

## Contents to Volume 1

**Preface** XXIX

**List of Contributors** XXXIII

### **Part One Climate Change 1**

#### **1 Climate Change: Challenges for Future Crop Adjustments 3**

*Jerry L. Hatfield*

- 1.1 Introduction 3
- 1.2 Climate Change 4
- 1.3 Crop Responses to Climate Change 7
  - 1.3.1 Temperature Responses 7
    - 1.3.1.1 Annual Crops 7
    - 1.3.1.2 Major Challenges 11
- 1.4 Water Responses 11
- 1.5 Major Challenges 17
  - 1.5.1 Growth and Development Processes and WUE 17
  - 1.5.2 Growth and Development Processes Linked to Quality 18
- 1.6 Grand Challenge 19
- References 19

#### **2 Developing Robust Crop Plants for Sustaining Growth and Yield Under Adverse Climatic Changes 27**

*Vijaya Shukla and Autar K. Mattoo*

- 2.1 Introduction 27
- 2.2 Elevated Temperature and Plant Response 29
- 2.3 Elevated CO<sub>2</sub> Levels and Plant Response 30
- 2.4 Genetic Engineering Intervention to Build Crop Plants for Combating Harsh Environments 30
  - 2.4.1 Transcription Factors 31
  - 2.4.2 bZIP Transcription Factors 35
  - 2.4.3 DREB/ERF Transcription Factors 36
  - 2.4.4 MYB Transcription Factors 37

2.4.5	NAC Transcription Factors	37
2.4.6	WRKY Transcription Factors	38
2.4.7	ZF Transcription Factors	38
2.5	Other Protein Respondents	39
2.5.1	LEA Proteins	39
2.5.2	Protein Kinases	39
2.5.3	Osmoprotectants (Osmolytes)	40
2.5.4	Polyamines and Stress Tolerance	42
2.6	Conclusions	43
	References	44

### **3 Climate Change and Abiotic Stress Management in India 57**

*R.B. Singh*

3.1	Introduction	57
3.2	Impact of Climate Change and Associated Abiotic Stresses on Agriculture	59
3.2.1	Trend of Change and Impact on Agricultural Production	59
3.2.2	Impact on Water and Soil	62
3.2.2.1	Water	62
3.2.2.2	Soil	63
3.3	CSA: Technologies and Strategies	63
3.3.1	Sustainable Productivity Enhancement	63
3.3.2	Adaptation	64
3.3.2.1	Rice–Wheat System	65
3.3.2.2	Stress-Tolerant Varieties	66
3.4	National Initiative on Climate Resilient Agriculture	67
3.4.1	Mitigation	69
3.5	Policy and Institutions	72
3.5.1	Mainstreaming CSA in National Policy	72
3.5.2	CSV	74
3.5.3	Agricultural Insurance and Risk Management	74
3.5.4	Information and Communication Technology for Climate Change Management	75
3.6	Partnership	75
	References	77

## **Part Two Abiotic Stress Tolerance and Climate Change 79**

### **4 Plant Environmental Stress Responses for Survival and Biomass Enhancement 81**

*Yuriko Osakabe, Keishi Osakabe, and Kazuo Shinozaki*

4.1	Introduction	81
4.2	Stomatal Responses in the Control of Plant Productivity	82
4.2.1	ABA Biosynthesis and Transport	83

4.2.2	Signal Mediation of Stomatal Aperture	84
4.2.3	Guard Cell Development	86
4.3	Signaling and Transcriptional Control in Water Stress Tolerance	87
4.3.1	Signaling Mediation by Membrane-Localized Proteins	87
4.3.2	Stress-Responsive Transcription	90
4.3.3	Key Transcription Factors	91
4.4	Protection Mechanisms of Photosynthesis During Water Stress	92
4.5	Metabolic Adjustment During Water Stress	94
4.5.1	Metabolomic Study of Primary Metabolites	94
4.5.2	Cell Wall Compounds	95
4.6	Future Perspective	96
	References	97
<b>5</b>	<b>Heat Stress and Roots</b>	<b>109</b>
	<i>Scott A. Heckathorn, Anju Giri, Sasmita Mishra, and Deepesh Bista</i>	
5.1	Roots, Heat Stress, and Global Warming: An Overview of the Problem	109
5.2	Effects of Heat Stress on Root Growth and Root versus Shoot Mass and Function	111
5.2.1	Root Growth	116
5.2.2	Effects of Heat Stress on Roots versus Shoots	119
5.2.3	Shoot and Root versus Root-Only versus Shoot-Only Heating	119
5.2.4	Chronic versus Acute Heat Stress	121
5.2.5	Direct versus Indirect Effects of Heat Stress on Roots and Shoots	122
5.2.6	Effects of Heat Stress on Nutrient Relations	123
5.2.7	Effects of Heat Stress on Root Respiration and Carbon Metabolism	125
5.2.8	Effects of Heat Stress on Root Water Relations	126
5.3	Interactions Between Heat Stress and Other Global Environmental-Change Factors on Roots	126
5.4	Heat Stress and Root–Soil Interactions	128
5.5	Summary: Synthesizing What We Know and Predict into a Conceptual Model of Heat Effects on Roots and Plant–Soil Links	129
	References	131
<b>6</b>	<b>Role of Nitrosative Signaling in Response to Changing Climates</b>	<b>137</b>
	<i>Panagiota Filippou, Chrystalla Antoniou, and Vasileios Fotopoulos</i>	
6.1	Introduction	137
6.2	Salinity	138
6.3	Drought	142
6.4	Heavy Metals	146
6.5	Heat Stress	148
6.6	Chilling/Freezing/Low Temperature	150
6.7	Anoxia/Hypoxia	151

