

# Contents

## Part A Introduction

|          |  |           |
|----------|--|-----------|
| <b>1</b> | <b>Introduction</b> . . . . .  | <b>3</b>  |
|          | J. NÖSBERGER and S.P. LONG   |           |
| 1.1      | Managed Ecosystems and the Future Supply<br>of Raw Materials . . . . .                                     | 3         |
| 1.2      | Why are [CO <sub>2</sub> ] Enrichment Studies with Managed<br>Ecosystems Important? . . . . .              | 4         |
| 1.3      | Free-Air [CO <sub>2</sub> ] Enrichment . . . . .   | 6         |
| 1.4      | Spatial and Temporal Scale . . . . .   | 7         |
| 1.5      | Elevated [CO <sub>2</sub> ] Affects Plant Growth and Ecosystems<br>via a Multitude of Mechanisms . . . . . | 9         |
| 1.6      | Conclusions . . . . .  | 12        |
|          | References . . . . .   | 12        |
| <br>     |  |           |
| <b>2</b> | <b>FACE Technology: Past, Present, and Future</b> . . . . .  | <b>15</b> |
|          | G.R. HENDREY and F. MIGLIETTA  |           |
| 2.1      | Introduction . . . . .   | 15        |
| 2.2      | Need for Controlled Experiments in the Field:<br>Historical Perspective . . . . .                          | 17        |
| 2.3      | Advantages of FACE . . . . .   | 21        |
| 2.4      | Problems and Limitations . . . . .   | 21        |
| 2.4.1    | CO <sub>2</sub> as a Step Treatment . . . . .  | 22        |
| 2.4.2    | High-Frequency Variation in [CO <sub>2</sub> ] . . . . .   | 23        |
| 2.4.3    | Limited Plot Size . . . . .  | 24        |

|       |   |    |
|-------|---|----|
| 2.4.4 | Blower Effect . . . . .                 | 24 |
| 2.5   | FACE Systems Engineering . . . . .      | 25 |
| 2.5.1 | Historical Perspective . . . . .        | 25 |
| 2.5.2 | BNL FACE Design . . . . .               | 26 |
| 2.5.3 | CNR FACE Design . . . . .               | 28 |
| 2.5.4 | Web-FACE . . . . .                      | 29 |
| 2.6   | Multiple Variable Experiments . . . . . | 30 |
| 2.7   | Future Perspectives . . . . .           | 32 |
| 2.7.1 | The GradFACE Design . . . . .           | 32 |
| 2.7.2 | HotFACE . . . . .                       | 34 |
| 2.8   | Conclusions . . . . .                   | 37 |
|       | References . . . . .                    | 39 |

## Part B Case Studies

|          |  |           |
|----------|--|-----------|
| <b>3</b> | <b>The Effects of Free-Air [CO<sub>2</sub>] Enrichment<br/>of Cotton, Wheat, and Sorghum . . . . .</b> | <b>47</b> |
|          | B.A. KIMBALL   |           |
| 3.1      | Introduction . . . . .   | 47        |
| 3.2      | Description of the FACE System<br>and Experimental Methodology . . . . .                               | 47        |
| 3.3      | Cotton . . . . .   | 51        |
| 3.3.1    | Resource Availability . . . . .  | 51        |
| 3.3.2    | Resource Acquisition and Transformation . . . . .  | 52        |
| 3.3.2.1  | CO <sub>2</sub> and Carbon . . . . .   | 52        |
| 3.3.2.2  | Light . . . . .  | 58        |
| 3.3.2.3  | Water . . . . .  | 58        |
| 3.3.2.4  | Nutrients . . . . .  | 59        |
| 3.3.3    | Consequences for Management . . . . .  | 59        |
| 3.3.4    | Consequences for Plant Breeding . . . . .  | 60        |
| 3.4      | Wheat . . . . .  | 60        |
| 3.4.1    | Resource Availability . . . . .  | 60        |
| 3.4.2    | Resource Acquisition and Transformation . . . . .  | 62        |
| 3.4.2.1  | CO <sub>2</sub> and Carbon . . . . .   | 62        |
| 3.4.2.2  | Water . . . . .  | 62        |
| 3.4.2.3  | Nutrients . . . . .  | 63        |
| 3.4.3    | Consequences for Management . . . . .  | 63        |
| 3.4.4    | Consequences for Plant Breeding . . . . .  | 64        |
| 3.5      | Sorghum . . . . .  | 64        |

