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NEWS AND COMMENTARY

Evolutionary genetics

Fight or flinch?

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Infectious disease is becoming increasingly recognised as having a major influence on the evolution of biological populations. Infected individuals have, broadly speaking, two ways of coping with the disease. One is resistance, in which the host prevents infection or growth of the pathogen. The other is tolerance, in which the host compensates for damage caused by a pathogen. A recent paper has explored the genetics of the two responses in a wild plant, *Mimulus guttatus*, the interaction between them and their effects on reproductive fitness (Carr *et al*, 2006).

In contrast to most other aspects of plant diseases, our knowledge of tolerance has largely come from natural populations. In agriculture, disease resistance is a key target in breeding new crop varieties, while tolerance scarcely rates a mention in textbooks. A recent revival of research on tolerance has been stimulated by the recognition that farming must become more sustainable. This will require the productivity of crops to be maintained despite unpredictable variability in the environment, including diseases. Control of disease is becoming ever more challenging as pathogens have evolved insensitivity to many previously effective crop protection chemicals (Ma and Michailides, 2005). Contrasts between studies of tolerance in wild plants, including that of Carr *et al* (2006), and in crops (Parker *et al*, 2004) raise several questions about tolerance in plants and indicate that the two communities of researchers would benefit from sharing experience and approaches.

First, a basic question: how should resistance and tolerance be defined? Different definitions are in use, but the two terms may be regarded as different stages of a single process (Figure 1). It is easier to distinguish them in some diseases than in others. Powdery mildew fungi, for example, grow as colonies of mycelium on leaf surfaces. Resistance limits the amount of fungus on the leaf, while tolerance increases both the plant's vegetative growth and its fecundity at a given level of infection.

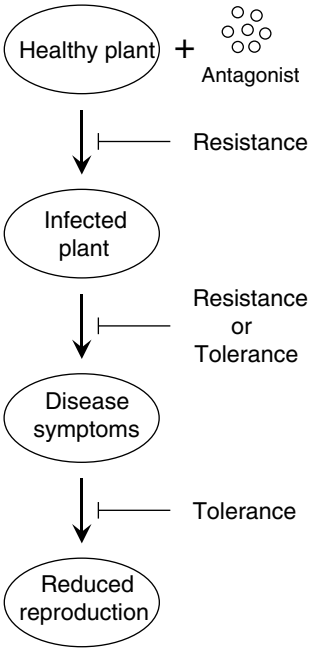

Figure 1 The pathway to fitness loss. Resistance reduces the severity of infection by an antagonist, such as a herbivore or a pathogen. Tolerance reduces the extent to which seed output is reduced by a given amount of disease. Both processes contribute to reducing the amount of damage caused by a given amount of antagonist at the initial site of infection.

Carr *et al* (2006) define resistance and tolerance in a similar way, the former as restriction of virus titres and the latter as reduction of the subsequent loss of growth and reproduction of infected plants. Septoria tritici blotch of wheat, studied by Parker *et al* (2004), is a less clear-cut case and is thus typical of the great majority of diseases. The symptoms are necrotic patches on the leaf bearing fruiting bodies (pycnidia) of the fungus. Resistance limits the amount of fungus in the leaf and thus the number of pycnidia, while tolerance maintains grain production of diseased plants. But what about a reduced area of necrosis, or, conversely, maintenance of green leaf area? This may be the result of resistance, restricting the growth of fungus in the leaf, or of tolerance, increasing the ability of infected leaf tissue to remain healthy. In the latter case, the leaf may be regarded as susceptible to the fungus but tolerant of, suffering limited damage.

How should tolerance be estimated? Two types of measure are in general use (Strauss and Agrawal, 1999). One, widely used in research on insect herbivory, compares the fitness of damaged and undamaged plants and defines tolerance as the difference between the latter and the former. Carr *et al* (2006) apply this concept to define tolerance as the difference of the fitnesses of undiseased and virus-infected, full-sib plants. If there is quantitative variation in the infection of diseased plants, however, this definition confounds tolerance with resistance because resistant plants, with lower levels of infection, almost inevitably have fewer disease symptoms and thus less loss of fitness.

This difficulty may be overcome in the second method of estimating tolerance, which uses regression of the fitness variable on disease levels. Here, the slope of the regression can be used as a measure of tolerance. Estimating the heritability of tolerance, defined in this way as genetic variation in the regression slope of one variable on another, clearly raises formidable challenges for biometrical genetic approaches that compare responses among families. It is much more easily done by comparing inbred lines, as Parker *et al* (2004) did in estimating tolerance to septoria among a set of cultivars of wheat. Doubled-haploid lines could also be used in a similar way to study the genetics of tolerance, as defined here.

Tolerance may seem to be a beneficial trait, but does it have any disadvantages? There is plenty of evidence for costs of disease resistance in wild plants (Bergelson *et al*, 2001; Tian *et al*, 2003) and some in crops (Brown, 2002). Likewise, it is reasonable to suppose that a plant's level of tolerance is adaptive, determined by a balance between costs and benefits. The most common way of defining such a cost is to examine the relationship between tolerance and fitness in the absence of disease. Some studies, but by no means all, have detected costs of tolerating herbivores (Strauss and Agrawal, 1999), but even less is known about the possible costs of tolerating pathogens. Although Carr *et al* (2006) detected no cost of

either resistance or tolerance, Parker *et al* (2004) found a weak association between greater tolerance of septoria and lower grain yield in the absence of septoria, which tentatively indicates that wheat pays a price for being tolerant.

Apart from a direct cost to plant fitness in the absence of disease, another potential cost of tolerance is a trade-off with resistance. van der Meijden *et al* (1988) proposed that resistance and tolerance are alternative strategies to cope with antagonists, but trade-offs between them are difficult to detect and the evidence is distinctly mixed (Strauss and Agrawal, 1999). In Carr *et al*'s (2006) populations, by contrast, there was a positive association between resistance and tolerance. Although the population studied may not have been optimally adapted to the virus, more data are clearly needed to discover the reason for this unexpected positive correlation or indeed to understand if there is a defect in current theory.

Does the predicted trade-off between resistance and tolerance mean that they are necessarily alternatives, or can plant breeders achieve both? Breeders have some control over disease levels in their trials. Simultaneous selection of lines with high yield in trials treated with pesticides and both low disease levels and high yield in untreated trials may achieve both resistance and tolerance. By contrast, modern European farming conditions, with fungicides used to suppress disease, may select for neither resistance nor tolerance if both are costly in the absence of disease.

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