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Durable Strategies for Fungicides Use: Lessons from the Past and Leads for Improving the Future

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ABSTRACT

The durability of strategies aiming to delay fungicide resistance evolution in populations of plant fungi relies on the skillful deployment in time and space of the various molecules registered for a specific usage. Therefore, the optimization of these strategies constitutes a major challenge of integrated pest management, all the more in the context of new regulations aiming to decrease pesticide use. The respective advantageouses and disadvantageouses of anti-resistance strategies are a matter of debate in the scientific community. However, anti-resistance strategies should be more efficiently deployed in agricultural landscapes.

In this context, this paper reports the preliminary results of the FONDU project, aiming at (1) identifying and characterizing sustainable anti-resistance strategies and (2) disentangling the social and economic limits to their wide use on large territories. This project has a generic outcome but was first focused on *Zymoseptoria tritici,* the causal agent of septoria leaf blotch. Empirical data (*e.g.* the pluriannual dataset “Performance”, managed by the technical institute Arvalis-Institut du Végétal), as well as a specific model were mined to answer the first objective. Interviews with key French resistance managers, as well as economic models were carried to answer the second aim.

INTRODUCTION

Several factors, including regulation, social demand, climatic change, (eco)toxicity and pests resistance, limit fungicides use and contributed to the restriction and/or removal of many molecules in Europe or to the reduction of novel market introductions. As a consequence, the number and the diversity of registered molecules is decreasing. This highlights the necessity of improving the durability of the available fungicides, which are a ressource shared by a large number of actors (farmers, advisers, companies, scientists, regulators…) and managed through adapted strategies (*i.e.* limitation, alternation, mixture, mosaic and dose modulation). In social science, this situation refers to „The Tragedy of the Commons“ (Garret Hardin 1968), *i.e.* a dilemna arising from a situation in which multiple individuals, acting independentlly and rationnally consulting their own self-interest, will ultimately deplete a shared limited resource, even if it is clear that it is not in anyone’s long-term interest for this to happen.

This contexts points out several questions: (1) What is the most adapted strategy to a given cropping system to maximise the durability of fungicidesefficacy and which important factors should be considered for anti-resistance strategies? (2) Is fungicide efficacy a „Common“ asset and can we avoid the Tragedy of the Commons? (3) What are the socio-economic incentives and limitations to the substainable management of fungicides?

These questions were addressed in the FONDU (Fungicide Durability) project, being funded by the SMaCH metaprogram of INRA. This project gathers agronomists, plant pathologists, modellers, statisticians, economists and sociologists. In a first approach, it focuses on the resistance management of *Zymoseptoria tritici*, the causal agent of wheat leaf blotch, but should have a more general outcome. This paper reports preliminary results of this on-going project.

RESISTANCE EVOLUTION IN FRANCE AND ITS DETERMINANTS

Describing the dynamics of fungicide resistance over time and space, and the determinants of this evolution, is the first step to design anti-resistance strategies that are adapted to a given situation. Resistance development is often observed in national monitorings but refers to a limited number of samples. Here, we took the opportunity to develop a statistical analysis of the „Performance“ database, compiled by the „Performance network“ led by Arvalis-Institut du Végétal. This database gathers efficacy and resistance data from 50-70 yearly field trials, over the period 2012-2014 (methods described in Couleaud & al, 2015). Control (untreated) plots from this dataset were used to establish maps of resistance evolution towards benzimidazoles, DMIs and strobilurins at the „département“ geographical scale. An example is given in Fig. 1.