6.8	Conclusions	153
	References	153
<b>7</b>	<b>Current Concepts about Salinity and Salinity Tolerance in Plants</b>	<b>163</b>
	<i>Askım Hediye Sekmen, Melike Bor, Filiz Ozdemir, and Ismail Turkan</i>	
7.1	Introduction	163
7.2	What is Salt Stress?	164
7.2.1	Perception of Salt Stress – Still a Mystery	167
7.2.2	Salt Stress Signaling: Now, We Know Better	168
7.2.2.1	Ca <sup>2+</sup> Signaling	168
7.2.2.2	pH in Stress Signaling	169
7.2.2.3	Abscissic Acid Signaling	169
7.2.2.4	Phospholipid Signaling	171
7.3	Effects: Primary and Secondary	172
7.3.1	Salt Primary Effects: Osmotic and Ionic Phases	172
7.3.1.1	Role of the SOS Pathway in Ion Homeostasis	174
7.3.2	Salt Secondary Effect: Oxidative Stress	176
7.4	Conclusion	178
	References	178
<b>8</b>	<b>Salinity Tolerance of <i>Avicennia officinalis</i> L. (Acanthaceae) from Gujarat Coasts of India</b>	<b>189</b>
	<i>Ashish Dahyabhai Patel, Kishor Lalcheta, Sarvajeet Singh Gill, and Narendra Tuteja</i>	
8.1	Introduction	189
8.2	Materials and Methods	191
8.2.1	Plant Material and Study Area	191
8.2.2	Salinization of Soil	191
8.2.3	Plant Establishment	191
8.2.4	Plant Growth	192
8.2.5	Organic Solutes (Soluble Sugars, Proline, and Glycine Betaine)	192
8.2.6	Chlorophyll Content, Total Free Amino Acids, Hydrogen Peroxide (H <sub>2</sub> O <sub>2</sub> ), and Protein Oxidation	193
8.2.7	Membrane Permeability and Lipid Peroxidation	194
8.2.8	Antioxidant Enzymes	194
8.2.9	Statistical Analyses	195
8.3	Results	195
8.3.1	Total Dry Weight of Plants	195
8.3.2	Organic Solutes (Soluble Sugars, Proline, and Glycine Betaine)	196
8.3.3	Chlorophyll Content, Total Free Amino Acids, H <sub>2</sub> O <sub>2</sub> , and Protein Oxidation	196
8.3.4	Lipid Peroxidation and Membrane Permeability	198
8.3.5	Antioxidant Enzymes (SOD, CAT, APX, and Glutathione Reductase)	199
8.4	Discussion	200
	References	203

## **9 Drought Stress Responses in Plants, Oxidative Stress, and Antioxidant Defense 209**

*Mirza Hasanuzzaman, Kamrun Nahar, Sarvajeet Singh Gill, and Masayuki Fujita*

- 9.1 Introduction 210
- 9.2 Plant Response to Drought Stress 211
  - 9.2.1 Germination 211
  - 9.2.2 Plant Growth 214
  - 9.2.3 Plant–Water Relations 216
  - 9.2.4 Stomatal Conductance and Gas Exchange 217
  - 9.2.5 Photosynthesis 219
  - 9.2.6 Reproductive Development and Seed Formation 223
  - 9.2.7 Yield Attributes and Yield 226
- 9.3 Drought and Oxidative Stress 229
- 9.4 Antioxidant Defense System in Plants Under Drought Stress 232
  - 9.4.1 Non-Enzymatic Components 233
  - 9.4.2 Enzymatic Components 234
- 9.5 Conclusion and Future Perspectives 236
- References 237

## **10 Plant Adaptation to Abiotic and Genotoxic Stress: Relevance to Climate Change and Evolution 251**

*Brahma B. Panda, V. Mohan M. Achary, Srikrishna Mahanty, and Kamal K. Panda*

- 10.1 Introduction 251
- 10.2 Plant Responses to Abiotic Stress 252
- 10.3 ROS Induce Genotoxic Stress 256
- 10.4 Adaptive Responses to Oxidative Stress 257
- 10.5 Transgenic Adaptation to Oxidative Stress 260
- 10.6 Adaptive Response to Genotoxic Stress 260
- 10.7 Role of MAPK and Calcium Signaling in Genotoxic Adaptation 267
- 10.8 Role of DNA Damage Response in Genotoxic Adaptation 269
- 10.9 Epigenetics of Genotoxic Stress Tolerance 272
- 10.10 Transgenerational Inheritance and Adaptive Evolution Driven by the Environment 274
- 10.11 Concluding Remarks 278
- References 278

## **11 UV-B Perception in Plant Roots 295**

*Ken Yokawa and František Baluška*

- 11.1 Introduction 295
- 11.2 Effect of UV-B on Plants 296
  - 11.2.1 UV-Mediated ROS Generation 296
  - 11.2.2 Response of Plant Roots to Light of a Broad Wavelength 297
  - 11.2.3 UV-B Receptors Found in Roots 298