|            |   |           |
|------------|---|-----------|
| Contents   |   | XI        |
| 3.5.1      | Resource Availability . . . . .   | 64        |
| 3.5.2      | Resource Acquisition and Transformation . . . . .   | 65        |
| 3.5.2.1    | CO <sub>2</sub> and Carbon . . . . .  | 65        |
| 3.5.2.2    | Water . . . . .   | 65        |
| 3.5.2.3    | Nutrients . . . . .   | 65        |
| 3.5.3      | Consequences for Management . . . . .   | 66        |
| 3.5.4      | Consequences for Plant Breeding . . . . .   | 66        |
| 3.6        | Conclusions . . . . .   | 66        |
| References | . . . . .   | 67        |
| <br>       |   |           |
| 4          | <b>SoyFACE: the Effects and Interactions<br/>of Elevated [CO<sub>2</sub>] and [O<sub>3</sub>] on Soybean . . . . .</b>  | <b>71</b> |
|            | D.R. ORT, E.A. AINSWORTH, M. ALDEA, D.J. ALLEN,<br>C.J. BERNACCHI, M.R. BERENBAUM, G.A. BOLLERO, G. CORNIC,<br>P.A. DAVEY, O. DERMODY, F.G. DOHLEMAN, J.G. HAMILTON,<br>E.A. HEATON, A.D.B. LEAKEY, J. MAHONEY, T.A. MIES,<br>P.B. MORGAN, R.L. NELSON, B. O'NEIL, A. ROGERS,<br>A.R. ZANGERL, X.-G. ZHU, E.H. DELUCIA, and S.P. LONG |           |
| 4.1        | Introduction . . . . .  | 71        |
| 4.2        | Site Description . . . . .  | 71        |
| 4.3        | Experimental Treatments . . . . .   | 72        |
| 4.3.1      | Field Layout and Blocking . . . . .   | 72        |
| 4.3.2      | CO <sub>2</sub> Treatment . . . . .   | 73        |
| 4.3.3      | O <sub>3</sub> Treatment . . . . .  | 73        |
| 4.3.4      | CO <sub>2</sub> × O <sub>3</sub> Treatment . . . . .  | 74        |
| 4.4        | Resource Acquisition . . . . .  | 74        |
| 4.4.1      | Effects of [CO <sub>2</sub> ] Treatment on Photosynthesis . . . . .   | 74        |
| 4.4.2      | Effects of [O <sub>3</sub> ] Treatment on Photosynthesis . . . . .  | 77        |
| 4.4.3      | Effects of [CO <sub>2</sub> ] and [O <sub>3</sub> ] on Canopy Development . . . . .   | 78        |
| 4.4.4      | Effects of [CO <sub>2</sub> ] and [O <sub>3</sub> ] on Insect Herbivory . . . . .   | 78        |
| 4.5        | Resource Transformation . . . . .   | 79        |
| 4.5.1      | Effects of e[CO <sub>2</sub> ] Treatment on Crop Production and Yield . . . . .   | 79        |
| 4.5.2      | Effects of O <sub>3</sub> Treatment on Crop Production and Yield . . . . .  | 81        |
| 4.6        | Consequences for Future Soybean Crop Management<br>and Plant Breeding . . . . .   | 81        |
| 4.7        | Conclusions . . . . .   | 83        |
| References | . . . . .   | 84        |

|          |  |            |
|----------|--|------------|
| <b>5</b> | <b>Paddy Rice Responses to Free-Air [CO<sub>2</sub>] Enrichment</b> . . . . .              | <b>87</b>  |
|          | K. KOBAYASHI, M. OKADA, H.Y. KIM, M. LIEFFERING,<br>S. MIURA, and T. HASEGAWA              |            |
| 5.1      | Introduction to Rice . . . . .   | 87         |
| 5.2      | The Rice FACE Experiment: Phase 1 . . . . .  | 88         |
| 5.2.1    | Site Description, Plot Layout and Crop Management . . . . .                                | 88         |
| 5.2.2    | Experimental Treatments . . . . .  | 89         |
| 5.2.2.1  | [CO <sub>2</sub> ] Enrichment . . . . .  | 89         |
| 5.2.2.2  | N Fertilizer Application . . . . .   | 89         |
| 5.3      | Effects of e[CO <sub>2</sub> ] on Paddy Rice . . . . .                                     | 89         |
| 5.3.1    | Effects on Resource Acquisition . . . . .  | 89         |
| 5.3.1.1  | Phenology . . . . .  | 89         |
| 5.3.1.2  | Light Capture by Leaves . . . . .  | 90         |
| 5.3.1.3  | Leaf Photosynthesis . . . . .  | 91         |
| 5.3.1.4  | Root Development . . . . .   | 92         |
| 5.3.1.5  | Tillering . . . . .  | 93         |
| 5.3.1.6  | Accumulation of Plant Biomass and Nitrogen . . . . .                                       | 93         |
| 5.3.2    | Effects on Resource Transformation . . . . .   | 95         |
| 5.3.2.1  | Distribution of Plant Biomass and N<br>During Reproductive Growth . . . . .                | 95         |
| 5.3.2.2  | Grain Yield, Yield Components and Harvest Index . . . . .                                  | 96         |
| 5.3.2.3  | Grain Quality . . . . .  | 97         |
| 5.3.3    | Synthesis of Rice Plant Responses to e[CO <sub>2</sub> ]<br>and N Fertilization . . . . .  | 98         |
| 5.4      | Implications for Rice Production in e[CO <sub>2</sub> ] . . . . .                          | 100        |
| 5.4.1    | Prediction of Global Change Impacts . . . . .  | 100        |
| 5.4.2    | Adaptations to e[CO <sub>2</sub> ] . . . . .   | 101        |
| 5.5      | Conclusions . . . . .  | 102        |
|          | References . . . . .   | 103        |
| <br>     |  |            |
| <b>6</b> | <b>Growth and Quality Responses of Potato to Elevated [CO<sub>2</sub>]</b> .               | <b>105</b> |
|          | M. BINDI, F. MIGLIETTA, F. VACCARI, E. MAGLIULO,<br>and A. GIUNTOLI                        |            |
| 6.1      | Introduction . . . . .   | 105        |
| 6.2      | Site Description . . . . .   | 106        |
| 6.2.1    | Physical: Location, Size, Elevation, Layout of Experiment<br>and Blocking . . . . .        | 106        |
| 6.2.2    | Soil Types, Tillage Practices, Fertilisation,<br>Crop Samplings and Measurements . . . . . | 106        |

