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Special Issue Editorial

Combatting drought: a multi-dimensional challenge

Water will be a major limitation to food production in the 21st century, and drought issues already prevail in many parts of the world. Finding solutions to ensure that farmers harvest profitable crops, and secure food supplies for families and feed for animals that will provide for them through to the next season are urgent necessities. The Interdrought community has been addressing this issue for almost 30 years in a series of international conferences, characterized by a multi-disciplinary approach across the domains of molecular biology, physiology, genetics, agronomy, breeding, environmental and social sciences, policy, and systems modeling. This special issue presents papers from the 7th edition of the conference, the first to be held in Africa, that paid special attention to drought in a smallholder context, adding a 'system' dimension to the crop focus from the previous Interdrought events (Varshney *et al.*, 2018; Hammer *et al.*, 2021).

Water limitation (or drought for brevity) has many definitions. The Interdrought series of conferences is focused on agricultural drought, and within that context, our community is seeking solutions at the gene, cell, organ, plant, and crop levels to improve crop performance under limited water (see Box 1 in Hammer *et al.*, 2021), with 'drought tolerance' being considered as above-average yield under drought. In the geographical context of the most recent Interdrought event, which for the first time was held on the African soil, an attempt was made to take a further step and add a system perspective to look at smallholder farming in drought-prone areas. Agricultural drought has direct connections to 'other' droughts, being a consequence of meteorological drought (below-average rainfall), and sometimes of hydrological drought (below-average levels in water bodies such as rivers, reservoirs, lakes, and groundwater tables), and it always results in consequences to economic drought (what happens when farming communities face an agricultural drought). These aspects are important to consider because they influence decision-making under situations of uncertainty. In view of this, the first session of the conference was devoted to giving a broad view on those other issues that surround agricultural drought. A systems perspective looking at water limitation in the context of smallholders living in mixed crop–livestock farming systems showed that finding the right balance among the many users of water was not only about breeding high-yielding grain crops but also about balancing food and feed over the season to make ends meet (for presentation, see https://www.youtube.com/watch?v=io4Wp_bBuoQ). A hydrological perspective in the context of drought in the Sahel and in Northern Africa showed the current paradox of having large water resources underground and questioned the feasibility and validity of its sustainable use to support/sustain agriculture and economic development (https://youtu.be/EMITl9TanSI). Following this inaugural session, the conference was then structured around four topical issues that generally provided follow-ups to previous events, and these topics are detailed in the following sections, then we provide a summary and some perspectives.

Maximizing water access/availability to plants

Much research has focused on water capture by roots. A paper in this special issue deals with the effects of the re-introgression of wild alleles on root architecture in wheat, showing how the re-introgression of emmer wheat alleles increases root elongation under drought (Bacher *et al.*, 2023). However, a recent re-examination of this topic has shown that focusing only on root architecture (i.e. deeper/denser root systems) might not be the solution to all drought situations. This is because water might not be available at depth (Vadez, 2014), the root system might not be able to satisfy the water demand created by the canopy leaf area (van Oosterom *et al.*, 2016), or because profuse root growth could also come with profuse shoot growth and hence fast soil-water depletion (Cairns *et al.*, 2009; Zaman-Allah *et al.*, 2011; Sivasakthi *et al.*, 2018). The importance of other aspects of root physiology have recently become apparent. Root hydraulics has been the subject of increased research in the past few years (Ahmed *et al.*, 2018; Cai *et al.*, 2022), and this has shown the importance of the distribution of root axial and radial conductances in facilitating and controlling the flux of water from the soil to the shoot and supporting transpiration. In particular, recent work has pointed to a role of soil and plant hydraulic conductance traits in the response of transpiration to soil drying and to high vapour pressure deficit (VPD; Vadez *et al.*, 2021; Koehler *et al.*, 2022, 2023a). An interesting insight presented in this special issue comes from the fact that hydraulic traits involved in the transpiration response to increasing VPD, which acts on a daily scale, can be different from traits involved in the transpiration response to soil drying (Koehler *et al.*, 2023b), implying that crop water use regulation has different timescales that can be managed differently. As the soil progressively dries, the rhizosphere conductance appears to become a crucial element in maintaining the contact between roots and soil and can trigger a restriction in transpiration, thereby participating in the regulation of crop water use (Carminati *et al.*, 2017). In this issue, the importance of the rhizosphere from the viewpoint of arbuscular mycorrhizal fungi (AMF) is reviewed and considered, highlighting the role of AMF in enhancing both soil and root hydraulic conductance (Abdalla *et al.*, 2023).