11.2.4	Tryptophan in UV-B Perception	299
11.2.5	Root Evolution Under a UV-B Environment	299
11.3	Land Plant Evolution was Shaped via Ancient Ozone Depletion	301
	References	302
<b>12</b>	<b>Improving the Plant Root System Architecture to Combat Abiotic Stresses Incurred as a Result of Global Climate Changes</b>	<b>305</b>
	<i>Ananda K. Sarkar, Karthikeyan Mayandi, Vibhav Gautam, Suvakanta Barik, and Shabari Sarkar Das</i>	
12.1	Introduction	305
12.2	RSA and its Basic Determinants	306
12.3	Breeding Approaches to Improve RSA and Abiotic Stress Tolerance	308
12.3.1	Conventional Breeding Approach	308
12.3.2	Identification of QTLs Associated with Specific RSA Traits and Stress Tolerance	309
12.4	Genomic Approaches to Identify Regulators of RSA Associated with Abiotic Stress Tolerance	311
12.5	Transgenic Approaches to Improve RSA for Abiotic Stress Tolerance	313
12.6	Use of Polyamines and Osmotic Regulators in Stress-Induced Modulation of RSA	314
12.7	Hormonal Regulation of Root Architecture and Abiotic Stress Response	315
12.8	Small RNA-Mediated Regulation of RSA and Abiotic Stress Response	317
12.9	Application of Phenomics in Understanding Stress-Associated RSA	319
12.10	Conclusion and Future Perspectives	320
	References	321
<b>13</b>	<b>Activation of the Jasmonate Biosynthesis Pathway in Roots in Drought Stress</b>	<b>325</b>
	<i>Palmiro Poltronieri, Marco Taurino, Stefania De Domenico, Stefania Bonsegna, and Angelo Santino</i>	
13.1	Background and Introduction	325
13.2	Plant Growth Factors: Key Role in Biotic and Abiotic Stress Signaling	326
13.3	Jasmonate Biosynthesis Pathway	328
13.4	Roots as the Primary Organ Sensing the Soil Environment	330
13.5	Symbiotic Microorganisms Affect Root Growth and Plant Performance	331
13.6	Symbiotic Organisms Alleviate and Improve Abiotic Stress Tolerance of Host Plants	332
13.7	Role of Jasmonates in Roots	333

- 13.8 Jasmonic Acid Signal Transduction in Roots and Jasmonic Acid Involvement in Abiotic Stress Response 333
- 13.9 Jasmonate in Root Response to Abiotic Stresses: Model Legumes and Chickpea Tolerant Varieties Showing Differential Transcript Expression During Salt and Drought Stress 334
- 13.10 Role of Transcription Factors and MicroRNAs in the Regulation of Jasmonic Acid Signaling 336
- 13.11 Conclusion 338
- References 338

## Contents to Volume 2

List of Contributors XXV

### Part Three Approaches for Climate Change Mitigation 343

- 14 Can Carbon in Bioenergy Crops Mitigate Global Climate Change? 345**  
*Abdullah A. Jaradat*
- 14.1 Introduction 345
- 14.2 The Many Faces of Carbon 348
  - 14.2.1 Carbon: A Scarce Commodity 349
  - 14.2.2 Carbon and Nitrogen Cycles 350
- 14.3 Are Bioenergy Crops Carbon-Neutral? 352
- 14.4 Recalcitrant Carbon in Bioenergy Crops 354
- 14.5 Climate Change Mitigation Potential of Bioenergy Crops 355
  - 14.5.1 Biomass versus Bioenergy Density 358
  - 14.5.2 Temporal Changes of Carbon in the Soil–Bioenergy Crops–Atmosphere Continuum 360
- 14.6 Carbon in Bioenergy Crops 361
  - 14.6.1 Carbon in Traditional Bioenergy Plants 362
  - 14.6.2 Carbon in First-Generation Bioenergy Crops 363
  - 14.6.3 Carbon in Second-Generation Bioenergy Crops 364
  - 14.6.4 Carbon in Third-Generation Bioenergy Crops 367
- 14.7 Genetic Improvement of Bioenergy Crops 369
  - 14.7.1 Genetics, Breeding, Transgenics, and Carbon Sequestration 370
  - 14.7.2 Genetic Models and Ideotypes of Bioenergy Crops 373
- 14.8 Carbon Management in Bioenergy Crops 374
  - 14.8.1 Managing Carbon Sources and Sinks 375
  - 14.8.2 Managing Nutrient Composition, Cycling, and Loss 377
  - 14.8.3 Managing Land-Use Change 379
  - 14.8.4 Biogeochemical Liabilities of Carbon in Bioenergy Crops 381
- 14.9 Carbon Quality in Bioenergy Crops 383

14.10	Life Cycle Assessment	385
14.11	Ecosystem Services of Carbon in Bioenergy Crops	387
14.12	Eco-Physiology and Carbon Sequestration	389
14.13	Climate Ethics and Carbon in Bioenergy Crops	391
14.13.1	Biofuel versus Food	392
14.13.2	Biofuel versus Water	394
14.13.3	Biofuel versus Biodiversity	397
14.14	Synthesis of Research Needs and Priorities	398
14.15	Conclusions	403
	References	405
<b>15</b>	<b>Adaptation and Mitigation Strategies of Plant Under Drought and High-Temperature Stress</b>	<b>421</b>
	<i>Pasala Ratna Kumar, Susheel Kumar Raina, Satish Kumar, Kiran P. Bhagat, Yogeshwar Singh, and Santanu Kumar Bal</i>	
15.1	Background and Introduction	421
15.2	Plant Molecular Adaptation and Strategies Under Drought Stress	422
15.2.1	Transcription Factors	424
15.2.2	Small RNAs	425
15.2.3	Involvement of Polyamines in Abiotic Stress Tolerance in Plants	425
15.2.4	Role of Microorganisms in Plant Drought Stress Tolerance	426
15.3	Plant Adaptation and Mitigation Strategies for Heat Stress Tolerance	427
15.3.1	Thermal Stability of Cell Membranes	429
15.3.2	HSPs	429
15.3.3	Other Thermotolerance Factors	431
15.4	Conclusions	433
	References	433
<b>16</b>	<b>Emerging Strategies to Face Challenges Imposed by Climate Change and Abiotic Stresses in Wheat</b>	<b>437</b>
	<i>Bharti Garg, Shreelekha Misra, and Narendra Tuteja</i>	
16.1	Introduction	437
16.2	Physiological and Molecular Adaptive Strategies in Wheat	438
16.3	Drought Tolerance	440
16.4	Salinity Tolerance	444
16.5	Heat Tolerance	445
16.6	Cold Tolerance	447
16.7	Functional and Comparative Genomics Approaches for Wheat Improvement	449
16.8	Conclusion and Future Perspectives	450
	References	452



