Foreword

Crops for a future climate

Roslyn Gleadow[A], *Alexander Johnson*[B] *and Michael Tausz*[C,D]

[A]School of Biological Sciences, Monash University, Clayton Campus Building 18, Clayton, Vic. 3800, Australia.
[B]School of Botany, The University of Melbourne, Parkville, Vic. 3010, Australia.
[C]Department of Forest and Ecosystem Science, Melbourne School of Land and Environment,
 The University of Melbourne, 4 Water Street, Creswick, Vic. 3363, Australia.
[D]Corresponding author. Email: michael.tausz@unimelb.edu.au

Abstract. The papers in this special issue were mainly derived from sessions at the International Botanical Congress in July 2011 in Melbourne, and at the ComBio meeting in Cairns, September 2011. They make contributions towards one of the most burning issues we face today: increasing sustainable crop production to provide sufficient high quality food to feed an ever increasing global human population, all in the face of climate change. Plant and crop science will have a major part in ensuring that agricultural production can meet these multiple demands. Contributions in this volume go beyond raising issues and highlighting potential effects of climate change factors, but also point out ways to better adapt to the inevitable.

Additional keywords: cassava, elevated CO_2, *Eucalyptus*, rice, soybean, wheat.

Breeding of new, better adapted crop varieties was one of the most successful agricultural strategies employed over the past century, particularly with regards to the 'Green Revolution' by contributing to sharp increases in crop production per area and expanding certain crops into previously unsuitable territories. Crop improvement, be it through breeding assisted by modern molecular genetic methods or through direct genetic engineering, or both, will undoubtedly play a major role in future-proofing crop production (Chapman *et al*. 2012).

Several papers in this issue highlight the opportunity to target crop improvement specifically to elevated CO_2 atmospheres. Atmospheric CO_2 concentrations [CO_2] are set to rise by 40% or more over 50 years (from ~385 μmol mol^{-1} at the start of the millennium to a predicted 550 μmol mol^{-1} by 2050; according to the IPCC scenario A1B, Carter *et al*. 2007), representing enormous changes to a single environmental factor that also happens to be the main plant nutrient. Suggestions that crop improvement must explicitly consider rising [CO_2] are not new (see review by Newton and Edwards 2007), but have seen recent resurgence in the literature. For example, Leakey and Lau (2012) pointed out that evolution has adapted plants to sub-ambient [CO_2] conditions. Reviews by Ainsworth *et al*. (2008), Tausz *et al*. (2011) or Ziska *et al*. (2012) reinforce the suggestion to explore breeding opportunities especially for elevated [CO_2]. Despite high profile papers and active research in the field, such as reported in Hasegawa *et al*. (2013), Thilakarathne *et al*. (2013), Dias de Oliveira *et al*. (2013) or Bourgault *et al*. (2013) in this volume, elevated [CO_2] effects are, in contrast to factors such as high and low temperatures,

water supply and salinity, not yet included in current breeding efforts.

In part, this may be due to practical difficulties: in contrast to other climate change factors such as temperature or drought, there are no easy spatial or temporal surrogates for high [CO_2]; one can simply do field experiments in warmer or drier regions to collect valuable information about heat and drought tolerance, but as atmospheric [CO_2] is globally rather uniform a similar approach is not possible for CO_2 (with the exception of natural CO_2 springs, which are small scale and commonly include other gases). Hence, CO_2 exposure needs more involved and expensive exposure technology, with glasshouse and growth chamber options (e.g. such as those employed in Bourgault *et al*. (2013) and Thilakarathne *et al*. (2013)), field chamber or 'tunnel' technology (e. g. in Dias de Oliveira *et al*. (2013)), to FACE (Free Air CO_2 Enrichment) systems (e. g. Hasegawa *et al*. (2013); Gray *et al*. (2013); Oehme *et al*. (2013); all in this volume). Whilst these technologies are well established for scientific purposes with limited plot size, scaling up to screen many genotypes in large replicated experiments (as required by traditional breeding approaches) is not yet achievable or affordable. Glasshouses or chambers would be most amenable to screening approaches, but the difficulties of translating glasshouse experiments directly into field applications is well known. For example, Bourgault *et al*. (2013) who tested multiple wheat genotypes under elevated [CO_2] found no genotype $\times$ [CO_2] interaction. On the other hand, Tausz-Posch *et al*. (2012*a*) who tested two of the same wheat genotypes in a FACE system under dryland agriculture conditions, reported

