# Characterisation of drought stress dynamics in European maize crops

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**Abstract**
Genotype-environment interactions (GEI) in breeding trials often impede genetic gain for yield. Understanding of GEI should be increased by broad-scale characterisation of environment types (within-season patterns of drought), since such methods improve insight into causes underlying the timing and severity of water stress. Crop models enable simulation of the temporal interplay between growth and development with soil water availability, allowing characterisation of water stress both within and across years. This study used APSIM with historical weather data, representative soil types and crop management to determine the mean drought-stress environment types encountered by European maize crops. Water stress indices were computed daily as the ratio of soil water supply to crop demand. Across all sites, soil types and years, environment types exposing crops to minor stress were the most common (40%). Environments imposing early- or late-terminal water stress after anthesis occurred in about 20% of cases, and environment types causing stress after anthesis but with later relief, or severe and prolonged stress during grain filling each occurred in around 10% of cases. Yield distributions were correlated with stress intensity and duration, with minor or severe grain filling stress environment types having the greatest or lowest yields, respectively. Results of this study can be used to interpret GEI or identify how crop traits affect water stress dynamics, and thus the likelihood that a given trait will increase yield in a given environment type.

**Key Words**
Water deficit, trait, yield, breeding, grain

## Introduction
Since more than 90% of grain maize crop area in Europe is rainfed, it is not surprising that water deficit underlies a large part of the variability in grain production across years (Eurostat, 2010). As a corollary, recent focus of maize breeders has been improvement of grain yields under drought. However breeding progress for genetic gain in yield in drought-prone environments is hampered by genotype × environment interactions (GEI; Messina et al., 2009). Such complexity reduces yield heritability and the ability to identify superior genotypes in the target population of environments (TPE; European maize cropping regions).

Characterising the relevance of results from multi-environment trials (MET) requires knowledge of the temporal dynamics of water deficit experienced by crops and the frequency with which each environment type occurs. This cannot be performed by using field trials to map the full space of possible scenarios due to time and cost constraints. Application of crop models to classify environment types has the potential of increasing the genetic gain over cycles of breeding selection, since models enable weighting of MET data according to the degree to which they represent the TPE (Messina et al., 2009).

With measured soil and weather data, crop models allow computation of temporal water stress, which in turn can be used to classify the pattern and frequency of a given environment type within a TPE. Indeed, past studies using this approach have demonstrated that allocation of a given field trial to an appropriate environment type helps control the GEI that are observed with yields within TPEs (Chapman et al., 2000). Since the timing and intensity of drought stress underpin the efficacy of a given crop trait in yield enhancement, environmental classification can also be used to examine the suitability of specific traits for yield gain. The current study used historical weather data with representative soils and crop management in APSIM to simulate crop water stress for 55 sites in Europe. To categorise water-stress traces from all sites, soils and seasons into broad environment types, a clustering analysis was performed and five mean environment types were identified.

## Methods
APSIM-Maize was calibrated using data from replicated experiments conducted in Mauguio (France) and validated with data from four independent field experiments conducted in France, Hungary and Italy. For the

sake of brevity, validation results are not described here but were deemed acceptable, and can be obtained from the authors on request.Ten European countries with the greatest average areas sown to maize over 2004-9 were determined from Eurostat data. The number of sites selected in each country was determined by weighting using the total area of maize sown. Soil and daily weather data (1975-2010) were obtained from the Joint Research Council (JRC). Selecting representative crop sowing dates for each region was a crucial step towards achieving realistic dates of anthesis and maturity. Sowing dates were simulated as the date when frost frequencies in 10d periods between 1 March and 1 May became less than 5%. The simulated sowing-date contour map in Figure 1 reveals that the earliest sowing of maize crops occurs in Mediterranean regions, whereas the latest sowing dates occur in north-eastern regions. Sites with continental climates such as Gomecello and Achenheim experience higher frequencies of late frosts, causing later sowing. The likelihood of late frost became greater with increasing latitude, causing later sowing in northern sites. Sowing dates in regions between 44 and 50°N also became later with increasing longitude, reflecting not only lower temperatures in north-eastern Europe but also the potential of cold air mass in this region to flow southward in March/April, delaying sowing in the south east. Crop densities were set to 7.3-8.0 plants/$m^2$, sowing depths to 30 mm and row spacing to 800 mm. Soil water content at sowing was set to 90% of PAWC. Sufficient N supply was simulated to prevent N stress. Thermal times for juvenile and grain filling phases were set as a function of latitude and resulting dates of anthesis and maturity (averaged over 35 years) were validated with local knowledge. The temporal pattern of daily crop water stress (water supply/demand; S/D) for each simulation was centred at anthesis and averaged every 100$^o$C.d from emergence to maturity. To identify mean environment types, the k-means clustering algorithm in R was applied to all water-deficit traces.

