Plants and Microclimate

A Quantitative Approach to Environmental Plant Physiology

Third Edition

This rigorous yet accessible text introduces the key physical and biochemical processes involved in plant interactions with the aerial environment. It is designed to make the more numerical aspects of the subject accessible to plant and environmental science students, and will also provide a valuable reference source to practitioners and researchers in the field.

The third edition of this widely recognised text has been completely revised and updated to take account of key developments in the field. Approximately half of the references are new to this edition, and relevant online resources are also incorporated for the first time. The text shows how recent developments in molecular and genetic research on plants can be used to advance our understanding of the biophysical interactions between plants and the atmosphere, and how progress in molecular biology can itself be informed by an understanding of whole-plant physiology. Remote sensing technologies and their applications in the study of plant function are also covered in greater detail.

Hamlyn G. Jones is Emeritus Professor of Plant Ecology at the University of Dundee and Adjunct Professor in Plant Biology at the University of Western Australia. His research uses experimental approaches and mathematical modelling to investigate the characters that enable plants to be adapted to specific environments and to tolerate environmental stress.

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PREFACE

I have been delighted, and somewhat surprised, at the continued widespread use of this text, in spite of the fact that much has changed in associated fields since the previous edition was published around 20 years ago. Perhaps the major change in plant biology over this period has been the explosion of research on the molecular and genetic basis of plant responses to the environment, though there have been important advances in other relevant fields such as in remote sensing. Although I have not attempted to cover molecular aspects in any detail, as there are many suitable alternative texts, I have tried to relate recent advances in molecular sciences to our understanding of whole-plant responses to the environment. In this context I have aimed especially to indicate the ways in which the powerful new molecular tools and other 'omics' technologies can contribute to advancing our understanding of the biophysical interactions between plants and the atmosphere. As in the previous editions, however, I have continued the approach of describing only briefly the biochemical and molecular mechanisms involved in plant responses to the environment, so interested readers are referred to specialist reviews and books mentioned at appropriate places in the text.

For this third edition I have chosen largely to retain the general structure and aims of the successful previous editions. In particular the key aim remains to provide an authoritative introduction to environmental plant physiology suitable both as a text for upper undergraduate and postgraduate courses and as a reference for researchers in the field. As previously, the first half of the text concentrates on the general principles, with the later chapters going more into the physiology and practical applications. The emphasis throughout remains on the more quantitative and physical aspects of plant responses to the aerial environment as these topics tend to be relatively poorly treated by the standard plant physiology texts, yet our need to understand how the whole plant functions and responds to its environment has never been greater if we are to respond effectively to the challenges that face the world in the coming years. These include responding to the problems and opportunities raised by climate change and by the need to continue to feed the burgeoning and increasingly wealthy world population in the coming years.

As it is now 20 years since the previous edition was published it has proved necessary to completely revisit and revise the content throughout. Around half the publications referred to are new; nevertheless many of the references to earlier papers have been retained, especially for data. Even though many thousands of potentially relevant new papers and texts have appeared, often these only provide refinements rather than substantial improvements (for example I still quote the data using 1% O_2 to suppress photorespiration even though more recent papers use 2%). The citations included fall into one of several categories: general texts and reviews that give access to useful references and a limited number of key original references, while the majority of citations are simply useful examples selected from among many possible papers. I have also, where appropriate, included a limited number of key internet addresses, though it should be recognised that these change rapidly.

In revising the text I am indebted to many colleagues from around the world who have provided helpful and constructive comments on the previous editions, and to those who have read and commented on sections of the text. Particular thanks go to Abdellah Barakate, David Deery, Olga Grant, Anthony Hall, Amanda Jones, Ian MacKay, Barry Osmond, John Raven, Philip Smith and Bill Thomas.