significant genotype $\times$ [CO_2] effects. Hasegawa *et al.* (2013) show consistent differences in responses of rice genotypes to elevated [CO_2] in FACE systems over multiple years and different environments.

Crop improvement is of course an ongoing process which involves selection for a variety of properties such as stress tolerance, yield potential, product quality whilst continuing the on-going battle against pathogens. Equally or perhaps more important than selecting crops for maximum yield return under elevated [CO_2] is the confidence that such current efforts will remain beneficial under increasing atmospheric [CO_2]. Maintaining and improving the quality of food is also essential. Consideration needs to be given to the impact of elevated [CO_2] and climate change on protein (Högy *et al.* 2009), micronutrients and toxic secondary metabolites such as cyanogenic glucosides (Vandergeer *et al.* 2013). Johnson (2013) in this volume reviews current research aimed at increasing Fe concentrations in (mainly rice) grain, which could significantly improve nutritional quality and health outcomes for large human populations. He points out that elevated [CO_2] may work against current achievements, because micronutrient concentrations in grain grown under elevated [CO_2] may decrease significantly (Högy *et al.* 2009; Fernando *et al.* 2012). Likewise, leaf and grain protein concentrations will also likely decrease in a high [CO_2] world (Taub *et al.* 2008).

Plant composition is a consequence of the acquisition as well as partitioning of resources, both of which are likely to be impacted by changes in atmospheric [CO_2] (Cavagnaro *et al.* 2011). The papers by Gray *et al.* (2013) and Vandergeer *et al.* (2013) in this volume emphasise the below ground processes and acquisition side of the equation, which are still considerably less explored than above ground plant functions. Plants appear to be able to capitalise on higher atmospheric CO_2 so long as they have access to adequate N, underlining the importance of nitrogen use efficiency in crops (Reich and Hobbie 2012). Legumes such as soybean are putatively better placed to take advantage of increasing [CO_2], because of their capability to fix N_2. The paper by Gray *et al.* (2013) reports direct observations of root nodules in a FACE setup using rhizotrons. Interestingly, elevated [CO_2] stimulated nodulation only under drought conditions. Plant composition may also affect resistance to pests and diseases, although the work by Oehme *et al.* (2013) suggests that the overall impact may be less under certain conditions.

Rainfall is not expected to decrease uniformly across the globe with climate change (Christensen *et al.* 2007). Indeed, some regions may become much wetter. Some regions such as those currently used for cropping in Australia and the USA are, however, expected to experience drying. Moreover, the increased severity and duration of heat waves, coupled with higher evapotranspiration, are likely to decrease soil moisture. In a study relevant to these probable scenarios, Dias de Oliveira *et al.* (2013) tested terminal drought in wheat lines under combinations of elevated temperatures and elevated [CO_2]. They found that for some lines, elevated [CO_2] in combination with a moderate 2°C temperature increase alleviated terminal drought and improved yield. However, the opposite was true for a different line, and for higher temperatures, further underlining the importance of understanding the complex interactions between environmental factors and plant traits. Root crops such as cassava have a growing importance as a staple in addition to grains. Whilst studies under FACE conditions demonstrated that because of its large potential sink in the root tubers, cassava yield responds well to elevated [CO_2] (Rosenthal *et al.* 2012), Vandergeer *et al.* (2013) showed that cassava yields and quality are sensitive to drought.

