björkman and Powles 1981). In this way, leaves can maintain maximum photosynthetic rates under a variety of light conditions. *Omalanthus novo-guineensis*, an Australian rainforest plant, can also change leaf angles in response to full sunlight within about 20 min (Watling *et al.* 1997b).



Another way of regulating light capture is to change leaf-surface properties. Many plants in high light environments increase the reflectance of their leaves by coating them in hairs or wax or even salt crystals. *Cotyledon orbiculata*, a crassulacean acid metabolism (CAM) plant from southern Africa, produces a wax coating which reflects 60% of incident light. If *C. orbiculata* is grown in low light, wax production stops and leaf reflectance drops to 9% (Figure 12.5; Robinson *et al.* 1993). Young eucalypt leaves also produce wax, while leaves of *Celmisia longifolia*, a plant of the Australian alps, are covered in a thick layer of silvery fibres. In these instances plants are avoiding high light by creating their own shade, but does leaf anatomy adjust to environments where light is limiting?

Epidermal cells in some rainforest shade specialists are shaped to enhance light capture by acting as a lens. The optical properties of such cells focus incident sunlight into the layer of photosynthetic tissue just below the epidermis, reducing light lost due to reflectance and transmittance.

Light interception can also be regulated at a tissue and organelle level. Photosynthetic tissue can be concentrated equally on both sides of a leaf (isobilateral) to maximise use of light absorbed from either side, or preferentially on one side (dorsiventral) as is common in species where leaves are predominantly horizontal.

Chloroplast density and location within leaves is also sensitive to light climate, and energy capture varies accordingly. Alignment along vertical cell walls will reduce overall absorption of incident light (recall Figures 1.4 and 1.5), and in *Oxalis* leaves absorbance can be reduced 20% when chloroplasts move from the horizontal to the vertical walls of mesophyll cells (Brugnoli and Björkman 1992; Park *et al.* 1996).

Chapter 16 - Nutrients: a sparse resource

Chapter 17 - Salt: an environmental stress

Chapter 18 - Waterlogging and submergence: surviving poor aeration

Chapter 19 - Fire: an ecosystem sculpture

Chapter 20 - Herbicide resistance: a case of rapid evolution

SEARCH

Once sunlight has been intercepted by an assimilatory organ, photon absorption then depends on the extent and nature of light-absorbing pigments in photosynthetic tissues. In terrestrial plants the major light-absorbing pigments are chlorophylls *a* and *b* plus a range of carotenoids which can act as accessory pigments (see Section 1.2 for more detail). Compared with high-light plants, plants grown in low light tend to allocate relatively more resources to these light-harvesting pigments and their associated proteins than to Rubisco and other soluble proteins involved in CO₂ fixation. This shift in allocation of nitrogen-based resources can be accompanied by marked changes in leaf anatomy, especially depth of mesophyll tissue (see Case study 12.1) and reflects a need for increased efficiency of light absorption when sunlight is limited.

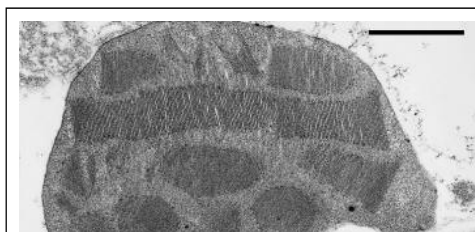


Figure 12.6 Electron micrograph of a chloroplast from a shade-grown *Alocasia macrorrhiza* (photon irradiance 10 $\mu\text{mol quanta m}^{-2} \text{s}^{-1}$, from incandescent lamps). An extensive development of randomly arranged granal stacks is a feature of photosynthetic acclimation to deep shade in this species. Scale bar = 1 μm

(Reproduced from Chow *et al.* 1988)

There are also differences in chloroplast structure between low- and high-light plants. Shade chloroplasts tend to be larger than those found in sun plants. They also contain more thylakoid membranes which show higher levels of stacking into appressed regions (see extreme development of grana in Figure 12.6). The higher proportion of appressed to non-appressed membranes found in shade chloroplasts is the result of increased photosynthetic system II (PSII) antenna (LHCII) content. LHCII is thought to be involved in thylakoid appression and formation of granal stacks. Plants grown in low light also tend to have lower Chl *a/b* ratios. Chlorophylls *a* and *b* are both associated with the light-harvesting antennae, while only Chl *a* is found in the reaction centres. A lower *a/b* ratio reflects an increase in LHCII complexes relative to reaction centres (Anderson *et al.* 1988; Section 1.2).

