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PERSPECTIVE

Climate, crops and lacking data underlie regional disparities in the CO_2 fertilization effect

David M Rosenthal and Nicholas J Tomeo
Department of Environmental and Plant Biology, Ohio University, Athens, OH, USA
rosentha@ohio.edu

Abstract
The recent study by McGrath and Lobell (2013 *Environ. Res. Lett.* **8** 014054) assesses the interaction of a changing climate and the carbon dioxide fertilization effect (CFE) on crop productivity. By accounting for the differential response of individual crops and using a finer geographic scale to assess climate effects on crops they have found that previous estimates of the CFE have likely overestimated future yields in some regions while underestimating yields in others. While this work improves our estimates of potential crop yields in an elevated CO_2 atmosphere, it also highlights knowledge gaps regarding the response of major crops to the effects of elevated CO_2 under the sub-optimal growing conditions predicted for many regions in the future.

It is well known that the accelerating increase in the global atmospheric carbon dioxide (CO_2) concentration (Conway and Tans 2012) is one of the most important drivers of global change (Le Quéré *et al* 2009). As the primary substrate of photosynthesis, CO_2 directly stimulates photosynthesis when its concentration increases; therefore, as CO_2 continues to increase, so will the productivity of C_3 crops such as wheat, rice, and most fruit and vegetable crops. Increasing CO_2 concentrations to levels expected by mid-century (about 550 ppm) has the potential to enhance C_3 crop yields by $\sim$15% (Long *et al* 2006). This so-called carbon fertilization effect therefore has important consequences for terrestrial net primary productivity in general and crop yields in particular (Cao and Woodward 1998). Moreover, elevating CO_2 has an additional effect of reducing stomatal conductance (i.e. the flow of water through pores on leaves) of C_3 species such as rice, wheat, soybeans, potatoes and cassava, and C_4 species such as maize, sorghum and sugarcane. Since water and CO_2 use the same path in and out of leaves, lower stomatal conductance at higher CO_2 concentrations effectively decreases water used per unit of CO_2 assimilated by the plant, thereby increasing water use efficiency. Thus, while the atmospheric CO_2 concentration is increasing uniformly, photosynthetic stimulation by CO_2 is expected to vary regionally, because predicted changes in climate will alter plant responses to CO_2.

The study by McGrath and Lobell (2013) sharpens our understanding of the interaction of the CO_2 fertilization effect and climate on crop production by coupling available data of carbon fertilization effect (CFE) for the world's most important crops with spatially explicit historical climate and yield data. By accounting for regional ($5'$ grid scale) variation in soil moisture, specifically the ratio of precipitation to evapotranspiration (P/PET), the authors separate the most salient effects of climate from the CFE for the most important crops worldwide. The authors show that their approach leads to regional estimates of CFE that are frequently, but not always, greater than previously reported. Two interacting factors contribute to their reported increase in CFE: first, they consider crop specific CFEs whereas previous estimates used regionally aggregated yield data. Second, the response of CFE to P/PET is non-linear because water use efficiency increases more under dry conditions. The latter response is due to the direct effect of soil moisture and CO_2 on stomatal conductance which is further indirectly affected by temperature through its effect on vapor pressure deficit. Thus the analysis by McGrath and Lobell reveals that a finer scale parsing of species is warranted to get regionally accurate estimate of CFE under climate change. They caution that using country level data, which is frequently used to estimate CFE since databases such as FAOSTAT necessarily aggregate by country, presents the potential to both under- or over-estimate CFEs.

Several important conclusions can be drawn from McGrath and Lobell's report. First, there is a large knowledge gap with regards to the response of crops to CO_2 fertilization when combined with drought and increasing temperature, particularly in regions that are prone to food insecurity and future climate perturbations. In order to utilize crop models to their fullest extent they must be parameterized with the best information possible. McGrath and Lobell were compelled to substitute CFE estimates from closely related or functionally similar crops (see their table 3) underscoring a knowledge gap for several crops. For instance, they used the CFE for potato for all tuberous crops, which is likely to misestimate the interaction of CFE and climate for tuberous crops other than potato. Second, consistent with other studies, tuberous crops stand out as particularly sensitive to CO_2 fertilization (e.g. Rosenthal *et al* 2012). The authors conclude that tuberous crops should be either carefully considered or evaluated separately, when making regional projections of CFE. Thus, more data are needed assessing the effects of climate change on tuberous crops. In general, substituting parameters from similar crops may be acceptable for initial estimates; nevertheless it is surprising that so little is known about the interaction of drought and temperature on the CFE of so many important crops. Third, McGrath and Lobell show that the variation in species' yield responses due to climate alone is as great as the regional variance due to CFE. The implication is that more experiments assessing the interactions of CFE with temperature, water, and nutrient availability are necessary to fully understand the magnitude of the individual and interacting effects for different species.

A final and important point is that many estimates of CFE are made under the assumption that nutrients (i.e. nitrogen or phosphorus) are not limiting. This is problematic because CFE is dependent upon nutrients status in a synergistic fashion even when other factors (i.e. drought, temperature) are not limiting to productivity. If estimates of CFE from well fertilized crops are the most positive estimates of crop yields under climate change, then CFEs of regions that are dry and where little N is applied may be the least optimistic. Unfortunately, experimental data assessing the latter case are few, which may explain why there is so little agreement between studies regarding which regions will benefit the most (or least) from future elevated CO_2 concentrations.

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