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Review

# The Ecology and Evolutionary Dynamics of Meiotic Drive

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**Meiotic drivers are genetic variants that selfishly manipulate the production of gametes to increase their own rate of transmission, often to the detriment of the rest of the genome and the individual that carries them. This genomic conflict potentially occurs whenever a diploid organism produces a haploid stage, and can have profound evolutionary impacts on gametogenesis, fertility, individual behaviour, mating system, population survival, and reproductive isolation. Multiple research teams are developing artificial drive systems for pest control, utilising the transmission advantage of drive to alter or exterminate target species. Here, we review current knowledge of how natural drive systems function, how drivers spread through natural populations, and the factors that limit their invasion.**

## Trends

Both naturally occurring and synthetic 'meiotic drivers' violate Mendel's law of equal segregation and can rapidly spread through populations even when they reduce the fitness of individuals carrying them.

Synthetic drivers are being developed to spread desirable genes in natural populations of target species. How ecology influences the population dynamics of meiotic drivers is important for predicting the success of synthetic drive elements.

An enduring puzzle concerns why some meiotic drivers persist at stable, intermediate frequencies rather than sweeping to fixation.

Drivers can have a wide range of consequences from extinction to changes in mating system.

## The Battle for Transmission

One of the few rules in biology is Mendel's law of equal segregation: the two copies of each gene and/or chromosome in a diploid organism are transmitted with equal probability to its offspring. Although often taken for granted, it is increasingly clear that equal segregation is a fragile détente in a world of constant **intragenomic competition** (see Glossary) for passage to the next generation. Such **conflict** plays out in the arenas of meiosis and gametogenesis, and results in meiotic drive [1], the biased transmission of a gene or chromosome against its alternative (Box 1). Because selection on meiotic drive elements operates at a level below that of the individual, drivers can spread through populations even if they reduce organism fitness [2]. By the same process, recently developed synthetic drive elements, which are currently still confined to laboratories, have the potential to rapidly modify genomes in wild populations [3]. Both natural and **synthetic drive systems** can have profound ecological, evolutionary, and genomic consequences.

### Meiotic Drive Systems in Nature

In this review, we explore the ecological and evolutionary dynamics of natural meiotic drive systems. We focus on three types of drive: **female meiotic drive**, **male meiotic drive** (**sperm killers**), and drive in haploid spores (**spore killers**, Box 1). However, meiotic drive can

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encompass a broad range of systems we do not discuss, including supernumerary B chromosomes, zygote killers, and paternal genome eliminators.

Female meiotic drive occurs when homologous chromosomes are differentially transmitted to the egg during meiosis. In plants and animals, female meiosis is asymmetric, with only one of the four meiotic products becoming an egg or, in plants, a megagametophyte ([4], Box 1). Any chromosomal variant that biases its own segregation (e.g., by preferentially associating with and moving toward the egg pole at Meiosis I) will be transmitted to more than half of the maturing eggs. Although this bias does not necessarily reduce the production of eggs (as only one egg matures per meiosis), the fitness of other alleles at the same locus, that do not bias transmission, and alleles linked to them, is reduced. Such **meiotic drivers** could reduce the fitness of individuals that carry them, if the driving variant is genetically linked to deleterious mutations or has deleterious pleiotropic effects.

Male meiotic drive takes multiple forms – some at least partially meiotic, some entirely post-meiotic – but all involve a driving element that prevents maturation or function of sperm that do not contain it. Because haploid sperm within a single ejaculate compete to fertilise the same pool of eggs, disabling noncarrier sperm results in transmission of the driving element to more than half of the functional gametes and resulting offspring ([5], Box 1). However, disabling noncarrier sperm often reduces fertility [6].

Spore drive in fungi, in which the products of meiosis are packaged together in an **ascus**, operates via similar mechanisms. Spores with one haploid genotype will kill or disable spores of the alternative haplotype ([7], Box 1). If spores disperse long distances sibling spores are unlikely to compete and killing them will not increase the killer's fitness. However, spore killing can be beneficial if there is local resource competition.

Exciting progress has been made in dissecting the genetic and cellular mechanisms of multiple drive systems that span eukaryotic diversity (Box 1). However, we are still in the early stages of understanding how these genetic systems interact with ecology to shape the dynamics of drivers in natural populations. The fate of a meiotic driver depends on the costs of transmission bias, the mating system, environmental factors, and population and geographic structure that affect the fitness of its carriers. These interactions might then affect how drivers contribute to genetic and phenotypic variation within and among populations, potentially contributing to speciation [8]. On a larger timescale, coevolution between drive elements and suppressors

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### Box 1. Definition, Mechanisms, and Species

Meiotic drive occurs when alleles, haplotypes, or chromosomes subvert mechanisms of fair segregation to obtain greater than Mendelian transmission at the expense of homologues. Sandler and Novitski [1] first used the term ‘meiotic drive’ to describe biased transmission that results as ‘a consequence of the mechanics of the meiotic divisions’. For instance, in taxa with asymmetric female meiosis, structural elements of chromosomes – for example, centromeres, **telomeres**, and heterochromatic neocentromeres (‘knobs’) – can compete for inclusion in the gamete and hence transmission to subsequent generations, with failing chromosomes discarded into the polar bodies. Examples of drive through female meiosis have been observed in mice [22,36], maize [80], and monkeyflowers ([35], Figure IA). However, ‘meiotic drive’ is often used in a broader sense to include biased transmission resulting from a variety of premeiotic, meiotic, and postmeiotic events during gametogenesis [17]. In males, for instance, drive elements can achieve biased transmission by killing sperm that lack the element (Figure IB). These gametic drivers typically involve a drive locus and a target locus. They can occur on autosomes – as in the mouse *t* haplotype [56] and the fruit fly *Segregation Distorter* [31] – or on sex chromosomes, causing distorted sex ratios among progeny – as in *Silene* flowering plants [81], stalk-eyed flies [82], mosquitoes [17], and many *Drosophila* species [17]. Finally, in fungi a heterozygous cross between strains carrying a spore killer allele and a sensitive allele results in elimination of haploid ascospores that lack the spore killer allele ([7], Figure IC). Spore killer genetics can involve a single locus [83], or be complex, involving multiple loci [33]. Even this brief summary highlights that selfish drive elements gain transmission advantages through diverse genetic mechanisms across the eukaryotes.