<b>17</b>	<b>Protein Structure–Function Paradigm in Plant Stress Tolerance</b>	<b>459</b>
	<i>Harshesh Bhatt, Anil Kumar, and Neel Sarovar Bhavesh</i>	
17.1	Introduction	459
17.2	Plant Signaling Machinery	460
17.3	Proteins Involved in Metabolic Regulation	465
17.4	Stabilization of Proteins and RNAs	469
17.5	Antifreeze Proteins	472
17.6	Disordered Stress Proteins	473
17.7	Summary	473
	References	474
<b>18</b>	<b>Abiotic Stress-Responsive Small RNA-Mediated Plant Improvement Under a Changing Climate</b>	<b>481</b>
	<i>Basel Khraiweh and Enas Qudeimat</i>	
18.1	Introduction	481
18.2	Classes of Small RNAs	483
18.2.1	miRNAs	483
18.2.1.1	Biogenesis of miRNAs	483
18.2.1.2	Role of miRNAs in Plant Stress Responses for Adapting to Climate Change	486
18.2.2	siRNAs	492
18.2.2.1	Biogenesis of siRNAs	492
18.2.2.2	Role of siRNAs in Plant Stress Responses for Adapting to Climate Change	492
18.3	Artificial miRNAs	494
18.4	Stress–miRNA Networks for Adapting to Climate Change	494
18.5	Application of Small RNA-Mediated Suppression Approaches for Plant Improvement Under a Changing Climate	497
18.6	Conclusions and Outlook	499
	Note	500
	References	500
<b>19</b>	<b>Impact of Climate Change on MicroRNA Expression in Plants</b>	<b>507</b>
	<i>Vallabhi Ghorecha, N.S.R. Krishnappa, and Ramanjulu Sunkar</i>	
19.1	Introduction	507
19.2	Small Non-Coding RNAs in Plants	508
19.3	Biogenesis and Function of miRNAs in Plants	509
19.4	Heat Stress	511
19.5	Drought	513
19.6	UV-B Radiation	514
19.7	Ozone	515
19.8	Conclusions and Future Directions	515
	References	517

<b>20</b>	<b>Role of Absciscic Acid Signaling in Drought Tolerance and Preharvest Sprouting Under Climate Change</b>	<b>521</b>
	<i>Yasunari Fujita, Kazuo Nakashima, Takuya Yoshida, Miki Fujita, Kazuo Shinozaki, and Kazuko Yamaguchi-Shinozaki</i>	
20.1	Introduction	521
20.2	Major ABA Signaling Components in Response to Cellular Dehydration	522
20.2.1	Perception of ABA by the PYR/PYL/RCAR–PP2C–ABA Receptor Complex	524
20.2.2	Subclass III SnRK2s are Major Positive Regulators in Osmotic Stress Signaling as well as in ABA Signaling	526
20.2.3	SnRK2–AREB/ABF Pathway Plays a Central Role in ABA-Mediated Gene Expression in Response to Cellular Dehydration	528
20.2.4	AREB/ABFs are Master Transcription Factors that Regulate ABA-Mediated ABRE-Dependent Gene Expression in Response to Dehydration Stress	529
20.2.5	ABRE Functions as a Major <i>cis</i> -Acting Element in ABA-Responsive Gene Expression	530
20.3	ABA-Mediated Gene Expression in Seed Dormancy	532
20.3.1	ABA has an Important Role in the Control of Seed Dormancy	532
20.3.2	SnRK2s are Central Regulators in ABA Signaling for Seed Dormancy	534
20.3.3	Quantitative Trait Locus Analyses Provide Novel Factors for the Control of Seed Dormancy	535
20.4	Role of ABA in Plant Adaptation to Land and Environmental Changes	536
20.5	Potential Application of ABA Signaling Components to Improve Crop Productivity Under Climate Change	537
20.6	Future Perspectives	538
	References	541
<b>21</b>	<b>Regulatory Role of Transcription Factors in Abiotic Stress Responses in Plants</b>	<b>555</b>
	<i>Dumbala Srinivas Reddy, Pooja Bhatnagar Mathur, and K.K.Sharma</i>	
21.1	Introduction	555
21.2	bZIP Proteins	557
21.3	MYB-Like Proteins	557
21.4	MYC-Like bHLH Proteins	558
21.4.1	Cooperation of MYC and MYB Proteins	560
21.5	HD-ZIP Proteins	561
21.6	AP2/EREBP Domain Proteins	562
21.7	DREB Subfamily	562
21.8	CBF/DREB Genes from <i>Arabidopsis</i>	564
21.9	CBF/DREB Regulation in <i>Arabidopsis</i>	565
21.9.1	Promoter Regions of the CBF/DREB Genes of <i>Arabidopsis</i>	565