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SYMBOLS

Where possible I have tried to use the most commonly accepted symbols for different quantities, though in some areas such as the treatment of radiation there appears to be no universal consensus. Where possible the use of the same symbol for different quantities has been minimised, though where duplication is unavoidable there should usually be little chance of confusion. Note that different fonts are used to distinguish quantities, for example molar and mass units for gas transfer. The individual superscripts and subscripts given for each main symbol may be combined to make compound symbols.

a	amplitude of oscillation (a′, modified amplitude)
a, A	constants
a_W	activity *subscript:* a_W water
A	amp (coulomb s^{-1})
A	area (m^2)
A	absorbance (= ln [$\mathbf{I}_o/\mathbf{I}$])
b, B	constants
b_i	control parameters (sensitivity analysis)
c	concentration (kg m^{-3} or mol m^{-3}) *subscripts:* c_C carbon dioxide; c_H heat (J m^{-3} = $\rho c_p T$); c_M momentum (kg m^{-2} s^{-1} = ρu); c_O oxygen; c_W water; c_X concentration of pollutant X; c_a in the outside air; c_c at carboxylase; c_e in inlet air; c_i in intercellular spaces at surface of cell walls; c_x effective concentration internal to biochemistry (for CO_2); c_ℓ leaf; c_o in outlet air; c_{Pr} phytochrome concentration; c_s solute *superscripts:* c^m molar concentration; c' carbon dioxide (= c_C)
c_D	total drag coefficient
c_f	form drag coefficient
c_p	specific heat of air (c_p* specific heat capacity of leaf tissue) (J kg^{-1} K^{-1})
c	speed of light (2.998 m s^{-1})
C	capacitance (m MPa^{-1} or m^3 MPa^{-1})
C_r	relative capacitance (MPa^{-1})
C	sensible heat exchange (W m^{-2}) *subscripts:* $\mathbf{C}_{(d)}$ dry; $\mathbf{C}_{(w)}$ wet
C	control or sensitivity coefficients
d	days
d	zero plane displacement (m)
d	diameter (m) (e.g. d_p particle diameter)
d	characteristic dimension (m)
D	drainage (mm)
D	atmospheric vapour pressure deficit (kPa) *modifiers:* D* integrated average daily vapour pressure deficit; D_ℓ leaf to air vapour pressure deficit; D_{cW} absolute humidity deficit of air; D_{xW} water vapour mole fraction deficit of air
D	thermal time, growing degree days or temperature sum (°C day) *subscript:* D_{eff} effective day-degrees
$\boldsymbol{D}$	diffusion coefficient (m^2 s^{-1}) *subscripts:* $\boldsymbol{D}_A$ air; D_C CO_2, $\boldsymbol{D}_{CA}$ mutual diffusion coefficient for CO_2 in air; $\boldsymbol{D}_H$ heat; $\boldsymbol{D}_i$ the ith species; $\boldsymbol{D}_M$ momentum; $\boldsymbol{D}_O$ oxygen; $\boldsymbol{D}_W$ water; $\boldsymbol{D}_X$ pollutant X *superscript:* $\boldsymbol{D}^\circ$ reference value
$\mathscr{D}$	dielectric constant (dimensionless)
e	base for natural logarithm (2.71828)
e	water vapour pressure (Pa) (see also D) *subscripts:* e_a in bulk air; e_e in inlet; e_o in outlet; e_s surface; e_s saturation; $e_{s(T\ell)}$ saturation water vapour pressure at leaf temperature (= e_ℓ); e_{ice} vapour pressure over pure ice
e	equation of time (min)
E	radiant energy (e.g. of a photon) *subscript:* E_λ radiant energy per unit wavelength
E_a	activation energy
E	evaporation (or transpiration) rate (kg m^{-2} s^{-1}, mol m^{-2} s^{-1} or mm h^{-1})

modifiers: $\mathbf{E}_\ell$ transpiration; $\mathbf{E}^m$ evaporation or transpiration (molar units); $\mathbf{E}_o$ potential evaporation from free water surface; $\mathbf{E}_{eq}$ equilibrium evaporation; $\mathbf{E}_{imp}$ imposed evaporation

ET evapotranspiration
subscripts: $\mathbf{ET}_o$ reference evapotranspiration from short grass surface well supplied with water; $\mathbf{ET}_c$ expected value of **ET** for a specific crop and growth stage; $\mathbf{ET}_{c,adj}$ actual evapotranspiration for any crop

f Pfr/Pr ratio

f fraction (e.g. fraction of O_2 unconsumed, fraction carbon allocated to leaves as compared with roots, f_{PSII} the fraction of absorbed PAR that is received by PSII, f_{open} fraction of reaction centres that are open)

f_{veg} fractional vegetation cover

f enhancement factor

f fraction of water in unfrozen state (dimensionless)

F fluorescence (arbitrary or mol m^{-2} s^{-1})
modifiers: F' fluorescence at any time ($=F_t$); F_m maximum value after equilibration in dark; F'_m fluorescence at any time obtained with saturating flash; F_o basal fluorescence with open reaction centres; F'_o basal fluorescence at any time; F_v variable fluorescence ($F_m - F_o$); F_v' ($F'_m - F'_o$)