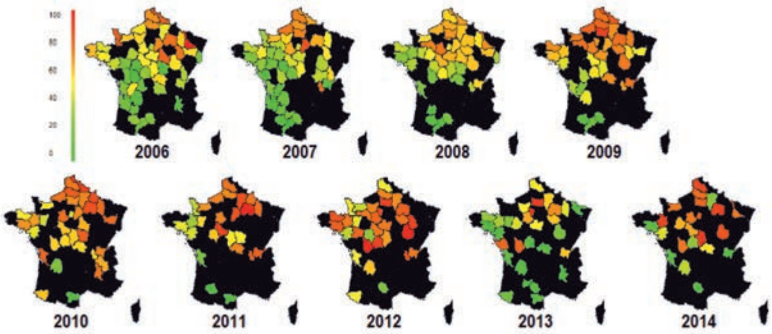

Figure 1 Evolution over time and space of TriR6 resistance to DMIs in the Performance network in France (2006-2014). *Colours indicate the frequency of TriR6 resistance in populations.*

The "Performance" database was also used to quantify the developement of resistance, while adjusting a Gompertz model on data and calculating growth rate for each phenotype (Fig. 2). This allowed to compare in a quantitative manner the resistance risk associated to each mode of action. We were also able, using geographical partition approaches, to detect significant spatial structure for QoIs and DMIs, at supra-regional scales (not shown). This should allow regional recommendation of fungicides use and the local adaptation of strategies.

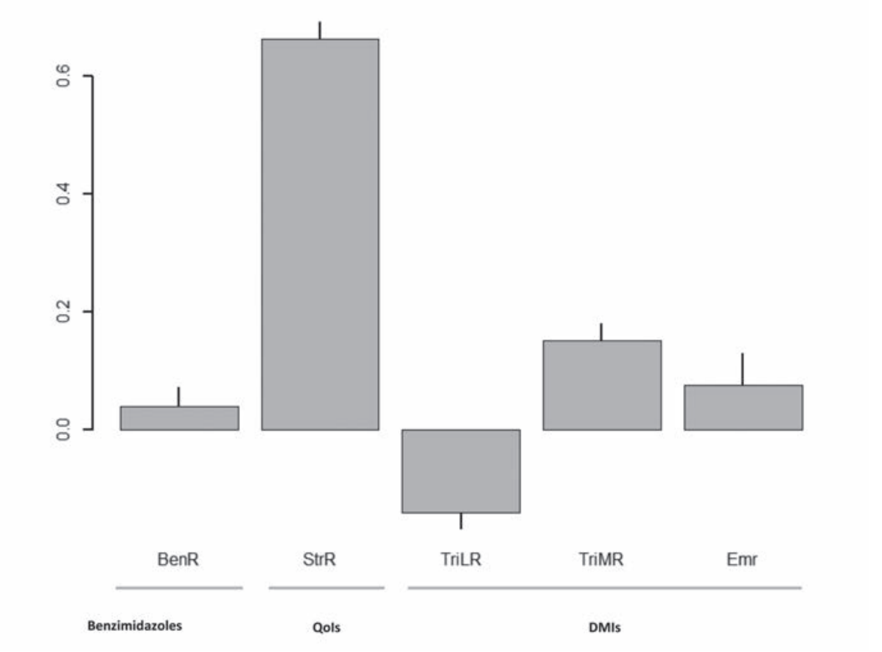

Figure 2 Growth rates of resistance according to modes of action in the Performance network in France (2006-2014).

If fungicide application is expected to select resistance in treated plots, little is known about other factors that may influence resistance evolution in a landscape. Therefore, we developped a mathematical model aiming to test the impact of pedo-climatic conditions, the length of crop rotation, the cultivar diversity and the regional use of fungicides on the evolution of resistance towards benzimidazoles, DMIs and strobilurins. Using panels of fungicide use at the regional scale, we found that this factor had a significant effect on local plots, in selecting the associated resistance phenotypes, meaning that the regional application may contribute to the local variation of resistance frequency, possibly due to spores migration, which is in agreement with *Z. tritici* biology (Parnell et *al.* 2006).

Additionnal work is needed to compare resistance evolution in plots treated *via* contrasted anti-resistance strategies, which should give indication on their durability.