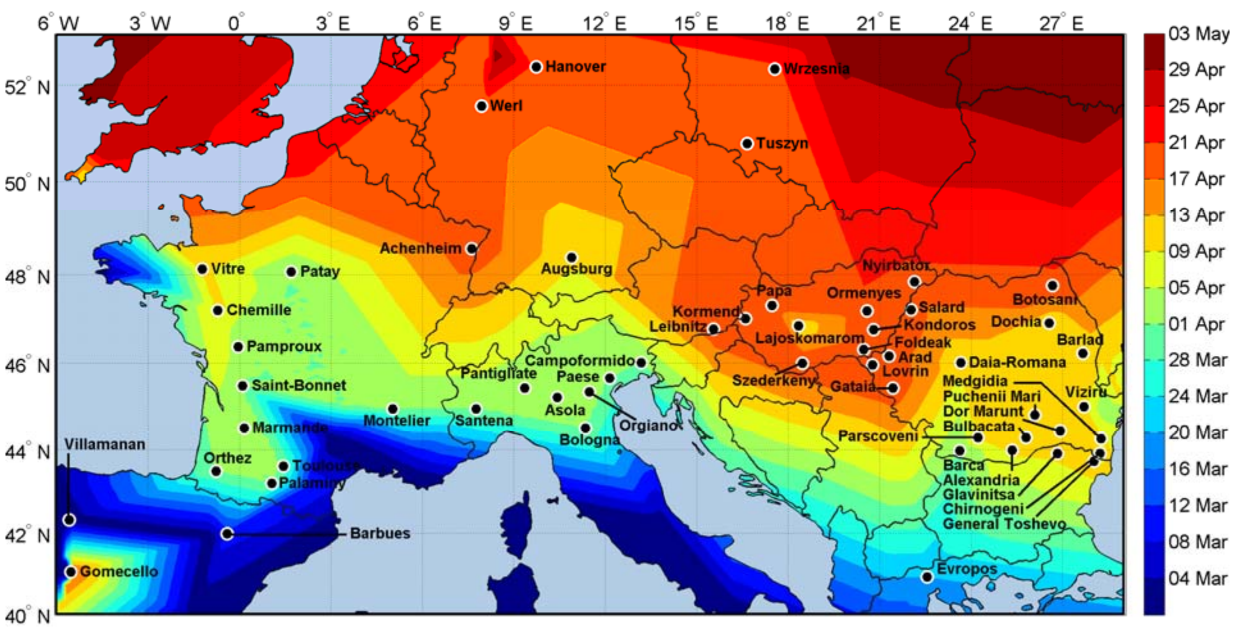


**Figure 1. Site locations and sowing dates used in simulations.**

## Results

*Mean environment types and their frequency of occurrence between 1975 and 2010*

In well-watered (WW) scenarios, crops experience favourable conditions for the majority of the growing season, with supply/demand (S/D) ratios close to unity for the 1600°C.d period centred on anthesis (Figure 2A). Crops exposed to late terminal water deficit (LT) experienced favourable conditions around anthesis, but by around 400°C.d after anthesis began to experience greater water deficits, with S/D ratios becoming progressively less than 0.70. Early terminal (ET) water deficit environments were similar to LT environments, but exposed crops to water deficit at an earlier phase after anthesis. Severe grain filling (SGF) environment types were defined as those in which S/D was about 0.7 by anthesis, 0.2 by 300°C.d after anthesis and remained at this level until maturity. The final water deficit scenario was that exposing crops to moderate water stress after anthesis (S/D reduced to around 0.4), but with later relief (LR) of water stress. Across all sites and soils, the most frequent environment types were WW, occurring in 40% of years over the long-term (Figure 2A). The LT and ET scenarios occurred in about one of every five simulations, accounting for 22% and 17% of all locations, respectively. The SGF and LR environment types were least common

