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Global synthesis of drought effects on cereal, legume, tuber and root crops production: A review

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ABSTRACT

As a result of climate change, drought is predicted to pose greater pressure on food production system than in the past. At the same time, crop yield co-varies with both environmental (e.g., water, temperature, aridity) and agronomic variables (i.e., crop species, soil texture, phenological phase). To improve our quantitative understanding on the effects of these co-varying factors on agricultural productivity, we synthesized previous *meta*-analysis studies summarizing the results of numerous independent field experiments on drought and its effect on the production of cereal, legume, root and/or tuber (root/tuber) crops. We also included new crops species that were not covered in previous *meta*-analyses and the effects of heat stress. Our results indicated that cereals tended to be more drought resistant than legumes and root/tubers. Most crops were more sensitive to drought during their reproductive (i.e., grains filling, tuber initiation) than during their vegetative phase, except for wheat, which was also sensitive during vegetative phase. Recovery from drought impact at reproductive phase was either: (i) unfeasible for crops experiencing damage to their reproductive organs (e.g., maize, rice) or (ii) limited for root/tuber crops, provided that water was abundant during the subsequent root/tuber bulking period. Across soil texture, the variability of yield reduction for cereals was also lower in comparison to legume or root/tuber crops, probably due to the extensive and deep rooting system of cereal crops. As crop species, plant phenology, and soil texture were important co-varying factors in determining drought-induced crop yield reduction, no single approach would be sufficient to improve crop performance during drought. Consequently, a combination of approaches, particularly site-specific management practices that consider soil conditions (i.e., intercropping, mulching, and crop rotation) and selection of crop varieties adjusted to the local climate should be adopted in order to improve the sustainability of agricultural production in a changing climate.

1. Introduction

The majority of human food source has been largely supplied by three different types of crop groups: cereals, legumes, roots and/or tubers (root/tuber). Globally, three major cereal grains (i.e., maize, wheat and rice) and other minor grains (e.g., barley, sorghum, oat, rye, millet) provided 56% of the food energy and 50% of the protein consumed on earth (Cordain, 1999). Legumes ranked second after cereal in terms of food production, which accounted for 27% of the world's primary crop production and contributed 33% of protein needs (Graham and Vance, 2003). They also contributed more than 35% of the world's vegetable oil production, particularly from the processing of soybean and groundnut (Graham and Vance, 2003). The other major crop group, root and tuber, is an important calorie source in certain regions. For example, in the sub-Saharan Africa, root and tuber provided up to 30% of total calorie consumption, and could even reach 50% in some countries such as Congo and Rwanda (Alexandratos and Bruinsma, 2012). Humanity's dependence on these three groups of crop is expected to continue although their demand may increase at different rate due to, for example, shifts towards livestock products and vegetable oils, resulting in a projected decline in the share of cereals in total calorie to 47% in 2050 (Alexandratos and Bruinsma, 2012).

During the last few decades, major drought events have been recorded and were projected to intensify in many parts of Asia and beyond (Miyan, 2014), which could make farming exceedingly challenging in some countries (e.g., Pakistan), particularly in dryland regions (Wang et al., 2012) such as Sahelian zone (Fussell et al.,

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1991) and Mediterranean (Hoerling et al., 2012). Early termination of rainy season in the lowland rain-fed areas of the Mekong region of Cambodia and Laos negatively affected the productivity of rice genotypes that flowered late and required a longer growing period (Tsubo et al., 2009). In the Mediterranean climate of North Africa, erratic and inadequate rainfall significantly depressed the important durum wheat production (El Hafid et al., 1998). The yield of food legumes grown in arid to semi-arid environments or drylands such as the Mediterranean (e.g., faba beans, chickpea and lentil), was usually variable or low due to terminal droughts that characterize these areas (Karou and Oweis, 2012; Mafakheri et al., 2010). Even in non-dryland countries like Brazil where precipitation was generally sufficient for legume (i.e., soybean) cultivation, water deficiency might still occur over a period of a few weeks, causing significant yield loss (Oya et al., 2004). Similar findings were also observed for various tuber/root crops, including those generally regarded as "drought-resistant" such as cassava (Burns et al., 2010) and sweet potato (Onwuome and Charles, 1994).

More than in the past, the sustainability of food production systems for a growing world population has become a much greater concern, particularly with the changing climate. Global maize and wheat productions, for example, were projected to decline by 3.8% and 5.5%, respectively with increasing temperature but decreasing precipitation, despite improved agricultural technologies and the "carbon dioxide fertilization" effect (Lobell et al., 2011). Similarly, world's cereal production was only projected to grow by 0.9% annually from 2007 to 2050, down from 1.9% per year in the past four decades, largely as a consequence of reductions in irrigated food production systems (Alexandratos and Bruinsma, 2012). Further expansion of irrigation is questionable due to, among other factors, competition for water from urban and industrial sectors, lowering of water table, and potential salinization (Alexandratos and Bruinsma, 2012). Indeed, the conversion of irrigated cropland to rainfed system in heavily-populated China and South Asia as well as western United States (US) due to projected freshwater limitations by the end of the century could translate in the loss of 600–2900 Petacalories (Pcal) of food production (equivalent to 8–43% of present day total production) (Elliott et al., 2014).

