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Characterization of spatial and temporal combinations of climatic factors affecting yields: An empirical model applied to the French barley belt

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ABSTRACT

The adaptation of genotypes to environmental conditions is one of the main levers for maintaining an acceptable level of production, both in terms of quality and quantity. To breed suitable genotypes and for the farmers to choose the most adapted one to his farm conditions, the factors affecting production must be precisely characterized. Here, we analyzed the impacts of the climatic factors on winter barley yield in 35 *départements* (French geographic units) over 25 years, by partial least squares (PLS) regression analysis. Using ascendant hierarchical clustering based on PLS results, we defined the main combinations of climatic factors affecting yield in the French barley belt, hereafter referred as "climatic-stress patterns" (CPs).

Four CPs captured 27% of total yield variability and widely differ in term of yield. Crops experienced low winter rainfall and few days with heat stress (31.8% of environments- mean yield of 7.2 t ha^{-1}), high winter frost levels and high amounts of precipitation during stem elongation (34.7% of environments- mean yield of 6.5 t ha^{-1}), high temperature during grain filling either with low vernalization temperatures (28.9% of environments- mean yield of 6.2 t ha^{-1}), or high winter rainfall (4.6% of environments –mean yield of 5.5 t ha^{-1}). Two-thirds of the French *départements* experienced all the four CPS over the years studied. Three clusters of regions with homogeneous frequencies of the CPs were identified.

The regions with similar climatic-stress patterns could help breeders to design genotypes better adapted to the different local French growing conditions. It could also help farmers to choose the most appropriate cultivars to grow.

1. Introduction

French malting barley is grown on about 1 million hectares, covering diverse environments, from shallow sandy to deep clay soils, in both maritime and continental climates. With a mean annual production of about 3 million tonnes of grain (Agreste, 2016), France is the second largest exporter of malting barley in Europe (Brasseurs de France, 2015). Barley yield, like other crops, is strongly influenced by environmental conditions: large variations of production is observed both between years and between sites (Le Bail and Meynard, 2003). Climatic factors are one of the main drivers of these variations (Gouache et al., 2015; Lecomte, 2005). Farmers and grains collectors will seek to maintain an acceptable level of production, in terms of both quality and quantity despite this climatic variability.

Choosing a genotype adapted to the local environmental conditions is one of the principal lever to reach high and stable yields (Mickelbart et al., 2015; Murphy et al., 2007). One of the key tasks of breeders is, therefore, to produce genotypes adapted to the pedoclimatic conditions of a given set of farms and a given set a future growing seasons, a set of environments called the "target population of environments" *(TPE)* (Comstock, 1977; Cooper et al., 1997). To ensure that both breeding strategies and cultivar recommendations are effective, a precise characterization of the climatic stress patterns likely to affect the environments is required (Calhoun et al., 1994; Podlich et al., 1999).

Various approaches have been proposed for the characterization and classification of TPEs. The occurrence of yield-limiting factors in a TPE can be determined *a posteriori,* from field cultivar trials (Basford and Cooper, 1998; Hernandez-Segundo et al., 2009; Setimela et al., 2005). In such trials, an agronomic diagnosis could identify the climatic and biotic factors explaining the gap between the mean yield of the

Abbreviations: CP, climatic-stress patterns; GC, geographic cluster; PLS, partial least squares regression; RMSEP, root mean square error of prediction; RRMSEP, relative root mean square error of prediction; TPE, target population of environments

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genotypes tested and their potential yields in the absence of stress (Brancourt-Hulmel et al., 1999; Cooper and Fox, 1996). These trials are, however, generally performed over only a few year and sampling of sites, and thus may lead to a misrepresentation of the TPE (Chenu et al., 2013). Such characterization may not provide a precise description of the temporal and spatial patterns of factors affecting yields. Large-scale environments characterizations have also been conclusively performed, without the need for experiments, on the basis of climatic and soil data (e.g. Hodson and White, 2007; Löffler et al., 2005) or based on similarities in sites physical characteristics (e.g. altitude, photoperiod, rainfall). Its main limitation is that it does not take into account the impact of the studied variables considered on crop production. Recent studies have characterized TPEs on the basis of stress indicators calculated from crop models taking into account the interactions between plants, soil, and climate (e.g. Chenu et al., 2013). However, most crop models struggle to capture the effects of adverse or extreme climate events accurately (Rötter et al., 2011). Due to the uncertainty of model inputs and formalisms (Iizumi et al., 2009; Tao et al., 2009), it has recently been argued that empirical modeling may be more suitable for analyses of past and current crop yield variability than process-based crop models (Soltani et al., 2016). Gouache et al. (2015) recently used such a model for wheat. Their model focused on predicting yield, but did not characterize the spatial and temporal climatic patterns of the environments.

