

Autopolyploid establishment through polygenic adaptation

Abstract

We define the infinitesimal model of quantitative genetics (*sensu* Barton et al. (2017)) for the inheritance of an additive quantitative trait in a mixed-ploidy population consisting of diploid, triploid and autotetraploid individuals producing haploid and diploid gametes. We implement efficient simulation methods and use these to study the quantitative genetics of mixed-ploidy populations and the establishment of autotetraploids in a new habitat. We show that ~~for rare~~, when migration from the source population is rare, autotetraploids are more likely to ~~found a successful population~~ establish in the new habitat than diploids under a very broad range of conditions, but that this is unlikely to sufficiently counter the scarcity of tetraploid founders when the source is predominantly diploid. We assess in more detail how minority cytotype exclusion interacts with migration load in the establishment process and evaluate the impact of additional sources of prezygotic isolation, specifically selfing and assortative mating, on the relative establishment probabilities of the different cytotypes. In the discussion we consider how inbreeding depression may impact our findings.

Keywords: polyploidy, adaptation, establishment, inbreeding, quantitative genetics

Introduction

Many plant species exhibit ploidy variation (Levin, 2002; Soltis et al., 2007; Rice et al., 2015), and many of these *mixed-ploidy* species have populations in which different cytotypes coexist or form contact zones (Kolář et al., 2017). How such mixed-ploidy populations emerge and are maintained has proven somewhat challenging to understand.

Consider for instance a randomly mating diploid population. Under the commonly accepted view that new polyploid plants are mostly formed through the union of unreduced gametes (Bretagnolle and Thompson, 1995; Herben et al., 2016; Kreiner et al., 2017b), a new tetraploid individual originating by a chance encounter of two unreduced diploid gametes (an event occurring at an appreciable rate; Kreiner et al. (2017a)) is highly unlikely to establish a stable tetraploid subpopulation, as most of its gametes will end up in unfit hybrids of odd ploidy level (a phenomenon referred to as ‘triploid block’, see Ramsey and Schemske (1998); Köhler et al. (2010); Brown et al. (2024)). This ~~negative~~ positive frequency dependence effect in mixed-ploidy populations is commonly referred to as *minority cytotype exclusion* (MCE), after Levin (1975). It is well-appreciated that, as a consequence of MCE, the rate of unreduced gamete formation needs to be extraordinarily high for tetraploids to establish a stable subpopulation in a large random mating ~~initially diploid population~~ population initially dominated by diploids (Felber and Bever (1997), see also section S2.1).

Hence, to explain the widespread occurrence of mixed-ploidy populations, additional factors besides the continuous formation of polyploids through the union of unreduced gametes need to be considered. Firstly, chance establishment of tetraploids through drift could occur. Indeed, the problem is somewhat analogous to the spread of underdominant chromosomal rearrangements, where local establishment through genetic drift and subsequent spreading in a subdivided population ~~through by means of~~ local extinction and recolonization ~~dynamics~~ has been suggested as a plausible model (Lande, 1985). However, MCE is quite strong ~~in randomly mating mixed-ploidy populations under random mating~~, and the population size has to be very small for local tetraploid establishment to occur at an appreciable rate (Rausch and Morgan (2005), see also section S2.2). Secondly, any form of *prezygotic isolation* between cytotypes could promote establishment of polyploid cytotypes by alleviating MCE. Particularly relevant are assortative mating by cytotype (for instance through phenological differences across cytotypes, or differences in pollinators; ~~Kolář et al. (2017)~~ Husband and Sabara (2004); ~~Kolář et al. (2017)~~), self-fertilization (Rausch and Morgan, 2005; Novikova et al., 2023), ~~and~~ localized dispersal (Baack, 2005; Kolář et al., 2017) ~~and asexual reproduction (Van Drunen and Friedman, 2022)~~. Finally, selection may be invoked to explain the establishment of polyploids. Tetraploids may have higher relative fitness than their diploid counterparts due to reduced inbreeding depression (~~Ronfort, 1999; Otto and Whitton, 2000~~) (~~Husband and Schemske, 1997; Ronfort, 1999; Otto~~), or due to being better adapted to (changing) environmental conditions (Van de Peer et al., 2021).

