

# Contents

## Part I Models for Plant Development

|                                                                                                                                |           |
|--------------------------------------------------------------------------------------------------------------------------------|-----------|
| <b>1 Gene Regulatory Models for Plant Development and Evolution</b>                                                            | <b>3</b>  |
| E.R. Alvarez-Buylla, M. Benítez, M. Aldana, G.J. Escalera-Santos,<br>Á. Chaos, P. Padilla-Longoria, and R. Verduzco-Vázquez    |           |
| 1.1 Introduction: the Need for Mathematical Models to Understand<br>Plant Development                                          | 3         |
| 1.2 Dynamic GRN Models                                                                                                         | 4         |
| 1.3 Inference of GRN Topology from Microarray Experiments                                                                      | 7         |
| 1.3.1 Bayesian Networks                                                                                                        | 8         |
| 1.3.2 Mutual Information                                                                                                       | 8         |
| 1.3.3 Continuous Analysis Models                                                                                               | 8         |
| 1.4 GRN Models for Modules of Plant Development                                                                                | 9         |
| 1.4.1 Single-Cell Gene Regulatory Network Models: the Case<br>of <i>Arabidopsis</i> Flower Organ Primordial Cell Specification | 10        |
| 1.4.2 Spatiotemporal Models of Coupled GRN Dynamics                                                                            | 10        |
| 1.4.3 Auxin Transport Is Sufficient to Generate Morphogenetic<br>Shoot and Root Patterns                                       | 12        |
| 1.4.4 Signal Transduction Models                                                                                               | 14        |
| 1.5 The Constructive Role of Stochasticity in GRN and Other<br>Complex Biological Systems                                      | 14        |
| 1.6 GRN Structure and Evolution                                                                                                | 15        |
| 1.7 Conclusions                                                                                                                | 17        |
| References                                                                                                                     | 17        |
| <b>2 Arabidopsis as Model for Developmental Regulation and Crop<br/>Improvement</b>                                            | <b>21</b> |
| C.M. Liu                                                                                                                       |           |
| 2.1 Introduction                                                                                                               | 21        |
| 2.2 Knowledge Gained in Arabidopsis Is Available<br>for Crop Scientists                                                        | 22        |

|                                                                    |    |
|--------------------------------------------------------------------|----|
| 2.3 Plant Architecture-Related Genes and Their Potential Uses      |    |
| in Crop Improvement .....                                          | 22 |
| 2.3.1 Genes Regulating the Function of Shoot Apical Meristem ..... | 22 |
| 2.3.2 Lateral Organ Formation and Branching .....                  | 23 |
| 2.3.3 Regulation of Stem Elongation .....                          | 24 |
| 2.3.4 Regulation of Leaf Development .....                         | 26 |
| 2.3.5 Regulation of Inflorescence Shape .....                      | 26 |
| 2.4 Understanding Abiotic Stresses to Improve Tolerance            |    |
| to Abiotic Stresses .....                                          | 27 |
| 2.4.1 Stress Responses .....                                       | 27 |
| 2.4.2 DREB Genes and Their Uses in Coping with Drought .....       | 27 |
| 2.4.3 <i>SOS</i> Genes and Salt Tolerance .....                    | 28 |
| 2.5 Prospective Remarks                                            | 28 |
| References                                                         | 29 |