Leaf level transpiration efficiency is another trait of great interest to breeders, particularly for water limited environments (Passioura 2012). As elevated [CO_2] typically increases transpiration efficiency in virtually all plants (Long and Ort 2010), benefits of such a transpiration efficiency trait may diminish in the future. Tausz-Posch *et al.* (2012*b*) recently demonstrated that, in contrast, a wheat cultivar known to be transpiration-efficient under current atmospheric conditions maintained and/or increased its advantage under elevated [CO_2]. Sherwin *et al.* (2013) demonstrate considerable gains in water use efficiency (WUE) in the forest timber tree *Eucalyptus saligna* grown at elevated [CO_2], and found that this gain is enhanced when grown at temperatures above ambient. All of these papers highlight the importance of moving towards the study of various climate change factors in interaction, rather than in isolation.

Further development of mechanistic plant models may help to identify the likely changes in tradeoffs. For example, in a theoretical modelling exercise, Song *et al.* (2013) showed that optimum canopy architecture relationships may be different for elevated [CO_2] as compared to current ambient concentrations. Other examples of breeding strategies that may need careful re-evaluation for elevated [CO_2] include efforts to increase photosynthetic capacity, the introduction of C4 metabolism into C3 crops, and initiatives to increase nutrient use efficiency, because tradeoffs in all of these processes will change significantly under high [CO_2].

New tools are available that could assist in screening crops to assess genotype differences so that suitable species and varieties can be selected for use in future breeding programs or timber plantations. Genomic and phenomic systems will be useful (Pieruschka and Poorter 2012), as will remote sensing for quickly assessing growth, yield and quality both above and below ground (e.g. Walter *et al.* (2012)). However, it will be important to link these technological advances with actual measurements of plant performance in the field, and to identify easily quantifiable plant properties of direct relevance. Leaf mass area (LMA) is easy to measure and is suggested here by Thilakarathne *et al.* (2013) to be a good predictor for yield response to elevated [CO_2] in wheat. However, as this work relies on a glasshouse study, field evaluation is still pending. Root traits are more difficult to measure nondestructively, but the rhizotron system described by Gray *et al.* (2013) for soybeans could be adapted for use with other crops. As we progress our understanding of what plant traits determine responses to climate changes and elevated [CO_2], and how they interact, measurements could be focused to such traits and better tested in field settings.

Climate change is multifaceted, yet the current constraints on time, space and money mean that too often experiments are limited in scope, and not validated in field settings. Nitrogen, soil moisture, irradiance, temperature, and other environmental

factors can confound, obscure, or enhance the direct effects of elevated [CO_2], and vice versa. The world's climate is changing. In order to prepare for the future, we need more factorial, long-term field experiments that measure not just growth and yield, but plant function, quality aspects and the implication for pests and diseases. While challenging, the prospect of not being able to grow enough of our most important food crops to feed the world is too serious to ignore.

References

Ainsworth EA, Beier C, Calfapietra C, Ceulemans R, Durand-Tardif M, Farquhar GD, Godbold DL, Hendrey GR, Hickler T, Kaduk J, Karnosky DF, Kimball BA, Koerner C, Koornneef M, Lafarge T, Leakey ADB, Lewin KF, Long SP, Manderscheid R, McNeil DL, Mies TA, Miglietta F, Morgan JA, Nagy J, Norby RJ, Norton RM, Percy KE, Rogers A, Soussana JF, Stitt M, Weigel HJ, White JW (2008) Next generation of elevated [CO_2] experiments with crops: a critical investment for feeding the future world. *Plant, Cell & Environment* **31**, 1317–1324. doi:10.1111/j.1365-3040.2008.01841.x

Bourgault M, Dreccer MF, James AT, Chapman SC (2013) Genotypic variability in the response to elevated CO_2 of wheat lines differing in adaptive traits. *Functional Plant Biology* **40**, 172–184. doi:10.1071/FP12193

