

Stability of genetic polymorphism in host–parasite interactions

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Allelic diversity is common at host loci involved in parasite recognition, such as the major histocompatibility complex in vertebrates or gene-for-gene relationships in plants, and in corresponding loci encoding antigenic molecules in parasites. Diverse factors have been proposed in models to account for genetic polymorphism in host–parasite recognition. Here, a simple but general theory of host–parasite coevolution is developed. Coevolution implies the existence of indirect frequency-dependent selection (FDS), because natural selection on the host depends on the frequency of a parasite gene, and *vice versa*. It is shown that polymorphism can be maintained in both organisms only if there is negative, direct FDS, such that the strength of natural selection for the host resistance allele, the parasite virulence allele or both declines with increasing frequency of that allele itself. This condition may be fulfilled if the parasite has more than one generation in the same host individual, a feature which is common to most diseases. It is argued that the general theory encompasses almost all factors previously proposed to account for polymorphism at corresponding host and parasite loci, including those controlling gene-for-gene interactions.

Keywords: natural selection; host–parasite interactions; coevolution; frequency-dependent selection; victim–exploiter dynamical systems; gene-for-gene relationship

1. INTRODUCTION

Infectious disease limits reproductive fitness, while resistance to disease increases reproductive success and is thus a target for natural selection. In both plants and animals, defences are induced on recognition of parasite molecules, while parasites avoid detection by loss or mutation of those molecules (Dangl & Jones 2001). There is allelic diversity at parasite-recognition loci such as those controlling the major histocompatibility complex (MHC) in vertebrates (Apanius *et al.* 1997; Hill 2001) or gene-for-gene (GFG) relationships in plants (Thrall *et al.* 2001) and at parasite loci encoding proteins detected by the host (Thrall *et al.* 2001).

Current theories for the maintenance of polymorphism at these loci are diverse and complex, with a limited range of biological applicability, because they involve interactions between many genetic, epidemiological and ecological factors (Hughes & Nei 1992; Bergelson *et al.* 2001*a*). This has given rise to a view that complex interactions between many factors may be required for polymorphism (Bergelson *et al.* 2001*a*; Brown 2003*a,b*; De Meaux & Mitchell-Olds 2003).

This paper simplifies and generalizes the theory of coevolution of host–parasite specificities. We derive a simple, general condition for stability in a two-component system of an exploiter and a victim, such as a parasite and its host (§2). We then investigate its relevance to coevolution by analysing the GFG relationship, a paradigm for host–parasite interactions (Flor 1971; Thompson & Burdon 1992; Dangl & Jones 2001; Holub 2001). By showing that the classic GFG theory does not fulfil this condition, we demonstrate the need to include

epidemiological factors in models of coevolution (§3). We then show that GFG interactions are stabilized by features of epidemiology which are common to almost all diseases of animals as well as plants (§4). Finally, we argue that features of genetics, epidemiology and ecology proposed to account for stable polymorphism in GFG models are special cases of the general condition (§5).

2. GENERAL THEORY OF STABLE POLYMORPHISM IN COEVOLUTION

A condition for stable polymorphism in host–parasite interactions is derived from principles of linear algebra (Kot 2001). We focus on stability because it predicts situations in which polymorphism may be maintained in both species and thus be detectable. If a system is unstable, polymorphism will be lost in one or both species and therefore will not be detected.

A host–parasite interaction is a victim–exploiter (V – E) interaction, in which increased growth of the exploiter (E) reduces the growth rate of the victim (V) and increased availability of the victim increases growth of the exploiter, such that

$$\frac{\partial(dV/dt)}{\partial E} < 0 \quad \text{and} \quad \frac{\partial(dE/dt)}{\partial V} > 0. \quad (2.1)$$

Conditions for stability in this dynamical system are obtained by analysis of its Jacobian matrix. In continuous time, V and E evolve to stable values if

$$\frac{\partial}{\partial V} \left(\frac{dV}{dt} \right) + \frac{\partial}{\partial E} \left(\frac{dE}{dt} \right) < 0. \quad (2.2)$$

(see section 1 of electronic supplementary material).

In host–parasite interactions, host resistance (H) and parasite infectivity (P) coevolve. For an interior equilibrium point to be stable, the rate of increase of H , P or

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Electronic supplementary material is available at <http://dx.doi.org/10.1098/rspb.2006.0281> or via <http://www.journals.royalsoc.ac.uk>.