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A framework to characterize the commercial life cycle of crop varieties: Application to the case study of the influence of yellow rust epidemics on French bread wheat varieties

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ABSTRACT

We examined the commercial life cycle of varieties of arable crops that could bring a better understanding of the drivers of their commercial success. In the current study, we propose indicators to describe the commercial life cycle of a variety and test their relevance on a case study centered on bread wheat varieties in France. We focus on yellow (stripe) rust, caused by *Puccinia striiformis* Westend. f. sp. *tritici* Eriks., an important disease that led to the rapid withdrawal from the French market of susceptible varieties during the last decades. In the present study, we assess how yellow rust pressure influenced the commercial life cycle of 31 bread wheat varieties over the period 1987–1991 which was characterized by the breakdown of resistance based on two race-specific genes *Yr6* and *Yr9*. We defined areas of bread wheat production located in the northern half of France based on homogeneity for yellow rust pressure, virulence frequencies, varietal composition and varietal replacement. We identified four groups of non-redundant indicators and retained one indicator per group based on its biological relevance when considering *a priori* hypotheses on the influence of yellow rust epidemics on the commercial life cycle of susceptible varieties. These four indicators describe the commercial life-cycle duration, the growth phase duration, the coincidence between an epidemic peak and the end of the growth phase, and the cumulative percentages of acreage of the variety during the growth phase duration. For each homogeneous production area, we calculated these four indicators for a set of varieties and performed a principal component analysis associated with a clustering algorithm. In the northwest coastline production area, known to be highly affected by yellow rust, we identify eight varieties presenting a combination of indicator values suggesting a rapid withdrawal from the market. All these varieties were susceptible to yellow rust, among which five were concerned by the breakdown of resistance based on *Yr6* or *Yr9* race-specific gene. In contrast, in the northeast production area, much less affected by yellow rust over the period studied, no variety presented a combination of indicator values related to a rapid withdrawal. Beyond the identification of susceptible varieties, our statistical procedure has also permitted to highlight two varieties, Soissons and Scipion, with potential durable resistance in the northwest coastline production area. A promising perspective for breeders could be a more complete identification of varieties with durable resistance that could promote the long-term durability of yellow rust control to face future epidemics.

1. Introduction

The expansion of modern agriculture since the mid-twentieth century is usually regarded as the main cause of the decrease of crop diversity worldwide. Over the twentieth century, the major cereal and oilseed crops have in fact experienced a genetic erosion (Rauf et al., 2010) due to the replacement of landraces by modern pure lines or hybrids (van de Wouw et al., 2010) and then the homogenization of landscape varietal composition over large geographical areas (e.g. Witcombe et al., 1998; Srinivasan et al., 2003; Krishna et al., 2016). During this period, several examples have highlighted that a lack of within-crop diversity renders the agricultural production more vulner-

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able to pests and pathogens, thus potentially leading to devastating epidemics (e.g. Ullstrup, 1972). Maintaining an adequate level of diversity and a rapid and continuous varietal replacement thus appears important for instance to minimize the impacts of rusts on cereal yields (Pingali, 1999). Such pathogens are now considered among the most important diseases of arable crops worldwide (Dean et al., 2012) and present a recurrence of epidemics characterized by successive breakdown of resistances based on race-specific genes (Brennan and Byerlee, 1991; Heisey and Brennan, 1991; Souza et al., 1994; Dixon et al., 2006).

Until now, several indicators have been proposed to characterize the genetic vulnerability of a crop across large agricultural production areas, including the weighted average age of varieties, largely used to describe the rate of varietal replacement (Brennan and Byerlee 1991; Srinivasan et al., 2003). However, the crop diversity between varieties based only on the varietal denomination may mask a genetic homogeneity regarding the disease resistances. Indeed, resistance to numerous pathogens are at least partly based on major race-specific resistance genes, monogenically inherited, and expressed at all stages of plant development (Chen, 2005). The deployment over large areas of only one race-specific resistance gene over time, often simultaneously introduced in many varieties and released by several breeders from different countries, creates a strong selective pressure on pathogen populations. This selective pressure leads to the rapid breakdown of this race-specific resistance gene and explains why these genes usually confer resistance of short duration (Bayles et al., 2000; Hovmøller et al., 2002; Wan et al., 2007; Brown, 2015). Moreover, varieties may have complementary resistances expressed only at later stages of plant development, also known as adult-plant resistances. These resistances usually confer long-term durable resistance against the pathogen, and can be either quantitatively inherited (Singh et al., 2011), or be due to major genes associated with adult-plant disease resistances (Börner et al., 2000; Dedryver et al., 2009; Milus et al., 2015).