MODELLING ANTI-RESISTANCE STRATEGIES

Similarly to van den Berg & el (2016), we developed a model of resistance evolution for *Z. tritici* designed to be exploited at the landscape level, in order to be able to investigate landscape-scale fungicide application strategies. The life cycle is composed of (1) a stage where the dynamics is purely local, during the wheat growing season, where several cycles of asexual reproduction result in pycnidiospores being disseminated very locally, and of (2) another stage in between wheat growing seasons, where sexual reproduction produces ascospores spread over long distances, from June to winter.

In this model, the landscape is represented as a grid made of patches, in which we observe the evolution along time of a number of sites –corresponding to foliar area units- which quantity increases throughout the growing season and which status varies depending on the epidemics.

It has been conceived to be connected with a simulator of agricultural landscapes (that simulates physical landscapes with particular characteristics and distributes treatments in each field). These simulated landscapes will be superimposed on the grid, which will enable to analyse the evolution of resistance as a function of different patterns of fungicide deployment, *i.e.* strategies, in realistic landscapes.

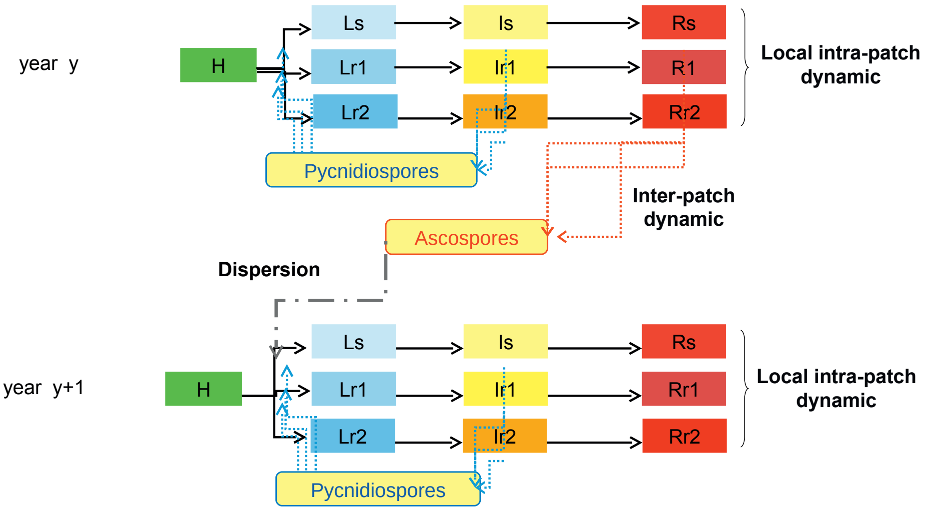

Figure 3 A mathematical model to study the durability of anti-resistance strategy in *Z. tritici*. This HLIR model considers the different stages "undergone" by sites potentially infected by the pathogen (healthy/latent/infectious/removed) and takes account of the simultaneous presence of several fungi strains. Each of these strains is characterized by its own life-history traits and response to specific fungicides. This model enables to explore different modalities of anti-fungi treatments.

Preliminary runs of this model confirmed that within a landscape, dose reduction could improve the substainability of a fungicide concerned by a qualitative resistance. It also showed that, at a constant dose, the heterogeneous application of a fungicide in a landscape would also decrease resistance selection, despite migration of resistant alleles occurring between plots.

INCENTIVES FOR RESISTANCE MANAGEMENT

Interviews carried out with 32 resistance managers from the French wheat cluster (chemical companies, cooperatives, agribusiness association…) confirmed that efficace fungicides were a common pool resource, because there is competition to use this finite ressource and also non-exclusion to prevent over-use. At last, as mentionned previously, the incoming flux and the stock are decreasing, the latter partly due to resistances. According to social sciences, the „Tragedy of the Commons“ may be avoided if collective actions are organized to manage the shared ressource. In the French wheat clusters, no effective coordination was detected, but collective active is in motion. For example, public (*e.g.* the „Performance network“) and private (the coordination of cooperative in hubs) dashboards to have collective decision have been set up. Emerging collective rules are set every year (*e.g.* the „note commune“, or general public recommendations on fungicides use and resistance management). These examples demonstrate that the dialog between stakeholders strenghtens, which could favor larger empowerment and the territorial coordination needed for resistance management.