~~None~~ ~~However, none~~ of these factors is likely to explain by itself the establishment of polyploids, and the consensus in the field appears to be that some mix of the above is required to explain the occurrence of mixed-ploidy populations in nature (Kolář et al., 2017; Mortier et al., 2024). ~~In particular, polyploids are thought to establish mainly in novel, unoccupied habitats where they evade MCE (for instance at range edges, or after local extinction due to environmental change) (Griswold, 2021)~~

~~Many empirical studies of mixed-ploidy populations find that polyploids established in peripheral habitats at the edge of a species' range (reviewed in Griswold (2021)), and this is in accord with large scale biogeographical patterns (Rice et al., 2019). This raises the question: which aspects of the process of adaptation to marginal habitats could promote the establishment of polyploid populations? In a peripheral habitat, a new polyploid population may be more likely to reach an appreciable size as it evades to some extent the negative effects of MCE. However, at the same time, such peripheral habitats are likely to present adaptive challenges to establishment (Kawecki, 2008) (Kawecki, 2008; Sachdeva et al., 2022), and if polyploids are able to colonize such habitats at an appreciable rate, they must somehow be better adapted to local conditions, or more able to adapt to those conditions despite inbreeding and maladaptive migration, compared to diploids. Indeed, when the source population is dominated by diploids, the probability that a migrant individual is tetraploid will be very small ($\sim u^2$, where u is the probability that a diploid produces an unreduced gamete in meiosis), so that tetraploids need a substantial advantage during colonization if they are to establish before diploids do.~~ More often than not, local adaptation is polygenic in nature (Pritchard and Di Rienzo, 2010; Barghi et al., 2020), involving many weakly selected variants across the genome, and adaptation during polyploid establishment is unlikely to be an exception. Recent studies on local adaptation in autopolyploids indeed tend to find a polygenic basis of adaptation (Bohutínská et al., 2021; Konečná et al., 2022), however it is not clear how observed adaptive differentiation in established tetraploid populations relates to adaptation that occurred during initial establishment.

While there have been substantial modeling efforts aimed at understanding autotetraploid establishment within diploid populations (Levin, 1975; Felber, 1991; Felber and Bever, 1997; Rausch and Morgan, 2005; Oswald and Nuismer, 2011; Clo et al., 2022), the problem of polyploid establishment in peripheral habitats remains largely unaddressed (but see Griswold (2021)), despite its centrality to verbal arguments about the establishment of polyploids in natural populations (Kolář et al., 2017; Van de Peer et al., 2021; Clo, 2022b).

Here we develop a model for the establishment of a mixed-ploidy population in a novel, unoccupied habitat based on Barton and Etheridge (2018). In order to establish in the novel habitat, the population has to adapt to local environmental conditions. We assume fitness is determined by directional selection on a single polygenic trait, which can be interpreted as log fitness at low density in the new habitat. As in Barton and Etheridge (2018), we assume the trait follows the infinitesimal model (*sensu* Barton et al. (2017), i.e. the ‘Gaussian descendants’ infinitesimal model (Turelli, 2017)). We extend the infinitesimal model, and the approach for exact simulation of trait evolution under the infinitesimal model, to mixed-ploidy populations. This is a first contribution of the present paper. We then use simulations to study tetraploid establishment, both from single migrants and under continuous migration from a predominantly diploid source population, examining the effects of autopolyploid genetics, maladaptive migration, selfing and assortative mating on the probability that autotetraploids establish in the novel habitat.

Model and Methods

Mixed-ploidy population model

Our notation is summarized in table 1. We consider a mixed-ploidy population of size N consisting of N_2 diploid, N_3 triploid and $N_4 = N - N_2 - N_3$ tetraploid individuals. We assume an individual of ploidy level k forms haploid and diploid gametes with proportions u_{k1} and u_{k2} , as well as a proportion $1 - u_{k1} - u_{k2}$ inviable (e.g. aneuploid or polyploid) gametes. The (relative) fecundity of a k -ploidy individual is hence $u_{k1} + u_{k2}$. Unless stated otherwise, we will assume

$$\begin{pmatrix} u_{21} & u_{22} \\ u_{31} & u_{32} \\ u_{41} & u_{42} \end{pmatrix} = \begin{pmatrix} 1 - u & u \\ v & v \\ 0 & 1 - u \end{pmatrix} \quad (1)$$

where u is referred to as the proportion of unreduced gametes, and $2v$ is the proportion of euploid gametes produced by a triploid individual. The rate of unreduced gamete production is hence fixed across individuals, and is assumed to be the same in diploids and tetraploids.