Despite the consequences of diseases on crop yield and food quality, little attention has been paid so far on the consequences of epidemics on the commercial life cycles of crop varieties. On the one hand, the withdrawal from the market of highly susceptible varieties has been frequently reported in different countries (Bayles et al., 2000; de Vallavieille-Pope et al., 2000). On the other hand, many durable resistances, which could be defined as effective resistances lasting at least ten years (Johnson, 1984) have been found in varieties sown over a prolonged period, such as the varieties Camp Rémy, Renan and Apache (Mallard et al., 2005; Dedryver et al., 2009; Paillard et al., 2012). Except for the duration of the complete commercial life of a variety (Srinivasan et al., 2003), it seems no indicator has been proposed to describe the commercial life cycle of crop varieties, be it in a context of recurrent epidemics or not.

To bridge this gap, we first propose in the present study a set of new indicators and a dedicated methodological framework to characterize the commercial life cycle of a variety. Our approach takes into account special aspects of the study model, such as varieties having a short duration of commercial life cycle due to the potential impact of multiple drivers. These include changes of end-use markets, yield potentials and pathogen pressures associated with epidemics. We then apply our framework to a relevant case study to better understand the influence of yellow (stripe) rust epidemics (caused by *Puccinia striiformis* Westend. f. sp. *tritici* Eriks., thereafter *Pst*) on the commercial life cycle of bread wheat varieties (*Triticum aestivum* L.). We focused on France, an important production area of bread wheat well characterized in terms of varietal diversity and composition (Perronne et al., 2017) and *Pst* pathotype dynamics (de Vallavieille-Pope et al., 2012) at a fine spatio-temporal scale.

The study of the influence of yellow rust epidemics on bread wheat varieties allows us to demonstrate the usefulness of a set of indicators of the commercial life cycle of crop varieties in an epidemic context. Specifically, we addressed the following questions:

(1) Which indicators are most suitable to characterize the commercial life cycle of bread wheat varieties?
(2) Is there a reduced set of indicators allowing one to identify (i) susceptible varieties and (ii) varieties presenting a durable resistance based on the sole description of their commercial life cycles? We hypothesized that susceptible varieties could be characterized by (a) a short duration of the commercial life cycle, (b) a decrease in acreage sown starting at the year after the epidemic peak, and (c) a short duration of the growth phase of the commercial life cycle, even though the proportion of acreage sown during this phase should be higher than during the decline phase. Overall, we suggested that these features could allow one to differentiate between susceptible varieties, especially varieties whose resistance will be overcome a few years after their releases, and varieties presenting durable resistance to yellow rust.

2. Materials and methods

2.1. Description of the commercial life cycle of a variety and definition of indicators

The commercial life cycle of a variety can be described using a set of indicators that can take into account − or not − particular influential events that occurred during this commercial life cycle, such as the breakdown of a resistance based on a race-specific gene during an epidemic (Fig. 1, Table 1), or any radical change in end-use market or production standards. These indicators can be computed on semi-quantitative data because the commercial life cycle of varieties is generally short, from a few years to two decades for major cereals in France over the last decades (Silhol, 2010). These indicators are based on acreage percentages of varieties sown within a relevant agricultural production area (Table 1). We hypothesized that the commercial life cycle of a variety can be divided into only two phases, a growth phase and a decline phase. It should be noted that the plateau phase found in many life cycles (e.g. Golder and Tellis, 2004) was lacking in our data, probably because of the rapid and continuous replacement of varieties

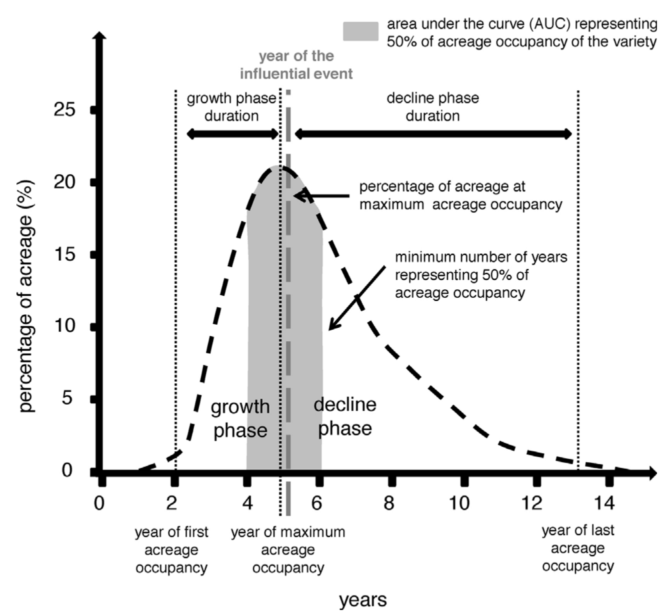

Fig. 1. Schematic representation of a commercial life cycle of a variety and its main indicators. The area under the curve (AUC), which sum to 1, corresponds to the total acreage of the variety during its complete commercial life cycle, since the year of first occupancy (usually the year of registration, here year 2) until the year of last acreage occupancy (here year 13). This schematic representation needs to be considered as a simplified view of the commercial life cycle of a variety, for instance, because the year of complete withdrawal is generally difficult to identify for bread wheat varieties that can be conserved via farm-saved seeds over a long period of time.