Increasing water use efficiency with a focus at the crop level

Increasing water use efficiency (WUE) with a focus at the crop level has been the subject of much research in the last few decades, following the publication of Passioura's model (Passioura, 1977). This triggered a lot of studies, many of which were at the leaf scale and used instantaneous measurements of WUE (intrinsic WUE, WUE_{int}), with limited impacts in terms of the development of improved varieties (the only exception being Richards and Passioura, 1989), and often with a yield penalty (Blum, 2009; Tardieu, 2022). More recently, methods to scale-up WUE have allowed the identification of genotypic variation at the plant level (WUE_{plant}; Vadez *et al.*, 2014; Fletcher *et al.*, 2018), and this has started to deconstruct the idea that breeding for WUE is bound to result in a yield penalty. Several studies have focused on high-throughput phenotyping approaches (Dalal, 2021). Understanding the physiological basis of the differences in WUE_{plant} is now a major focus of research. Restricting transpiration under high VPD has been shown to contribute to increasing WUE_{plant} (Sinclair *et al.*, 2005; Vadez *et al.*, 2014; Ryan *et al.*, 2016; Affortit *et al.*, 2022), although this is not always the case (Vadez *et al.*, 2013). In this special issue, a large variation is reported in the VPD break-point value at which transpiration declines among a panel of wild lentil germplasm (Rouichi *et al.*, 2023), and this variation is much larger and with considerably lower break-point values than previously reported (Guiguitant *et al.*, 2017). An interesting insight comes from the fact that a robust transpiration response to the evaporative demand (which includes both VPD and light) of plants grown as a canopy has been found to be positively related to WUE_{plant} (Pilloni, 2022), which is in contrast to the studies cited above. High WUE_{plant} was also related to more light penetrating inside the crop canopy, and the differences in WUE_{plant} were interpreted as a consequence of having leaves inside the canopy that are exposed to lower VPD conditions contributing a larger share of the overall photosynthetic activity of the plants (Pilloni, 2022). Therefore, future work on the transpiration response to VPD may need to shift to looking at the response to the evaporative demand, and should clearly distinguish the response of individual plants from the response of canopies. Research is also focusing on what might explain this restriction of transpiration despite the fact that soil water is not limiting. One avenue to explore is root hydraulics, and this is the object of a review in this issue (Koehler *et al.*, 2023b).

Increasing WUE with a focus at the field level

Increasing WUE with a focus at the plot/farm level is a topic that we believe deserves more attention. Whilst it has a crop focus, a review in this special issue shows the importance of management practices to increase WUE at the field level (WUE_{field}), which consists in part of reducing the proportion of water evaporated from the soil surface, but also from improving WUE_{plant} (Echarte *et al.*, 2023). Going beyond the field level, WUE at the farm level (WUE_{farm}) has particular relevance in the context of crop–livestock farming systems, where the crops have multiple uses and WUE_{farm} is no longer limited to a question of biomass or grain per unit of water, but can be considered in terms of an amount of cash, calories, food, and feed per unit of water. For instance, Bluemmel *et al.* (2014) examined how to increase the WUE of feed production and utilization, and showed that major improvements could be made from a combination of genetic options (e.g. the stay-green QTLs) and feed management (food and feed, allowing for the division of the water allocation to dual crop outputs). In this issue, Vadez *et al.* (2023) cover the topic of WUE from genes to landscape, and try to make a link between studies carried out at an upstream level, for example on stomatal regulation to minimize water loss versus CO_2 uptake trade-offs (Davies *et al.*, 2002; Franks *et al.*, 2015), and studies being done at a larger scale, for example looking at WUE at the crop level (Echarte *et al.*, 2020, 2023) or at the system level such as seeking efficiency gains from using different irrigation techniques (Hatfield and Dold, 2019) or determining optimal landscape designs (Colin *et al.*, 2012; Habibi Davijani *et al.*, 2016). As an example, increasing sowing density has recently been shown to improve WUE_{plant} because of a lower VPD coupled with a better light distribution within the high-density canopy, which allows lower leaves to photosynthesize more and at a lower cost of water (Pilloni, 2022; Pilloni *et al.*, 2022).