When two individuals mate, we assume they produce gametes according to their ploidy level (eq. (1)), which randomly combine to produce offspring (which may be inviable if one of the contributing gametes is inviable). Intrinsic fitness disadvantages associated with particular zygotic ploidy levels or cross types (e.g. modeling phenomena such as ‘triploid block’) can be straightforwardly included at this level. An analysis of a deterministic model (i.e. where $N \rightarrow \infty$) for the cytotype dynamics and equilibrium cytotype composition under random mating is included in section S2.1 (see also Felber and Bever (1997);

Table 1: Glossary of the notation used in the main text.

| notation | description |
|-----------------|---|
| N | total population size |
| N_k | population size of the k -ploid cytotype |
| π_k | deterministic equilibrium frequency of the k -ploid cytotype |
| u | probability of unreduced gamete formation ($u = u_{22} = 1 - u_{42}$) |
| v | probability that a triploid produces a haploid/diploid gamete ($v = u_{31} = u_{32}$) |
| m | expected number of migrants per generation arriving in the new habitat |
| z_i | trait value of individual i |
| c_i | ploidy level of individual i |
| g_i | ploidy level of gamete produced by individual i in a particular cross |
| V | segregation variance in the reference diploid population |
| $V_{i,k}$ | gametic segregation variance associated with the production of a k -ploid gamete by individual i |
| \mathcal{V}_k | genetic variance associated with a haploid genome in the k -ploid reference population (i.e. a k -ploid non-inbred population at HWLE) |
| β_k | scaling factor for allelic effects in k -ploids |
| F_i | inbreeding coefficient in individual i |
| Φ_{ij} | coancestry coefficient for individuals i and j |
| α_k | probability that the two genes at a locus in a diploid gamete formed by a k -ploid individual descend from the same parental gene copy |
| γ | strength of directional selection in the new habitat |
| θ | trait value beyond which the growth rate becomes positive in the new habitat |
| w_{ij} | fitness of parental pair (i, j) (<u>expected fitness of offspring of pair (i, j)</u>) |
| w_{ij}^{kl} | expected fitness of offspring from <u>of</u> parental pair (i, j) when i contributes a k -ploid gamete and j contributes a l -ploid gamete |
| σ_k | rate of self-fertilization in k -ploids |
| ρ_k | probability of assortative mating in k -ploids |

129 Kauai et al. (2024)). The stochastic version for finite and constant N is analyzed briefly
130 in section S2.2.

131 Infinitesimal model

The basic infinitesimal model. Consider a population which expresses a quantitative trait determined by a large number of additive loci of small effect. The infinitesimal model approximates the inheritance of such a trait by assuming that the trait value Z_{ij} of a random offspring from parents with trait values z_i and z_j follows a Gaussian distribution with mean equal to the midparent value and variance which is independent of the mean:

$$Z_{ij} \sim \mathcal{N}\left(\frac{z_i + z_j}{2}, V_{ij}\right) \quad (2)$$

132 Here, V_{ij} is referred to as the *segregation variance* in family (i, j) . This is the variation
133 generated among offspring from the same parental pair due to random Mendelian segre-
134 gation in meiosis. This approximation can be justified as arising from the limit where
135 the number of loci determining the trait tends to infinity (Barton et al., 2017).

136 An alternative, and for our purposes useful, way to characterize the model is to write
137 $Z_{ij} = Y_i + Y_j$, where Y_i and Y_j are independent Gaussian random variables $Y_i \sim \mathcal{N}\left(\frac{z_i}{2}, V_i\right)$
138 (and similarly for Y_j). We refer to Y_i as the (random) *gametic value* of individual i , and to

V_i as the *gametic segregation variance* of individual i . This formulation is helpful in that it highlights that Mendelian segregation occurs independently in both parents to produce gametes, which then combine additively to determine the offspring trait value. This model applies readily to an autopolyploid population expressing a trait with infinitesimal genetics. However, the segregation variance will be determined by the details of tetraploid meiosis, which differ from those of diploid meiosis (see below).

