

Contents

Preface xxiii

Part I Origins

1 Plant life: a primer 3

1.1 An introduction to plant biology 3

1.2 Plant systematics 3

- 1.2.1 Each species has a unique scientific name that reflects its phylogeny 3
- 1.2.2 Modern classification schemes attempt to establish evolutionary relationships 4

1.3 The origin of land plants 6

- 1.3.1 The green plant clade, viridophytes, includes the green algae and land plants 6
- 1.3.2 Unlike their green algal ancestors, embryophytes have evolved adaptations to life on land 6

1.4 Bryophytes 8

- 1.4.1 Bryophytes have adapted to a range of environments and show a limited degree of differentiation into tissues and organs 9
- 1.4.2 Gametophytes dominate the bryophyte life cycle 9
- 1.4.3 Many features of bryophytes suggest a link to the vascular plants 11

1.5 Vascular plants 11

- 1.5.1 Lycophytes were among the first tracheophytes to evolve 11
- 1.5.2 Ferns, horsetails and whisk ferns constitute a single monophyletic clade, the monilophytes 12
- 1.5.3 Although adapted to land, ferns require water for reproduction 12
- 1.5.4 Seed plants are successful conquerors of land 13
- 1.5.5 Seeds encase the embryo and its food, facilitating dispersal of the new sporophyte generation 13

1.6 Gymnosperm phylogeny and reproduction 15

- 1.6.1 Gymnosperm phylogeny reveals five lineages 15

1.6.2 Conifers constitute an important natural resource 15

1.6.3 Sporangia and gametophytes of pines and other conifers are produced in cones 15

1.6.4 Pine reproduction is characterized by a long delay between pollination and fertilization 16

1.6.5 Pine seeds contain both diploid and haploid tissues 17

1.7 Angiosperm phylogeny and reproduction 18

1.7.1 The flower is the defining feature of angiosperms 19

1.7.2 Gametophytes of angiosperms are much smaller than those of gymnosperms 20

1.7.3 Double fertilization in angiosperms leads to the formation of a diploid embryo and polyploid endosperm 20

1.7.4 In angiosperms, fruits promote seed dispersal 23

1.8 The seed plant body plan I. Epidermis, ground tissue and vascular system 23

1.8.1 Epidermal tissue covers the outside of a plant while ground tissue makes up the bulk of a plant 24

1.8.2 Vascular tissues are specialized for long-distance transport 27

1.8.3 Long-distance transport of water occurs in tracheary elements 27

1.8.4 Long-distance transport of organic solutes occurs in sieve tubes 27

1.9 The seed plant body plan II. Form and function of organ systems 27

1.9.1 The root system acquires water and minerals 28

1.9.2 Primary tissues of the root consist of the central stele surrounded by the cortex and epidermis 30

1.9.3 The shoot system is organized into repeating modules 31

1.9.4 The tissues of an angiosperm leaf consist of an epidermis with stomata, photosynthetic mesophyll cells and veins 31

1.9.5 Primary tissues of the stem are organized differently in monocots and eudicots 32

1.10 The seed plant body plan III. Growth and development of new organs 33

- 1.10.1 Apical meristems produce the primary plant body 34
- 1.10.2 The root apex consists of the meristem covered by the root cap, and lateral roots originate as primordia in the pericycle 35
- 1.10.3 The shoot apical bud is the source of leaves, axillary buds and floral organs 35
- 1.10.4 Secondary growth is for the long haul, up to thousands of years 35
- 1.10.5 Lateral meristems allow for expansion in girth 35
- 1.10.6 Wood morphology is influenced by environmental and endogenous factors 38

2 Molecules, metabolism and energy 42

2.1 Introduction to biological chemistry and energetics 42

2.2 Biological molecules 42

- 2.2.1 Molecules consist of atoms linked by chemical bonds 42
- 2.2.2 Chemical structures are represented in a variety of ways 43
- 2.2.3 Water is an essential constituent of living cells 44
- 2.2.4 Biological molecules have carbon-carbon backbones 46
- 2.2.5 Monomers are linked to form macromolecules 46
- 2.2.6 Carbohydrates include simple sugars and complex polysaccharides 47
- 2.2.7 Lipids include oils, fats, waxes and sterols 50
- 2.2.8 Proteins function as catalysts, structural and mechanical entities, and signaling molecules 54
- 2.2.9 Nucleic acids contain the genetic information of an organism 57

2.3 Energy 59

- 2.3.1 Biological systems obey the laws of thermodynamics 60
- 2.3.2 Change in free energy can be used to predict the direction of a chemical reaction 60
- 2.3.3 Electrons are transferred in oxidation/reduction reactions 61
- 2.3.4 Energy in cells flows through phosphorylated intermediates 62
- 2.3.5 ATP is the central player in cellular energy flow 63

- 2.3.6 Synthesis of ATP occurs by two distinct mechanisms 64

2.4 Enzymes 64

- 2.4.1 Enzymes often require cofactors 64
- 2.4.2 Catalysis greatly increases the rates of thermo-dynamically feasible reactions by reducing energy barriers 67
- 2.4.3 A number of factors determine the rate of enzyme-catalyzed reactions 68
- 2.4.4 Enzyme activity is under tight regulation 70

3 Genome organization and expression 74

3.1 Introduction to genes and genomes 74

3.2 Organization of plant genomes I. Plastid, mitochondrial and nuclear genomes 74

- 3.2.1 Plastid genomes do not contain all the genes required for plastid function 74
- 3.2.2 Plant mitochondrial genomes vary greatly in size between different plant species 75
- 3.2.3 Some plant nuclear genomes are much larger than the human genome, others are much smaller 78
- 3.2.4 Repetitive DNA makes up much of the genome in many plants 79
- 3.2.5 Related plant species show conserved organization of gene content and order 81

3.3 Organization of plant genomes II. Chromosomes and chromatin 82

- 3.3.1 Chromosome arms are gene-rich 83
- 3.3.2 Each chromosome arm terminates in a telomere 84
- 3.3.3 The centromere is a complex structure visible as a constriction in the chromosome 85
- 3.3.4 Chromosomes have other distinctive structural features 86
- 3.3.5 DNA in the nucleus is packaged with histones to form chromatin 87
- 3.3.6 Each species has a characteristic chromosome number 88
- 3.3.7 Polyploidy and genome duplication are common in plants 89

