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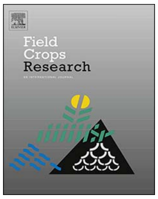

Variability of winter wheat yield in France under average and unfavourable weather conditions

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ABSTRACT

Winter wheat yield is affected not only by extreme climatic events like long-term drought or large-scale flood, but also by less severe unfavourable weather conditions that are liable to increase with future climate change. In this perspective, the goal of this paper is to assess the impacts of agricultural practices on yield robustness to unfavourable weather conditions. Toward that end, we develop a methodological framework based on a statistical typology of wheat cropping systems and a regression model relating wheat yield variability to an index of weather conditions. This framework is applied to a sample of French wheat-growing farms participating in the pesticide-reduction plan known as Ecophyto. The typology includes six classes of wheat cropping systems differentiated on the basis of two types of rotations (simplified versus diversified) and three types of management practices (high-intensive, inflexible management practices; moderately intensive, flexible management practices; and low-intensive, inflexible management practices). Wheat yield in normal or average weather conditions were significantly greater in the high- and moderately intensive cropping systems compared to the extensive cropping systems. By contrast, very few differences were statistically significant for wheat yield robustness to unfavourable weather conditions. This can be explained by the high variability of the robustness parameter derived from the regression model within each cluster. However, heterogeneity of wheat management practices emerges as a potential lever for increasing wheat yield robustness in the face of unfavourable weather conditions.

1. Introduction

Global food security is threatened by climate change, notably because of its uncertain impacts on crop yields. In recent years, a large number of studies have been conducted in different countries and with various crop models to analyse the impacts of climate change on crop productivity (Guo et al., 2010; Stöckle et al., 2010; Özdoğan, 2011; Liu et al., 2016). The uncertainty of the results is mainly due to the fact that the positive effects of increased CO_2 concentrations and longer crop growth periods in some latitudes may be counterbalanced by negative consequences linked to changes in temperature and rainfall on water availability, soil degradation, as well as the incidence of pests and diseases (Kang et al., 2009; Wilcox and Makowski, 2014). Despite these uncertainties, there is a growing consensus that crop yields will be negatively affected by climate change without adaptation of agricultural practices and systems. According to Challinor et al. (2014), for example, losses in aggregate production are expected for wheat, maize, and rice in both tropical and temperate regions within a climate change scenario of +2° Celsius, without adaptation. In France, Brisson et al. (2010) showed that cereal yields have tended to stagnate since the 1990s essentially because genetic improvements have been counteracted by the unfavourable impacts of climate change, including heat stress during grain fill and drought during stem elongation.

There is thus an urgent need to reduce the sensitivity of current agricultural systems to climate change while at the same time reducing greenhouse gas emissions from agricultural sources. The challenge is unprecedented, and a variety of adaptation and mitigation strategies have been proposed and are being experimented with worldwide (see, for example, Fuhrer and Gregory, 2014). Another difficulty is that farms must at the same time improve their productivity and profitability. This is true both at the global level and specifically in developed countries, such as France, where crop yields are high and cropping systems are generally intensive, relying heavily on chemical inputs (mineral fertilisers and synthetic pesticides).

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In this paper, an original analysis of winter wheat yield in France is proposed. This study is based on a typology of winter wheat cropping systems and an innovative analytical framework that allows to assess yield variability of contrasting wheat cropping systems under average or normal weather conditions, and under variable weather conditions. A number of researchers have considered the effects of farming characteristics, practices, and systems on yields of various crops under average weather conditions (for example, Easson et al., 1993; Meynard et al., 2003; Brisson et al., 2010). To our knowledge, no studies to date have focused specifically on winter wheat yield robustness in French agriculture. Following Urruty et al. (2016), robustness is here defined as the capacity of winter wheat cropping systems to maintain yields under unfavourable weather conditions.

The remainder of the paper is organised as follows. In Section 2, the database and analytical framework used to define wheat cropping system typology and to assess the robustness of these systems to unfavourable weather conditions are presented. Results are displayed in Section 3 and then discussed in Section 4.

2. Materials and methods

2.1. Data

Data inputs were based on a sample of 145 winter wheat cropping systems, corresponding to 145 farms for which yields, soil characteristics, weather conditions, and numerous agronomic practices were observed on a total of 2327 wheat parcels over four crop seasons during the period 2011–2014 (see Appendix A in the Supplementary material for more details). Each farm's parcels were considered to correspond to an ensemble of parcels managed in a homogeneous way and thus to constitute a wheat cropping system. All the farms are involved in a French government program known as Ecophyto, intended to significantly reduce agricultural and non-agricultural pesticide use (Ecophyto Plan, 2008).