In a finite population, the segregation variance will decay over time as the population becomes more inbred (Mendelian segregation at homozygous loci does not generate any variation). When F_i is the inbreeding coefficient relative to some ancestral reference population with gametic segregation variance V (i.e. the probability that two genes at a locus in individual i sampled without replacement are identical by descent), the gametic segregation variance of individual i will be $V_i = (1 - F_i)V$. This holds for both diploids and tetraploids (section S2.5.1, also Moody et al. (1993)).

Scaling of traits across ploidy levels. If we would naively assume that the allelic effects underlying an additive trait are identical across ploidy levels, a tetraploid offspring from a cross between two diploids would have, on average, a trait value which is the sum of the parental trait values. This is not likely to reflect biological reality: tetraploids do not tend to have, for instance, twice the size of their diploid progenitors on average (e.g. [Porturas et al. \(2019\)](#)). Furthermore, the genetic variance at Hardy-Weinberg and linkage equilibrium (HWLE) in a large non-inbred tetraploid population will be twice that of their diploid counterparts under such assumptions, which is similarly unrealistic (Clo, 2022a).

In order to account for this, we introduce a scaling factor β_k , accounting for the effects of polyploidization *per se* on trait expression in k -ploids. To introduce and interpret this parameter, we consider an L -locus additive model, with two alleles (0 and 1) at each locus. For a k -ploid individual, let $X_{i,j}$ be the allele at homolog j of locus i . We assume the trait value is determined by

$$z = \sum_{i=1}^L \sum_{j=1}^k a_{i,k} X_{i,j} \quad (3)$$

Where $a_{i,k}$ is the allelic effect of the 1 allele at locus i in k -ploids. The genetic variance at HWLE in k -ploids ($\tilde{V}_{z,k}$) will then be

$$\tilde{V}_{z,k} = k \sum_{i=1}^L a_{i,k}^2 p_i q_i = k \mathcal{V}_k \quad (4)$$

where we refer to \mathcal{V}_k as the variance associated with a haploid genome in k -ploids at HWLE. If we now assume $a_{i,k} = \beta_k a_{i,2}$, i.e. allelic effects in k -ploids are as in diploids, but scaled homogeneously by a factor β_k , and assume equal allele frequencies in the different cytotypes, we will have

$$\frac{\tilde{V}_{z,k}}{\tilde{V}_{z,2}} = \frac{k \mathcal{V}_k}{2 \mathcal{V}_2} = \frac{k}{2} \beta_k^2 \quad (5)$$

Note that by definition $\beta_2 = 1$. Under the infinitesimal model (where $a_{i,2} \rightarrow 0$ as $L \rightarrow \infty$), we have $\tilde{V}_{z,2} = 2 \mathcal{V}_2 = 2V$ (Barton et al., 2017), where V is the segregation variance in the diploid population. Hence, in the infinitesimal limit we have $\mathcal{V}_k = \beta_k^2 \mathcal{V}_2 = \beta_k^2 V$.

Table 2: Gametic segregation variance for haploid and diploid gametes produced by the three cytotypes in the mixed-ploidy model. F_i is the inbreeding coefficient of individual i (producing the gamete), whereas α_k is the probability that a diploid gamete from a k -ploid individual receives two copies of the same parental gene. We assume $\alpha_3 \leq 1/4$ and $\alpha_4 \leq 1/6$ (see section S2.6).

| cytotype | haploid gamete variance | diploid gamete variance |
|------------|-------------------------|--|
| diploid | $\frac{1}{2}(1 - F_i)V$ | $2\alpha_2(1 - F_i)V$ |
| triploid | $\frac{2}{3}(1 - F_i)V$ | $\frac{2}{3}(1 + 3\alpha_3)(1 - F_i)V$ |
| tetraploid | — | $(1 + 2\alpha_4)(1 - F_i)V$ |