F force (N)

g conductance (m s^{-1})
subscripts: g_A canopy boundary layer conductance; g_L canopy physiological conductance; g_C carbon dioxide; g_H heat; g_M momentum; g_O oxygen; g_R radiation ($= 4\varepsilon\sigma T_a^3/\rho c_p$); g_{HR} parallel heat and radiative transfer; g_W water; g_a boundary layer; g_c cuticle; g_g gas phase; g_ℓ leaf; g_i intercellular space; g_m diffusive component in mesophyll; g_o reference value; g_s stomatal; g_w wall; g_x internal biochemical conductance
superscripts: g^m molar conductance ($= g$); g' carbon dioxide ($= g_C$)

g molar conductance ($=g^m$) (mol m^{-2} s^{-1})
modifiers: as for conductance (g)

$\mathbf{g}$ acceleration due to gravity (m s^{-2} = 9.8 at sea level)

G Gibbs free energy (J)

G soil heat storage (W m^{-2})

h hour

h Planck's constant (6.626 × 10^{-34} J s)

h relative humidity (dimensionless)

h hour angle of the sun (the angular distance from the meridian of the observer; degree or radian)

h height or thickness (m)

$HSAI$ hemi-surface area index (dimensionless)

I moment of inertia (kg m^{-2})

I electric current (A)

I thermal indices
subscripts: I_{CWSI} index analogous to CWSI; I_g conductance index

I irradiance (W m^{-2})
subscripts: $\mathbf{I}_S$ shortwave; $\mathbf{I}_{S(diffuse)}$ diffuse shortwave; $\mathbf{I}_{S(dir)}$ direct shortwave; $\mathbf{I}_L$ longwave; $\mathbf{I}_{(PAR)}$ photosynthetically active radiation; $\mathbf{I}_c$ light compensation point; $\mathbf{I}_p$ photon irradiance; $\mathbf{I}_e$ irradiance in terms of energy; $\mathbf{I}_A$ solar irradiance at top of atmosphere; $\mathbf{I}_{pA}$ solar constant; $\mathbf{I}_o$ reference value

J joule (1 kg m^2 s^{-2})

J_{max} maximum electron transport rate (ETR)

J flux density or mass transfer rate per unit area (kg m^{-2} s^{-1})
subscripts: $\mathbf{J}_v$ volume flux density (m s^{-1}); for other modifiers see ***D***

k thermal conductivity (W m^{-1} K^{-1})

k rate constant or other constant
subscripts: k_F, k_H, k_T and k_P, respectively, are the rate constants for de-excitation through fluorescence, thermal dissipation as heat, energy transfer to photosystem I, and PSII photochemistry with all reaction centres open; k_d rate of development ($= 1/t$)