Carter TR, Jones RN, Lu X, Bhadwal S, Conde C, Mearns LO, O'Neill BC, Rounsevell MDA, Zurek MB (2007) New assessment methods and the characterisation of future conditions. In 'Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change'. (Eds ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson) pp. 133–171. (Cambridge University Press: Cambridge, UK)

Cavagnaro TR, Gleadow RM, Miller RM (2011) Viewpoint: Plant nutrition in a high CO_2 world. *Functional Plant Biology* **38**, 87–96. doi:10.1071/FP10124

Chapman SC, Chakraborty S, Fernanda Dreccer M, Howden SM (2012) Plant adaptation to climate change–opportunities and priorities in breeding. *Crop and Pasture Science* **63**, 251–268. doi:10.1071/CP11303

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P (2007) Regional climate projections. In 'Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change'. (Eds S Solomon, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor, HL Miller). pp. 847–940. (Cambridge University Press: Cambridge, UK)

Dias de Oliveira E, Bramley H, Siddique KHM, Henty S, Berger J, Palta JA (2013) Can elevated CO_2 combined with high temperature ameliorate the effect of terminal drought in wheat? *Functional Plant Biology* **40**, 160–171. doi:10.1071/FP12206

Fernando N, Panozzo J, Tausz M, Norton R, Seneweera S (2012) Rising atmospheric CO_2 concentration affects mineral nutrient and protein concentration of wheat grain. *Food Chemistry* **133**, 1307–1311. doi:10.1016/j.foodchem.2012.01.105

Gray SB, Strellner RS, Puthuval KK, Ng C, Shulman RE, Siebers MH, Rogers A, Leakey ADB (2013) Minirhizotron imaging reveals that nodulation of field-grown soybean is enhanced by free-air CO_2 enrichment only when combined with drought stress. *Functional Plant Biology* **40**, 137–147. doi:10.1071/FP12044

Hasegawa T, Sakai H, Tokida T, Nakamura H, Zhu C, Usui Y, Yoshimoto M, Fukuoka M, Wakatsuki H, Katayanagi N, Matsunami T, Kaneta Y, Sato T, Takakai F, Sameshima R, Okada M, Mae T, Makino A (2013) Rice cultivar responses to elevated CO_2 at two free-air CO_2 enrichment (FACE) sites in Japan. *Functional Plant Biology* **40**, 148–159. doi:10.1071/FP12357

Högy P, Wieser H, Kohler P, Schwadorf K, Breuer J, Erbs M, Weber S, Fangmeier A (2009) Does elevated atmospheric CO_2 allow for sufficient wheat grain quality in the future? *Journal of Applied Botany and Food Quality* **82**, 114–121.

Johnson AAT (2013) Enhancing the chelation capacity of rice to maximise iron and zinc concentrations under elevated atmospheric carbon dioxide. *Functional Plant Biology* **40**, 101–108. doi:10.1071/FP12029

Leakey AD, Lau JA (2012) Evolutionary context for understanding and manipulating plant responses to past, present and future atmospheric [CO_2]. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* **367**, 613–629. doi:10.1098/rstb.2011.0248

Long SP, Ort DR (2010) More than taking the heat: crops and global change. *Current Opinion in Plant Biology* **13**, 240–247. doi:10.1016/j.pbi.2010.04.008

Newton PCD, Edwards GR (2007) Plant breeding for a changing environment. In 'Agroecosystems in a changing climate'. (Eds PCD Newton, RA Carran, GR Edwards, PA Niklaus), pp. 309–319. (Taylor & Francis: London, UK)

Oehme V, Högy P, Franzaring J, Zebitz CPW, Fangmeier A (2013) Pest and disease abundance and dynamics in wheat and oilseed rape as affected by elevated atmospheric CO_2 concentrations. *Functional Plant Biology* **40**, 125–136. doi:10.1071/FP12162