|         |  |     |
|---------|--|-----|
| 6.2.3   | Meteorological Description . . . . .                         | 109 |
| 6.3     | Experimental Treatments . . . . .                            | 110 |
| 6.3.1   | Elevated [CO <sub>2</sub> ] . . . . .                        | 110 |
| 6.4     | Resource Acquisition . . . . .                               | 110 |
| 6.4.1   | Effect of Treatments . . . . .                               | 110 |
| 6.4.1.1 | Photosynthesis . . . . .                                     | 110 |
| 6.4.1.2 | Canopy Temperature and Energy Balance . . . . .              | 112 |
| 6.4.1.3 | Water Consumption . . . . .                                  | 113 |
| 6.4.1.4 | Crop Phenology and Development . . . . .                     | 113 |
| 6.4.1.5 | Herbivory . . . . .  | 113 |
| 6.5     | Resource Transformation . . . . .                            | 114 |
| 6.5.1   | Effect of Treatments on Biomass Growth . . . . .             | 114 |
| 6.5.1.1 | Aboveground . . . . .  | 114 |
| 6.5.1.2 | Belowground . . . . .  | 114 |
| 6.5.2   | Effect of Treatments on Yield Quantity and Quality . . . . . | 116 |
| 6.5.2.1 | Above- and Belowground Biomass . . . . .                     | 116 |
| 6.5.2.2 | Tuber Physical Quality . . . . .                             | 116 |
| 6.5.2.3 | Tuber Chemical Quality . . . . .                             | 117 |
| 6.6     | Conclusions . . . . .  | 118 |
|         | References . . . . .   | 119 |

**7 Responses of an Arable Crop Rotation System to Elevated [CO<sub>2</sub>] . . . . . 121**  
 H.J. WEIGEL, R. MANDERSCHIED, S. BURKART, A. PACHOLSKI,  
 K. WALOSZCZYK, C. FRÜHAUF, and O. HEINEMEYER

|         |  |     |
|---------|--|-----|
| 7.1     | Introduction . . . . .   | 121 |
| 7.2     | Site Description . . . . .   | 123 |
| 7.2.1   | Location, Climate, Meteorological and Soil Conditions . . . . .  | 123 |
| 7.2.2   | Crop Rotation and Agricultural Management . . . . .  | 123 |
| 7.2.3   | Treatment Design . . . . .   | 125 |
| 7.3     | Results . . . . .  | 126 |
| 7.3.1   | Resource Acquisition . . . . .   | 126 |
| 7.3.1.1 | [CO <sub>2</sub> ] Effects on Photosynthesis (Canopy CO <sub>2</sub> Exchange Rates) . . . . .               | 126 |
| 7.3.1.2 | [CO <sub>2</sub> ] Effects on Canopy Evapotranspiration ET (Canopy H <sub>2</sub> O Exchange Rate) . . . . . | 127 |
| 7.3.1.3 | [CO <sub>2</sub> ] Effects on Leaf Area Index . . . . .  | 129 |
| 7.3.2   | Resource Transformation . . . . .  | 130 |
| 7.3.2.1 | [CO <sub>2</sub> ] Effects on Above-ground Biomass Production . . . . .                                      | 130 |
| 7.3.2.2 | [CO <sub>2</sub> ] Effects on Below-ground Biomass Production . . . . .                                      | 131 |

|            |   |     |
|------------|---|-----|
| 7.3.2.3    | [CO <sub>2</sub> ] Effects on Soil Microbial Biomass . . . . .              | 132 |
| 7.3.2.4    | [CO <sub>2</sub> ] Effects on In Situ Soil CO <sub>2</sub> Efflux . . . . . | 133 |
| 7.4        | Conclusions . . . . .   | 134 |
| References | . . . . .   | 135 |

**8 Short- and Long-Term Responses of Fertile Grassland to Elevated [CO<sub>2</sub>]** . . . . . 139  
 A. LÜSCHER, U. AESCHLIMANN, M.K. SCHNEIDER,  
 and H. BLUM

|            |   |     |
|------------|---|-----|
| 8.1        | Introduction . . . . .  | 139 |
| 8.2        | Site Description . . . . .  | 140 |
| 8.3        | Experimental Treatments . . . . .   | 141 |
| 8.4        | Nutrient Availability: A Key Factor<br>for the Plant's Response to e[CO <sub>2</sub> ] . . . . .        | 142 |
| 8.4.1      | Above-Ground Yield . . . . .  | 142 |
| 8.4.2      | Resource Acquisition and Resource Allocation . . . . .  | 144 |
| 8.5        | Changes over 10 Years in the e[CO <sub>2</sub> ] Response<br>of Pure <i>L. perenne</i> Swards . . . . . | 145 |
| 8.6        | N Availability in Soil . . . . .  | 158 |
| 8.7        | C and N Sequestration . . . . .   | 150 |
| 8.8        | Conclusions . . . . .   | 151 |
| References | . . . . .   | 152 |

