Trends in Microbiology

CellPress

Review

# Trade-off Mechanisms Shaping the Diversity of Bacteria

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**Strain-to-strain variations in bacterial biofilm formation, metabolism, motility, virulence, evolvability, DNA repair and resistance (to phage, antibiotics, or environmental stresses) each contribute to bacterial diversity. Microbiologists should be aware that all of these traits are subject to constraints imposed by trade-offs, so adaptations improving one trait may be at the cost of another. A deeper appreciation of trade-offs is thus crucial for assessing the mechanistic limits on important bacterial characteristics. Studies of the negative correlations between various traits have revealed three molecular mechanisms, namely, trade-offs involving resource allocation, design constraint, and information processing. This review further discusses why these trade-off mechanisms are important in the establishment of models capable of predicting bacterial competition, coexistence, and sources of diversity.**

## Trends

Trade-offs have been identified in nearly every important microbial characteristic.

Trade-offs constrain evolutionary adaptations in bacterial properties and prevent ecological fitness in all environments.

The identification and classification of trade-offs has progressed from the ecological and phenomenological to the molecular level.

Artificial control of trade-offs has produced unprecedented understanding of how traits are linked and how intermediate settings of trade-offs behave.

The continuing mutational change of trade-off settings in varying environments is the likely source of a great deal of intra- and interspecies diversity.

## The Role of Trade-offs in Microbiology

The observation that biological adaptations have some secondary effects on fitness precedes even the ideas of Darwin. As early as Goethe's Law of Compensation [1], it was recognized that 'in order to spend on one side, nature is forced to economise on the other side'. Interpreted for bacteria, this notion suggests that cellular resources allocated to one characteristic can lead to reduced fitness in another. Such negative correlations between traits are called trade-offs, and their common features and the relationship between two traits are introduced in Box 1.

As more widely recognized with plants and animals, trade-offs constrain the range of phenotypes open to organisms [2,3]. Negative correlations between life-history characteristics, such as longevity, growth rate, offspring number, and resistance to stress or predation, have been observed in a wide range of organisms [4]. As proposed by Levins and discussed by Stearns, the partitioning of resources in food to reproduction or to survival processes such as stress resistance (i.e., resource allocation) may be a cause of trade-offs [2,5]. Although initially proposed for plants, insects, and animals, there is no reason why these notions do not apply to microbes as well.

Trade-offs are recognized to be central to issues ranging from speciation and adaptive radiation to coexistence in communities [6]. As Tilman noted [7], the answer to the great diversity of species on Earth 'may lie in quantifying the trade-offs that organisms face in dealing with the constraints of their environment'. What is utterly amazing is that the natural diversity of bacteria revealed by genome sequences is rarely discussed in terms of trade-offs. Microbiology textbooks, even microbial ecology texts, rarely discuss how trade-offs shape organisms. This review will discuss why microbiologists, especially molecular biologists and biochemists, should put a greater emphasis on understanding how trade-offs underpin both intra- and interspecies diversity in bacteria.

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Box 1. The Essentials of a Trade-off between Two Traits

When two negatively correlated traits (such as the pairs in Figure 1) are measured in a range of natural bacterial isolates (e.g., organisms $x_1$ to $x_5$), the magnitude of Trait 1 and Trait 2 can be plotted along the axes as in Figure I. The $x_1$ and $x_5$ organisms represent the most extreme settings of the trade-off, having specialized on one or other trait. The black boxes describe the organisms at the two extremes if a growth-resistance trade-off is used as the example. Organisms ($x_2$ to $x_4$) can be found at intermediate settings of a trade-off that fall on the curve in Figure I. The curve (light blue) is the cleanest example of a survival-multiplication trade-off shape of *Escherichia coli*, determined using synthetic strains with fixed trade-off settings [14]. This particular curve shape (plotting growth on lactate versus acid resistance [14]) allows organism $x_2$ to $x_4$ to have both appreciable resistance and growth in an intermediate setting of the trade-off. In principle, trade-off curves can be of any shape, being linear, sigmoidal, or with convex or concave curvatures [2]. Accurate trade-off shapes are unknown for most pairs of traits however.

Trade-offs allow diversity to develop for two reasons. First, organisms can adapt along trade-off shapes, depending on the environment. For example, organism $x_2$ could gain fitness in a more stressed environment through the selection of mutations in $x_2$ that change its trade-off settings to position $x_3$ (or $x_4$ or other points to the right along the curve). The consequence of living in a nonconstant environment is that free-living bacteria will develop a variety of trade-off settings. The species-wide diversity of trade-off settings is a consequence of this and is discussed in the text.

The second feature needed for diversity to be maintained is the ability of different types to coexist in an environment. Coexistence of organisms is possible with different trade-off settings because the overall fitness of, say $x_2$ and $x_3$, may be the same in some environments where both traits contribute to fitness. Equal fitness of $x_2$ and $x_3$ could occur in an environment with partial stress and intermediate nutrient availability. This trade-off-dependent coexistence has been experimentally demonstrated [10,14,66].

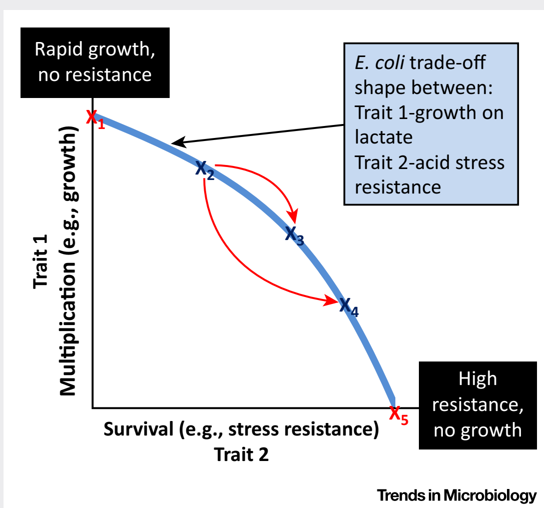


Figure I. A Composite Diagram of the Relationship between Two Traits Exhibiting a Trade-off. The traits in the example involve growth on lactate minimal medium (multiplication) and acid-stress resistance (survival) of *Escherichia. coli* strains that have fixed but distinct levels of a global stress regulator. The experimental details for getting the shape plotted in the figure are described in [14]. The symbols $x_1$ to $x_5$ represent organisms that have distinct levels of the two traits and which fall on the plotted line.

The precise relationships between traits and the trade-off shapes in Box 1 are difficult to unravel, especially with higher organisms [8]. The partitioning of resources in food to either reproduction or to survival [2,5] is extremely hard to dissect in complex organisms [8], but considerably easier in bacteria [9,10]. The simplicity of bacteria indeed allows trade-offs to be analysed in molecular detail, and bacteria have been particularly useful in demonstrating that alternative molecular mechanisms underpin trade-offs. Progress in this direction is of recognized importance [11,12] because, as stated ever since Stearns [11], 'we have a lot of evidence that trade-offs exist; we have very little understanding of the mechanisms that cause them'. An understanding of trade-offs is important because the mechanisms are crucial in the establishment of credible models capable of predicting the effects of trade-offs on competition and coexistence [13,14].