The incentives of fungicides producers were explored while modelling their gain in managing resistance (Lemarié & Marcoul, in press). This theoritical model calculates the gain for companies, in a monopolistic or oligopolistic setting, where a new mode of action is registered, and not concerned by resistance in a first period, and then concerned by resistance in a second period, after fungicide use. This model showed that companies had a financial interest to increase fungicide prices to delay resistance and then get a better benefit in the second period. It also showed that fungicide users would benefit from a better coordination of resistance management, at the expense of companies, facing a lower demand. When information on resistance evolution is available (*e.g.* in monitorings), companies would have greater profits (i) while using this information to adapt fungicide price and then its use, and (ii) while sharing it with other companies to have a coordinated management. At last, the model showed that companies have financial interest to share information about resistance evolution with users if these are coordinated and already have (partial) resistance information. They would have no interest in sharing this information if it helps the users to get coordinated. In this context, this lays stress on the importance of public monitoring.

At last, the incentives of users to manage resistance in time and space were explored in a second, spatialized, model. Agricultural landscapes where formalized as a grid of lots grown by different farmers, being able to choose between a first fungicide, highly efficient, at high cost and at high risk of resistance, and a second fungicide, less efficient but cheaper and at lower resistance risk, to protect their lots (Fig. 4). According to the geographical setting, as not all lots are equivalent, not all farmers have the same incentive to deviate their treatment. This context induces an economic trade-off between the long-term costs of deviating and the short-term benefit of deviating.

This model shows that when farmers are perfectly informed on the consequences of their treatment choice, the farmer who hast he highest incentive to deviate may be easily compensated not to do so in order to minimize the negative spatial effect, and therefore, to maximize the collective gains (for all farmers in both periods). Further work is needed to optimize the spatial coordination, and identify the kind of incentive (tax, bonus, policy) which would favor coordination.

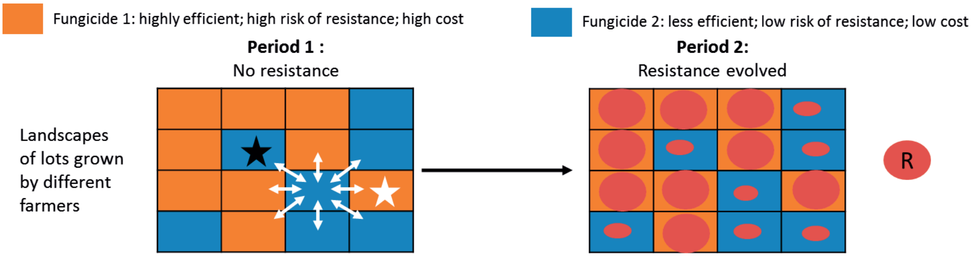

Figure 4 A mathematical model to study the incentives of fungicide users to manage resistance in a given cropping season. Resistance evolves in lots over time, in a different manner according to the resistance risk associated each fungicide. The impact of local choices has consequences on the whole community because fungi migrate between lots.

CONCLUSION

This paper only reports preliminary results from the FONDU project and on-going work should give more information on the durability of the various strategies developped to manage resistance on *Z. tritici*, after two complementary approaches (namely, the statistical analysis of empirical data, and the matemathical modelling of resistance evolution). Nevertheless, these first results underline that resistance management is a complex issue and that inputs not only from biological sciences but also from social sciences may help proposing efficient strategies in response tot he incentives of the different resistance managers.

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