**9 Impacts of Elevated CO<sub>2</sub> on a Grassland Grazed by Sheep: the New Zealand FACE Experiment** . . . . . 157  
 P.C.D. NEWTON, V. ALLARD, R.A. CARRAN, and M. LIEFFERING

|            |   |     |
|------------|---|-----|
| 9.1        | Introduction . . . . .                              | 157 |
| 9.2        | Site Description . . . . .                          | 158 |
| 9.3        | Experimental Treatments . . . . .                   | 159 |
| 9.4        | Resource Acquisition . . . . .                      | 160 |
| 9.4.1      | Photosynthesis . . . . .                            | 160 |
| 9.4.2      | Nutrients . . . . .                                 | 161 |
| 9.4.3      | Soil Moisture . . . . .                             | 163 |
| 9.5        | Resource Transformation . . . . .                   | 164 |
| 9.5.1      | Aboveground Yield and Species Composition . . . . . | 164 |
| 9.5.2      | Belowground Yield . . . . .                         | 165 |
| 9.5.3      | Chemical Composition and Feed Quality . . . . .     | 167 |
| 9.6        | Conclusions . . . . .                               | 169 |
| References | . . . . .   | 169 |

**10 Responses to Elevated [CO<sub>2</sub>] of a Short Rotation, Multispecies Poplar Plantation: the POPFACE/EUROFACE Experiment . . . 173**  
**G. SCARASCIA-MUGNOZZA, C. CALFAPIETRA, R. CEULEMANS, B. GIELEN, M.F. COTRUFO, P. DEANGELIS, D. GODBOLD, M.R. HOOSBEEK, O. KULL, M. LUKAC, M. MAREK, F. MIGLIETTA, A. POLLE, C. RAINES, M. SABATTI, N. ANSELMi, and G. TAYLOR**