## Part II Vegetative Growth and Development

|                                                               |               |
|---------------------------------------------------------------|---------------|
| <b>3 Axillary Shoot Branching in Plants .....</b>             | <b>37</b>     |
| M.W.F. Yaish, D.R. Guevara, A. El-Kereamy, and S.J. Rothstein |               |
| 3.1 Introduction .....                                        | 37            |
| 3.2 Axillary Shoot Development .....                          | 38            |
| 3.2.1 Bud Initiation .....                                    | 39            |
| 3.2.2 Genes Control Axillary Shoot Branching .....            | 40            |
| 3.3 Hormones Involved in Axillary Bud Formation .....         | 43            |
| 3.3.1 Auxin, Cytokinin and Novel Hormone .....                | 43            |
| 3.3.2 Axillary Bud Outgrowth Hypotheses .....                 | 44            |
| 3.3.3 Absciscic Acid and Branching .....                      | 45            |
| 3.4 Regulatory Pathways Involved in Shoot Branching .....     | 46            |
| 3.4.1 Carotenoid-Derived Signalling Molecules .....           | 46            |
| 3.4.2 Polyamines .....                                        | 47            |
| 3.4.3 Inositol Phosphates .....                               | 48            |
| 3.5 Future Perspectives .....                                 | 49            |
| References                                                    | 49            |
| <br><b>4 Bud Dormancy and Growth .....</b>                    | <br><b>53</b> |
| D. Horvath                                                    |               |
| 4.1 Introduction .....                                        | 53            |
| 4.2 Regulation of Paradormancy .....                          | 54            |
| 4.2.1 Hormonal Control of Paradormancy .....                  | 54            |
| 4.2.2 The RMS/MAX/DAD System Regulates Bud<br>Dormancy .....  | 55            |
| 4.2.3 Other Factors Regulating Bud Outgrowth                  | 57            |
| 4.3 Regulation of Endodormancy                                | 57            |
| 4.3.1 Hormones in Endodormancy Induction                      | 57            |

|                                                                                                       |           |
|-------------------------------------------------------------------------------------------------------|-----------|
| 4.3.2 Metabolism, Transport, and Cell-Cell Communication<br>Are Altered During Endodormancy .....     | 59        |
| 4.3.3 Regulation of Endodormancy by Environmental<br>and Physiological Signals .....                  | 60        |
| 4.3.4 Endodormancy Release .....                                                                      | 62        |
| 4.4 Ecodormancy .....                                                                                 | 64        |
| 4.5 Regulation of Cell Division and Development Is Important<br>for All Forms of Dormancy .....       | 64        |
| 4.6 Future Perspectives .....                                                                         | 66        |
| References .....                                                                                      | 66        |
| <b>5 Root Development .....</b>                                                                       | <b>71</b> |
| L. Jansen, B. De Rybel, V. Vassileva, and T. Beeckman                                                 |           |
| 5.1 Introduction .....                                                                                | 71        |
| 5.2 Plant Root Systems, All But Uniform .....                                                         | 71        |
| 5.2.1 Root Types .....                                                                                | 71        |
| 5.2.2 Genetic Variation in Root Architecture .....                                                    | 73        |
| 5.2.3 Hormonal Control of Root Architecture .....                                                     | 73        |
| 5.2.4 Environmental Factors Influencing Root Architecture .....                                       | 74        |
| 5.3 Patterning During Root Embryogenesis .....                                                        | 76        |
| 5.3.1 Early Embryogenesis Patterning Events .....                                                     | 76        |
| 5.3.2 Establishment of the Primary Root Meristem .....                                                | 78        |
| 5.3.3 Radial Organisation of the Root .....                                                           | 79        |
| 5.4 Lateral Root Development .....                                                                    | 80        |
| 5.5 Conclusions .....                                                                                 | 83        |
| References .....                                                                                      | 84        |
| <b>6 Legume Nodule Development .....</b>                                                              | <b>91</b> |
| K. D'haeseleer, S. Goormachtig, and M. Holsters                                                       |           |
| 6.1 Introduction .....                                                                                | 91        |
| 6.2 Evolution Towards Nitrogen-Fixing Bacterial Endosymbiosis .....                                   | 92        |
| 6.3 Legume Nodule Initiation and Development .....                                                    | 93        |
| 6.4 NF Perception, Signal Transduction and Genes Involved<br>in the Establishment of Nodulation ..... | 96        |
| 6.4.1 The Search for NF Receptors .....                                                               | 96        |
| 6.4.2 NF Signalling .....                                                                             | 98        |
| 6.4.3 Transmitting the Signal .....                                                                   | 101       |
| 6.5 Genes Involved in Infection, Formation and Development<br>of Nodules .....                        | 104       |
| 6.5.1 Marker Genes to Study Early Nodulation Stages .....                                             | 105       |
| 6.5.2 Genes Involved at Early Nodulation Stages .....                                                 | 105       |
| 6.5.3 Genes Involved in Bacterial Differentiation<br>and Nodule Development .....                     | 106       |
| 6.5.4 Genes Involved in Nitrogen Fixation .....                                                       | 107       |
| 6.6 The Latest Stage of Nodulation: Nodule Senescence .....                                           | 109       |

