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Drought effects on root and tuber production: A meta-analysis

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ABSTRACT

Roots and tubers such as potatoes and cassava rank within the top six among the world's most important food crops, yet the extent to which their global production has been adversely affected by drought remains unclear. Greater uncertainties exist on how drought effects co-vary with: (1) root and tuber species, (2) soil texture, (3) agro-ecological region, and 4) drought timing. It is often assumed that potato is drought-sensitive whereas cassava and sweet potato are resistant to drought, but this assumption has not been quantitatively tested. To address these uncertainties, we collected literature data between 1980 and 2015 that reported monoculture root and tuber yield responses to drought under field conditions, and analyzed this large data set using meta-analysis technique. Our results showed that the amount of water reduction was positively related with yield reduction, but the extent of the impact varied with root or tuber species and the phenological phase during which drought occurred. In contrast to common assumptions regarding drought resistance of certain root and tuber crops, we found that yield reduction was similar between potato and species thought to be drought-resistant such as cassava and sweet potato. Here we suggest that drought-resistance in cassava and sweet potato could be more related to survival rather than yield. All root or tuber crops, however, experienced greater yield reduction when drought struck during the tuberization period compared to during their vegetative phase. The effect of soil texture on yield reduction was less obvious, and similarly we did not find any significant effects of region (and related climatic factors) on either yield reduction or drought sensitivity. Our study provides useful information that can inform agricultural planning, and influence the direction of research for improving the productivity and resilience of these under-utilized crops in the drought-prone regions of the world.

1. Introduction

According to the FAO definition (FAO, 1994), roots and tubers are plants that produce starchy roots, tubers, rhizomes, corms and stems commonly consumed as human food, animal feed, and as manufactured food products. There are six major root and/or tuber (i.e., root/tuber) crops: potato, cassava, sweet potato, yam, taro, and yautia (Table 1), some of them are important cash and food crops particularly for resource-limited farmers in Asia, Africa, Latin America, and the Caribbean (Okogbenin et al., 2013). Yam and cassava, for example account for a sizable portion of the daily calorie intake for people in West Africa (Asiedu and Sartie, 2010).

Root/tuber crops have much potential in terms of water use efficiency (WUE) and nutrient content compared to other food crops. Potatoes, for example, produce more dry matter and protein per hectare than major cereal crops (Birch et al., 2012). They also have higher water productivity than cereals, and are considered among the most energy productive crops, producing 5600 kcal per cubic meter of water, compared to 3860 in maize, 2300 in wheat, and 2000 in rice (Birch et al., 2012; Monneveux et al., 2013). Similarly, sweet potatoes are considered among the other major crops as plants that produce the most human-edible energy, as much as 194 MJ ha^{-1} day^{-1} (Mukhopadhyay et al., 2011). Other root/tuber crops such as taro (seven known species mostly originated from Asia), yautia (40 species mostly from the American continent), and yam (600 species of different origins) (Asiedu and Sartie, 2010; Degras, 1993) also have significant energy values and variable nutritional properties, including dietary fiber, vitamin C, and carotenoids (Asiedu and Sartie, 2010; Degras, 1993).

While drought has been considered a major constraint to root/tuber crop production, research on drought tolerance in potato only started between 1960 and 1980, compared to cereal crops which have been extensively studied in that regard since the early 1900′s (Monneveux et al., 2013). Consequently, our knowledge regarding: (i) drought tolerance of roots and tubers and the underlying physiological mechanisms, as well as (ii) the agronomic practices and water-saving techniques (e.g., mulching, no-till) (Monneveux et al., 2013), is still limited compared to other staples

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such as cereals and legumes despite the earlier cultivation of roots and tubers (i.e., >10,000 years for taro) (Lebot, 2009). Compared to roots and tubers, there has been two and four times more studies examining the effects of drought on legumes and cereal production, respectively (Daryanto et al., 2015, 2016a,b). Yet several climate models have predicted a much stronger impact of climate change on potato production than on cereal production (Monneveux et al., 2013; Tubiello et al., 2002). Potato production in various low latitude regions, for example, is expected to decrease between 18 and 32% without shift in planting date and varieties as opposed to 9–18% if such mitigation strategies are adopted (Monneveux et al., 2013). Given the significance of root/tuber crops to food security in various regions of the world and the uncertainties regarding the global climate, there is a need for greater understanding of the resilience of root/tuber species to water stress and how different root/tuber species respond to drought (e.g., changes in timing and intensity of water stress).