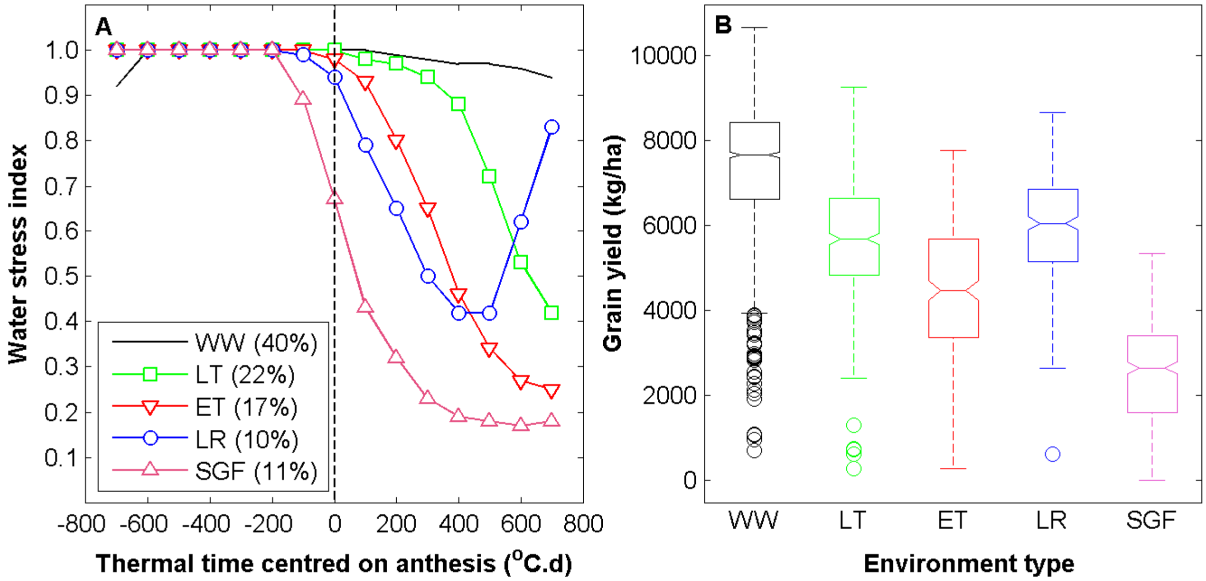


**Figure 2. (A) Mean water stress environment types experienced by European maize crops and (B) associated grain yield distributions. Values in parenthesis denote frequency of occurrence. WW = well watered, LT = late terminal, ET = early terminal, LR = late relief and SGF = severe grain filling.**

and respectively occurred in 11% and 10% across all sites and seasons (Figure 2A).

*Grain yields of environment types*

The distribution of grain yields for each drought scenario across all sites, soils and years is shown in Figure 2B. Well-watered scenarios had the greatest simulated median yield (7.6 t/ha). The LR and LT scenarios had similar median grain yields (5.7-6 t/ha). Median yields of ET scenarios were lower (4.5 t/ha), and the lowest yielding scenario was SGF.

## Discussion

*Five main water stress environment types successfully classified European maize cropping regions*

Well-watered scenarios accounted for around 40% of drought scenarios experienced by European maize crops. By comparison this value is greater than that found in previous studies of sorghum or wheat crops in northern Australia (Chapman et al., 2000; Chenu et al., 2011). This difference is perhaps not surprising given the lower annual average rainfall in Australian cropping regions compared with those found in Europe. Indeed, in the U.S corn belt, a cropping region with similar average growing season rainfall to many sites in the present study, the proportion of WW environment types was similar to those reported here (37%; Messina et al., 2009).

A key finding of this analysis is that long-term water stress of maize crops before anthesis is likely to be minimal, even for the most severe water stress environment types (Figure 2A). It must be heeded, however, that the curves in Figure 2A are the *average* environment types generated using cluster analysis, meaning that in the long-term, severe water stress during vegetative development is less probable. This does not imply severe water stress does not occur in a given soil type, season or location. The absence of major water stress during vegetative development of maize crops in Europe contrasts previous studies conducted for maize or wheat crops in Brazil (Chenu et al., 2009) and Australia (Chenu et al., 2011), which have shown that vegetative stress environment types occur in more than 30% and 80% of all cases, respectively.

Comparison of Figures 2A and 2B reveals both expected and more subtle trends between water stress and grain yield within environment types. As expected, WW environment types had the greatest median yields in the long-term, and severe water stress during maize grain filling resulted in the lowest yields. Although water stress in ET and LR environment types generally initiated at a similar phenological time, the median grain yield of LR environment types was greater than that in ET environment types. This suggests that any relief of water stress after anthesis, however temporary, is likely to benefit grain yields in the long-term.

*Using environmental characterisation to predict the adequacy of crop traits in diverse environments*
The timing and pattern of drought stress often underpin the relevance of a given trait with respect to yield improvement. Chapman (2008) showed that sorghum genotypes best adapted to late terminal stress were of early maturity, had high expression of transpiration efficiency and normal expression of tillering. In contrast, late maturing genotypes could still perform well in environments with early terminal drought, provided they had other water-conserving traits like high transpiration efficiency and reduced tillering. These results corroborate the statement of Tardieu (2012), which state that that no trait is conducive to increased yield in all environments. Indeed, other studies have shown that although later flowering increases yield in mild terminal stress environments, the converse occurs in severe terminal stress environments (Hammer et al., 2005). In the latter, later maturity foreshadows greater leaf number and canopy leaf area, causing greater crop demand for water, which in turn is detrimental to yield. In contrast, in mild terminal stress environments, later maturity and greater leaf area contribute to greater biomass at anthesis, and with greater plant available water, more stem assimilate is translocated to grain.

In future, the current study will be expanded to an analysis of how well key traits, such as leaf elongation rate, anthesis-silking interval and maturity, affect environment type classification. Such results would be of immediate value to maize breeding programs, because they would pinpoint traits most conducive to increasing yield via reduced water stress in a given environment type. Since crops in the same environment type experience similar water stress dynamics, yield improvement expected from a given trait in a TPE should also apply in a different TPE with the same drought stress environment type, regardless of differences in soil type, annual rainfall or crop yield potential.

**Conclusions**
Five main environment types accounted for more than 70% of the water stress situations likely to be experienced by European maize crops over the long-term. Environments exposing crops to minor stress were most common. Early terminal and late terminal water deficits after anthesis were equally likely (~20%), whilst severe water stress during grain filling was least likely (10%). These results can be used to help simplify GEI analyses by partitioning variance associated with location or season into a common environment type. This method of environmental characterisation can be used to unravel complex context interdependencies, such as crop trait effects on water stress and grain yield that would be expected over the long-term.

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