

Crops for a future climate

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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 CO₂, *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 CO₂ atmospheres. Atmospheric CO₂ concentrations [CO₂] 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 [CO₂] 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 [CO₂] 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 [CO₂]. 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 [CO₂] 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 [CO₂]; one can simply do field experiments in warmer or drier regions to collect valuable information about heat and drought tolerance, but as atmospheric [CO₂] is globally rather uniform a similar approach is not possible for CO₂ (with the exception of natural CO₂ springs, which are small scale and commonly include other gases). Hence, CO₂ 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 CO₂ 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 [CO₂] found no genotype × [CO₂] interaction. On the other hand, Tausz-Posch *et al.* (2012a) who tested two of the same wheat genotypes in a FACE system under dryland agriculture conditions, reported

significant genotype \times [CO₂] effects. Hasegawa *et al.* (2013) show consistent differences in responses of rice genotypes to elevated [CO₂] 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 [CO₂] is the confidence that such current efforts will remain beneficial under increasing atmospheric [CO₂]. Maintaining and improving the quality of food is also essential. Consideration needs to be given to the impact of elevated [CO₂] 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 [CO₂] may work against current achievements, because micronutrient concentrations in grain grown under elevated [CO₂] may decrease significantly (Högy *et al.* 2009; Fernando *et al.* 2012). Likewise, leaf and grain protein concentrations will also likely decrease in a high [CO₂] 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 [CO₂] (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 CO₂ 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 [CO₂], because of their capability to fix N₂. The paper by Gray *et al.* (2013) reports direct observations of root nodules in a FACE setup using rhizotrons. Interestingly, elevated [CO₂] 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 [CO₂]. They found that for some lines, elevated [CO₂] 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 [CO₂] (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 [CO₂] 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.* (2012b) 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 [CO₂]. Sherwin *et al.* (2013) demonstrate considerable gains in water use efficiency (WUE) in the forest timber tree *Eucalyptus saligna* grown at elevated [CO₂], 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 [CO₂] as compared to current ambient concentrations. Other examples of breeding strategies that may need careful re-evaluation for elevated [CO₂] 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 [CO₂].

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 [CO₂] 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 [CO₂], 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 $[\text{CO}_2]$, 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.

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