10.1 Introduction . . . . . 173

10.1.1 Research Leading to This Experiment . . . . . 173

10.1.2 Focus on Agroforestry Plantations . . . . . 173

10.1.3 Objectives and Hypotheses . . . . . 174

10.2. Site Description . . . . . 174

10.2.1 Location and Layout of Experiment . . . . . 174

10.2.2 Soil Types, Fertilisation, Irrigation . . . . . 176

10.2.3 Meteorological Description . . . . . 176

10.2.4 Stand History and Description . . . . . 177

10.3. Experimental Treatment . . . . . 177

10.3.1 Atmospheric [CO<sub>2</sub>] Enrichment . . . . . 177

10.3.2 Nitrogen Fertilisation . . . . . 178

10.3.3 Species Comparison . . . . . 178

10.3.4 Interactions . . . . . 178

10.4 Resource Acquisition . . . . . 179

10.4.1 Photosynthesis and Respiration . . . . . 179

10.4.2 Stomatal Conductance . . . . . 181

10.4.3 Nitrogen and Other Nutrient Concentrations and Dynamics 181

10.4.4 LAI and Light Interception . . . . . 182

10.4.5 Canopy Architecture . . . . . 184

10.4.6 Root Development and Mycorrhizal Colonization . . . . . 184

10.5 Resource Transformation . . . . . 185

10.5.1 Aboveground Productivity . . . . . 185

10.5.2 Belowground Productivity . . . . . 185

10.5.3 Soil Carbon: Litter Production, Soil Respiration and C-Pools 188

10.5.4 Wood Quality and Biochemical Composition  
of Wood and Roots . . . . . 189

10.5.5 Pest and Disease Susceptibility . . . . . 189

10.6 Consequences and Implications . . . . . 190

10.6.1 Forest Management . . . . . 190

10.6.2 Global Carbon Cycle . . . . . 190

10.6.3 Other Ecosystem Goods and Services . . . . . 191

10.7 Conclusions . . . . . 192

References . . . . . 193

|           |  |            |
|-----------|--|------------|
| <b>11</b> | <b>The Duke Forest FACE Experiment: CO<sub>2</sub> Enrichment of a Loblolly Pine Forest</b> . . . . .  | <b>197</b> |
|           | W.H. SCHLESINGER, E.S. BERNHARDT, E. H. DELUCIA,<br>D.S. ELLSWORTH, A.C. FINZI, G. R. HENDREY, K.S. HOFMOCKEL,<br>J LICHTER, R. MATAMALA, D. MOORE, R. OREN, J.S. PIPPEN,<br>and R.B. THOMAS |            |
| 11.1      | Introduction . . . . .   | 197        |
| 11.2      | Site Description . . . . .   | 198        |
| 11.3      | Results . . . . .  | 200        |
| 11.3.1    | Resource Acquisition . . . . .   | 200        |
| 11.3.2    | Resource Transformation . . . . .  | 201        |
| 11.3.3    | Nitrogen Limitation . . . . .  | 205        |
| 11.4      | Estimated Global Carbon Sink in Forests . . . . .  | 207        |
| 11.5      | Conclusions . . . . .  | 208        |
|           | References . . . . .   | 208        |
| <br>      |  |            |
| <b>12</b> | <b>Impacts of Elevated Atmospheric [CO<sub>2</sub>] and [O<sub>3</sub>] on Northern Temperate Forest Ecosystems: Results from the Aspen FACE Experiment</b> . . . . .                        | <b>213</b> |
|           | D.F. KARNOSKY and K.S. PREGITZER   |            |
| 12.1      | Introduction . . . . .   | 213        |
| 12.2      | Site Description . . . . .   | 214        |
| 12.3      | Experimental Treatments . . . . .  | 215        |
| 12.4      | Resource Acquisition . . . . .   | 216        |
| 12.4.1    | Photosynthesis and Conductance . . . . .   | 216        |
| 12.4.2    | Respiration . . . . .  | 218        |
| 12.4.3    | Nitrogen Dynamics . . . . .  | 218        |
| 12.4.4    | Leaf Area . . . . .  | 218        |
| 12.4.5    | Root Development . . . . .   | 219        |
| 12.5      | Resource Transformation . . . . .  | 220        |
| 12.5.1    | Growth and Productivity . . . . .  | 220        |
| 12.5.2    | Soil Carbon . . . . .  | 221        |
| 12.5.3    | Wood Quality . . . . .   | 221        |
| 12.5.4    | Pest, Disease and Herbivore Susceptibility . . . . .   | 221        |
| 12.6      | Consequences and Implications . . . . .  | 222        |
| 12.7      | Conclusions . . . . .  | 226        |
|           | References . . . . .   | 226        |



**13 CO<sub>2</sub> Enrichment of a Deciduous Forest:  
The Oak Ridge FACE Experiment . . . . . 231**  
**R.J. NORBY, S.D. WULLSCHLEGER, P.J. HANSON,  
 C.A. GUNDERSON, T.J. TSCHAPLINSKI, and J.D. JASTROW**

13.1 Introduction . . . . . 231  
 13.2 Site Description . . . . . 232  
 13.2.1 Physical . . . . . 232  
 13.2.2 Soil Types . . . . . 233  
 13.2.3 Meteorological Description . . . . . 233  
 13.2.4 Stand Description . . . . . 233  
 13.3 Experimental Treatments . . . . . 234  
 13.4 Resource Acquisition . . . . . 234  
 13.4.1 CO<sub>2</sub> Effects on Physiological Functions and Metabolites . . . . . 234  
 13.4.1.1 Carbon . . . . . 234  
 13.4.1.2 Water . . . . . 236  
 13.4.1.3 Nitrogen . . . . . 237  
 13.4.2 CO<sub>2</sub> Effects on Tree and Stand Structure . . . . . 237  
 13.4.2.1 Leaf Area Index . . . . . 237  
 13.4.2.2 Root System Structure . . . . . 237  
 13.4.3 Structure–Function Integration . . . . . 238  
 13.4.3.1 Carbon Uptake . . . . . 238  
 13.4.3.2 Stand Water Use . . . . . 238  
 13.4.3.3 Nitrogen Cycling . . . . . 240  
 13.5 Resource Transformation . . . . . 240  
 13.5.1 Productivity . . . . . 240  
 13.5.1.1 Aboveground Production . . . . . 240  
 13.5.1.2 Belowground Production . . . . . 241  
 13.5.1.3 Ecosystem Productivity . . . . . 241  
 13.5.2 Soil C . . . . . 243  
 13.5.2.1 Carbon Input and Decomposition . . . . . 243  
 13.5.2.2 Carbon Pools . . . . . 243  
 13.5.2.3 Microbial Activity and Nutrient Cycling . . . . . 244  
 13.5.3 Products . . . . . 245  
 13.5.4 Biotic Interactions . . . . . 245  
 13.6 Consequences and Implications . . . . . 245  
 13.6.1 Forest Management . . . . . 245  
 13.6.2 Global C Cycle . . . . . 246  
 13.7 Conclusions . . . . . 248  
 References . . . . . 249