21.9.2	Expression of CBFs is Modulated by Temperature	565
21.9.3	Regulation of the CBF Pathway in <i>Arabidopsis</i>	566
21.9.3.1	Upstream Regulators of the CBF Pathway	567
21.9.3.2	Downstream Regulators of the CBF Pathway	569
21.9.4	CBF3 Integrates the Activation of Multiple Components of the Cold Response	569
21.9.4.1	ESK1	570
21.9.5	Parallel Pathway to CBFs	570
21.9.5.1	RAV1 and ZAT12 May Follow Parallel Pathways to CBFs	571
21.10	<i>DREB1A</i> -Targeted Genes	571
21.11	Overexpression of DREB Genes in Plant Species	572
21.11.1	Overexpression of DREB Genes in Transgenic <i>Arabidopsis</i>	572
21.11.2	Heterologous Expression of <i>Arabidopsis</i> DREB Genes in Transgenic Plants	573
21.11.3	DREB Genes Have Discrepant Expression in Monocots and Dicots	576
21.11.4	CBF/DREB1 Genes of <i>Arabidopsis</i> and Rice are Functionally Different	576
21.12	Conclusion	577
	References	577
<b>22</b>	<b>Transcription Factors: Modulating Plant Adaption in the Scenario of Changing Climate</b>	<b>589</b>
	<i>Swati Puranik and Manoj Prasad</i>	
22.1	Catastrophes of the Changing Climate	589
22.2	Molecular Reprogramming Events Mitigate Environmental Constraints	590
22.3	Classification of Transcription Factors	592
22.3.1	AREB/ABF Proteins	593
22.3.2	MYC/MYB Transcription Factors	593
22.3.3	CBF/DREB Transcription Factors	594
22.3.4	NAC and ZF-HD Proteins	595
22.3.5	WRKY Transcription Factors	596
22.3.6	ZF Proteins	596
22.4	Conclusion and Future Perspectives	597
	References	597
<b>23</b>	<b>Role of Transcription Factors in Abiotic Stress Tolerance in Crop Plants</b>	<b>605</b>
	<i>Neelam R. Yadav, Jyoti Taunk, Asha Rani, Bharti Aneja, and Ram C. Yadav</i>	
23.1	Introduction	606
23.2	AP2/ERF Regulon	607
23.3	CBF/DREB Regulon	609
23.4	NAC Regulon	611

23.5	ZF-HD Regulon	614
23.6	MYB/MYC Regulon	615
23.6.1	MYBs and Cold Stress	618
23.6.2	MYBs and Salinity Tolerance	619
23.7	AREB/ABF Regulon	621
23.8	Transcription Factor WRKY	624
23.9	Conclusions	626
	References	627
<b>24</b>	<b>Coping with Drought and Salinity Stresses: Role of Transcription Factors in Crop Improvement</b>	<b>641</b>
	<i>Karina F. Ribichich, Agustín L. Arce, and Raquel Lia Chan</i>	
24.1	Transcription Factors: A Historical Perspective	641
24.2	Plant Transcription Factor Families Implicated in Drought and Salinity	644
24.2.1	MYB Family	645
24.2.2	bHLH Family	649
24.2.3	bZIP Family	649
24.2.4	NAC Family	650
24.2.5	AP2/ERF Family	651
24.2.6	WRKY Family	652
24.2.7	HD Family	653
24.3	Crop Domestication: Examples of the Major Role of Transcription Factors	654
24.3.1	Maize Domestication: Increasing Apical Dominance	654
24.3.2	Rice Domestication: Reducing Grain Shattering	655
24.3.3	Barley Domestication: Yield to the Yield	656
24.4	Drought and Salinity: From Perception to Gene Expression	657
24.4.1	Early Signaling Events	658
24.4.2	ABA-Dependent Pathway	659
24.4.3	ABA-Independent Pathway	662
24.5	Transcription Factor Gene Discovery in Stress Responses	663
24.6	The Long and Winding Road to Crop Improvement	665
	References	672
<b>25</b>	<b>Role of Na<sup>+</sup>/H<sup>+</sup> Antiporters in Na<sup>+</sup> Homeostasis in Halophytic Plants</b>	<b>685</b>
	<i>Pradeep K. Agarwal, Narendra Singh Yadav, and Bhavanath Jha</i>	
25.1	Introduction	685
25.2	Tissue-Specific Adaptation of Halophytes	687
25.2.1	Succulence	687
25.2.2	Salt Secretion by Salt Glands	688
25.2.3	Salt Secretion by Bladder Cells	688
25.2.4	Salt-Secreting Hairs	689

25.2.5	Salt Exclusion by Ultrafiltration at the Membranes of Root Cells	689
25.2.6	Salt-Saturated Organs	689
25.3	Ion Transporters	690
25.3.1	Plasma Membrane Transporters	690
25.3.1.1	SOS1	690
25.3.1.2	Plasma Membrane $H^+$ -ATPase	692
25.3.2	Vacuolar Transporters	692
25.3.2.1	NHX1	692
25.3.2.2	Vacuolar $H^+$ -ATPase	694
25.3.2.3	$H^+$ -PPase (V-PPase)	695
25.4	Conclusion and Perspectives	697
	References	698
<b>26</b>	<b>Role of Plant Metabolites in Abiotic Stress Tolerance Under Changing Climatic Conditions with Special Reference to Secondary Compounds</b>	<b>705</b>
	<i>Akula Ramakrishna and G.A. Ravishankar</i>	
26.1	Introduction: Plant Secondary Metabolites	705
26.2	Climate Change	706
26.3	Role of Secondary Metabolites Under Changing Climatic Conditions	706
26.3.1	Carotenoids	707
26.3.2	Polyamines	708
26.3.3	Carbohydrates	708
26.3.4	Antioxidants	708
26.3.5	Phenolic Compounds	709
26.3.6	Stress Proteins	710
26.3.7	Antifreeze Proteins	710
26.3.8	Heat Shock Proteins	710
26.3.9	Dehydrins	710
26.4	Role of Signaling Molecules During Abiotic Stress	711
26.4.1	Nitric Oxide	711
26.4.2	Jasmonates	711
26.4.3	Brassinosteroids	712
26.4.4	Salicylic Acid	712
26.4.5	Phytohormones	712
26.5	Role of Secondary Metabolites in Drought, Salt, Temperature, Cold, and Chilling Stress	713
26.5.1	Drought Stress	713
26.5.2	Salt Stress	713
26.5.3	Temperature Stress	714
26.5.4	Cold Stress	715
26.5.5	Chilling Stress	715
26.6	Conclusion	716
	References	716