3.4 Expression of the plant genome I. Transcription of DNA to RNA 91

- 3.4.1 Plant nuclear genes have complex structures 91
- 3.4.2 Histones and chromatin organization play important roles in gene expression 92
- 3.4.3 Higher-order chromatin structure also regulates gene expression 92

- 3.4.4 Promoters and other regulatory elements control the timing and extent of gene transcription 93
 - 3.4.5 RNA polymerases catalyze transcription 93
 - 3.4.6 Transcription factors bind to DNA regulatory sequences 96
 - 3.4.7 Homeobox proteins are important in regulating development and determining cell fate 96
 - 3.4.8 The MADS-box family includes homeotic genes and regulators of flowering time 97
 - 3.4.9 Many genes are named after mutant phenotypes 98
 - 3.4.10 Transcription proceeds via initiation, elongation and termination 98
 - 3.4.11 Messenger RNA molecules undergo post-transcriptional modifications 99
 - 3.4.12 Micro RNAs are regulators of gene expression at the post-transcriptional level 100
 - 3.5 Expression of the plant genome II. Epigenetic regulation of gene expression 100**
 - 3.5.1 DNA methylation is an important mediator of epigenetic regulation of gene expression 100
 - 3.5.2 Epigenetic changes through paramutation can be passed on from one generation to the next 100
 - 3.5.3 Transgenes can silence a plant's own genes by cosuppression 101
 - 3.5.4 Imprinting occurs only at certain stages in plant development 101
 - 3.6 Expression of the plant genome III. Translation of RNA to protein 101**
 - 3.6.1 Transfer RNAs are the link between mRNA codons and amino acids 103
 - 3.6.2 Protein biosynthesis takes place on ribosomes 104
 - 3.6.3 Protein synthesis is initiated from the 5' end of the mRNA 105
 - 3.6.4 Polypeptide chain elongation occurs by the sequential addition of amino acid residues to the growing polypeptide chain 106
 - 3.6.5 Protein synthesis terminates when a stop codon is reached 109
 - 3.6.6 Most proteins undergo post-transcriptional modifications 109
 - 3.7 Expression of organellar genes 111**
 - 3.7.1 The machinery of chloroplast gene expression resembles that of bacteria more than that of nuclear genes 111
 - 3.7.2 Transcripts encoded by the plastid genome are often polycistronic and are translated by prokaryotic-type mechanisms 112
- ## 4 Cell architecture 114
- 4.1 Introduction to cell structure 114**
 - 4.2 The cell wall 114**
 - 4.2.1 Cellulose is a major component of the fundamental framework of primary cell walls 116
 - 4.2.2 Cross-linking glycans interlock the cellulosic scaffold 116
 - 4.2.3 Pectin matrix polymers can form a second network in primary cell walls 117
 - 4.2.4 Non-polysaccharide constituents form a third structural network in primary cell walls 118
 - 4.2.5 Biosynthesis and assembly of primary cell walls occurs during cell expansion 120
 - 4.2.6 Secondary walls are produced after growth of the primary wall has stopped 120
 - 4.3 Membranes of the cell 122**
 - 4.3.1 Biological membranes have common structural and functional properties 122
 - 4.3.2 The plasma membrane is the boundary between living protoplast and the external environment 124
 - 4.4 The nucleus 125**
 - 4.5 The endomembrane system 125**
 - 4.5.1 The endoplasmic reticulum is a membrane system that is continuous with the nuclear envelope 126
 - 4.5.2 Many proteins are synthesized on the rough endoplasmic reticulum 126
 - 4.5.3 Smooth endoplasmic reticulum participates in fatty acid modification, lipid synthesis and the production of oil bodies 128
 - 4.5.4 The Golgi apparatus processes and packages newly synthesized macromolecules 129
 - 4.5.5 Transport through the Golgi is directional 131
 - 4.5.6 Vesicles exchange materials with the cell exterior by exocytosis and endocytosis 131
 - 4.5.7 Vacuoles are multifunctional compartments 131
 - 4.6 Plastids 132**
 - 4.6.1 Plastids are bounded by two membranes and possess prokaryotic-type genomes and protein synthesis machineries 132
 - 4.6.2 Different types of plastids are developmentally related to one another 133

- 4.6.3 Plastids reproduce by division of existing plastids and are inherited differently in angiosperms and gymnosperms 135
- 4.7 **Mitochondria and peroxisomes** 136
- 4.8 **The cytoskeleton** 137
 - 4.8.1 The cytoskeleton consists of a network of fibrous proteins 137
 - 4.8.2 Microtubules and actin filaments have an intrinsic polarity 139
 - 4.8.3 Spontaneous assembly of cytoskeletal components occurs in three steps 139
 - 4.8.4 Accessory proteins regulate the assembly and function of the cytoskeleton 142
 - 4.8.5 Cytoplasmic streaming and movement and anchoring of organelles require actin 142
 - 4.8.6 Actin filaments participate in secretion 143
 - 4.8.7 Cortical microtubules help orientate cell expansion by aligning cellulose microfibrils 145

Part II

Germination

5 Membrane transport and intracellular protein trafficking 149

- 5.1 **Introduction to the movement of solutes and macromolecules** 149
- 5.2 **Physical principles** 151
 - 5.2.1 Diffusion is a spontaneous process and obeys Fick's law 151
 - 5.2.2 The chemical potential of a solute is expressed as free energy per mole 151
 - 5.2.3 Differences in chemical potential drive solute movement 152
 - 5.2.4 Unequal distributions of charged solutes across membranes give rise to a membrane potential 153
 - 5.2.5 The Nernst equation predicts internal and external ion concentrations for a given membrane potential 153
- 5.3 **Regulation of solute movement by membranes and their associated transporters** 154
- 5.4 **Pumps** 157
 - 5.4.1 Plasma membrane H^+ -ATPase plays a key role in membrane transport 158