**Part C Processes**

|           |  |            |
|-----------|--|------------|
| <b>14</b> | <b>Long-Term Responses of Photosynthesis and Stomata to Elevated [CO<sub>2</sub>] in Managed Systems . . . . .</b> | <b>253</b> |
|           | S.P. LONG, E.A. AINSWORTH, C.J. BERNACCHI, P.A. DAVEY,<br>G.J. HYMUS, A.D.B. LEAKEY, P.B. MORGAN, and C.P. OSBORNE |            |
| 14.1      | Introduction . . . . .   | 253        |
| 14.1.1    | The Theory of Responses of Photosynthesis and Stomatal Conductance to Elevated [CO <sub>2</sub> ] . . . . .        | 253        |
| 14.1.2    | Chamber Acclimation and Down-Regulation of Photosynthesis . . . . .  | 256        |
| 14.1.3    | A Purpose to Down-Regulation of Photosynthesis and Stomatal Conductance? . . . . .                                 | 257        |
| 14.1.4    | Expectations of FACE . . . . .   | 258        |
| 14.2      | Why FACE for Photosynthesis and Conductance? . . . . .   | 258        |
| 14.3      | Which FACE? . . . . .  | 260        |
| 14.4      | Have Findings From FACE Altered Perspectives? . . . . .  | 262        |
| 14.4.1    | Photosynthesis is Increased Less and Stomatal Conductance Decreased More in FACE . . . . .                         | 262        |
| 14.4.2    | Photosynthesis is Stimulated Less at the Beginning and End of the Day . . . . .                                    | 262        |
| 14.4.3    | Stimulation of Photosynthesis is Sustained and Little Affected by Nitrogen Supply . . . . .                        | 263        |
| 14.4.4    | In Vivo Rubisco Activity is Decreased More than Capacity for RubP Regeneration . . . . .                           | 265        |
| 14.5      | Conclusion . . . . .   | 266        |
|           | References . . . . .   | 267        |
| <b>15</b> | <b>Carbon Partitioning and Respiration – Their Control and Role in Plants at High CO<sub>2</sub> . . . . .</b>     | <b>271</b> |
|           | P.W. HILL, J.F. FARRAR, E.L. BODDY, A.M. GRAY, and D.L. JONES  |            |
| 15.1      | Introduction . . . . .   | 271        |
| 15.2      | A Brief Background to Partitioning of Dry Matter and Carbon . . . . .  | 272        |
| 15.3      | Export From Source Leaves . . . . .  | 273        |
| 15.4      | Whole-Plant Partitioning . . . . .   | 275        |
| 15.4.1    | Growth and Development . . . . .   | 277        |
| 15.5      | Within Root Partitioning . . . . .   | 278        |
| 15.5.1    | Roots are a Sink for Photosynthetically Fixed C . . . . .  | 279        |

|            |  |            |
|------------|--|------------|
| Contents   |  | XIX        |
| 15.5.2     | Root Growth . . . . .  | 280        |
| 15.5.3     | Exudation, Mucilage, and Cell Death . . . . .  | 280        |
| 15.5.4     | Root Death and Turnover . . . . .  | 281        |
| 15.5.5     | Elevated CO <sub>2</sub> and FACE Experiments . . . . .  | 281        |
| 15.6       | Respiration . . . . .  | 282        |
| 15.6.1     | Direct and Indirect Effects of CO <sub>2</sub> . . . . .   | 282        |
| 15.6.2     | Above-Ground Respiration and FACE . . . . .  | 284        |
| 15.6.3     | Roots in Soil . . . . .  | 284        |
| 15.6.4     | Below-Ground Respiration and FACE . . . . .  | 285        |
| 15.7       | Conclusion . . . . .   | 286        |
| References | . . . . .  | 287        |
| <br>       |  |            |
| <b>16</b>  | <b>The Response of Foliar Carbohydrates to Elevated [CO<sub>2</sub>] . . . . .</b>                                     | <b>293</b> |
|            | A. ROGERS and E.A. AINSWORTH   |            |
| 16.1       | Introduction . . . . .   | 293        |
| 16.1.1     | Why is it Important to Understand the Response<br>of Foliar Carbohydrates to Growth at e[CO <sub>2</sub> ] ? . . . . . | 293        |
| 16.1.2     | What Were the Known Effects of e[CO <sub>2</sub> ]<br>on Foliar Carbohydrates Before FACE? . . . . .                   | 294        |
| 16.2       | Do Carbohydrates Accumulate in the Leaves of Plants<br>Grown in the Field Using FACE Technology? . . . . .             | 295        |
| 16.3       | Manipulations of Source–Sink Balance . . . . .   | 298        |
| 16.4       | The Effect of Nitrogen Supply on Sink Capacity . . . . .   | 301        |
| 16.5       | What Are the Signs of a Limited Sink Capacity? . . . . .   | 303        |
| 16.6       | Conclusion . . . . .   | 305        |
| References | . . . . .  | 305        |
| <br>       |  |            |
| <b>17</b>  | <b>Evapotranspiration, Canopy Temperature,<br/>and Plant Water Relations . . . . .</b>                                 | <b>311</b> |
|            | B.A. KIMBALL and C.J. BERNACCHI  |            |
| 17.1       | Introduction . . . . .   | 311        |
| 17.2       | Canopy Temperature . . . . .   | 311        |
| 17.3       | Evapotranspiration . . . . .   | 314        |
| 17.3.1     | Changes in ET with e[CO <sub>2</sub> ] . . . . .   | 314        |
| 17.3.2     | Correlations of ET with Canopy Temperature<br>and Shoot Biomass Changes . . . . .                                      | 315        |
| 17.3.3     | Applicability of Plot-Scale ET Measurements<br>to Regional Scales . . . . .  | 317        |
| 17.3.4     | Combined Physiological and Global-Warming Effects<br>of e[CO <sub>2</sub> ] on ET . . . . .                            | 318        |

|            |                                      |     |
|------------|--------------------------------------|-----|
| 17.4       | Soil Water Content . . . . .         | 319 |
| 17.5       | Plant Water Use Efficiency . . . . . | 320 |
| 17.6       | Plant Water Relations . . . . .      | 320 |
| 17.7       | Conclusions . . . . .                | 321 |
| References | . . . . .                            | 322 |