<b>27</b>	<b>Metabolome Analyses for Understanding Abiotic Stress Responses in Plants to Evolve Management Strategies</b>	<b>727</b>
	<i>Usha Chakraborty, Bhumika Pradhan, and Rohini Lama</i>	
27.1	Introduction	728
27.2	Metabolite Changes During Abiotic Stresses	729
27.2.1	Proline and Glycine Betaine	729
27.2.2	Carbohydrates	733
27.2.3	Polyamines	735
27.3	Stress Hormones	736
27.3.1	ABA	737
27.3.2	Salicylic Acid	738
27.3.3	Jasmonic Acid and Ethylene	738
27.4	Antioxidants	739
27.5	Stress Proteins and Protein Kinases	740
27.6	Stress-Responsive Gene Expression	741
27.7	Role of MicroRNAs in Abiotic Stress	742
27.8	Conclusion	743
	References	744
<b>28</b>	<b>Metabolomic Approaches for Improving Crops Under Adverse Conditions</b>	<b>755</b>
	<i>Prabodh Kumar Trivedi, Nehal Akhtar, Parul Gupta, and Pravendra Nath</i>	
28.1	Introduction	755
28.2	Different Approaches to Study Metabolomics	756
28.3	Plant Metabolome Alterations During Adverse Conditions	757
28.3.1	Light	758
28.3.2	Temperature	760
28.3.2.1	High Temperature	760
28.3.2.2	Cold Stress	761
28.3.3	Drought	763
28.3.4	Salinity	766
28.3.5	Hypoxia	767
28.3.6	Heavy Metals	768
28.4	Genetic Engineering for Metabolite Modulation for Stress Tolerance	770
	References	774
<b>29</b>	<b>Improvement of Cereal Crops through Androgenesis and Transgenic Approaches for Abiotic Stress Tolerance to Mitigate the Challenges of Climate Change in Sustainable Agriculture</b>	<b>785</b>
	<i>S.M. Shahinul Islam, Israt Ara, and Narendra Tuteja</i>	
29.1	Background	786
29.2	Androgenesis for Crop Improvement	787
29.2.1	Major Factors Influencing Androgenesis	788

29.2.1.1	Genotype and Other Physical Conditions of the Donor Plant	788
29.2.1.2	Anther Wall	789
29.2.1.3	Culture Medium	789
29.2.1.4	Stage of Microspore or Pollen Development	789
29.2.1.5	Pretreatment and Stress Factors	789
29.2.1.6	Confirmation of Ploidy Status	789
29.2.2	Problems Associated with Albinisms in Androgenesis	790
29.2.3	Genetic Transformation and in Combination with Androgenesis	790
29.2.4	Development of Major Abiotic Stress-Tolerant Crops by Androgenesis, Transformation, and the Combination of Both Methods	791
29.2.4.1	Salinity	792
29.2.4.2	Drought	801
29.2.4.3	Heavy Metals	801
29.2.4.4	Extreme Temperature (Cold/Heat)	802
29.2.4.5	Flood/Water Logging	802
29.2.4.6	Herbicide Resistance	803
29.2.4.7	Osmotic and Oxidative Stress	803
29.3	Concluding Remarks	804
	References	805

### **30 Bioprospection of Weed Species for Abiotic Stress Tolerance in Crop Plants Under a Climate Change Scenario: Finding the Gold Buried within Weed Species** 815

*Meenal Rathore, Raghwendra Singh, and Bhumes Kumar*

30.1	Introduction	815
30.2	Climate Change and Agriculture	816
30.2.1	Average Surface Temperature	817
30.2.2	Change in Rainfall Amount and Pattern	817
30.2.3	Atmospheric CO <sub>2</sub> Level	818
30.2.4	Tropospheric Ozone	818
30.2.5	Drought	818
30.2.6	UV-B Radiation	819
30.3	Weeds as a Source of Genetic Materials for Abiotic Stress Tolerance	820
30.3.1	Thermotolerance	821
30.3.2	Drought Tolerance	823
30.3.3	Salinity Tolerance	824
30.3.4	Excess Water (Flooding) Tolerance	826
30.3.5	Tolerance to UV-B Radiation	828
30.3.6	Tolerance to Ozone	829
30.4	Conclusion	830
	References	830