Using multiscale data integration to guide decisions

This section of the special issue is focused on tackling drought variability by different means and seeking a better understanding of variations and causes, and it proposes better ways to deal with and adapt to drought. The seminal issue of drought is its extremely large variability in time and space, and the fact that different types of drought in terms of timing, frequency, and intensity all require different sets of traits and management practices to cope with it. Plant breeders develop varieties for drought-prone regions by considering the mix of environment types that are present in the target region in which the plants will be grown. Because genotype × environment interactions (G×E) are ubiquitous and underpin the trade-offs among sets of traits, breeders often make poorer genetic progress than is attained in the absence of G×E (Cooper and Messina, 2023). In maize breeding, selection for yield under the target environmental conditions has been based on combining extant standing genetic variation for physiological traits that confer broad adaptation (e.g. tolerance to crowding is genetically correlated with tolerance to drought stress) and/or improving the fit between crop development and availability of resources (e.g. flowering time; canopy size) (Messina *et al.*, 2011, 2021; Welcker *et al.*, 2022; Cooper and Messina, 2023).

The increasing imbalance between water supply and demand for agricultural production prompts us to ask how current and future breeding and agronomic efforts to harness sets of traits and management to improve specific adaptation to drought can be harmonized. To be able to answer this question, it is imperative to create much more precise environmental characterizations for current and future climates worldwide and across different crops. An increasing number of case studies have been reported in recent years (e.g. Löffler *et al.*, 2005; Kholova and Vadez, 2013; Harrison *et al.*, 2014; Fletcher *et al.*, 2018; Hajjarpoor *et al.*, 2021) and more sophisticated ways to undertake environmental characterization are being considered. In this issue, Messina *et al.* (2023) provide an illuminating description of 20 years of work in the context of a well-funded breeding program in which it has been demonstrated that modelling coupled with genomic selection can better guide breeding decisions than genomic selection alone, especially in more complex situations. The use of crop simulation models then opens up questions about how they could be used as tools for making decisions at the farm level and their potential for reducing risks in decision making (Brown *et al.*, 2011).

Summary and perspectives

This special issue arising from the latest event of the Interdrought conference series showcases much progress in our understanding and modelling from soil and root processes up to farming systems that incorporate animals. It highlights a continued interest in increasing WUE_{plant} and in understanding the mechanistic and genetic basis of the traits contributing to it, and how this knowledge can be applied to increasing the availability of appropriate varieties and technologies—and hence ultimately food–in water-scarce environments. Going beyond WUE_{field}, this special issue also opens up to consideration WUE_{farm}, taking into account the crops on a farm as a whole, and this is of great importance in attempting to stimulate adoption of improved varieties and agronomic practices. Significant progress has been made with the modelling tools used to support breeding decisions, and this issue also considers the possibility of using modelling to reduce and manage risks. Thus, this special issue demonstrates that the Interdrought community continues developing and integrating options and solutions to drought across a broad range of scales.

Keywords: Agriculture risks, climate change, climatic variability, drought adaptive traits, water use efficiency.

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