k Boltzmann's constant

k	extinction coefficient (dimensionless)
k	von Karman's constant (= 0.41, dimensionless)
kg	kilogram
K	kelvin temperature
K_c	crop coefficient (for evaporation from a well watered crop)
	modifiers: $K_{c\text{-adj}}$ adjusted crop coefficient allowing for drought effects; K_{cb} basal coefficient for crop; K_{stress} stress modifier; K_s soil coefficient
K	hydraulic conductance (m MPa^{-1} s^{-1} or m^3 MPa^{-1} s^{-1}; see also L_p)
	modifiers: K_r root; K_{st} stem; K_ℓ leaf
$\boldsymbol{K}$	transfer coefficient (m^2 s^{-1})
	subscripts: as for $\boldsymbol{D}$
K_m	Michaelis constant (dimensions as for concentration or irradiance)
	modifiers: K_m^C for carbon dioxide; K_m^I for light
ℓ	length, thickness (m)
	superscript: ℓ^* thickness of leaf tissue
ℓ	photosynthetic limitation (s m^{-1})
	modifiers: superscripts as for resistance (r); ℓ' relative limitation (dimensionless)
ln	natural logarithm
log	logarithm to base 10
L	hydraulic conductivity (m^2 s^{-1} Pa^{-1})
L_p	hydraulic conductance (m s^{-1} Pa^{-1})
L_v	volumetric hydraulic conductance (s^{-1} Pa^{-1})
L	radiance or intensity (W sr^{-1})
	subscripts: L_{in}, L_{out} for radiance within or outside a Fraunhofer line
L	leaf area index
	modifier: L' leaf area index expressed per unit area of shaded ground (dimensionless)
m	metre
m	mass fraction (dimensionless)
	modifiers: as for concentration (c)
m	mass (kg)
m	air mass (dimensionless)
M	molecular mass
	subscripts: as for $\boldsymbol{D}$
$\mathbf{M}$	radiant exitance (W m^{-2})
$\mathbf{M}$	metabolic heat storage (W m^{-2})
mol	mole (amount of substance containing Avogadro's number of particles)
n	hours bright sunshine; number
n	number of moles
	subscripts: n_p photons; n_s solute; other subscripts as for $\boldsymbol{D}$
$n(E)$	number of moles with energy exceeding E (mol)
N	Newton
N	daylength (h)
N	reflectance in the near infrared (= ρ_{NIR})
O	run-off (mm)
p	partial pressure (Pa)
	modifiers: as for $\boldsymbol{D}$ and for concentration (c)
P	precipitation (mm)
P	pressure (Pa)
	modifiers: P^o reference; P^* balance pressure
P	period of oscillation (s)
P_e	power output (W m^{-2})
$\mathbf{P}$	photosynthesis (mg m^{-2} s^{-1} or µmol m^{-2} s^{-1})
	subscripts: $\mathbf{P}_c$ rubisco-limited rate; $\mathbf{P}_g$ gross photosynthesis; $\mathbf{P}_j$ RuBP-limited rate; $\mathbf{P}_n$ net photosynthesis; $\mathbf{P}_{max}$ maximum value with either light of CO_2 saturating; $\mathbf{P}_t$ triose phosphate-limited rate
	superscripts: $\mathbf{P}^m$ molar; $\mathbf{P}^{max}$ maximum with light and CO_2 saturating; $\mathbf{P}^o$ reference value
q	fluorescence quenching
	subscripts: q_I photo-inhibition; q_L estimate of the fraction of open PSII reaction centres using 'lake' model; q_N non-photochemical; q_o F_o quenching; q_P photochemical quenching; q_T state transition
qr	quantum requirement
Q_{10}	temperature coefficient: the ratio of the rate at one temperature to that at a temperature ten degrees lower (dimensionless)
$\mathbf{Q}$	radiant flux (J s^{-1} or W)
	modifiers: as for radiant flux density ($\mathbf{R}$)
r	radius (m)
r	resistance (s m^{-1} or m^2 s mol^{-1})
	modifiers: as for conductance (g); also $r'_* = \mathrm{d}x'_w/\mathrm{d}\mathbf{P}_n$ at normal ambient CO_2