Once characterized, TPEs can be classified, on the basis of groups of sites. This is, for example, the approach generally adopted by the International Maize and Wheat Improvement Center (e.g. Braun et al., 1996; Hernandez-Segundo et al., 2009). Classifications of this type thus generally extend over very large scales (e.g., at the continental scale: Hernandez-Segundo et al., 2009 for barley; Hodson and White, 2007 and Braun et al., 1996 for wheat). This result of group of environment areas covering sometimes more than one country at the expense of poor characterization of the local factors affecting yields. Classification may also be based on site-by-year combinations. Groups of environments are, thus, constituted on the basis of specific combinations of factors experienced by crops (Chenu et al., 2011). This second approach seems more precise to describe local factors affecting yield, as the variability in stress intensity (e.g. Chenu et al., 2013 for drought in Australia) or combinations of stress (e.g. Zhang et al., 2006 for disease in France) for a same site.

There has, to our knowledge, never been a precise quantitative characterization and classification of the combinations of climatic-stress factors affecting barley yields in the French barley belt. Here, we propose to characterize the TPE of French barley by empirical modeling, taking into account the various climatic stresses affecting yield. We based our characterization of the TPE on site-by-year combinations rather than purely on site. In France, given the diversity of climatic factors and their high inter-annual variability, the classification of environments directly and solely on the basis of the site might lead to a misrepresentation of the diversity of combinations of factors affecting yields. Finally, to provide relevant information for farmers to choose the varieties to grow on their farms, we also analyze the frequency of the different stress patterns as a function of the sites. The aims of this study were, therefore, (i) to use an empirical site-by-year model to identify similar combinations of climatic factors affecting barley yields in French barley environments, and ii) to characterize the spatial and temporal structure of the combinations of climatic factors affecting barley yields for the definition of geographic clusters experiencing similar climatic stress patterns.

2. Materials and methods

2.1. Dataset description

2.1.1. Geographic and temporal limits of the yield series studied

French winter-barley yield time series were analyzed for a period of 25 years (from 1989 to 2013) at the spatial scale of *départements* (which corresponds to the NUTS3, i.e. the classification of territorial statistical units corresponding to 95 geographical administrative units in France). Data were provided by the French Ministry of Agriculture (Agreste, 2015 - http://agreste.agriculture.gouv.fr). Yield concerned both feed and malting types of winter barley, as the database does not distinguish between production uses.

We focused on the main *départements* producing malting barley. We considered 35 French geographic units, accounting for 51% of the total winter barley acreage (i.e., 669 763 ha) in 2015, and more than 90% of the total acreage under the winter malting varieties preferred for malting (FranceAgriMer, 2015). Overall, 875 *département*-by-year combinations were analyzed.

2.1.2. Climatic data and calculation of climatic factors

Daily interpolated weather data for France on a regular 25 km-grid were produced by the Joint Research Center (*European Commission*, DG, JRC, https://ec.europa.eu/jrc/en). Six climatic variables (minimum and maximum temperature, potential evapotranspiration, rainfall, total incident radiation, and vapor pressure deficit) were averaged at *département* scale.

Based on these climatic variables, we defined factors potentially affecting yield. The climatic factors were defined on the basis of i) published evidence of impacts on yield for other crops, and ii) the presence of sufficient variability for the set of environments considered in this study. Climatic factors were calculated by phenological period, as performed by Gouache et al. (2015) and Landau et al. (1998). We considered three periods: i) from sowing to the start of stem elongation (winter period), ii) from the start of stem elongation to anthesis (stem elongation period), and iii) from anthesis to maturity (grain-filling period). The dates of anthesis and harvest were estimated based on phenological model based on cumulative thermal units obtained from records for the studied *départements* provided by the French organization for variety registration (GEVES) for the 1990–2010 period. Dates for the start of stem elongation were estimated with a simple phenological model based on cumulative thermal units (Robert, personal communication). In total, 14 climatic factors were defined (Table 1).

Table 1
Description of the climatic factors potentially affecting barley yield included in the study.

Type of climatic factor	Phenological stage considered	Example of references showing impacts of the variable on cereal production
-Number of days with a mean temperature over 25 °C	S.E., G.F.	Lecomte (2005)- *threshold 25 °C* Acevedo et al. (2002), *threshold 30 °C*, Gouache et al. (2015)
-Cumulative rainfall	W., S.E., G.F.	Lecomte (2005), Gouache et al. (2015), Qian et al. (2009)
-Cumulative minimum temperature	W., S.E.	Lecomte, 2005, Gate (1995)
-Cumulative temperature for vernalization (low temperature)	W.	Mary et al. (2009)
-Photothermal quotient	W., S.E, G.F.	Lecomte (2005), Fischer (1985), Gouache et al. (2015)
-Mean vapor pressure deficit	W., S.E., G.F.	Allen et al. (1998)

W.: winter period, S.E.: stem elongation period, G.F.: grain-filling period.