**18 Biological Nitrogen Fixation: A Key Process for the Response of Grassland Ecosystems to Elevated Atmospheric [CO<sub>2</sub>] . . . . . 325**  
 U.A. HARTWIG and M.J. SADOWSKY

|            |   |     |
|------------|---|-----|
| 18.1       | Introduction . . . . .  | 325 |
| 18.2       | Elevated Atmospheric [CO <sub>2</sub> ] Appears Not to Affect the Activity of Symbiotic N <sub>2</sub> Fixation . . . . .   | 326 |
| 18.3       | The Initial Response of Symbiotic N <sub>2</sub> Fixation to Elevated Atmospheric [CO <sub>2</sub> ] Under Field Conditions is Different From That Under Continuous Nutrient Supply . . . . . | 326 |
| 18.4       | What Are the Possible Reasons For the Differential Responses of Symbiotic N <sub>2</sub> Fixation to Elevated Atmospheric [CO <sub>2</sub> ] in Laboratory and Field Experiments? . . . . .   | 328 |
| 18.5       | The Time Component, While Often Suggested, Is Now Evident in the 10-Year Swiss FACE Experiment . . . . .  | 330 |
| 18.6       | The Significance of Symbiotic N <sub>2</sub> Fixation Under Elevated Atmospheric [CO <sub>2</sub> ] in Terrestrial Ecosystems: An Attempt to Reach a General Conclusion . . . . .             | 331 |
| 18.7       | Conclusion . . . . .  | 332 |
| References | . . . . .   | 333 |

**19 Effects of Elevated [CO<sub>2</sub>] and N Fertilization on Interspecific Interactions in Temperate Grassland Model Ecosystems . . . . . 337**  
 A. LÜSCHER and U. AESCHLIMANN

|        |   |     |
|--------|---|-----|
| 19.1   | Introduction . . . . .                              | 337 |
| 19.2   | Materials and Methods . . . . .                     | 338 |
| 19.2.1 | Experimental Site . . . . .                         | 338 |
| 19.2.2 | Experimental Treatments . . . . .                   | 339 |
| 19.2.3 | Data Collection and Statistical Analysis . . . . .  | 340 |
| 19.3   | Results . . . . .                                   | 340 |
| 19.3.1 | Proportion of <i>T. repens</i> in Mixture . . . . . | 340 |
| 19.3.2 | Biomass and Nitrogen Yield . . . . .                | 340 |

|            |  |            |
|------------|--|------------|
| Contents   |  | XXI        |
| 19.3.3     | Relative Yield of Biomass and Nitrogen . . . . .   | 342        |
| 19.4       | Discussion . . . . .   | 343        |
| 19.4.1     | Interspecific Differences in the Response to e[CO <sub>2</sub> ]<br>Were Augmented in the Mixed Community<br>When Compared to the Pure Sward . . . . . | 343        |
| 19.4.2     | Competitive Ability Depended Strongly on the Species,<br>the N and [CO <sub>2</sub> ] Treatments . . . . .   | 344        |
| 19.4.3     | Resource Complementarity Strongly Depended<br>on the N and [CO <sub>2</sub> ] Treatments . . . . .   | 345        |
| 19.5       | Conclusions . . . . .  | 347        |
| References | . . . . .  | 348        |
| <br>       |  |            |
| <b>20</b>  | <b>The Potential of Genomics and Genetics to Understand<br/>Plant Response to Elevated Atmospheric [CO<sub>2</sub>] . . . . .</b>                      | <b>351</b> |
|            | G. TAYLOR, P.J. TRICKER, L.E. GRAHAM, M.J. TALLIS,<br>A.M. RAE, H. TREWIN, and N.R. STREET   |            |
| 20.1       | Introduction . . . . .   | 351        |
| 20.1.1     | What We Know and What We Need to Know . . . . .  | 351        |
| 20.1.2     | Can an Integrative (Systems) Biology Approach be Useful? . . . . .   | 352        |
| 20.2       | Genomics in Field-Grown Plants . . . . .   | 354        |
| 20.2.1     | Transcript Profiling . . . . .   | 354        |
| 20.2.2     | Use of Expression Arrays in FACE Experiments . . . . .   | 356        |
| 20.2.3     | QTL Discovery for Responsive Traits . . . . .  | 358        |
| 20.2.4     | Association Genetics . . . . .   | 359        |
| 20.3       | Proteomics and Metabolomics in Field-Grown Plants . . . . .  | 361        |
| 20.4       | The Importance of Experimental Design<br>and Sampling Strategy in FACE Facilities . . . . .  | 364        |
| 20.5       | The Future . . . . .   | 366        |
| 20.6       | Conclusions . . . . .  | 366        |
| References | . . . . .  | 367        |
| <br>       |  |            |
| <b>21</b>  | <b>The Impact of Elevated Atmospheric [CO<sub>2</sub>] on Soil C<br/>and N Dynamics: A Meta-Analysis . . . . .</b>                                     | <b>373</b> |
|            | K.-J. VAN GROENIGEN, M.-A. DE GRAAFF, J. SIX, D. HARRIS,<br>P. KUIKMAN, and C. VAN KESSEL  |            |
| 21.1       | Introduction . . . . .   | 373        |
| 21.2       | Materials and Methods . . . . .  | 374        |