r	molar resistance ($= r^{m}$) (m^2 s mol^{-1}) *modifiers:* as for conductance (g)
R	liquid phase hydraulic resistance (MPa s m^{-1} or MPa s m^{-3}) *subscripts:* R_ℓ leaf; R_p plant; R_s soil; R_{st} stem
R	isotopic ratio (e.g. $^{18}O/^{16}O$) *subscript:* R_0 reference value
R	electrical resistance (ohm = W A^{-2})
R	reflectance in the red ($= \rho_R$)
$\mathbf{R}$	respiration rate (mg m^{-2} s^{-1} or µmol m^{-2} s^{-1}) *subscripts:* $\mathbf{R}_d$ dark; $\mathbf{R}_\ell$ light; $\mathbf{R}_g$ growth; $\mathbf{R}_m$ maintenance; $\mathbf{R}_{non\text{-}ps}$ from non-photosynthesising tissue
$\mathbf{R}$	radiant flux density (W m^{-2}) *subscripts:* subscripts 'e' and 'p' are used to distinguish radiant ($\mathbf{R}_e$) flux density (W m^{-2}) and photon ($\mathbf{R}_p$) flux density (mol m^{-2}) where necessary; $\mathbf{R}_{absorbed}$ absorbed; $\mathbf{R}_{emitted}$ emitted; $\mathbf{R}_{(d)}$ dry; $\mathbf{R}_{(w)}$ wet; $\mathbf{R}_d$ downward; $\mathbf{R}_u$ upward; $\mathbf{R}_n$ net radiation; $\mathbf{R}_{ni}$ net isothermal radiation; $\mathbf{R}_R$ radiative heat loss = $\mathbf{R}_n - \mathbf{R}_{ni}$
$\mathscr{R}$	gas constant (8.3144 J mol^{-1} K^{-1} or Pa m^3 mol^{-1} K^{-1})
s	rate of change of saturation vapour pressure with temperature (Pa K^{-1})
s	second
sr	steradian
S	stress (Pa)
$S_i(z)$	source density profile of entity i with height
$S(t)$	state of development at time t
$\mathbf{S}$	heat flux into storage (W m^{-2})
t	time (s, h or day) *subscripts:* t_o time at solar noon; t_d number of day in the year; $t_{1/2}$ half-time
T	temperature (°C or K) *subscripts:* T_a air; T_{dew} dew point; T_d dry; T_e equilibrium; T_ℓ leaf; T_w wet; T_{wb} wet-bulb temperature; T_{base} non-water-stressed-baseline temperature; T_h heated replica; T_m mean; T_o optimum; T_{max} maximum; T_s surface; T_s saturation; T_{sky} apparent radiative temperature of the sky; T_t threshold; T_u unheated replica; T_x observed temperature at given D *superscript:* T° reference temperature
$T(t)$	temperature as function of time
T	growing season length (days)
$\mathbf{T}$	torque or turning moment (N m or J)
$\mathcal{T}$	transmission in discontinuous canopies (dimensionless) *subscript:* $\mathcal{T}_f$ fraction that would reach the ground if all leaves non-transmitting
u	molar air flow rate (mol s^{-1})
u	wind velocity (m s^{-1}) *subscripts:* u_z wind velocity at height z; u_* friction velocity
v_s	sedimentation velocity (m s^{-1})
v	volume flow rate (m^3 s^{-1})
V_d	deposition velocity (m s^{-1})
V	rate of reaction *subscripts:* V_c velocity of carboxylation; V_o velocity of oxygenation; $V_{c,max}$ maximum velocity of Rubisco for carboxylation
V	volume (m^3) *modifiers:* V_e expressed sap; V_o turgid volume of cell; $\overline{V}_W$ partial molal volume of water (18.048×10^{-6} m^3 mol^{-1} at 20°C)
V	electrical potential difference (volt = W A^{-1})
w	mixing ratio (dimensionless) *subscripts*: as for $\boldsymbol{D}$
w	vertical wind velocity (m s^{-1})
W	watt (J s^{-1})
W	water content (kg m^{-2} or kg m^{-3}) *subscripts:* W_ℓ leaf; W_{max} maximum
W	leaf mass per unit area in CO_2 equivalents (g m^{-2})
x	mole fraction *modifiers:* as for $\boldsymbol{D}$ and concentration (c)
x	distance or displacement (m)
Y	yield threshold (Pa)
Y	economic yield (tonne ha^{-1} or kg m^{-2}) *subscript:* Y_d dry matter yield
z	distance, height or depth, or atmosphere thickness (m) *subscript:* z_o roughness length
Z	damping depth (m)
α	contact angle (degree or radian)
α	absorptivity, absorption coefficient or absorptance (dimensionless)