## Part Four Crop Improvement Under Climate Change 837

- 31 Climate Change and Heat Stress Tolerance in Chickpea 839**  
*Pooran M. Gaur, Aravind K. Jukanti, Srinivasan Samineni, Sushil K. Chaturvedi, Partha S. Basu, Anita Babbar, Veera Jayalakshmi, Harsh Nayyar, Viola Devasirvatham, Nalini Mallikarjuna, Laxmanan Krishnamurthy, and C.L. Laxmipathi Gowda*
  - 31.1 Introduction 840
  - 31.2 Effect of Heat Stress on Chickpea 842
  - 31.3 Screening Techniques for Heat Tolerance 844
  - 31.4 Physiological Mechanisms Underlying Heat Tolerance 846
  - 31.5 Genetic Variability for Heat Tolerance 847
  - 31.6 Breeding Strategies for Heat Tolerance 848
  - References 850
- 32 Micropropagation of *Aloe vera* for Improvement and Enhanced Productivity 857**  
*Narpat S. Shekhawat, Mangal S. Rathore, Smita Shekhawat, Sumitra K. Choudhary, Mahendra Phulwaria, Harish, Manoj K. Rai, J.B. Vibha, Nitika S. Rathore, A.K. Patel, and Vinod Kataria*
  - 32.1 Introduction 858
  - 32.1.1 Human-Induced Climate Changes and Constraints on Ecosystem Services 859
  - 32.1.2 Challenges of Arid Lands (Drylands) 859
  - 32.2 *Aloe* as a Plant Resource of Dry Habitats 860
  - 32.3 *Aloe* Biology 863
  - 32.4 Genetic Resources and Biodiversity of *Aloe* 864
  - 32.5 Biotechnology for Characterization, Conservation, Improvement, and Productivity Enhancement of *Aloe* 865
  - 32.6 Cloning and Mass Propagation of *Aloe* Through Tissue Culture 866
  - 32.7 Cloning of *A. vera* (Ghee-Kanwar/Gwar-Patha) 868
  - 32.7.1 Materials and Methods 868
  - 32.7.1.1 Establishment of Cultures and Multiplication of Clonal Shoots 868
  - 32.7.1.2 Rooting of *In Vitro* Produced Shoots 871
  - 32.7.1.3 Hardening and Acclimatization of the Cloned Plantlets of *A. vera* 871
  - 32.7.2 Results 872
  - 32.8 Conclusions 873
  - References 874
- 33 Climate Change and Organic Carbon Storage in Bangladesh Forests 881**  
*Mohammed Alamgir and Stephen M. Turton*
  - 33.1 Introduction 882
  - 33.2 Forests in Bangladesh: A General Overview 883
  - 33.2.1 Mangrove Forests 884
  - 33.2.2 Hill Forests 886



33.2.3	Village Forests	886
33.2.4	Plain Land Sal Forests	887
33.3	Climate Change Scenarios in Bangladesh	887
33.4	Trends of Organic Carbon Storage in Different Forest Types	889
33.5	Abiotic Stress Tolerance of Trees of Different Forest Types	892
33.6	Likely Impacts of Climate Change on Organic Carbon Storage in Forests	894
33.7	Question of Sustainability of Organic Carbon Storage	896
33.8	Conclusion	899
	References	899
<b>34</b>	<b>Divergent Strategies to Cope with Climate Change in Himalayan Plants</b>	<b>903</b>
	<i>Sanjay Kumar</i>	
34.1	Why Himalaya?	903
34.2	Climate Change is Occurring in Himalaya	907
34.3	Plant Response to Climate Change Parameters in Himalayan Flora	908
34.3.1	How to Enhance Efficiency of Carbon Uptake? Plants at High Altitude Offer Clues	910
34.3.2	Managing Oxidative Stress Nature's Way	911
34.3.2.1	Engineering SOD for Climate Change	913
34.3.3	Transcriptome Analysis Offers Genes and Gene Suits for Tolerance to Environmental Cues	914
34.3.3.1	Clues from Plants at High Altitude	914
34.3.3.2	Clues from Plants at Low Altitude	916
34.3.3.3	Summing Up the Information from Transcriptome Analysis	919
34.4	Impact on Secondary Metabolism Under the Climate Change Scenario	919
34.5	Path Forward	924
	References	926
<b>35</b>	<b><i>In Vitro</i> Culture of Plants from Arid Environments</b>	<b>933</b>
	<i>Harchand R. Dagla, Shari Nair, Deepak K. Vyas, and Juleri M. Upendra</i>	
35.1	Introduction	933
35.2	Materials and Methods: Establishment of <i>In Vitro</i> Cultures	936
35.2.1	Mature Explants	936
35.2.2	Juvenile Explants	936
35.3	Results and Discussion	936
	References	938
<b>36</b>	<b>Salicylic Acid: A Novel Plant Growth Regulator – Role in Physiological Processes and Abiotic Stresses Under Changing Environments</b>	<b>939</b>
	<i>Pushp Sharma</i>	
36.1	Introduction	940
36.2	Metabolic and Biosynthetic Pathways	940

36.3	Signaling and Transport	941
36.4	Salicylic Acid-Regulated Physiological Processes	942
36.4.1	Seed Germination	943
36.4.2	Seed Germination Under Abiotic Stress	943
36.4.3	Salicylic Acid Cross-Talk with ABA and Gibberellins During Germination	944
36.4.4	Ubiquitin-Proteasome System	944
36.5	Growth and Productivity	945
36.5.1	Vegetative Growth	946
36.5.2	Salicylic Acid Signaling and Growth Rate	947
36.5.3	NPR1: Regulation of Cell Growth and Death	948
36.5.4	Metabolic Networks Between Salicylic Acid and Auxin Signaling During Vegetative Growth	948
36.5.5	Plant Growth Regulation: Role of Salicylic Acid, ROS, and the Mitogen-Activated Protein Kinase Pathway	949
36.6	Flowering	950
36.6.1	Interaction with Photoperiod and Autonomous Pathways	951
36.7	Photosynthesis and Plant-Water Relations	952
36.7.1	Salicylic Acid and Pigments	952
36.7.2	Photosynthesis and Related Traits	953
36.7.3	Light Acclimation and Redox Homeostasis	953
36.7.4	Role in Stomatal Closure	954
36.7.5	Leaf, Chloroplast Structure, and RuBisCO Activity	955
36.8	Respiration: Salicylic Acid Regulation of the Alternative Oxidase Pathway	956
36.9	Nitrogen Fixation	957
36.9.1	<i>Rhizobium</i> -Legume Symbiosis	958
36.10	Salicylic Acid Regulates Antioxidant Systems	959
36.11	Senescence	960
36.11.1	Salicylic Acid Regulation of Senescence-Associated Genes	960
36.11.2	WRKY53 in the Integration of Salicylic Acid and Jasmonic Acid Signaling for Senescence Regulation	960
36.11.3	Conservation of the Salicylic Acid Signaling Pathway in the Senescence Process of Different Tissues	961
36.11.4	Autophagy During Leaf Senescence	961
36.12	Salicylic Acid and Stress Mitigation	963
36.12.1	Biotic Stress	963
36.12.2	Abiotic Stresses	965
36.12.2.1	Heavy Metal Stress	965
36.12.2.2	Salinity Stress	966
36.12.2.3	Temperature Stress	967
36.12.2.4	UV Radiation or Ozone Stress	969
36.12.2.5	Water Stress	970
36.12.3	Salicylic Acid and Macrophyta Adaptation	971
36.13	Conclusion and Future Strategies	971
	References	972

