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Impact of meteorological drivers on regional inter-annual crop yield variability in France

Andrej Ceglar*, Andrea Toreti, Rémi Lecerf, Marijn Van der Velde, Frank Dentener

European Commission, Joint Research Centre, Institute for Environment and Sustainability, Via Enrico Fermi 2749, 21027 Ispra, Varese, Italy

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ABSTRACT

The impact of intra-seasonal climate variability on inter-annual variation in winter wheat and grain maize yields over 92 French administrative regions is assessed. Observed monthly time series of temperature, precipitation and solar radiation during the growing season are analysed together with reported annual crop yields with a statistical approach based on partial least square regression. Results highlight remarkable spatial differences in the contribution of the main meteorological drivers to crop yield variability and in the timing of the maximum impact. Overall, temperature and global solar radiation are identified as the most important variables influencing grain maize yields over the southern, eastern and northern parts of France, while rainfall variability dominates yields over the central and north-western parts of the country. Positive rainfall anomalies during the summer months lead to an increase in maize yields, while positive temperature and radiation anomalies have the opposite effect. Extensive irrigation suppresses the rainfall signal in dry years. Winter wheat yields are predominantly influenced by temperature variations in eastern France and by rainfall variations over the northern, north-western and south-eastern France. In general, variation in global radiation plays a more important role in the southern than in the northern part of the country. Our study contributes to a better understanding of the impact of intra-seasonal climate variability on crop yields. Potential applications of the inferred models are discussed, especially in terms of seasonal crop yield forecasting and validation of dynamic crop model simulations.

1. Introduction

Prevailing climatic conditions underpin the suitability of agriculture to produce food, feed, fuel and fibre. At the same time agricultural production is greatly affected by weather extremes and climate variability (e.g. Cantelaube and Terres, 2005), the latter referring to the variations beyond synoptic timescales of the mean state and other properties of the climate system (Cubasch et al., 2013). Disentangling the influence of climatic variability on recorded crop yield variability has been an age-old activity of farmers, agronomists, and agro-meteorologists (e.g. Porter and Semenov, 2005). A renewed impetus for this research has emerged due to concerns related to climate change and the associated expected changes of the principal climatic factors determining crop growth. Understanding the relationship of climate variability with past crop production is of high importance to assess the resilience of our agricultural production systems to future climate conditions as well as the identification of adequate measures to adapt to climate change.

Intra-seasonal climate variability can affect crop production during all phases of the crop growing cycle: directly through the effects of temperature, water availability, radiation interception, and carbon fixation; indirectly by modulating nutrient availability and the occurrence of diseases and pests (Olesen et al., 2000). The sensitivity of optimal crop growth and development to specific weather conditions depends on the crop and growth stage. For instance, during the early growth stages of grain maize, unfavourable weather conditions (e.g. wet and cold weather) can limit the size of the leaves and therefore the photosynthetic capacity. In the later stages, adverse conditions (e.g. heatwave and drought) can reduce the number of silks produced, resulting in poor pollination of the ovules and restricting the number and/or the size of the developing kernels (Ritchie et al., 1993). Importantly, the same extreme weather event can also lead to contrasting responses

* Corresponding author. Tel.: +39 0332786256; fax: +39 0332783033.
E-mail address: andrej.ceglar@jrc.ec.europa.eu (A. Ceglar).

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of crops, for example as a function of growth stage (e.g. Van der Velde et al., 2012). Finally, crop quality and field workability are highly weather dependent.

Two approaches to identify the driving factors behind crop yields can be distinguished: mechanistic (dynamic) crop modelling (e.g. Van der Velde et al., 2012) and statistical modelling (aiming at relating reported crop yields variability to a set of explanatory variables; e.g. Lobell and Burke, 2010), even though hybrid approaches have also been developed (e.g. Lobell, 2013). The main advantage of using a crop model is the comprehensive characterization of the crop production system. Once properly calibrated, and evaluated with observed data, crop models can also provide information on possible management interventions to better cope with expected changes in temperature and precipitation (e.g. Laux et al., 2010; Balkovič et al., 2014). The main disadvantage of applying dynamic crop models (originally developed to run at the field scale) at the larger scale is the requirement of an extensive set of input data with information on soils, meteorological variables, agro-management practices (sowing and harvesting date, fertilization rate and irrigation) and eco-physiological parameters describing the crop variety. Since these models have generally been calibrated to local field conditions, their use in other regions would require a recalibration (Folberth et al., 2012). Nevertheless, large scale implementations of crop models can reproduce average observed yields (Liu, 2009; Balkovic et al., 2013), often by using agricultural management inputs that are centred around one year. In any case, detailed and complete spatially resolved datasets with information on crop rotation, spatial distribution of varieties and cultivars, spatial and temporal heterogeneity of fertilization rates as well as irrigation practices (required for a complete model parameterization) are rarely available (Lobell et al., 2008). Recent advances in the ability of ensembles of field-scale crop models to reproduce the effects of climate variability on crop yield provide a promising way ahead (Asseng et al., 2013).

