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Editorial

From biochemical pathways to the agro-ecological scale: Carbon capture in a changing climate☆

Anthropogenic climate change on Earth has emerged as one of the defining problems of our time. It is a systemic phenomenon, involving biogeochemical changes occurring on continental, atmospheric, and oceanic scales, and affecting most (if not all) life on earth. It has begun to alter the distribution of species (*e.g.*, VanDerWal et al., 2013), due to radical changes in the availability of life's most fundamental requirements, nutrients and energy, while superimposing new stresses on organisms, including elevated temperatures and an increased frequency of extreme weather events (Stott, 2016). In addition, there is now a consensus that under global change conditions, water use efficiency in higher plants will play a crucial role in natural ecosystems as well as in agriculture. However, water use efficiency is the result of a very complex regulation of many processes including leaf development (stomatal density), stomatal opening dynamics, water uptake and translocation, and efficiency of carboxylation reactions in photosynthetically active cells. The list of plant responses to changes in environmental parameters due to global change can be far more extended.

Therefore, an intensive discussion about how global change will impair food security is currently underway (Myers et al., 2014). Recent studies show that the hope that increased [CO_2] in the atmosphere will drastically stimulate plant growth is far too optimistic. In C_4 plants, the higher risk of drought during the vegetation period may potentially overcompensate the CO_2 fertilization effect, while increased dark respiration under higher temperatures is expected to reduce net photosynthesis in both C_3 and C_4 plants. Markelz et al. (2011) demonstrated that elevated CO_2 altered plant respiration and N demand and metabolism, giving evidence that not only photosynthesis but many other processes are targets of rising [CO_2]. As global change proceeds, we will need a better understanding from the molecular level to the whole plant, and even plant communities, to assess the risk of reduced primary production under global change conditions in terrestrial as well aquatic environments.

In this Special issue of *Journal of Plant Physiology*, the conceptual richness of the subject of plants facing climate change can be seen in the variety of articles presented, and in the many levels of biological organization represented.

These levels range from the complex operation of individual enzymes and biochemical pathways, such as carbonic anhydrase (Dąbrowska-Bronk et al., 2016) and Rubisco (Feller, 2016), and the metabolism of reactive oxygen species (ROS; Carmody et al., 2016), to the spatial reorganization of functional cell types that characterizes C_4 photosynthesis (Sage and Sultmanis, 2016), to the performance of photosynthetic organisms at ecosystem and biome levels, including agricultural systems (Coskun et al., 2016; Hüner et al., 2016), forests (Sage and Sultmanis, 2016), communities of freshwater algae (Wagner et al., 2016), as well as the marine environment of the Southern Ocean (Petrou et al., 2016).

Given the central importance of CO_2 emissions and rising atmospheric [CO_2] to climate change (Montzka et al., 2011), many of the papers in this issue focus on pathways of acquisition and assimilation of this key greenhouse gas. The articles consider carbon capture at multiple scales, starting with the CO_2-concentrating function of carbonic anhydrase (Dąbrowska-Bronk et al., 2016), to the first major step of CO_2 fixation via Rubisco (Feller, 2016). The fascinating contrast between pathways of CO_2 acquisition in C_3 and C_4 plants is discussed in the context of forests in an intriguing new way by Sage and Sultmanis (2016), who ask the important question as to why there are no major arborescent C_4 groups, and therefore, no C_4 forests. Coskun et al. (2016) identify how the potential for mitigation of anthropogenic CO_2 emissions by plant carbon capture can be strongly dependent on the nutritional value of the soil, with a special emphasis on nitrogen, the nutrient most often limiting to growth in terrestrial ecosystems, while Petrou et al. (2016) reveal how nutrient limitation in marine environments can affect the massive planktonic carbon sink in the Southern Ocean. Hüner et al. (2016) discuss the centrality of photosynthesis in a stimulating piece on the divergent strategies of CO_2 capture, redox poising, and energy flow among photosynthetic organisms, ranging from algae to cereal crops. In addition, a wealth of new information and insight is presented in a number of papers on the modeling of the complex phenomena underlying carbon capture, in terms of energy flow from photons to biomass production in freshwater algae (Wagner et al., 2016), the influence of rising [CO_2] on terrestrial vegetation and the need for the continuous revision of established models using recent discoveries (Pugh et al., 2016), and the estimation of soil respiration (CO_2 release) on patchy to global scales, with an emphasis on necessary refinements of techniques and integration of databases (Xu and Shang, 2016).

Carbon assimilation and release, however, comprise only part of the story of the interface between plants (and other photosynthesizers) and a changing climate. Another major aspect is that of

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the rapid changes in environmental stresses that accompany climate change, the most important of which are rising temperature, and increasingly frequent severe weather events. In this context, Wagner et al. (2016) consider the impact of rising temperature on the acclimation and growth of phytoplankton, while Feller (2016) discusses the influence of temperature and drought on stomatal function and C assimilation in leaves of higher plants. Carmody et al. (2016) focus on the role of ROS and their regulation, in the response of plants to stress conditions, and Wojtyla et al. (2016) present the state of the art in the practice and molecular understanding of seed priming to produce plants with increased stress resistance.

Agriculture is simultaneously a major contributor to greenhouse gas emissions (Vermeulen et al., 2012), and vulnerable to the effects of climate change (Challinor et al., 2014). Accordingly, many of the reports in this special issue consider questions of crop productivity under high-CO_2 conditions and a changing climate. Multiple scales are again encountered in this context, from the positive influence of root-fed bicarbonate on plant growth (Dąbrowska-Bronk et al., 2016), the improved stress tolerance of plants grown from primed seeds (Wojtyla et al., 2016), and the potential for breeding plants with improved ROS detoxification and osmoregulation (Carmody et al., 2016; Feller, 2016), to more comprehensive scales covered by Ludewig and Sonnewald, (2016) and Hüner et al. (2016). Respectively, these authors tackle fundamental questions of food demand and plant sink development, and divergent strategies of energy flow from sunlight to biomass in major crop plants, both in the context of nourishing a growing human population in an age of climatic uncertainty. The paper by Ludewig and Sonnewald (2016) also presents a call for greater combinatorial use of newly developed techniques in genome editing and breeding, as well as an emphasis on improved food quality, such as through biofortification, while the paper by Hüner et al. (2016) draws important parallels between the development of semi-dwarf varieties of cereals during the green revolution, and the major, and largely untapped, growth and yield advantages of winter cultivars in northern climates.

The Journal of Plant Physiology is honored to bring out such a wide-ranging collection of articles on this rich though troubling subject. The subjects presented here reflect our philosophy of promoting excellent plant biology at multiple scales, from tightly focused enzyme studies to grand conceptual syntheses. Both ends of the continuum are essential to the study of photosynthetic organisms and their place in the biosphere, and in the world of human society.

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D.T. Britto
University of Toronto, Toronto, ON, Canada

C. Wilhelm
University of Leipzig, Leipzig, Germany

H.J. Kronzucker*
University of Toronto, Toronto, ON, Canada

* Corresponding author.
E-mail addresses: britto@utsc.utoronto.ca (D.T. Britto), cwilhelm@rz.uni-leipzig.de (C. Wilhelm), herbert.kronzucker@utoronto.ca (H.J. Kronzucker).

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