Mixed-ploidy infinitesimal model. We can extend the infinitesimal model to the mixed-ploidy case, assuming that the gametic value, on the diploid trait scale, associated with a k -ploid gamete ($k \in \{1, 2\}$) from individual i of ploidy level $c_i \in \{2, 3, 4\}$ is a Gaussian random variable $Y_{i,k}$ with distribution

$$Y_{i,k} \sim \mathcal{N}\left(\frac{k}{c_i} \frac{z_i}{\beta_{c_i}}, V_{i,k}\right) \quad (6)$$

where $V_{i,k}$ is the gametic segregation variance associated with the production of a k -ploid gamete by individual i (see below). The trait value of an individual originating from the union of a k -ploid gamete of individual i and an l -ploid gamete from individual j is then

$$Z_{ij}^{kl} = \beta_{k+l} (Y_{i,k} + Y_{j,l})$$

i.e., Z_{ij}^{kl} is a Gaussian random variate with distribution

$$Z_{ij}^{kl} \sim \mathcal{N}\left(\beta_{k+l} \left(\frac{k}{c_i} \frac{z_i}{\beta_{c_i}} + \frac{l}{c_j} \frac{z_j}{\beta_{c_j}}\right), \beta_{k+l}^2 (V_{i,k} + V_{j,l})\right) \quad (7)$$

The gametic segregation variance associated with the production of diploid gametes depends not only on the segregation variance in the base population (V) and the inbreeding coefficient (F), but also on the detailed assumptions of how the meiotic process takes place. Importantly however, the latter only affect the gametic segregation variance through the quantity α_k , which is the probability that a k -ploid transmits two copies of the same homolog to a diploid gamete. Note that α_4 , the probability that a diploid gamete of a tetraploid individual carries two copies of the same homolog, is the probability of *double reduction* (e.g. Lynch and Walsh (1998) p.57), and is upper bounded by $1/6$ (Stift et al., 2008). The value of α_2 depends on the relative frequency of unreduced gamete formation through so-called *first* and *second division restitution* (Bretagnolle and Thompson, 1995; De Storme and Geelen, 2013). We summarize the expressions for the gametic segregation variance in table 2. Detailed derivations can be found in section S2.6.

Writing \bar{z}_2 for the mean trait value in the diploid subpopulation, eq. (7) implies that a tetraploid offspring from a random diploid parental pair has an expected trait value equal to $\bar{z}_4 = 2\beta_4\bar{z}_2$. This hence implies that $|\bar{z}_4| \geq |\bar{z}_2|$, with equality only when $\beta_4 = 1/2$ or $\bar{z}_2 = \bar{z}_4 = 0$. In other words, when $\beta_4 > 1/2$, we would have for all but $\bar{z}_2 = 0$ that newly formed tetraploids have more extreme phenotypes on average than their diploid parents. In our establishment model (see below), we shall therefore always consider the case where $\bar{z}_2 = 0$ in the source population, and think of the trait value modeled as the deviation from the mean phenotype in the source population.

The property that polyploid phenotypes are more extreme on average makes sense if we consider the underlying genetic model: if we assume the source population is at an

equilibrium between mutation, drift and stabilizing selection, segregating genetic variants that affect the trait will be equally likely to have positive or negative allelic effects (Hayward and Sella, 2022). At equilibrium, any diploid individual with trait value $z - \bar{z}_2 > 0$ then carries an excess of variants with positive allelic effects on the trait, and this excess should be exaggerated in its polyploid offspring, which carry *twice* the excess of their parent on average. In other words, the mixed-ploidy model is not ‘coordinate free’ as the basic infinitesimal model is: eq. (7) only makes sense when the trait values that are modeled correspond to deviations from the mean values associated with an underlying equilibrium state.

Recursions for inbreeding coefficients We can simulate the mixed-ploidy infinitesimal model for a finite population through a straightforward extension of the approach outlined in Barton et al. (2017), provided we can efficiently track inbreeding and coancestry coefficients across the different ploidy levels. Denoting the parents of individual i by k and l , the recursion for the inbreeding coefficients in the mixed-ploidy case becomes

$$\begin{aligned} F_i &= \Phi_{kl} & \text{if } c_i = 2 \\ F_i &= \frac{1}{3} (F_k^* + 2\Phi_{kl}) & \text{if } c_i = 3, g_k = 2, g_l = 1 \\ F_i &= \frac{1}{3} (F_l^* + 2\Phi_{kl}) & \text{if } c_i = 3, g_k = 1, g_l = 2 \\ F_i &= \frac{1}{6} (F_k^* + F_l^* + 4\Phi_{kl}) & \text{if } c_i = 4 \end{aligned} \quad (8)$$