|          |                                                                      |            |
|----------|----------------------------------------------------------------------|------------|
| 6.7      | Hormones in Nodulation .....                                         | 111        |
| 6.7.1    | Auxin .....                                                          | 111        |
| 6.7.2    | Cytokinins .....                                                     | 113        |
| 6.7.3    | Ethylene .....                                                       | 115        |
| 6.7.4    | Gibberellins .....                                                   | 117        |
| 6.7.5    | Absciscic Acid .....                                                 | 118        |
| 6.8      | Autoregulation .....                                                 | 118        |
| 6.9      | Tools to Study Nodulation in Legumes .....                           | 121        |
| 6.9.1    | Genome and Sequence Analysis .....                                   | 121        |
| 6.9.2    | Transcriptomics .....                                                | 122        |
| 6.9.3    | Mutagenesis of Model Legumes .....                                   | 123        |
| 6.9.4    | From Model Legume to Crop Legumes .....                              | 124        |
|          | References .....                                                     | 125        |
| <b>7</b> | <b>Tuber Development .....</b>                                       | <b>137</b> |
|          | W.L. Morris and M.A. Taylor                                          |            |
| 7.1      | Introduction .....                                                   | 137        |
| 7.1.1    | Tuber Composition and Nutrition .....                                | 138        |
| 7.1.2    | Focus on Potato .....                                                | 139        |
| 7.2      | Potato Tuber Development .....                                       | 139        |
| 7.2.1    | Control of Tuber Initiation .....                                    | 141        |
| 7.2.2    | Changes in Carbohydrate Metabolism During<br>Tuber Development ..... | 143        |
| 7.2.3    | Other Aspects of Metabolism—Sugar and Amino Acid<br>Content .....    | 145        |
| 7.2.4    | Control of Potato Tuber Dormancy .....                               | 145        |
| 7.3      | Summary .....                                                        | 147        |
|          | References .....                                                     | 147        |
| <b>8</b> | <b>Senescence .....</b>                                              | <b>151</b> |
|          | C. Zhou and S. Gan                                                   |            |
| 8.1      | Introduction .....                                                   | 151        |
| 8.2      | Senescence in Plants .....                                           | 152        |
| 8.3      | Symptoms of Senescence .....                                         | 152        |
| 8.3.1    | Chlorophyll Degradation .....                                        | 153        |
| 8.3.2    | Membrane Degradation .....                                           | 153        |
| 8.3.3    | Protein Degradation .....                                            | 154        |
| 8.3.4    | Degradation of Nucleic Acids .....                                   | 155        |
| 8.3.5    | Nutrient Remobilization .....                                        | 155        |
| 8.4      | Regulation of Leaf Senescence .....                                  | 155        |
| 8.4.1    | Age .....                                                            | 156        |
| 8.4.2    | Sugars .....                                                         | 156        |
| 8.4.3    | Reproductive Growth .....                                            | 157        |
| 8.4.4    | Plant Growth Regulators .....                                        | 157        |
| 8.5      | Molecular Genetic Regulation of Leaf Senescence .....                | 160        |

|                                                                   |     |
|-------------------------------------------------------------------|-----|
| 8.5.1 Gene Expression During Leaf Senescence .....                | 160 |
| 8.5.2 Identification of SAGs .....                                | 161 |
| 8.6 Genetic Manipulation and Application of Leaf Senescence ..... | 163 |
| 8.7 Conclusions and Outlooks .....                                | 164 |
| References .....                                                  | 165 |