Crop yield is affected by agronomic factors and various environmental variables with water availability and temperature being the most critical environmental factors (Awika, 2011). As yield variability in many rainfed areas tends to be large, it could affect food security in these marginal environments (e.g., semi-arid regions) due to water limitation and year to year fluctuations of meteorological conditions. Frequent multi-year droughts over large areas have been observed in both tropical and subtropical regions, and this trend is expected to continue with changes in atmospheric composition and rising global temperature (Dore, 2005). In the US, major drought events were recorded during the 1930s, early 1950s, and more recently in 2007, 2012, and 2014 (Mallya et al., 2013). These alterations in the hydrological cycle (e.g., declines in soil moisture and precipitation during critical plant growth periods) could create high level of uncertainty, particularly for rainfed agricultural system. Groundnut yield in India, for example, varied between 550 and 1100 kg ha^{-1} mainly due to fluctuation in annual rainfall (Reddy and Reddy, 1993). The impact of those factors across different crop groups and site conditions, however, have not been fully elucidated, but this understanding is necessary to develop agricultural practices aimed at minimizing the impact of drought. One approach to documenting such effects is by examining past results using *meta*-analysis of large datasets to identify general trends among numerous independent drought-related experiments (Hedges et al., 1999). The effects of drought on global legume (Daryanto et al., 2015), wheat, maize (Daryanto et al., in review-a) and root/tuber (Daryanto et al., in review-b) production were assessed separately using *meta*-analysis techniques. However, we still lack: (i) quantitative comparisons among the three major crop groups with regard to their performance under drought, and (ii) information on the response to drought of other major cereal crops such as rice, sorghum, barley, and millet. In this review, we synthesized published studies that investigated the effect of drought on various crop species within the three major crop groups listed above and examined the data with due consideration of phenological phases, agro-ecological regions, and soil texture. In addition to legume, wheat, maize and root/tuber group, we included cereal crops such as rice, sorghum, barley, and millet that were not examined in the earlier assessments. We also discussed the importance of heat as another co-varying factor affecting crop yield during drought events, as well as agronomic and plant breeding approaches that could be adopted to mitigate the impact of drought on the production of these major crop groups.

2. Materials and methods

In this review, besides the data synthesized in three previous *meta*-analysis studies on maize, wheat, legume, and root/tuber crops, we included the following cereal species that were not covered in those earlier *meta*-analyses: durum wheat (*Triticum durum*), aerobic and anaerobic rice (*Oryza sativa*), barley (*Hordeum vulgare*), sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), proso millet (*Panicum miliaceum*), and oat (*Avena sativa*). The database for this study was collected from peer-reviewed journal articles published in English from 1980 to 2015 based on Google Scholar search using the following two sets of keywords: (i) species common name; water; stress; yield; and field; or (ii) species common name; irrigation; deficit; yield; and field. Only articles that meet the following criteria were included in the database: (i) plants that experienced drought under field conditions (excluding pot studies); (ii) the effect of water deficit was considered in comparison with well-watered condition and not in combination with other treatments (e.g.; addition of fertilizers or growth hormones; modification of temperature or CO_2); (iii) the reported plants were monoculture species cultivation; and (iv) the articles reported crop response as yield per unit area. For cereal crops; the total number of data points before averaging (including genotypes and cultivars) was 5485 from 228 studies. After averaging to the species level; the total number of data points used for cereal *meta*-analysis was 1674. Although we were only interested in evaluating the effect of drought on crop performance at the species level; we separated the response of aerobic and anaerobic rice due to their disparity in water requirement during cultivation. The other two groups have the same number of data points as Daryanto et al. (2015) and Daryanto et al. (in review-b).

The magnitude of yield responses was examined based on the following categorical variables: (i) species, (ii) agro-ecosystem types (dryland and non-dryland), (iii) drought timing (i.e., vegetative phase or early season, reproductive phase or late season, and during both the vegetative and reproductive phases or throughout season), and (iv) soil texture (fine-, medium-, or coarse-textured soil). To compare the differences in observed yield reduction between each categorical variable, *meta*-analysis was used to construct the confidence intervals. We performed an unweighted analysis using the log response ratio (lnR) to calculate bootstrapped confidence limits in order to include those studies that did not adequately report sample size or standard deviation using the statistical software MetaWin 2.0 (Rosenberg et al., 2000). The response ratio is the ratio between the outcome of experimental group (i.e., drought) to that of the control group (i.e., well-watered condition) and the difference is considered significant if the bootstrap confidence interval does not overlap with each other using a statistical significance level of $P < 0.05$.