where $F_k^* = \alpha_{c_k} + (1 - \alpha_{c_k})F_k$ (section S2.5.1). The recursion for the coancestry coefficients is given by

$$\begin{aligned} \Phi_{ii} &= \frac{1}{c_i} (1 + (c_i - 1)F_i) \\ \Phi_{ij} &= \sum_k \sum_l P_{ik} P_{jl} \Phi_{kl} & i \neq j \end{aligned} \quad (9)$$

where the sums are over individuals in the parental population, and where $P_{ik} \in \{0, \frac{1}{3}, \frac{1}{2}, \frac{2}{3}, 1\}$ is the probability that a gene copy in individual i is derived from parent k .

Establishment model

Our model for the establishment of a population in an initially unoccupied habitat is based on Barton and Etheridge (2018). We assume a large non-inbred ‘mainland’ mixed-ploidy population at HWLE and cytotype equilibrium, with $\mathbb{E}[z] = 0$ irrespective of the cytotype. The equilibrium trait value distribution for the different cytotypes on the mainland is complicated in general, but a very accurate approximation (which we use throughout) is readily obtained for the case where u is small (see section S2.7).

In generation t , $M(t)$ migrant individuals arrive on an island (the new habitat) joining $N^*(t)$ resident individuals, where $M(t)$ is Poisson distributed with mean m , and $N^*(0) = 0$ unless stated otherwise. The migrant individuals are assumed to be unrelated to the resident individuals. After migration ~~in generation t , the~~ there are $N(t) = N^*(t) + M(t)$ individuals on the island which reproduce sexually, and the offspring thus produced survives until the next generation with a probability determined by

their trait value. Note that this corresponds to a life cycle where selection occurs before migration within a generation. In the basic model, random selfing is allowed (but see below for a model with self-incompatibility). We assume the trait is under directional selection, with fitness $w(z) = e^{\gamma(z-\theta)}$, where γ is the intensity of directional selection and θ is the trait value for which the growth rate of the island population becomes positive. As the population becomes better adapted, eventually, some form of density regulation must limit its growth. We ignore density regulation throughout and focus on the initial establishment phase, defining establishment as reaching a population of size 100.

Again following Barton and Etheridge (2018), we simulate the model by first calculating the fitness of each parental pair (i, j) , which is the expected fitness of offspring of this pair

$$w_{ij} = \sum_{k=1}^2 \sum_{l=1}^2 w_{ij}^{kl} = \sum_{k=1}^2 \sum_{l=1}^2 u_{c_i, k} u_{c_j, l} \mathbb{E} \left[e^{\gamma(Z_{ij}^{kl} - \theta)} \right] \quad (10)$$

The expectation on the right hand side can be calculated from eq. (7) using the moment-generating function of the Gaussian, i.e.

$$\mathbb{E} \left[e^{\gamma(Z_{ij}^{kl} - \theta)} \right] = e^{\gamma(\mathbb{E}[Z_{ij}^{kl}] - \theta) + \frac{\gamma^2}{2} \text{Var}[Z_{ij}^{kl}]} \quad (11)$$

Having calculated the w_{ij} , the number of offspring surviving into the next generation is calculated as $N^*(t+1) = \sum_{i,j} w_{ij}/N(t)$. Next, $N^*(t+1)$ offspring individuals are sampled by sampling parental pairs and gametes proportional to w_{ij}^{kl} , and sampling a trait value in accordance with eq. (7).

Self-fertilization and assortative mating

We model partial self-fertilization by assuming that a proportion σ_{c_i} of the ovules of individual i with ploidy level c_i are fertilized by self-pollen, while the remaining proportion $1 - \sigma_{c_i}$ are fertilized by randomly sampled pollen (which may be self-pollen with probability $1/N$). That is, the expected number of offspring from individual i as mother surviving after selection is

$$\mathbb{E}[w_i] = \sigma_{c_i} w_{ii} + (1 - \sigma_{c_i}) \left[\frac{1}{N} \sum_{j=1}^N w_{ij} \right] \quad (12)$$

We hence assume no pollen limitation (all outcrossing ovules are fertilized), and no pollen discounting (the probability of being a father is unaffected by an individual's selfing rate). When modeling self-incompatibility, we assume there is no intrinsic disadvantage to self-incompatibility, except when there is only a single individual in the population, i.e.