	modifiers: subscripts define waveband (e.g. α_{660} or α_S)
α	the azimuth or aspect of a surface (measured east from north)
α	the ratio between the woody tissue (hemispheric) area index and the total plant (hemispheric) area index
α	Priestley–Taylor coefficient
β	solar elevation (degree or radian; complement of θ)
$\boldsymbol{\beta}$	Bowen ratio (dimensionless = $\mathbf{C}/\lambda\mathbf{E}$)
γ	psychrometer constant (Pa K^{-1} = $Pc_p/0.622\lambda$) *superscript:* γ^* the modified psychrometer constant (= $\gamma g_H/g_W$)
γ_W	activity coefficient for water that measures departure from ideal behaviour
Γ	total soil heat flux ratio (dimensionless) *modifier:* Γ′ energy partitioning at the soil surface
Γ	carbon dioxide compensation concentration (mg m^{-3} or mmol m^{-3}) *modifier:* Γ_* concentration at which CO_2 loss by oxygenation equals uptake by carboxylation
δ	deviation of isotope abundance from ratio in a standard sample (e.g. $\delta^{13}C$) *subscripts:* δ_a air; δ_p plant
δ	solar declination (degree)
δ	average thickness of laminar boundary layer (m) *subscript:* δ_{eq} thickness of equivalent boundary layer (m)
∂	partial differential
Δ	isotopic discrimination (dimensionless, ‰) *subscripts:* Δ_a AOX discrimination; Δ_c COX discrimination
Δ	finite difference
Δ*F*	difference between steady state and maximal fluorescence
ΔT_f	freezing point depression (K)
ε_i	elasticities of individual reactions in a pathway
ε	emissivity
ε	efficiency (dimensionless) *modifiers:* ε_p photon efficiency; ε_q quantum efficiency; $\varepsilon_{q(Pr)}$ quantum yield for phytochrome conversion
ε_Y	Young's modulus (Pa)
ε_B	bulk modulus of elasticity (Pa)
$\boldsymbol{\varepsilon}$	s/γ
ζ	ratio of the photon flux densities in the red (655–665 nm) and far-red (725–735 nm) portions of the spectrum
η	dynamic viscosity (N s m^{-2} or kg m^{-1} s^{-1})
θ	relative water content (dimensionless, %)
θ	angle from beam to normal; zenith angle of the sun (degree or radian)
Δθ	change in soil moisture content
λ	wavelength (m) *subscript:* λ_m peak wavelength of Planck distribution
λ	latent heat of vaporisation of water (J kg^{-1})
λ	latitude (degree or radian)
λ_o	clumping index
$\boldsymbol{\lambda}$	constant; climate sensitivity parameter
μ_W	chemical potential (J mol^{-1}) *modifiers:* μ_W of water; μ° reference value
v	frequency (hertz)
v	frequency of stomata (mm^{-2})
υ	wavenumber (cm^{-1})
$\boldsymbol{v}$	kinematic viscosity (m^2 s^{-1} = $\boldsymbol{D}_M$)
π	pi, the ratio of circumference of a circle to its diameter (3.14159)
Π	osmotic pressure (MPa = $-\psi_\pi$)
ρ	density (often of dry air) (kg m^{-3}) *modifiers:* ρ_a dry air (sometimes abbreviated to ρ); ρ_{as} air saturated with water vapour; ρ_i *i*th component of mixture; ρ^* density of leaf or replica
ρ	reflectivity; reflection coefficient; reflectance or albedo (dimensionless) *subscripts:* ρ_{NIR} near infrared (= *N*); ρ_R red (= *R*); $\rho_{(\theta)}$ at any zenith angle θ; others as for α
σ	Stefan–Boltzmann constant (5.6703 × 10^{-8} W m^{-2} K^{-4})
σ	reflection coefficient (dimensionless)
$\boldsymbol{\sigma}$	surface tension (N m^{-1} = 7.28 ×10^{-3} for water at 20°C)

$\sigma_{1,2}$	the fractional contribution of stomata to a change in limitation between two states $\mathbf{P}_{n1}$ and $\mathbf{P}_{n2}$
τ	time constant (s)
τ	transmissivity, transmission coefficient or transmittance (dimensionless) *subscripts*: as for α
τ_a	proportion of flow through AOX
$\boldsymbol{\tau}$	shearing stress (Pa = N m^{-2}) *subscript:* $\boldsymbol{\tau}_f$ form drag
ϕ	evaporative fraction (dimensionless)
$\boldsymbol{\phi}_C$	losses of CO_2 not associated with losses through stomata
$\boldsymbol{\phi}_W$	losses of H_2O not associated with losses through stomata
ϕ	phytochrome photoequilibrium $Pfr/P_{total} = f/(1+f)$
ϕ	extensibility (s^{-1} Pa^{-1})
ϕ	phase lag (s)
ϕ	photorespiratory stoichiometry
ϕF	quantum yield for fluorescence (dimensionless)
χ	the zenith angle (= slope) of a surface (radian or degree)
ψ	water potential (MPa) *subscripts*: ψ_p, ψ_π, ψ_m and ψ_g respectively are components due to pressure, osmotic, matric and gravitational forces; ψ_ℓ leaf water potential, ψ_{st} stem water potential; $\psi_{\ell 0}$ initial value
ω	angular frequency (= $2\pi \times$ period)
ω	angular velocity (rad sec^{-1})
Ω	solid angle (sr)
$\boldsymbol{\Omega}$	decoupling coefficient (dimensionless)