- 5.4.2 Plasma membrane H^+ -ATPase is regulated predominantly through enzyme activity rather than gene expression 159
- 5.4.3 A Ca^{2+} pumping ATPase on endomembranes regulates cytosolic Ca^{2+} concentrations 159
- 5.4.4 V-type H^+ -ATPases in plants are related to F-type ATPases 160
- 5.4.5 Two types of H^+ pumping pyrophosphatase are found in plants 161
- 5.4.6 ABC transporters are P-type ATPases that facilitate solute transport 162
- 5.5 **Channels** 162
 - 5.5.1 Ion channel activity is studied using patch clamping 163
 - 5.5.2 The movement of ions through channels results in current flow 164
 - 5.5.3 Opening and closing of channels is tightly regulated 164
 - 5.5.4 Aquaporins are a class of channels facilitating water movement 165
 - 5.5.5 Flux of water through aquaporins is regulated by many factors 166
- 5.6 **Carriers and co-transporters, mediators of diffusion and secondary active transport** 167
- 5.7 **Intracellular transport of proteins** 168
 - 5.7.1 Protein transport requires peptide address labels and protein-sorting machinery 169
 - 5.7.2 To reach its destination, a protein often crosses at least one membrane 169
 - 5.7.3 Transport into chloroplasts and mitochondria involves translocation through several membrane barriers 170
 - 5.7.4 Passage across a single membrane is required for proteins to enter peroxisomes 172
 - 5.7.5 Proteins enter the nucleus through the nuclear pore 172
- 5.8 **The protein secretory pathway** 173
 - 5.8.1 Signal peptides target proteins to the endoplasmic reticulum 173
 - 5.8.2 Post-translational modification of proteins begins in the endoplasmic reticulum 175
 - 5.8.3 Coat proteins govern the shuttling of vesicles between the endoplasmic reticulum and Golgi 176
 - 5.8.4 Proteins are transported from the Golgi to a range of destinations 177
- 5.9 **Protein turnover and the role of the ubiquitin–proteasome system** 177

- 5.9.1 Ubiquitin targets proteins for degradation 178
- 5.9.2 The 26S proteasome is a molecular machine that breaks down ubiquitinated proteins 178
- 5.9.3 Cytosolic and endoplasmic reticulum localized proteins are degraded by the UbPS 179

6 Seed to seedling: germination and mobilization of food reserves 181

- 6.1 Introduction to seeds and their germination 181
- 6.2 Seed structure 182
 - 6.2.1 Seeds contain an embryonic plant 182
 - 6.2.2 Seed coats, made of layers of dead cells, protect the embryo 183
 - 6.2.3 Endosperm, a tissue unique to angiosperms, contains stored food 184
- 6.3 Use of seed storage reserves by the germinating embryo 186
 - 6.3.1 Starch is the major carbohydrate reserve of plants 188
 - 6.3.2 Cell walls are also an important store of polysaccharides in many seeds 191
 - 6.3.3 Storage proteins in eudicot seeds include globulins and albumins 192
 - 6.3.4 Storage proteins in cereal grains differ from those found in eudicot seeds 193
 - 6.3.5 The amino acid content of seed proteins affects their nutritional value for humans and livestock 194
 - 6.3.6 Seed storage proteins may act as antinutrients 195
 - 6.3.7 Unlike most plant tissues, seeds often contain storage lipids 196
 - 6.3.8 The fatty acid content of seed oil is important for human uses 197
 - 6.3.9 Seeds store the bulk of mineral elements in a complexed form 200
 - 6.3.10 Phytate is another antinutrient in seeds 201
 - 6.3.11 Seed maturation produces seeds that can survive for long periods 202
- 6.4 Germination and early seedling growth 202
 - 6.4.1 Imbibition of water is necessary for seed germination 203
 - 6.4.2 Dormant seeds do not germinate after imbibition 203
 - 6.4.3 Environmental signals may trigger the breaking of dormancy 205

- 6.4.4 Light can be an important trigger for germination 205
- 6.4.5 Plant hormones play important roles in the maintenance and breaking of seed dormancy 207

6.5 Mobilization of stored reserves to support seedling growth 209

- 6.5.1 Mobilization of protein involves the enzymatic breakdown of proteins to amino acids 209
- 6.5.2 Stored protein mobilization in eudicots takes place in living cells 210
- 6.5.3 Mobilization of stored starch may be catalyzed by phosphorolytic enzymes 211
- 6.5.4 Amylases also play a role in starch breakdown 212
- 6.5.5 Cell walls are another source of carbohydrates 213
- 6.5.6 Mobilization of stored lipids involves breakdown of triacylglycerols 213
- 6.5.7 Stored minerals are mobilized by breaking down phytic acid 215

7 Metabolism of reserves: respiration and gluconeogenesis 218

- 7.1 Introduction to catabolism and anabolism 218
- 7.2 Anaerobic phase of carbohydrate breakdown 219
 - 7.2.1 Glycolysis converts glucose to pyruvate 220
 - 7.2.2 Alcoholic fermentation allows glycolysis to continue in the absence of oxygen 222
- 7.3 The tricarboxylic acid cycle 223
 - 7.3.1 Pyruvate is converted to acetyl-CoA in preparation for entry to the TCA cycle 223
 - 7.3.2 The TCA cycle completes the breakdown of pyruvate to carbon dioxide and reduced electron carriers 224
 - 7.3.3 Amino acids and acylglycerols are oxidized by glycolysis and the TCA cycle 226
 - 7.3.4 The TCA cycle and glycolysis provide carbon skeletons for biosynthesis 227
- 7.4 Mitochondrial electron transport and ATP synthesis 228
 - 7.4.1 Mitochondrial electron transport and oxidative phosphorylation generate ATP 228