### **Part III Reproductive Growth and Development**

|                                                                |            |
|----------------------------------------------------------------|------------|
| <b>9 Floral Organ Initiation and Development .....</b>         | <b>173</b> |
| M. Berner and G.C. Angenent                                    |            |
| 9.1 Introduction: the Angiosperm Flower .....                  | 173        |
| 9.2 The MADS Box Family of Transcription Factors .....         | 174        |
| 9.3 Change from Vegetative Growth to Reproductive Growth ..... | 175        |
| 9.3.1 Transition to the Reproductive Phase .....               | 175        |
| 9.3.2 Induction of the Floral Meristem .....                   | 176        |
| 9.3.3 Initiation of Flower Primordia .....                     | 178        |
| 9.3.4 Floral Organ Specification .....                         | 178        |
| 9.4 Floral Quartet Model .....                                 | 180        |
| 9.4.1 A Function .....                                         | 181        |
| 9.4.2 B Function .....                                         | 182        |
| 9.4.3 C Function .....                                         | 183        |
| 9.4.4 D Function .....                                         | 184        |
| 9.4.5 E Function .....                                         | 185        |
| 9.4.6 Variations on the Typical (A)BCDE Model .....            | 186        |
| 9.5 Autoregulatory Mechanisms .....                            | 187        |
| 9.6 Other Genes Involved in Floral Organogenesis .....         | 187        |
| 9.7 Targets of the Floral Organ Identity Genes .....           | 188        |
| 9.8 Summary .....                                              | 189        |
| References .....                                               | 189        |
| <b>10 Control of Flower Development .....</b>                  | <b>195</b> |
| H. Yamashita and Y. Komeda                                     |            |
| 10.1 Introduction .....                                        | 195        |
| 10.2 Regulation of Floral Organ Development .....              | 196        |
| 10.2.1 Genes Associated with Floral Development .....          | 196        |
| 10.2.2 Photoperiodism .....                                    | 197        |
| 10.2.3 Vernalization .....                                     | 198        |
| 10.2.4 Florigen .....                                          | 198        |
| 10.3 Genetic Network of Flowering Control .....                | 199        |
| 10.3.1 Light-Dependent Pathway .....                           | 199        |
| 10.3.2 Gibberellin Pathway .....                               | 201        |
| 10.3.3 Autonomous Pathway .....                                | 201        |
| 10.3.4 Vernalization Pathway .....                             | 202        |
| 10.4 Perspectives .....                                        | 206        |
| References .....                                               | 206        |

|                                                                            |     |
|----------------------------------------------------------------------------|-----|
| <b>11 Development and Function of the Female Gametophyte</b>               | 209 |
| N. Sánchez-León and J.-P. Vielle-Calzada                                   |     |
| 11.1 Introduction                                                          | 209 |
| 11.2 The Formation of Female Gametes                                       | 210 |
| 11.2.1 Megasporogenesis                                                    | 210 |
| 11.2.2 Megagametogenesis                                                   | 212 |
| 11.3 Genetic Dissection of Female Gametogenesis                            | 213 |
| 11.4 Transcriptional Analysis of the Female Gametophyte                    | 214 |
| 11.4.1 Gene Expression in the Differentiated Female Gametophyte            | 215 |
| 11.4.2 Transcriptional Repression in Sporophytic Cells of the Ovule        | 218 |
| 11.5 Double Fertilization                                                  | 218 |
| 11.6 Future Trends                                                         | 220 |
| References                                                                 | 221 |
| <b>12 Male Gametophyte Development</b>                                     | 225 |
| D. Twell                                                                   |     |
| 12.1 Introduction                                                          | 225 |
| 12.2 Overview of Pollen Development                                        | 226 |
| 12.3 Gametophytic Mutants Affecting Pollen Development                     | 227 |
| 12.4 Mutants Affecting Gametophytic Cell Divisions (Morphological Screens) | 232 |
| 12.5 Genes with Roles in Asymmetric Microspore Division                    | 233 |
| 12.6 Genes Controlling Male Germline Development                           | 234 |
| 12.7 Transcriptomics of Pollen Development                                 | 236 |
| 12.8 Two Global Male Gametophytic Gene Expression Programmes               | 237 |
| 12.9 Post-Transcriptional Regulation                                       | 239 |
| 12.10 Integrating Genetic and Transcriptomic Data                          | 239 |
| References                                                                 | 240 |
| <b>13 Pollen Germination and Tube Growth</b>                               | 245 |
| D.-Q. Shi and W.-C. Yang                                                   |     |
| 13.1 Introduction                                                          | 245 |
| 13.2 Mature Pollen Grains                                                  | 246 |
| 13.2.1 Pollen Wall                                                         | 247 |
| 13.2.2 Pollen Maturation                                                   | 248 |
| 13.3 Pollen-Stigma Interaction                                             | 251 |
| 13.3.1 The Stigma                                                          | 251 |
| 13.3.2 Pollen Recognition                                                  | 252 |
| 13.3.3 Pollen Adherence and Hydration                                      | 253 |
| 13.4 Pollen Germination and Tube Growth                                    | 255 |
| 13.4.1 Calcium Signalling in Pollen Germination and Tube Growth            | 256 |