Passioura JB (2012) Phenotyping for drought tolerance in grain crops: when is it useful to breeders? *Functional Plant Biology* **39**, 851–859. doi:10.1071/FP12079

Pieruschka R, Poorter H (2012) Phenotyping plants: genes, phenes and machines. *Functional Plant Biology* **39**, 813–820. doi:10.1071/FPv39n11_IN

Reich PB, Hobbie SE (2012) Decade-long soil nitrogen constraint on the CO_2 fertilization of plant biomass. *Nature Climate Change.* doi:10.1038/nclimate1694

Rosenthal DM, Slattery RA, Miller RE, Grennan AK, Cavagnaro TR, Fauquet CM, Gleadow RM, Ort DR (2012) Cassava about-FACE: greater than expected yield stimulation of cassava (*Manihot esculenta*) by future CO_2 levels. *Global Change Biology* **18**, 2661–2675. doi:10.1111/j.1365-2486.2012.02726.x

Sherwin GL, George L, Kannangara K, Tissue DT, Ghannoum O (2013) Impact of industrial-age climate change on the relationship between water uptake and tissue nitrogen in eucalypt seedlings. *Functional Plant Biology* **40**, 201–212. doi:10.1071/FP12130

Song Q, Zhang G, Zhu X-G (2013) Optimal crop canopy architecture to maximise canopy photosynthetic CO_2 uptake under elevated CO_2 – a theoretical study using a mechanistic model of canopy photosynthesis. *Functional Plant Biology* **40**, 109–124. doi:10.1071/FP12056

Taub DR, Miller B, Allen H (2008) Effects of elevated CO_2 on the protein concentration of food crops: a meta-analysis. *Global Change Biology* **14**, 565–575. doi:10.1111/j.1365-2486.2007.01511.x

Tausz M, Tausz-Posch S, Norton RM, Fitzgerald GJ, Nicolas ME, Seneweera S (2011) Understanding crop physiology to select breeding targets and improve crop management under increasing atmospheric CO_2 concentrations. *Environmental and Experimental Botany.* doi:10.1016/j.envexpbot.2011.12.005

Tausz-Posch S, Seneweera S, Norton RM, Fitzgerald G, Tausz M (2012*a*) Growth and yield performance of two wheat cultivars contrasting in transpiration efficiency under elevated CO_2. *Field Crops Research* **133**, 160–166. doi:10.1016/j.fcr.2012.04.007

Tausz-Posch S, Norton R, Seneweera S, Fitzgerald G, Tausz M (2012*b*) Will intra-specific differences in transpiration efficiency in wheat be maintained in a high CO_2 world? A FACE study. *Physiologia Plantarum.* doi:10.1111/j.1399-3054.2012.01701.x

Thilakarathne CL, Tausz-Posch S, Cane K, Norton RM, Tausz M, Seneweera S (2013) Intraspecific variation in growth and yield response to elevated CO_2 in wheat depends on the differences of leaf mass per unit area. *Functional Plant Biology* **40**, 185–194. doi:10.1071/FP12057

Vandergeer R, Miller RE, Bain M, Gleadow RM, Cavagnaro TR (2013) Drought adversely affects tuber development and nutritional quality of the staple crop cassava (*Manihot esculenta* Crantz). *Functional Plant Biology* **40**, 195–200. doi:10.1071/FP12179

Walter A, Studer B, Kölliker R (2012) Advanced phenotyping offers opportunities for improved breeding of forage and turf species. *Annals of Botany* **110**, 1271–1279. doi:10.1093/aob/mcs026

Ziska LH, Bunce JA, Shimono H, Gealy DR, Baker JT, Newton PCD, Reynolds MP, Jagadish KSV, Zhu C, Howden M, Wilson LT (2012) Food security and climate change: on the potential to adapt global crop production by active selection to rising atmospheric carbon dioxide. *Proceedings of the Royal Society B Biology.* doi:10.1098/rspb.2012.1005