- 7.4.2 The electron transport chain moves electrons from reduced electron carriers to oxygen 228
- 7.4.3 Proton pumping at Complex III occurs via the Q cycle 231
- 7.4.4 The F_0F_1 -ATP synthase complex couples proton gradient to ATP formation 233
- 7.4.5 An overall energy balance sheet for oxidative phosphorylation can be worked out from moles of NADH in and ATP out 233
- 7.4.6 Bypass dehydrogenases are associated with mitochondrial Complex I 234
- 7.4.7 Plant mitochondria have an alternative oxidase that transfers electrons to oxygen 236
- 7.5 The oxidative pentose phosphate pathway 237**
 - 7.5.1 The pentose phosphate pathway has oxidative and regenerative phases 237
 - 7.5.2 The pentose phosphate pathway is a source of intermediates for a number of biosynthetic pathways 237
- 7.6 Lipid breakdown linked to carbohydrate biosynthesis 239**
 - 7.6.1 The glyoxylate cycle converts acetyl-CoA to succinate 239
 - 7.6.2 Mitochondria convert succinate to malate, a precursor of carbohydrates 239
 - 7.6.3 Gluconeogenesis converts phosphoenolpyruvate to hexoses 241
- 7.7 Control and integration of respiratory carbon metabolism 242**
 - 7.7.1 Fine control of respiration is exercised through metabolic regulation of enzyme activities 243
 - 7.7.2 Respiration interacts with other carbon and redox pathways 244
 - 7.7.3 Coarse control of respiratory activity is exerted through regulation of gene expression 245
- 8.1.2 Light interacts with matter in accordance with the principles of quantum physics 253
- 8.1.3 Photobiology is the study of the interaction of light with living organisms 255
- 8.2 Phytochrome 256**
 - 8.2.1 Light acts through isomerization of the phytochrome chromophore 256
 - 8.2.2 Phytochrome protein has a complex multidomain structure 257
 - 8.2.3 Different forms of phytochrome are encoded by multiple genes 259
 - 8.2.4 Phytochrome regulates gene expression by interacting with a number of proteins 261
- 8.3 Physiological responses to blue and ultraviolet light 263**
 - 8.3.1 Cryptochromes are responsible for regulating several blue light responses, including photomorphogenesis and flowering 264
 - 8.3.2 Phototropins are blue light receptors that contribute to optimizing growth, tropic responses and plastid orientation 266
 - 8.3.3 Other phototropin-like LOV receptor proteins act as photoreceptors in a wide range of species and plant processes 267
 - 8.3.4 Wavelengths of light that are reflected or transmitted by leaves may be used to detect the presence of neighboring plants 268
 - 8.3.5 Plants respond to wavelengths of light in addition to blue, red and far red 269
- 8.4 Biosynthesis of chlorophyll and other tetrapyrroles 270**
 - 8.4.1 Aminolevulinic acid is the precursor of tetrapyrrole biosynthesis 270
 - 8.4.2 Cyclic intermediates in tetrapyrrole metabolism are potential photosensitizers 272
 - 8.4.3 Protoporphyrin stands at the branch point leading to chlorophyll or heme 272
 - 8.4.4 The chromophore of phytochrome is synthesized from heme 273
 - 8.4.5 Conversion of protochlorophyllide to chlorophyllide in seed plants is light-dependent 273
 - 8.4.6 Phytol is added to chlorophyllide to make chlorophylls a and b 275
- 8.5 Circadian and photoperiodic control 275**
 - 8.5.1 The circadian rhythm and day–night cycle must be synchronized in order to regulate biological functions correctly 276

Part III Emergence

8 Light perception and transduction 251

8.1 Introduction to light and life 251

- 8.1.1 Visible light is part of the electromagnetic spectrum 252

- 8.5.2 Genetically controlled interlocking feedback loops underlie the circadian clock mechanism 277
- 8.5.3 Plants are classified as long-day, short-day or day-neutral according to their developmental responses to photoperiod 279
- 8.5.4 The gene *FT*, which encodes a mobile floral inducer, is regulated by the transcription factor CO 281
- 8.5.5 The CO–FT system is regulated by the circadian clock, photoperiod and light quality 282

9 Photosynthesis and photorespiration 284

- 9.1 Introduction to photosynthesis 284
 - 9.1.1 Photosynthesis in green plants is a redox process with water as the electron donor and carbon dioxide as the electron acceptor 284
 - 9.1.2 Photosynthesis in green plants takes place in chloroplasts 285
 - 9.1.3 Thylakoids convert light energy to ATP and NADPH utilized in the stroma for carbon reduction 285
- 9.2 Pigments and photosystems 287
 - 9.2.1 Light energy used in photosynthesis is captured by chlorophylls, carotenoids and, in certain algae and cyanobacteria, phycobilins 288
 - 9.2.2 Reaction centers are the sites of the primary photochemical events of photosynthesis 290
 - 9.2.3 Antenna pigments and their associated proteins form light-harvesting complexes in the thylakoid membrane 292
- 9.3 Photosystem II and the oxygen-evolving complex 292
 - 9.3.1 The PSII reaction center is an integral membrane multiprotein complex containing P680 and electron transport components 293
 - 9.3.2 The light-harvesting antenna complex of PSII accounts for half of total thylakoid protein 294
 - 9.3.3 Oxidation of water and reduction of PSII electron acceptors requires four photons per molecule of oxygen released 295
 - 9.3.4 Plastoquinone is the first stable acceptor of electrons from PSII 296
- 9.4 Electron transport through the cytochrome b_6f complex 298
 - 9.4.1 The cytochrome b_6f complex includes three electron carriers and a quinone-binding protein 298
 - 9.4.2 The cytochrome b_6f complex generates a proton gradient through the operation of a Q cycle 299
 - 9.4.3 Plastocyanin is a soluble protein that carries electrons from cytochrome b_6f to PSI 299
- 9.5 Photosystem I and the formation of NADPH 300
 - 9.5.1 PSI reaction center subunits are associated with plastocyanin docking, P700 and primary and secondary electron acceptors 301
 - 9.5.2 The PSI antenna consists of four light-harvesting chlorophyll-binding proteins 302
 - 9.5.3 Ferredoxin, the PSI electron acceptor, is a reductant in photosynthetic NADPH formation and many other redox reactions 302
- 9.6 Photophosphorylation 303
 - 9.6.1 The products of non-cyclic electron transport are ATP, oxygen and NADPH 304
 - 9.6.2 ATP is the sole product of cyclic electron flow around PSI 304
 - 9.6.3 CF_0CF_1 is a multiprotein ATP synthase complex that uses the proton gradient across the thylakoid membrane to phosphorylate ADP 305
- 9.7 Carbon dioxide fixation and the photosynthetic carbon reduction cycle 305
 - 9.7.1 Rubisco catalyzes the first reaction in the Calvin–Benson cycle 307
 - 9.7.2 Rubisco is a complex enzyme with subunits encoded in both the nuclear and the plastid genomes 307
 - 9.7.3 The two-step reduction phase of the Calvin–Benson cycle uses ATP and NADPH 310
 - 9.7.4 During the regeneration phase of the Calvin–Benson cycle, ten enzyme reactions convert five 3-carbon to three 5-carbon intermediates 311
 - 9.7.5 Photosynthesis is dependent on the exchange of metabolites across the chloroplast envelope 312
 - 9.7.6 The Calvin–Benson cycle provides the precursors of carbohydrates for translocation and storage 313
- 9.8 Photorespiration 315
 - 9.8.1 The initial step of photorespiration is catalyzed by the oxygenase activity of rubisco 315