|           |                                                                                     |            |
|-----------|-------------------------------------------------------------------------------------|------------|
| 13.4.2    | The Cytoskeleton .....                                                              | 257        |
| 13.4.3    | Crosstalk Between Calcium Signalling and Cytoskeleton<br>in the Pollen Tube .....   | 261        |
| 13.4.4    | Small GTPases and Pollen Tube Growth .....                                          | 262        |
| 13.4.5    | Pectin Methyltransferase and Pectin Modification .....                              | 267        |
| 13.4.6    | Pollen Tube Guidance .....                                                          | 267        |
| 13.5      | Conclusions .....                                                                   | 272        |
|           | References .....                                                                    | 272        |
| <b>14</b> | <b>Fertilization in Angiosperms .....</b>                                           | <b>283</b> |
|           | S.D. Russell                                                                        |            |
| 14.1      | Introduction .....                                                                  | 283        |
| 14.2      | Angiosperm Reproduction: a Matter of Structure, Timing,<br>and Physiology .....     | 284        |
| 14.3      | Pollen Biology and Maturation .....                                                 | 284        |
| 14.3.1    | Bicellular Versus Tricellular Pollen .....                                          | 284        |
| 14.3.2    | Pollen and Sperm Maturation, Cell Cycle,<br>and Cellular Identity .....             | 285        |
| 14.3.3    | Attraction of Pollen Tubes to the Female Gametophyte ....                           | 287        |
| 14.4      | Fertilization: Receipt of Pollen Tube and Plasmogamy .....                          | 288        |
| 14.5      | Female Gametophyte Cell Multiplication Control and Identity ...                     | 290        |
| 14.6      | Cell Fusion Determinant GCS1/HAP2 .....                                             | 291        |
| 14.7      | Fertilization Limiting Genes .....                                                  | 291        |
| 14.8      | Nuclear Fusion .....                                                                | 293        |
| 14.9      | Cytoplasmic Transmission in Gametes .....                                           | 294        |
| 14.10     | Chromatin Modeling: Expressional Control in Gametes,<br>Embryo, and Endosperm ..... | 295        |
| 14.11     | Conclusions and Prospects .....                                                     | 296        |
|           | References .....                                                                    | 297        |
| <b>15</b> | <b>Fruit Development .....</b>                                                      | <b>301</b> |
|           | H. Ezura and K. Hiwasa-Tanase                                                       |            |
| 15.1      | Introduction .....                                                                  | 301        |
| 15.2      | Floral Development and Fruit Set .....                                              | 302        |
| 15.2.1    | Fruit Size .....                                                                    | 302        |
| 15.2.2    | Fruit Shape .....                                                                   | 303        |
| 15.2.3    | Fruit Set .....                                                                     | 303        |
| 15.3      | Early Fruit Development .....                                                       | 304        |
| 15.3.1    | Cell Division and <i>HMGRs</i> .....                                                | 304        |
| 15.3.2    | Loci Associated with Cell Division .....                                            | 305        |
| 15.4      | Fruit Enlargement .....                                                             | 306        |
| 15.4.1    | Fruit Developmental Patterns .....                                                  | 306        |
| 15.4.2    | Fruit Expansion .....                                                               | 307        |
| 15.4.3    | Environmental Factors, Phytohormones<br>and Fruit Growth .....                      | 309        |