Over the last decade, the use of statistical approaches to characterize the relationship between yields and meteorological variables has increased with the increasing availability and improved quality of observed data (e.g. from remote sensing and reported statistics). Lobell (2010) suggested a superior performance of statistical approaches w.r.t. crop models to identify this relationship. However, most statistical analyses of inter-annual crop yield variability have been focused on the seasonal or growing-season time scale (e.g. Lobell et al., 2008; Tebaldi and Lobell, 2008; Schlenker and Roberts, 2009; Lobell and Burke, 2010; Ceglar and Kajfež-Bogataj, 2012; Michel and Makowski, 2013). Therefore, opportunities exist to use statistical approaches to better characterize intra-seasonal impacts on inter-annual crop yield variability. This is especially pertinent given the improved quality of weather forecasts during the last decades (e.g. ECMWF, 2013). Modern agriculture has been increasingly using information from operational weather forecasts, for instance to: plan the preparation of fields (ploughing), sow or plant, apply agricultural chemicals, schedule irrigation, weed, crop harvest and storage, prevent damages due to chilling, frost and freezes, forestry operations, etc.

The main objective of our study is to identify the key meteorological variables and their period of maximum influence on the inter-annual variability of grain maize and winter wheat yields during crop growth. We propose a statistical approach that is able to: tackle the problem of co-variation and provide information on the main intra-seasonal driving meteorological factors of crop yield inter-annual variability. Subsequently, we evaluate whether the results from the statistical approach are in agreement with the agronomic knowledge on the principal meteorological drivers and timing with respect to sensitive growth stages. Our analysis requires statistical crop yield and meteorological information for sufficiently long time scales at sub-national spatial scales. Therefore, we analyse winter wheat and grain maize yield variability by using reported data from 92 French administrative regions (hereafter called *départements*). Four major climate types (maritime, Mediterranean, continental and mountainous) meet and interweave in France (Joly et al., 2010; Peel et al., 2007); this allows a comparison of climate variability-crop yield relationships over different climate types.

2. Data

Time series (from 1989 to 2014) of grain maize and winter wheat yields from 92 French *départements* (Fig. S.1) were provided by AGRESTE Ministère de l'Agriculture (AGRESTE, 2015). Wheat is predominantly produced in the northern part of France, while grain maize is more predominantly cultivated in south-western France (Van der Velde et al., 2012). Weather data were retrieved from the MARS Crop Yield Forecasting System (MCYFS) database, established and maintained by the Joint Research Centre for the purpose of crop growth monitoring and seasonal forecasting (Biavetti et al., 2014). In short, daily meteorological data are obtained every day from around 4000 weather stations and interpolated into a regular 25 × 25 km grid over Europe and neighbouring countries (635 stations are located in France). In this study, we use monthly mean temperature, monthly cumulated precipitation and global solar radiation for the entire growing season. The analysed period, therefore, stretches from October to July for winter wheat and from April to September for grain maize. Gridded meteorological data are spatially aggregated at the *département* level, only considering the agricultural areas as provided by the Global Land Cover 2000 project (GLC2000; Bartholome and Belward, 2005) within each *département* (Fig. S.1). Even though the quality of the French agricultural statistics is very high, few issues (unlikely related to climate or agronomical practices) were identified in several grain maize time series. These suspicious time series exhibited either one or a combination of the following issues:

(a) equal crop yield values in three or more consecutive years,
(b) biophysically implausible yield values (e.g. yields higher than 14 t/ha),
(c) sudden drops or increases in yield values, i.e. a break point in the time series associated with an almost negligible inter-annual variability afterwards.

The affected *départements* for grain maize are: Haute-Garonne, Aude, Isère, Bouches-Du-Rhône, Var, Alpes-De-Haute-Provence, Lozère, Alpes Maritimes and Cantal. They were discarded from further analysis. All *départements* were kept for the winter wheat analysis.

3. Methods

3.1. De-trending

In order to analyse the impact of climate variability on crop yield inter-annual variability, time series must be de-trended. Crop yields are strongly influenced by intra-seasonal and inter-annual climate variability, but also by improvements and responses in agro-management practices and other socio-economic factors. To maximize and enhance ecosystem service benefits from agricultural fields (including crop yield), appropriate agro-management is often required, for instance, to control soil erosion and reduce nutrient applications. Generally, it takes several years before new crop varieties or new agro-management practices come into practice. Here, we assume that the influence of these factors is mainly reflected in the multi-annual trend component of the