MAIN ABBREVIATIONS AND ACRONYMS

ABA	abscisic acid
ADP	adenosine diphosphate
AOX	alternative oxidase
ATP	adenosine-5′-triphosphate
BRDF	bidirectional reflectance distribution function
BRF	bidirectional reflectance factor
BVOC	biogenic volatile organic compound
BWB	Ball–Woodrow–Berry model
C_3	three-carbon photosynthetic pathway
C_4	four-carbon photosynthetic pathway
CAM	crassulacean acid metabolism
CFCs	chlorofluorocarbons
CGR	crop growth rate (kg m^{-2} day^{-1})
COX	cytochrome oxidase
CRB	C-repeat binding proteins
CWSI	crop water stress index
DELLA	DELLA proteins are transcriptional regulators that regulate gibberellic acid signalling
DREB	deyhdration-responsive element binding proteins
DVI	difference vegetation index
ETR	electron transport rate through PSII
EUW	Effective use of water
FACE	free-air carbon dioxide enrichment experiment
$FADH_2$	reduced flavin adenine dinucleotide
fAPAR	fraction of absorbed photosynthetically active radiation
FR	far red
FSPM	functional–structural plant models
FvCB	the Farquhar–von Caemmerer–Berry model of photosynthesis
GCM	global circulation model
GDD	growing degree days (see *D*)
GNDVI	green normalised difference vegetation index
GWP	global warming potential
HFC	hydrofluorocarbons
HI	harvest index
HIR	high irradiance response
HU	‘heat’ units (should be avoided)
IAA	indole acetic acid
IR	infrared
IRGA	infrared gas analyser
LAD	leaf area duration
LAR	leaf area ratio
LD_{50}	minimum survival temperatures
LD	long-day (also LSD for long–short day)
LFR	low fluence rate response
LHC	light harvesting complex
LOV	light-oxygen-voltage domains
LUE	light use efficiency
MAS	marker-assisted selection
MIPs	major intrinsic proteins
MOST	Monin–Obukhov similarity theory
N_2	nitrogen
NAC	a superfamily of transcription factors
$NADP^+$	nicotinamide adenine dinucleotide phosphate
NADPH	reduced nicotinamide adenine dinucleotide phosphate
NAR	net assimilation rate
NDVI	normalised difference vegetation index
NPQ	non-photochemical quenching $((F_m/F_m') - 1)$
OAA	oxaloacetate
OTC	open-top chamber
P_{680}	reaction centre in PSII
P_{700}	reaction centre in PSI
Pa	pascal (N m^{-2} or kg m^{-1} s^{-2})
PAR	photosynthetically active radiation (400–700 nm)
PBM	process-based models
PCO	photorespiratory carbon cycle
PCR	photosynthetic carbon reduction cycle

PDB	Peedee belemnite formation in South Carolina
PEP	phospho*enol*pyruvate
Pfr	far-red absorbing form of phytochrome
PGA	phosphoglyceric acid
pH	negative logarithm of hydrogen ion activity
phy	phytochrome
PHY	PHY-A, PHY-B, etc. phytochrome proteins (genes in italic)
phot1, phot2	phototropins
PIF	phytochrome interacting factor (e.g. PIF4 and PIF5)
PIPs	plasma membrane intrinsic proteins
ppb	volume parts per billion (10^9)
ppt	volume parts per trillion (10^{12})
Pr	red light absorbing form of phytochrome
PRI	photochemical reflectance index
PSI	photosystem I
PSII	photosystem II
Q_A, Q_B	quinone acceptors
QTL	quantitative trait loci
R	red light
RF	radiative forcing (W m^{-2})
RGR	relative growth rate (day^{-1})
RNA	ribonucleic acid
RNAi	RNA interference
ROS	reactive oxygen species
Rubisco	ribulose-1,5-bisphosphate carboxylase-oxygenase
RuBP	ribulose-1,5-bisphosphate
RVI	ratio vegetation index
SAVI	soil adjusted vegetation index
SD	short-day (also SLD for short–long day)
SHAM	salicylhydroxamic acid
SLA	specific leaf area
SNP	single nucleotide polymorphism
TCA	tricarboxylic acid
TE	transpiration efficiency
TIPs	tonoplast intrinsic proteins
TPU	triose phosphate utilisation
UAV	unmanned aerial vehicles
UV	ultraviolet (UV-A: 315–400 nm, UV-B: 280–315 nm, UV-C: <280 nm)
VI	vegetation index
VLFR	very low fluence rate response
vpm	volume parts per million
WUE	water use efficiency
WUE*	water use efficiency integrated over the life of a plant
ZTL	ZEITLUPE family proteins