- 9.8.2 Enzymatic reactions of photorespiration are distributed between chloroplasts, peroxisomes and mitochondria 317
 - 9.8.3 Ammonia produced during photorespiration is efficiently reassimilated 319
 - 9.8.4 Energy costs and environmental sensitivities of photorespiration are significant for the impact of climate change on the biosphere 319
 - 9.9 Variations in mechanisms of primary carbon dioxide fixation 320**
 - 9.9.1 C_4 plants have two distinct carbon dioxide-fixing enzymes and a specialized leaf anatomy 320
 - 9.9.2 The C_4 pathway minimizes photorespiration 322
 - 9.9.3 In CAM plants, the processes of CO_2 capture and photosynthesis are separated in time 324
 - 9.9.4 The transpiration ratio relates carbon dioxide fixation to water loss 325
 - 9.9.5 Clues to the evolutionary origins of C_4 and CAM photosynthesis come from studies of the enzyme carbonic anhydrase 325
- ## Part IV Growth
- ### 10 Hormones and other signals 329
- 10.1 Introduction to plant hormones 329**
 - 10.2 Auxins 331**
 - 10.2.1 Both synthesis and catabolism of IAA are important in auxin signaling 331
 - 10.2.2 Polar transport of auxins plays an important role in regulating development 332
 - 10.2.3 The auxin receptor is a component of an E3 ubiquitin ligase 334
 - 10.3 Gibberellins 337**
 - 10.3.1 The initial steps in gibberellin biosynthesis are similar to those for several other groups of hormones 339
 - 10.3.2 Gibberellin concentration in tissues is subject to feedback and feed-forward control 339
 - 10.3.3 The gibberellin receptor *GID1* is a soluble protein that promotes ubiquitination of repressor proteins 340
 - 10.4 Cytokinins 342**
 - 10.4.1 Cytokinin biosynthesis takes place in plastids 342
 - 10.4.2 There are two pathways for cytokinin breakdown 346
 - 10.4.3 The cytokinin receptor is related to bacterial two-component histidine kinases 346
 - 10.5 Ethylene 348**
 - 10.5.1 Ethylene, a simple gas, is synthesized in three steps from methionine 349
 - 10.5.2 Ethylene receptors have some characteristics of histidine kinase response regulators 350
 - 10.5.3 Homologs of MAP kinases transmit the ethylene signal from the receptor to target proteins 350
 - 10.6 Brassinosteroids 352**
 - 10.6.1 Brassinosteroid biosynthesis from campesterol is controlled by feedback loops 353
 - 10.6.2 The brassinosteroid receptor is a plasma membrane-localized LRR-receptor serine/threonine kinase 354
 - 10.7 Abscisic acid 356**
 - 10.7.1 Carotenoids are intermediates in abscisic acid biosynthesis 356
 - 10.7.2 There are several classes of abscisic acid receptors 358
 - 10.8 Strigolactones 359**
 - 10.8.1 Strigolactones were first isolated from cotton root exudates 360
 - 10.8.2 Strigolactones regulate lateral bud dormancy 360
 - 10.9 Jasmonates 362**
 - 10.9.1 Jasmonate biosynthesis begins in the plastid and moves to the peroxisome 363
 - 10.9.2 The jasmonate receptor is an F-box protein that targets a repressor of jasmonate-responsive genes 363
 - 10.10 Polyamines 364**
 - 10.10.1 Polyamines are synthesized from amino acids 364
 - 10.10.2 Polyamines play roles in xylem differentiation 367
 - 10.11 Salicylic acid 367**
 - 10.11.1 There are two biosynthetic pathways of salicylic acid biosynthesis in plants 367

- 10.11.2 Salicylic acid induces flowering and heat production in some plants 368
- 10.11.3 Salicylic acid is involved in localized and systemic disease resistance 369
- 10.12 Nitric oxide 369

11 The cell cycle and meristems 371

11.1 Introduction to cell division and meristems 371

- 11.1.1 The mitotic cell cycle consists of four phases: M, G1, S and G2 371
- 11.1.2 Rigid plant cell walls impose some unique features upon the plant cell cycle 374
- 11.1.3 Meiosis is a specialized form of the cell cycle that gives rise to haploid cells 374

11.2 Molecular components of the cell cycle: kinases, cyclins, phosphatases and inhibitors 376

- 11.2.1 Specific kinase complexes push the cell through the cell cycle 376
- 11.2.2 CDK–cyclin complexes can phosphorylate protein substrates to regulate cell cycle progression and other cell processes 378
- 11.2.3 Binding of cyclins determines three-dimensional structure, specificity and subcellular localization of cell-dependent kinases 379
- 11.2.4 Kinases, phosphatases and specific inhibitors all have roles in regulating the activity of CDK–cyclin complexes 380
- 11.2.5 Proteolysis by the ubiquitin–proteasome system ensures that the cell cycle is irreversible 381

11.3 Control of progress through the cell cycle 383

- 11.3.1 Transition from G1 to S phase is controlled by the interaction between CDK–CYCD complexes and the RBR/E2F pathway 383
- 11.3.2 S-phase progression is controlled by many proteins 385
- 11.3.3 DNA replication is strictly controlled during the cell cycle 386
- 11.3.4 The MSA element in plant B-type cell-dependent kinases is important for the G2 to M transition 387
- 11.3.5 Condensation of replicated chromosomes marks the beginning of the M phase 387

- 11.3.6 Chromatid separation and exit from mitosis is mediated by phosphorylation of the anaphase-promoting complex by cell-dependent kinases and proteolysis of securin 388
- 11.3.7 DNA damage and incomplete cell cycle progression are policed by checkpoint controls 390

11.4 Cell cycle control during development 392

- 11.4.1 Cell division is tightly regulated in meristems and during organogenesis 392
- 11.4.2 Many plant cells remain totipotent throughout the plant's life cycle 393
- 11.4.3 Endopolyploidy is common in differentiated plant cells 395
- 11.4.4 Plant cells must replicate and maintain three genomes 397

11.5 The meiotic cell cycle 398

- 11.5.1 During meiotic prophase I homologous chromosomes pair and recombination usually occurs 398
- 11.5.2 Synapsis is the process of pairing homologous chromosomes 399
- 11.5.3 Recombination is most commonly initiated by double-stranded breaks in the DNA 402
- 11.5.4 Recombination is followed by two divisions to produce four haploid cells 403