|        |   |            |
|--------|---|------------|
| 21.2.1 | Database Compilation . . . . .  | 374        |
| 21.2.2 | Statistical Analyses . . . . .  | 376        |
| 21.3   | Results . . . . .   | 377        |
| 21.3.1 | Soil C and N Contents . . . . .   | 377        |
| 21.3.2 | Microbial Biomass and Activity . . . . .  | 379        |
| 21.4   | Discussion . . . . .  | 381        |
| 21.4.1 | Soil C Contents . . . . .   | 381        |
| 21.4.2 | Microbial Biomass and Activity . . . . .  | 383        |
| 21.4.3 | Soil N Dynamics . . . . .   | 384        |
| 21.5   | Future Research Needs . . . . .   | 385        |
| 21.6   | Conclusions . . . . .   | 386        |
|        | References . . . . .  | 388        |
| <br>   |   |            |
| 22     | <b>The Influence of Elevated [CO<sub>2</sub>] on Diversity, Activity<br/>and Biogeochemical Functions of Rhizosphere<br/>and Soil Bacterial Communities . . . . .</b> | <b>393</b> |
|        | S. TARNAWSKI and M. ARAGNO  |            |
| 22.1   | Introduction . . . . .  | 393        |
| 22.2   | Interactions Between Soil Microbiota<br>and Rhizosphere Conditions . . . . .  | 394        |
| 22.3   | Effect of e[CO <sub>2</sub> ] on Rhizodeposition . . . . .  | 397        |
| 22.4   | Responses of Microbial Biomass, Cell Number and Activity  | 398        |
| 22.5   | Effects on Soil Structure and Enzyme Activities . . . . .   | 400        |
| 22.6   | Responses of Bacterial Community Structure to e[CO <sub>2</sub> ] . . .   | 400        |
| 22.7   | Elevated [CO <sub>2</sub> ] and Nitrogen Cycle in Soil and Rhizosphere  | 402        |
| 22.7.1 | N-pools, Uptake and Mineralization . . . . .  | 402        |
| 22.7.2 | N <sub>2</sub> Fixation . . . . .   | 403        |
| 22.7.3 | Nitrification . . . . .   | 403        |
| 22.7.4 | Denitrification . . . . .   | 404        |
| 22.8   | Plant-Growth Promoting Rhizobacteria . . . . .  | 406        |
| 22.9   | Discussion and Perspectives . . . . .   | 406        |
| 22.10  | Conclusions . . . . .   | 408        |
|        | References . . . . .  | 409        |
| <br>   |   |            |
| 23     | <b>Increases in Atmospheric [CO<sub>2</sub>] and the Soil Food Web . . .</b>  | <b>413</b> |
|        | D.A. PHILLIPS, T.C. FOX, H. FERRIS, and J.C. MOORE  |            |
| 23.1   | Introduction . . . . .  | 413        |
| 23.1.1 | Soil Food Webs: The Concept . . . . .   | 414        |

23.2 Effects of Elevated [CO<sub>2</sub>] on Soil Organic Matter and the Food Web . . . . . 415

23.3 Root Exudation and the Effects of Elevated [CO<sub>2</sub>] . . . . . 417

23.4 Linking Plants to Soil Food Webs under Changing [CO<sub>2</sub>] . . . 419

23.5 Conclusions . . . . . 422

References . . . . . 423

**Part D Perspectives**

**24 FACE Value: Perspectives on the Future of Free-Air CO<sub>2</sub> Enrichment Studies . . . . . 431**  
 A. ROGERS, E.A. AINSWORTH, and C. KAMMANN

24.1 The Value of FACE Experiments . . . . . 431

24.2 What Have We Learnt From FACE? . . . . . 432

24.2.1 Photosynthesis and Aboveground Productivity . . . . . 432

24.2.2 Photosynthetic Acclimation . . . . . 433

24.2.2.1 Response of Different Functional Groups . . . . . 434

24.2.2.2 Belowground Responses . . . . . 435

24.3 What Is Missing From Current FACE Research and What Are the Gaps in Understanding? . . . . . 437

24.3.1 Additional Treatments . . . . . 437

24.3.2 Future Challenges . . . . . 438

24.3.3 What Is the Fate of C Partitioned Belowground? . . . . . 439

24.3.3.1 N Cycling . . . . . 440

24.3.3.2 Soil Faunal Food Webs and Soil Structure . . . . . 440

24.3.3.3 Trace Gases . . . . . 440

24.4 Technologies for Future FACE Science . . . . . 441

24.4.1 The Use of Stable Isotopes . . . . . 441

24.4.2 Genomic Technologies and Tools in FACE . . . . . 442

24.5 A Potential Problem for Long-Running FACE Experiments? 443

24.6 Conclusion . . . . . 444

References . . . . . 445

**Subject Index . . . . . 451**