## **37 Phosphorus Starvation Response in Plants and Opportunities for Crop Improvement 991**

*Bipin K. Pandey, Poonam Mehra, and Jitender Giri*

- 37.1 Introduction 991
- 37.2 Phosphate Acquisition from Soil Solution 992
- 37.3 Sensing of Pi Status in Plants 993
- 37.4 Local and Systemic Response in Pi Deficiency 995
  - 37.4.1 Local Pi Responses 995
    - 37.4.1.1 Effect on Primary Root Growth 995
    - 37.4.1.2 Root Hair Proliferation 997
    - 37.4.1.3 Formation of Lateral Roots 999
  - 37.4.2 Systemic Pi Response 999
    - 37.4.2.1 Genetic Network Regulating Systemic Response in Pi Starvation 1000
    - 37.4.2.2 Sugars are Essential for the Pi-Deficiency Response 1001
- 37.5 Phytohormones Mediate both Local and Systemic Response in Pi Deficiency 1001
  - 37.5.1 Role of Auxin in Pi Deficiency 1001
  - 37.5.2 Cytokinin and Pi Deficiency 1002
  - 37.5.3 Ethylene and Pi Deficiency 1002
  - 37.5.4 Gibberellic Acid and Pi Deficiency 1003
- 37.6 Strategies for Improving Pi-Acquisition Efficiency and Pi-Use Efficiency in Crop Plants 1003
- 37.7 Conclusions and Future Prospects 1007
- References 1008

## **38 Bacterial Endophytes and their Significance in the Sustainable Production of Food in Non-Legumes 1013**

*Aparna Raturi, Prasad Gyaneshwar, Sunil K. Singh, Nisha Tak, and Hukam S. Gehlot*

- 38.1 Introduction 1014
- 38.2 Soil, Microbes, and Plants (Rhizosphere/Rhizodeposition) 1015
- 38.3 Bacterial Endophytes 1016
  - 38.3.1 Bacterial Endophytes Help Plants to Defend Against Biotic and Abiotic Stress 1018
    - 38.3.2 Mechanism of Action of Endophytes 1018
- 38.4 Nitrogen Fixation by Free-Living versus Endophytic Bacteria 1019
- 38.5 Diazotrophic Bacterial Endophytes 1020
- 38.6 Non-Legumes (Cereals and Grasses) and Diazotrophic Bacterial Endophytes 1022
  - 38.6.1 Sugarcane (*Saccharum officinalis*) 1022
  - 38.6.2 Rice (*Oryza sativa*) 1022
  - 38.6.3 Maize/Sorghum 1023
  - 38.6.4 *Pennisetum glaucum* 1023
  - 38.6.5 Grasses 1024
  - 38.6.6 Other Plants 1024
- 38.7 Bacterial Endophytes and Stress Tolerance 1025

38.8	Natural Products from Endophytic Bacteria	1025
38.9	Antagonistic and Synergistic Interactions	1027
38.10	Role in Phytoremediation	1028
38.11	Genomics of Bacterial Endophytes	1029
38.12	Metagenomics of Rhizospheric Microbes to Study Molecular and Functional Diversity	1029
38.13	Concluding Remarks	1031
	References	1032
<b>39</b>	<b>Endophytic Fungi for Stress Tolerance</b>	<b>1041</b>
	<i>Nutan Kaushik and Vikram Kumar</i>	
39.1	What are Endophytes?	1041
39.2	Endophytic Fungi and Stress Tolerance	1042
39.2.1	Drought Stress	1043
39.2.2	Temperature Stress	1043
39.2.3	Salt Stress	1045
39.2.4	Heavy Metal Stress	1046
39.3	Stress Tolerance Mechanisms	1046
39.3.1	Osmotic Adjustment	1047
39.3.2	Water-Use Efficiency	1048
39.3.3	Reactive Oxygen Species (ROS)	1048
39.3.4	Antioxidant Enzymes	1049
39.4	Conclusion	1049
	References	1050
<b>40</b>	<b>Polyamines and their Role in Plant Osmotic Stress Tolerance</b>	<b>1053</b>
	<i>Kamala Gupta, Abhijit Dey, and Bhaskar Gupta</i>	
40.1	Introduction	1053
40.2	Polyamine Metabolism in Plants	1055
40.3	Polyamines and Osmotic Stress Response	1056
40.3.1	Plant Response to Hypo- and Hyperosmotic Stress Tolerance	1056
40.3.2	Role of Exogenously Applied Polyamines to Alleviate Osmotic Stress in Plants	1058
40.3.3	Transgenics in Plant Polyamines Research Related to Osmotic Stress	1061
40.3.4	Polyamine-Mediated Plant Osmotic Stress Signal Transduction: Molecular Aspects and Cross-Talk	1062
40.4	Conclusion	1065
	References	1065
	<b>Index</b>	<b>1073</b>