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Sustainable plant resistance management in agricultural landscapes

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The deployment of resistant crops often leads to the emergence of resistance-breaking pathogens that suppress the yield benefit provided by the resistance. The theoretical analyses presented here are designed to provide guidelines for farmers aiming altogether to optimise the deployment of a resistant cultivar in a landscape over several years. We explored how farmer main leverages (resistant cultivar choice, resistance deployment strategy, landscape planning, cultural practices) can be best combined in a given epidemiological context (defined in a fully susceptible landscape by epidemic intensity and landscape structure) to achieve resistance durability while minimising yield losses due to plant viruses.

Assuming a gene-for-gene type of interaction, virus epidemics are modelled in a landscape composed of a mosaic of resistant and susceptible fields, subjected to seasonality, and of a reservoir hosting viruses year round. The model links the genetic and the epidemiological processes shaping at nested scales the demo-genetics dynamics of viruses. The description of the seasonality leads us to use a semi-discrete modelling approach that is a hybrid dynamical system that undergoes continuous dynamics in ordinary differential equations most of the time (describing the in-season epidemic dynamics in fields) and that experiences discrete dynamics (mimicking pathogen overwintering in reservoirs) at some given time instants.

The choice of the resistance gene (characterized by the equilibrium frequency of the resistance-breaking virus at mutation-selection balance in a susceptible plant) is the most influential leverage of action. In landscapes with low to intermediate epidemic intensities (*i.e.* when the mean proportion of plants infected during a season is lower than 0.5 before resistance deployment), resistance genes defeated by the accumulation of two mutations in the viral genome are likely to be durable, whatever the proportion of resistance released. The deployment of such resistance genes significantly reduces the overall damage caused by the pathogen. Depending on the landscape structure considered (*i.e.* on the connectivity between the fields and the reservoir hosts), this reduction can be much more than proportional to the proportion of resistance released. By contrast, resistance genes defeated by a single mutation are only likely to be durable in landscapes with low epidemic intensities (*i.e.* when the mean proportion of plants infected during a season is lower than 0.1).

Our results also showed that optimal strategies of resistance deployment (*i.e.* strategies maximizing the yield increase provided by resistance deployment) range from mixture (where susceptible and resistant cultivars coexist) to pure strategies (with only resistant cultivar) depending on the resistance characteristics and on the epidemiological context (epidemic incidence, landscape connectivity). For example, for most resistance genes, it is almost possible to suppress the virus from the reservoir by deploying a high proportion of resistance in landscapes where epidemics are primarily driven by infection from the reservoir hosts (*i.e.* situation of pathogen spillover).

Finally, we demonstrate and discuss gaps concerning virus epidemiology across the agro-ecological interface that must be filled to achieve sustainable disease management.

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Keywords: Deployment strategy; Durable resistance; Evolutionary epidemiology; Gene-for-gene model; Landscape epidemiology.