12 Growth and development 405

12.1 Introduction to plant development 405

12.2 Cell origins and growth 406

- 12.2.1 Apical meristems are organized into distinct regions 407
- 12.2.2 Morphogenesis is determined by polarity and differential growth 408
- 12.2.3 Plant growth is described by the universal S-shaped curve and is driven by water 410
- 12.2.4 Growing structures exhibit plastic growth at first and subsequently develop elastic properties as they mature and rigidify 411
- 12.2.5 Cells enlarge by tip growth or diffuse growth 415
- 12.2.6 Cells of primary vascular tissues originate in stem and root apical meristems; cambium is the origin of secondary vascular tissues 415

- 12.3 Embryogenesis 417
 - 12.3.1 Pattern formation is the result of polarity in the developmental fates of embryo cells 418
 - 12.3.2 Axis formation during embryogenesis is the prelude to differentiation into root and shoot 421
 - 12.3.3 Many genes with functions in pattern formation have been identified by studies of embryogenesis mutants 422
- 12.4 Growth and differentiation of roots 423
 - 12.4.1 Root architecture is important for functions that include support, nutrient acquisition, storage and associations with other organisms 423
 - 12.4.2 Lateral root initiation and growth are under complex genetic and hormonal control 425
 - 12.4.3 Nutrients act as regulators of root development 427
 - 12.4.4 The formation of symbiotic associations with nitrogen-fixing bacteria modifies root development 428
 - 12.4.5 Mycorrhizal symbioses also modify root development 433
- 12.5 Growth and differentiation of leaves 434
 - 12.5.1 The vegetative shoot meristem produces leaf primordia at sites determined by a morphogenetic field 436
 - 12.5.2 During leaf epidermis development, three cell types are differentiated: pavement cells, trichomes and stomates 437
 - 12.5.3 Development of the internal structure of the leaf involves vascular and photosynthetic cell differentiation 440
 - 12.5.4 Flattening, orientation and outgrowth of the lamina determine ultimate leaf size and shape 442
- 12.6 Shoot architecture and stature 444
 - 12.6.1 Plant structure is modular 444
 - 12.6.2 Branching is the result of interactions between apical and lateral growth 445
 - 12.6.3 Crop breeding has exploited genetic variation in stature to produce dwarf and semi-dwarf 'Green Revolution' cereals 447

Part V Maturation

13 Mineral nutrient acquisition and assimilation 455

- 13.1 Introduction to plant nutrition 455
 - 13.1.1 Deficiency symptoms reflect the function and mobility of an element within the plant 455
 - 13.1.2 Other organs in addition to roots may function in nutrient acquisition 459
 - 13.1.3 Technologies used to study mineral nutrition include hydroponics and rhizotrons 460
 - 13.1.4 The rhizosphere affects mineral availability to plants 461
- 13.2 Nitrogen 463
 - 13.2.1 In the biosphere nitrogen cycles between inorganic and organic pools 463
 - 13.2.2 Nitrogen fixation converts dinitrogen gas into NH_3 465
 - 13.2.3 Biological nitrogen fixation is catalyzed by nitrogenase 465
 - 13.2.4 Dinitrogen fixation occurs via a catalytic cycle 467
 - 13.2.5 Uptake of ammonium into the symplasm occurs via specific membrane channels 469
 - 13.2.6 Roots take up nitrate in preference to other forms of nitrogen 469
 - 13.2.7 Nitrate reduction is the first step in nitrogen assimilation 471
 - 13.2.8 Nitrate reduction is regulated by controlling the synthesis and activity of nitrate reductase 473
 - 13.2.9 Nitrogen enters into organic combination through the GS-GOGAT pathway 475
- 13.3 Phosphorus 477
 - 13.3.1 Phosphorus enters the biosphere as phosphate 478
 - 13.3.2 Phosphate is actively accumulated by root cells 479
 - 13.3.3 Plants modify the rhizosphere and form mycorrhizal associations to improve phosphorus availability 481
- 13.4 Sulfur 483
 - 13.4.1 The sulfur cycle involves the interconversion of oxidized and reduced sulfur species 484
 - 13.4.2 Plants acquire sulfur mainly as sulfate from the soil 485

- 13.4.3 The reduction of sulfate and its assimilation is catalyzed by a series of enzymes 487
- 13.4.4 Two enzymes catalyze the final steps of sulfate assimilation into cysteine 489
- 13.4.5 Sulfur assimilation shares some features with nitrogen assimilation 491

13.5 Cationic macronutrients: potassium, calcium and magnesium 491

- 13.5.1 Potassium is the most abundant cation in plant tissues 492
- 13.5.2 Tightly regulated channels and transporters ensure cytosolic calcium is maintained at submicromolar concentrations 494
- 13.5.3 Channels in the plasma membrane deliver magnesium to the cytosol, and an antiporter mediates transfer from cytosol to vacuole 496

13.6 Micronutrients 496

- 13.6.1 Iron is an essential component of biological electron transfer processes 497
- 13.6.2 Several micronutrient elements are toxic in excess 499
- 13.6.3 Aluminum is a non-nutrient mineral responsible for toxic reactions in many plants growing on acid soils 499
- 13.6.4 Heavy metal homeostasis is mediated by metal-binding metabolites and proteins 502

14 Intercellular and long-distance transport 504

14.1 Introduction to transport of water and solutes 504

14.2 The concept of water potential 505

- 14.2.1 Solutes lower the water potential 506
- 14.2.2 Pressure can increase or decrease water potential 506
- 14.2.3 Gravity increases water potential and is a large component of Ψ_w in trees 507

14.3 Water uptake by plant cells 507

- 14.3.1 The permeability of biological membranes to water influences water uptake by plant cells 507
- 14.3.2 Diffusion and bulk flow drive movement of water and solute in plants 508

14.4 The role of plasmodesmata in solute and water transport 509

- 14.4.1 Plasmodesmata increase the flow of water and solutes between cells 510

- 14.4.2 Fluorescent probes provide an estimate of the size exclusion limit of plasmodesmata 511

- 14.4.3 Endogenous macromolecules move from cell to cell via plasmodesmata 512

- 14.4.4 Viral RNA can move from cell to cell via plasmodesmata 513

14.5 Translocation of photosynthate in the phloem 514

- 14.5.1 Sieve elements and companion cells are unique cell types in the phloem of flowering plants 514

- 14.5.2 Sieve elements contain high concentrations of solutes and have high turgor pressure 515

- 14.5.3 Sieve elements have open sieve plates that allow pressure-driven solute flow 516

14.6 Phloem loading, translocation and unloading 518

- 14.6.1 At the source, phloem loading can occur from the apoplast or through the symplasm 518