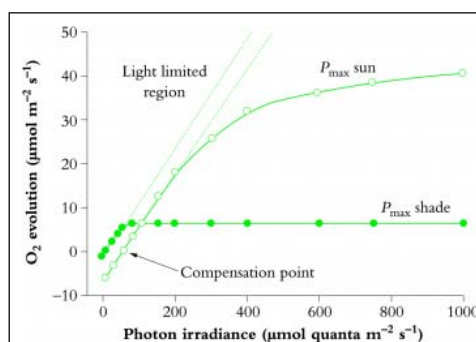


Figure 12.7 Photosynthesis-light response curve for typical shade and sun plants, showing relationships between photosynthetic rate (measured as O₂ evolution) and absorbed light (expressed as a photon irradiance). Dashed lines are extrapolations of initial linear slopes where photosynthesis is light limited, and represent quantum yield (moles of O₂ evolved per mole quanta absorbed). Quantum yield (based on absorbed energy) is the same in both sun and shade plants, although the light-compensation point is higher in the sun plant (photon irradiance required to offset respiration; net exchange of CO₂ is then zero) due to faster dark respiration. The sun plant also achieves a higher rate of light-saturated photosynthesis (P_{max}) than the shade plant

(Representative original data courtesy of S.A. Robinson)

On top of striking differences in leaf anatomy and chloroplast fine structure, energy derived from absorbed sunlight is then processed in ways that differ subtly between shade-grown and sun-grown plants. In high light there is a requirement for greater capacity in both light and dark reactions of photosynthesis. Photosynthesis-light response curves for shade and sun plants (Figure 12.7) illustrate such differences. The initial slope of each light response curve represents the quantum efficiency of photosynthesis. This is the same for sun and shade plants. The reason it does not change is that the efficiency of the light reactions is the same no matter how much light has been received during growth (i.e. eight photons are required for the evolution of one molecule of O₂ and fixation of one molecule of CO₂). However, sun plants tend to have a greater capacity for photosynthetic electron transport (greater abundance of components such as Cyt *b*₅₅₉, Cyt *b*₅₆₃, Cyt *f* and plastoquinone). They also have a greater capacity for ATP synthesis per unit of chlorophyll compared with shade plants. Taken together, those capacities allow them to process more sunlight into ATP and NADPH for use in CO₂ assimilation and other synthetic events. Such capacity is matched by a greater investment in biochemical machinery for CO₂ fixation, resulting in a higher light-saturation point and a higher maximum rate of

photosynthesis (P_{\max}) for sun plants (Figure 12.7). In particular, this greater capacity for CO_2 fixation is achieved via greater investment in enzymes of the photo-synthetic carbon reduction (PCR) cycle relative to shade plants. As a further distinction, sun leaves tend to be thicker and have more cell layers (see Case study 12.1). They also have higher stomatal conductances to facilitate rapid uptake of CO_2 .

A higher photosynthetic capacity in sun plants does, however, incur some costs. Their leaves tend to have higher respiration rates which increase light-compensation point relative to shade plants (Figure 12.7). Higher respiration rates probably result from (1) increased carbohydrate processing in high light, (2) increased costs of constructing sun leaves and (3) a higher cost of maintaining sun leaves (further details on maintenance costs are given in Section 6.5).

Greater transpiration is a further cost of higher photosynthetic capacity due to higher stomatal conductance. Sun plants often respond to this by increasing their root : shoot ratios. Under conditions where water is limiting, however, stomatal conductance may be reduced, sacrificing photosynthesis in favour of slower transpiration.

< 12.1 Photosynthesis in sun and shade

up

12.1.2 Photoinhibition and photoprotection >

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