|           |                                                                                                                                |            |
|-----------|--------------------------------------------------------------------------------------------------------------------------------|------------|
| 15.5      | Fruit Maturation and Ripening .....                                                                                            | 309        |
| 15.5.1    | Climacteric Fruit .....                                                                                                        | 309        |
| 15.5.2    | Non-Climacteric Fruit .....                                                                                                    | 311        |
| 15.5.3    | Changes in Fruit Composition .....                                                                                             | 312        |
| 15.6      | Perspectives .....                                                                                                             | 313        |
|           | References .....                                                                                                               | 314        |
| <b>16</b> | <b>Mechanism of Fruit Ripening .....</b>                                                                                       | <b>319</b> |
|           | M. Bouzayan, A. Latché, P. Nath, and J.C. Pech                                                                                 |            |
| 16.1      | Introduction: Fruit Ripening as a Developmentally Regulated Process .....                                                      | 319        |
| 16.2      | Climacteric and Non-Climacteric Fruit Ripening .....                                                                           | 321        |
| 16.2.1    | Ethylene Production, and Its Role in Climacteric and Non-Climacteric Fruit .....                                               | 322        |
| 16.2.2    | Ethylene Perception and Signal Transduction .....                                                                              | 324        |
| 16.2.3    | Control of Ethylene Response in Fruit .....                                                                                    | 325        |
| 16.3      | Hormone Cross-Talk and Fruit Ripening .....                                                                                    | 327        |
| 16.4      | Biochemical Changes and Sensory Traits Associated with Fruit Ripening .....                                                    | 327        |
| 16.5      | Molecular Markers and QTL Mapping of Fruit Ripening Traits ....                                                                | 329        |
| 16.6      | Natural Mutants Affected in the Ripening Phenotype .....                                                                       | 331        |
| 16.7      | Conclusions and Future Directions .....                                                                                        | 332        |
|           | References .....                                                                                                               | 334        |
| <b>17</b> | <b>Seed Development .....</b>                                                                                                  | <b>341</b> |
|           | B. Dubreucq, S. Baud, I. Debeaujon, C. Dubos, A. Marion-Poll, M. Miquel, H. North, C. Rochat, J.-M. Routaboul, and L. Lepiniec |            |
| 17.1      | Introduction .....                                                                                                             | 341        |
| 17.2      | The Use of a Model Plant for the Study of Embryo Development and Maturation .....                                              | 342        |
| 17.2.1    | Embryo Development .....                                                                                                       | 342        |
| 17.2.2    | Embryo Maturation .....                                                                                                        | 342        |
| 17.3      | The Genetic Control of the Embryo Maturation Phase .....                                                                       | 346        |
| 17.3.1    | Transcriptional Regulation .....                                                                                               | 346        |
| 17.3.2    | Control of Target Gene Expression .....                                                                                        | 347        |
| 17.4      | Seed Coat Development and Differentiation .....                                                                                | 348        |
| 17.4.1    | Structure of the Integuments .....                                                                                             | 348        |
| 17.4.2    | Regulation of Flavonoid Biosynthesis .....                                                                                     | 349        |
| 17.4.3    | Biological Functions .....                                                                                                     | 350        |
| 17.5      | Role of Phytohormones in the Control of Embryo Development and Seed Maturation .....                                           | 350        |
| 17.6      | Conclusions .....                                                                                                              | 352        |
|           | References .....                                                                                                               | 353        |

|                                                                                                                                            |     |
|--------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>18 Seed Dormancy: Approaches for Finding New Genes in Cereals</b>                                                                       | 361 |
| J.M. Barrero, J. Jacobsen, and F. Gubler                                                                                                   |     |
| 18.1 Introduction                                                                                                                          | 361 |
| 18.1.1 Dormancy and Adaptation                                                                                                             | 361 |
| 18.1.2 Plant Domestication and Dormancy                                                                                                    | 362 |
| 18.1.3 A Complex Trait                                                                                                                     | 363 |
| 18.2 Approaches for Discovering Dormancy-Related Genes                                                                                     | 365 |
| 18.2.1 Mutagenesis                                                                                                                         | 365 |
| 18.2.2 QTL Analysis                                                                                                                        | 369 |
| 18.2.3 Proteomics                                                                                                                          | 370 |
| 18.2.4 Metabolomics                                                                                                                        | 371 |
| 18.2.5 Gene Expression Analysis                                                                                                            | 371 |
| 18.3 Strategies for Modifying Dormancy in Cereals                                                                                          | 373 |
| 18.4 Conclusions and Perspectives                                                                                                          | 375 |
| References                                                                                                                                 | 375 |
| <b>19 Seed Germination</b>                                                                                                                 | 383 |
| R.C. Martin, W.E. Pluskota, and H. Nonogaki                                                                                                |     |
| 19.1 Introduction                                                                                                                          | 383 |
| 19.2 Seed Structure and Germination                                                                                                        | 383 |
| 19.2.1 Testa and Pericarp                                                                                                                  | 384 |
| 19.2.2 Endosperm                                                                                                                           | 385 |
| 19.2.3 Embryo                                                                                                                              | 386 |
| 19.3 Hormonal Regulation of Germination                                                                                                    | 388 |
| 19.3.1 ABA and GA Biosynthesis and Deactivation                                                                                            | 388 |
| 19.3.2 ABA-GA Balance, and Its Regulation by Light and Temperature                                                                         | 390 |
| 19.3.3 ABA and GA Perception and Signal Transduction                                                                                       | 391 |
| 19.3.4 Other Hormones                                                                                                                      | 393 |
| 19.4 Germination Determinants Other than Hormones                                                                                          | 394 |
| References                                                                                                                                 | 397 |
| <b>20 Apomixis in the Era of Biotechnology</b>                                                                                             | 405 |
| E. Albertini, G. Barcaccia, A. Mazzucato, T.F. Sharbel, and M. Falcinelli                                                                  |     |
| 20.1 Introduction                                                                                                                          | 405 |
| 20.2 General Definitions and Apomixis Mechanisms                                                                                           | 406 |
| 20.3 Embryological Pathways of Gametophytic Apomixis                                                                                       | 408 |
| 20.4 Genetic and Epigenetic Control of Apomixis                                                                                            | 411 |
| 20.5 Evolution of Apomixis and Population Genetics in Apomicts                                                                             | 415 |
| 20.6 Transferring Apomixis in Crops from Wild Relatives, Molecular Mapping of Apomixis Components and Map-Based Cloning of Candidate Genes | 418 |
| 20.7 Advanced Biotechnological Approaches: Looking for Candidate Genes and Engineering Apomixis                                            | 423 |
| References                                                                                                                                 | 428 |