The farms are distributed across six geographical regions corresponding to six contrasting climatic zones (Fig. 1; see Appendix B in the Supplementary material for a comprehensive presentation of the geographical distribution of the farms). The dataset was provided by Agrosolutions, a subsidiary consulting firm of the leading French agricultural cooperative group InVivo.

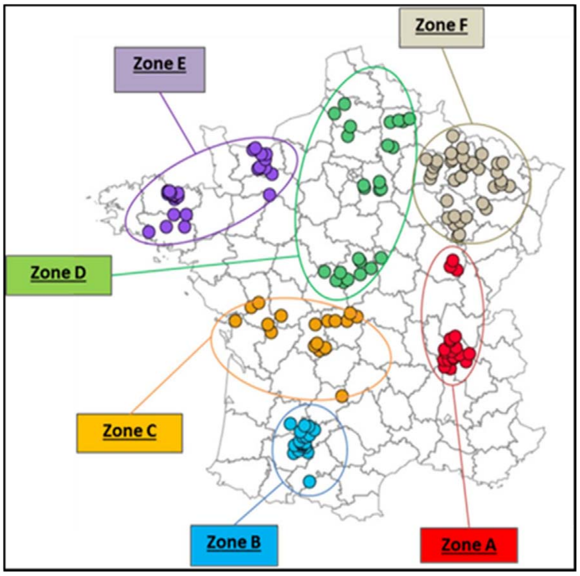

Fig. 1. The 145 farms distributed across six contrasting climatic zones (A–F).

Table 1
Variables used to describe rotation practices and construct the first typology.

Rotation practice	Acronym	Description
Rotation diversity	ROTA	Average number of species in the rotation
Frequency of summer crops	SUM	Percentage of wheat preceded by a summer crop (maize, sunflower, potato, *etc.*)
Frequency of legume crops	LEG	Percentage of wheat preceded by a legume (alfalfa, pea, soybean, *etc.*)
Frequency of cereals	CER	Percentage of cereals, including winter wheat, in the rotation
Frequency of temporary grassland	MEAD	Frequency of temporary grassland in the rotation

2.2. *Defining a typology for French wheat cropping systems*

As proposed by Sebillotte (1990), a cropping system can be described as the combination of a crop succession and a set of management practices used on each crop in the rotation. It follows that defining a typology for the 145 wheat cropping systems of this database can be broken down into three steps. The first step requires describing the main crop rotation practices; it defines a first typology on the basis of rotation practices. The second step involves identifying the key management practices used on wheat; it defines a second typology on the basis of wheat management practices. The third step combines information from steps 1 and 2 to create a full typology of wheat cropping systems on the basis of both crop rotation and wheat management practices.

2.2.1. *Step 1: first typology based on rotation practices*

Rotation characteristics were described by the set of variables presented in Table 1. In addition to the average number of species in the rotation, two variables sought to take into account the preceding crop (percentage of wheat preceded by a summer crop; percentage of wheat preceded by a legume), while two further variables captured the relative importance of cereals and temporary grassland in the rotation. The value of each of these five indicators was normalized by calculating them as the relative percentage difference between the observed value for each cropping system and the average value for that variable in the geographical zone where the farm is located, that is:

$$x_{k^z} = \frac{\left(X_{k^z} - \frac{1}{K^z}\sum_{1}^{K^z} X_{l^z}\right)}{\frac{1}{K^z}\sum_{1}^{K^z} X_{l^z}} \tag{1}$$

where x_{k^z} is the normalized value of the variable of interest for the cropping system k^z in zone z ($z = A, B, C, D, EorF$), X_{k^z} is the non-normalized value of the same variable for the cropping system k^z, K^z is the number of cropping systems in zone z, and X_{l^z} are the non-normalized values of the variable of interest for all cropping systems in zone z.

To define the first typology, the five variables in Table 1 were transformed into non-correlated variables using a Principal Component Analysis (PCA). The principal components of the PCA were then used as input variables in an Agglomerative Hierarchical Clustering (AHC). The AHC is a bottom-up approach in which each observation, *i.e.*, each farm, starts in its own cluster, and pairs of clusters are progressively merged as one moves up the hierarchy. At each step of the iteration, the closest (most similar) pairs of observations are aggregated using the Ward's minimum variance method which minimizes the increase in the total intra-class inertia. The optimal number of clusters was defined on the basis of the Hubert-Levin C index (Hubert and Levin, 1976), which measures at each iteration the difference between the maximal intra-cluster distance and the minimal inter-cluster distance (Gurrutxaga et al., 2011; Islam et al., 2015; Tomassen et al., 2016).

A key advantage of combining a PCA and an AHC is that it produces