- 14.6.2 Sucrose and other non-reducing sugars are translocated in the phloem 519

- 14.6.3 Long-distance pressure-flow in the phloem is not energy-dependent 521

- 14.6.4 Phloem unloading involves a series of short-distance transport events 521

14.7 Water movement in the xylem 521

- 14.7.1 Water-conducting tissue of the xylem consists of low-resistance vessels and tracheids 522

- 14.7.2 Transpiration provides the driving force for xylem transport 523

- 14.7.3 Under special circumstances sucrose may be transported from roots to shoots within the xylem 523

- 14.7.4 Cavitation in tracheary elements interferes with water transport 524

- 14.7.5 Tracheary elements can be refilled with water by root pressure 525

14.8 The path of water from soil to atmosphere 525

- 14.8.1 There are two pathways by which water enters the root 525

- 14.8.2 The uptake of solutes and loading and unloading of the xylem are active processes 526

- 14.8.3 A number of structural and physiological features allow plants to control evapotranspiration from their shoots 526

- 14.8.4 Differences in water vapor concentration and resistances in the pathway drive evapotranspiration 526

- 14.8.5 Stomatal guard cells are key regulators of water loss from leaves 528

- 14.8.6 Stomata open and close in response to a variety of environmental factors 530
- 14.8.7 The opening of stomata during the day represents a physiological compromise 532

15 Environmental interactions 534

15.1 Introduction to plant–environment interactions 534

15.2 General principles of plant–environment interactions 534

- 15.2.1 Environmental factors may have both positive and negative effects 535
- 15.2.2 Plants are equipped with mechanisms to avoid or tolerate stress 536
- 15.2.3 Plants respond to the environment over the short term by acclimation, and on an evolutionary timescale by adaptation 537
- 15.2.4 Plants make a vast array of secondary metabolites, many of which are protective against biotic and abiotic challenges 539

15.3 Metabolic responses to stress I. Phenolics 540

- 15.3.1 Phenylalanine and tyrosine are the metabolites that link primary metabolism to the secondary pathways of phenolic biosynthesis 541
- 15.3.2 Most phenolics are synthesized from phenylalanine or tyrosine via the phenylpropanoid pathway 543
- 15.3.3 The flavonoid pathway, leading to flavones, flavonols and anthocyanins, starts with chalcone synthase and chalcone isomerase 544
- 15.3.4 Lignin precursors are the products of a metabolic grid derived from 4-coumaric and cinnamic acids 545

15.4 Metabolic responses to stress II. Alkaloids 547

- 15.4.1 Tryptophan is the biosynthetic precursor of indole alkaloids 549
- 15.4.2 Morphine and related isoquinoline alkaloids are tyrosine derivatives 551

15.5 Metabolic responses to stress III. Terpenoids 552

- 15.5.1 Terpenoids are synthesized from IPP and DMAPP, frequently in specialized structures 553
- 15.5.2 Terpenoids of C_{10} and larger are made by condensation of IPP units on an initial DMAPP primer, catalyzed by prenyltransferases 556

- 15.5.3 Squalene and phytoene are precursors of phytosterols and carotenoids 557
- 15.5.4 Secondary modification of terpenoids results in a wide variety of bioactive compounds 559

15.6 Responses to abiotic stresses 560

- 15.6.1 Plants acclimate to water deficit and osmotic stress by adjustments in compatible solutes, transport processes and gene expression 560
- 15.6.2 Flooding deprives plants of oxygen, affecting respiratory processes, gene expression and acclimatory changes in structure 564
- 15.6.3 Reactive oxygen species, common factors in plant responses to a range of stresses, regulate, and are regulated by, antioxidant systems 566
- 15.6.4 Cold stresses are experienced through similar sensitivity, tolerance and acclimatory mechanisms to those of other abiotic challenges 569
- 15.6.5 Plants respond to high-temperature stress by making heat shock proteins 570
- 15.6.6 Plants have photochemical, acclimatory and adaptive mechanisms that defend against potentially harmful excess light 572
- 15.6.7 Gravity and touch are directional mechanical stresses that invoke tropic responses 576

15.7 Responses to biotic stresses 577

- 15.7.1 Plants deploy constitutive and induced defenses against potential pathogens 577
- 15.7.2 Plants compete by conducting chemical warfare with allelopathic secondary compounds 579
- 15.7.3 A range of generic local and systemic stress responses are invoked by herbivory, predation and wounding 580

Part VI Renewal

16 Flowering and sexual reproduction 585

16.1 Introduction to flowering 585

16.2 Induction of flowering 586

- 16.2.1 Floral induction requires both the perceptive organ and the shoot apex to acquire competence during plant maturation 586