|                                                                                   |     |
|-----------------------------------------------------------------------------------|-----|
| <b>21 Male Sterility</b> .....                                                    | 437 |
| C.D. Chase, A. Ribarits, and E. Heberle-Bors                                      |     |
| 21.1 Introduction .....                                                           | 437 |
| 21.2 Applications of Pollen Sterility .....                                       | 437 |
| 21.2.1 Hybrid Seed Production .....                                               | 438 |
| 21.2.2 Value-Added Traits .....                                                   | 439 |
| 21.2.3 Transgene Containment .....                                                | 440 |
| 21.3 Cytoplasmic Male Sterility Systems .....                                     | 440 |
| 21.3.1 CMS Genes .....                                                            | 440 |
| 21.3.2 CMS Phenotypes .....                                                       | 441 |
| 21.3.3 Fertility Restoration .....                                                | 443 |
| 21.3.4 Transgenic Approaches to CMS .....                                         | 444 |
| 21.4 Nuclear-Encoded Male Sterility Systems .....                                 | 445 |
| 21.4.1 Nuclear Male Sterility Genes .....                                         | 445 |
| 21.4.2 Genetically Engineered Nuclear Male Sterility .....                        | 446 |
| 21.5 Summary and Future Prospects .....                                           | 450 |
| References .....                                                                  | 450 |
| <b>22 Self-Incompatibility Systems in Flowering Plants</b> .....                  | 459 |
| P. Kaothien-Nakayama, A. Isogai, and S. Takayama                                  |     |
| 22.1 Introduction .....                                                           | 459 |
| 22.2 Sporophytic Self-Incompatibility in Brassicaceae .....                       | 461 |
| 22.2.1 Physiological Aspect .....                                                 | 461 |
| 22.2.2 Cloning of <i>S</i> -Genes, and the Nature of <i>S</i> -Gene Products .... | 462 |
| 22.2.3 Other Components of the SSI Pathway .....                                  | 466 |
| 22.2.4 Working Model and Prospects .....                                          | 467 |
| 22.3 S-RNase Based Gametophytic Self-Incompatibility .....                        | 468 |
| 22.3.1 Physiological Aspect .....                                                 | 468 |
| 22.3.2 Cloning of <i>S</i> -Genes, and the Nature of <i>S</i> -Gene Products .... | 469 |
| 22.3.3 Other Components of S-RNase Based GSI .....                                | 472 |
| 22.3.4 Working Model and Prospects .....                                          | 473 |
| 22.4 The Use of SI in Breeding Programs .....                                     | 476 |
| 22.4.1 Plant Breeding .....                                                       | 476 |
| 22.4.2 Integration of the SI System into F1-Hybrid<br>Breeding Programs .....     | 477 |
| 22.5 Conclusions .....                                                            | 479 |
| References .....                                                                  | 479 |
| <b>Subject Index</b> .....                                                        | 487 |