Meta-analysis is a powerful statistical tool that can be used to summarize results from numerous independent experiments on drought while accounting for variability across experiments (Hedges et al., 1999). By synthesizing the results of field experiments investigating drought effects on root/tuber production in different regions, this study aims to provide a quantitative summary of the factors that either amplify or minimize production loss associated with droughts. We aim to answer the following questions: (1) to what extent factors such as root/tuber species, soil texture, and climatic region contribute to variations in drought-induced yield reduction, and (2) how can the information gained from the analysis of these factors be used to minimize the impact of drought on root/tuber production? Specifically, we are interested in quantitatively assess the yield reduction of generally assumed drought-resistant root crops (i.e., cassava and sweet potato) (Onwoume and Charles, 1994) and comparing their response to that of the more drought-sensitive species (i.e., potato) (Monneveux et al., 2013). While anecdotal evidence suggests that cassava and sweet potato are widely grown, continue to expand in drought-affected regions, and can remain profitable in areas with annual rainfall as low as 500 mm (Hahn, 1977; Onwoume and Charles, 1994), the data that support the extent of yield reduction due to drought for both of these crops are still lacking. The results of this study could thus lead to the formulation of better agricultural practices by considering the aforementioned factors to increase the resilience of roots/tuber production systems in the drought-prone regions of the world.

2. Materials and methods

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) root or tuber species common name, water, stress, yield, and field, or (ii) root or tuber species common name, irrigation, deficit, yield, and field. The list of articles and geographical distribution of the study locations are provided in the Supplementary Material S1 and Supplementary Fig. S1. 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 roots or tubers of potato (*Solanum tuberosum*), cassava (*Manihot* spp.), sweet potato (*Ipomoea batatas*), taro (*Colocasia esculenta*), yautia (*Xanthosoma* spp.), and yam (*Dioscorea* spp.), and (iv) the articles reported crop response as yield per unit area. To minimize the impact of other agronomic factors (e.g., pests, nutrients, diseases) that might affect yield, we only included studies that examined the single effect of water reduction as these other factors were controlled during the water treatment experiments (Daryanto et al., 2015, 2016a,b).

The magnitude of yield responses was examined based on the following categorical variables: (i) root/tuber species, (ii) agroecosystem types (dryland and non-dryland), (iii) soil texture (fine, medium, or coarse), and (iv) drought timing (i.e., early season, mid-season, late season, mid- and late-season, and throughout season). For the purposes of meta-analysis, we established discrete levels for each variable and coded each observation accordingly. Unlike grain crops in which drought timing can be categorized based on distinct vegetative and reproductive phases (Daryanto et al., 2015, 2016a,b), for some root crops, photo-assimilates are partitioned continuously between different organs (Lebot, 2009). We therefore used the following development phases of the storage root organ to differentiate drought timing: before tuber initiation as early-season, during tuber initiation as mid-season, during tuber bulking as late-season, during the whole tuberization period as mid- and late-season, and during the entire growing period as throughout-season drought. Since we focused our analysis on the amount of water available and yield, we differentiated agro-ecosystem types based on aridity indices, which showed significant correlation with yield (Bannayan et al., 2010). We considered other environmental factors (e.g., temperature, light intensity) as the same between control and droughted condition since we only used paired study sites. Similarly, we divided soil texture into three categories (i.e., fine, medium and coarse) as each category had different water-related properties (i.e., field capacity, wilting point and water holding capacity) (Keulen and Stol, 1995). We considered clay, sandy-clay and silty-clay soils as fine texture, silt, silt-loam, silty-clay-loam, loam, sandy clay-loam and clay-loam soils as medium texture, and sand, loamy-sand, and sandy-loam soils as coarse texture (Keulen and Stol, 1995).

The total data points before averaging were 981 from 85 studies. We averaged responses across cultivars under the same drought treatment since we were only interested in evaluating the effect of drought on crop performance at the species level (for potato, sweet potato, and taro). For cassava, yam, and yautia, we did not differentiate among species, but grouped them based on their genus name due to limited number of data. Edible yam, for example, consisted of at least nine species of *Dioscorea spp*., which were native to different regions. *D. rotundata* and *D. cayanensiswere* indigenous to West Africa, while *D. alata* and*D. trifida* were Asian and American origin, respectively (Asiedu and Sartie, 2010). If the same treatment was repeated over several years or locations, the data were only averaged across the years or places if there was no significant year or location effect. After averaging, the total data points used in the meta-analysis were 352, except for soil texture which was not always mentioned in all studies. We did not differentiate among irrigation types and only recorded the amount of water applied since there have been many studies showing that the type of irrigation was not significant in comparison to the amount of water in determining yield, even in semi-arid (dryland) regions (Erdem et al., 2006; Onder et al., 2005; Sammis, 1980; Shalhevet et al., 1983; Ünlü et al., 2006). If a study reported more than one timing of drought or levels of water reduction, all observations were considered independent and included in the database. Since limited data were available for taro and yautia production, we used either single amount of water reduction or other quantitative indicators of water availability (e.g., soil moisture) reported in the corresponding article as proxy for observed water reduction (Supplementary Fig. S2).

We calculated the observed water availability ratio (i.e., the ratio between water during drought and during well-watered condition) for each categorical variable as a proxy to describe drought