- 16.2.2 Determinacy of the reproductive apex affects plant morphology and annual/perennial growth habit 587
 - 16.2.3 Different inductive pathways lead to flowering 589
 - 16.2.4 Regulation of floral induction by vernalization is epigenetic in nature 591
 - 16.3 Development of floral organs 592**
 - 16.3.1 Specification of floral structures in *Arabidopsis* is explained by the ABC model of gene expression 594
 - 16.3.2 The original ABC model has been enhanced to include E class factors 595
 - 16.3.3 The ABCE model, or modifications of it, applies to floral differentiation across the range of angiosperms 597
 - 16.3.4 Floral symmetry is determined by the interplay between TCP- and MYB-type transcription factors 599
 - 16.3.5 Inflorescence architecture can be modeled using *veg*, a meristem identity parameter 600
 - 16.3.6 Colors of flower parts are due to betalain, anthocyanin or carotenoid pigments 602
 - 16.4 Development of the male and female gametophytes 605**
 - 16.4.1 The male gametophyte is the pollen grain, which forms in the anther 605
 - 16.4.2 Many genes are expressed in the anther and nowhere else in the plant 605
 - 16.4.3 Mutations in genes that are active in the sporophyte can lead to male sterility 607
 - 16.4.4 The female gametophyte, or embryo sac, is produced by one meiotic division followed by several mitotic divisions 609
 - 16.5 Pollination and fertilization 610**
 - 16.5.1 Hydration and germination of the pollen grain require specific interaction between the pollen coat and stigmatic surface 611
 - 16.5.2 Pollen allergens, the cause of hay fever, have a range of functions in fertilization 613
 - 16.5.3 Incompatibility mechanisms prevent self-pollination and promote outbreeding 614
 - 16.5.4 In gametophytic self-incompatibility growth of the pollen tube is arrested by ribonucleases or programmed cell death 615
 - 16.5.5 Sporophytic self-incompatibility in the Brassicaceae is mediated by receptor kinases in the female and peptide ligands in the pollen coat 616
 - 16.5.6 The growing pollen tube is actively guided toward the embryo sac 617
 - 16.5.7 Double fertilization completes the alternation of generations 619
 - 16.5.8 Apomixis, asexual reproduction through seeds, occurs in a large number of taxa and is a target trait for crop breeding 620
 - 16.6 Seed and fruit development 622**
 - 16.6.1 Genomics analysis reveals tissue specificities and changes with time in gene expression patterns during seed development 623
 - 16.6.2 The development of nuclear endosperm comprises phases of syncytium formation, cellularization, endoreduplication and programmed cell death 625
 - 16.6.3 Differentiation of fruit tissues is associated with the activities of MADS-box transcription factors 627
- ## 17 Development and dormancy of resting structures 629
- 17.1 Introduction to resting structures in the plant life cycle 629**
 - 17.2 Forms and functions of resting organs 629**
 - 17.2.1 Dormancy of the embryo is conditioned by the associated storage tissue and seed coat 630
 - 17.2.2 Terminal buds consist of leaf or flower primordia and unexpanded internodes enclosed in protective scales 631
 - 17.2.3 Tree rings, the results of annual periods of vascular cambium growth and quiescence, are a historical record of environmental conditions 632
 - 17.2.4 Corms, rhizomes, stolons and tubers are modified stems 633
 - 17.2.5 Bulbs are vegetative resting organs in monocots and each consists of swollen reserve-storing leaf bases surrounding a compressed shoot 635
 - 17.2.6 Tuberous roots and swollen taproots are forms of underground perennating storage organs 636
 - 17.3 Synthesis and deposition of reserves 636**
 - 17.3.1 Starch is synthesized in plastids as semicrystalline granules by starch synthase and starch branching enzyme 637

- 17.3.2 Fructans are storage polymers accumulated in the resting structures and other vegetative organs of species from a number of taxa 640
 - 17.3.3 Fatty acids are biosynthesized from acetyl-CoA in plastids and stored as triacylglycerols in oil bodies derived from the endoplasmic reticulum 642
 - 17.3.4 Seed and vegetative storage proteins are synthesized in response to the supply of sugars or nitrogen and accumulate in vesicles and vacuoles 643
 - 17.3.5 Mass transfer of mobile mineral elements to perennating structures occurs during dieback and ultimate desiccation of above-ground biomass 648
 - 17.4 Dormancy 649**
 - 17.4.1 The relationship between embryo immaturity and capacity to germinate, which varies widely between species, is influenced by abscisic acid 650
 - 17.4.2 Many organs need to experience a period of low temperature to break dormancy 650
 - 17.4.3 Weed seeds in the soil seed bank may be released from dormancy by exposure to light 651
 - 17.4.4 In ecosystems adapted to frequent fires, the chemical products of combustion act as dormancy-breaking signaling compounds 652
 - 17.5 Regulation of development and dormancy of resting organs 652**
 - 17.5.1 The cell cycle is arrested in dormant meristems 653
 - 17.5.2 Dormancy of apical buds is regulated by photoperiod in many temperate species 653
 - 17.5.3 Resting structures are formed by modification of vegetative development 655
 - 17.5.4 Dormancy is controlled by the antagonistic actions of abscisic acid and gibberellin 656
 - 17.6 Adaptive and evolutionary significance of the resting phase 658**
 - 17.6.1 Most resting structures are propagules 658
 - 17.6.2 Phenology, the study of the timing of growth and quiescence phases in the annual life cycle, provides information on environmental change 659
 - 17.6.3 Different life forms have evolved through changes in integration of component developmental processes 660
 - 17.6.4 The consumption of plant resting organs has influenced the course of human evolution 663
- ## 18 Senescence, ripening and cell death 664
- 18.1 Introduction to terminal events in the life of a plant and its parts 664**
 - 18.1.1 The different categories of cell death share some features 664
 - 18.1.2 Cell viability is maintained during the developmental program leading to death 665
 - 18.1.3 Autolysis is a common form of cell death 666
 - 18.2 Cell death during growth and morphogenesis 668**
 - 18.2.1 Cell death is an essential process in the formation of vascular and mechanical tissues 669
 - 18.2.2 Lysigeny, schizogeny and abscission are responsible for the formation of tubes and cavities, and the shedding of organs 673
 - 18.2.3 Organs may be shaped by selective death of cells and tissues 673
 - 18.3 Leaf senescence 674**
 - 18.3.1 Cell structures and metabolism undergo characteristic changes during senescence 676
 - 18.3.2 Leaves change color during senescence 677
 - 18.3.3 During senescence macromolecules are broken down and nutrients are salvaged 680
 - 18.3.4 Energy and oxidative metabolism are modified during senescence 682
 - 18.3.5 Senescence is genetically regulated and under hormonal control 684
 - 18.4 Programmed senescence and death in the development of reproductive structures and seeds 689**
 - 18.4.1 Selective death of reproductive structures occurs during the development of unisexual flowers 689
 - 18.4.2 Petals and sepals undergo senescence 689
 - 18.4.3 Specific cells undergo senescence and death during gamete and embryo formation 690
 - 18.4.4 Programmed senescence and death occur during seed development and germination 691
 - 18.5 Fruit ripening 692**
 - 18.5.1 A respiratory burst occurs during fruit ripening in some species 693

- 18.5.2 Fruits change color during ripening 693
- 18.5.3 Fruit texture changes during ripening 694
- 18.5.4 Flavors and fragrances intensify during fruit ripening 695
- 18.5.5 Fruit ripening is subject to genetic and hormonal regulation 697
- 18.6 Environmental influences on programmed senescence and death 699**
- 18.6.1 Senescence varies with the seasons 699
- 18.6.2 Programmed senescence and death are common responses to abiotic stresses 701
- 18.6.3 Senescence and cell death are adaptive and pathological responses to biotic interactions 701
- 18.6.4 The relationships between programmed senescence, death and aging are complex 705
- Acknowledgments, credits and sources 707*
- Index 713*

Companion website

This book is accompanied by a companion website:

www.wiley.com/go/jones/molecularlifefplants

The website includes:

- Powerpoints of all figures
- PDFs of all tables from the book for downloading
- PDFs of the table of contents and index