$$\mathbb{E}[w_i] = \begin{cases} \frac{1}{N-1} \sum_{j \neq i} w_{ij} & \text{if } N > 1 \\ 0 & \text{if } N = 1 \end{cases} \quad (13)$$

We model assortative mating by ploidy level in a similar way, assuming that a fraction ρ_{c_i} of the ovules of individual i are fertilized by pollen sampled from the c_i -ploid portion of the population, while a fraction $1 - \rho_{c_i}$ is fertilized by pollen randomly sampled from the entire population.

$$\mathbb{E}[w_i] = \rho_{c_i} \frac{1}{N_{c_i}} \sum_{j=1}^N \delta_{c_i, c_j} w_{ij} + (1 - \rho_{c_i}) \left[\frac{1}{N} \sum_{j=1}^N w_{ij} \right] \quad (14)$$

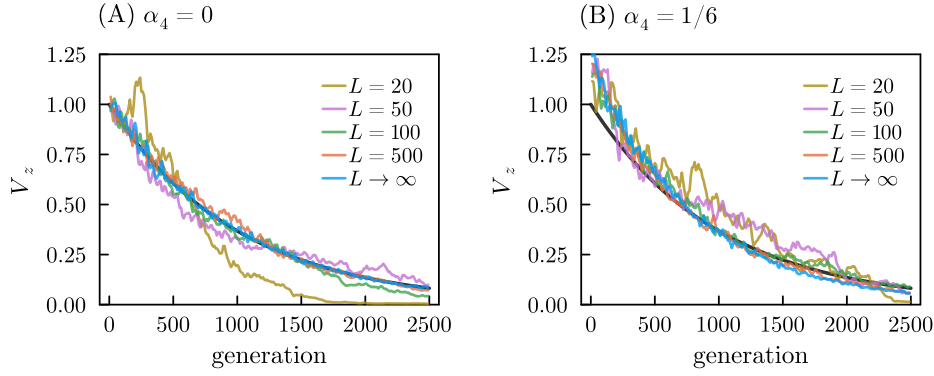


Figure 1: The infinitesimal model in autotetraploids. Comparisons are shown for the decay of the genetic variance (V_z) due to inbreeding in exact simulations of the infinitesimal model in autotetraploids against individual-based simulations of autotetraploid populations with L unlinked additive loci determining the quantitative trait. (A) Simulations of a model without double reduction ($\alpha_4 = 0$). (B) Simulations of a model with maximal double reduction ($\alpha_4 = 1/6$) (for all loci in the finite L simulations). We show window-smoothed values for visual clarity, with observed genetic variances averaged in windows of 20 generations every 10 generations. The black line marks $e^{-t/4N}$. We assume $N = 250$ and $V_z(0) = 1$.

Where $\delta_{x,y}$ is the Kronecker delta function.

Implementation and availability

Individual-based simulations for the mixed-ploidy infinitesimal model were implemented in Julia (Bezanson et al., 2017). Documented code and simulation notebooks are available at [anonymized].

Results

The results section is organized as follows: first we verify the correctness and accuracy of the infinitesimal model for mixed-ploidy populations by comparison against simulations of a model with finitely many loci. Next we assess how autotetraploid genetics and different assumptions on the genetic variance of neotetraploids affect the probability of tetraploid establishment in a marginal habitat relative to diploid establishment, starting from a single maladapted migrant individual. We then study how continuous migration from a predominantly diploid maladapted source population affects the relative establishment probability, assessing the impact of migration load and MCE. Finally, we consider the impact of prezygotic isolation mechanisms on tetraploid establishment in the marginal habitat. Throughout, we assume $\beta_3 = \sqrt{2/3}$, $\beta_4 = \sqrt{1/2}$ and $\alpha_2 = \alpha_3 = \alpha_4 = 0$, unless stated otherwise. Note that while the former assumption is a natural default, the latter is not easy to motivate, and we do investigate the impact of the α parameters in some detail below.

Autotetraploid and mixed-ploidy infinitesimal model

We evaluate the accuracy of the autotetraploid infinitesimal model as an approximation to the evolution of a quantitative trait determined by L additive loci. We find that the infinitesimal model with inbreeding generally yields accurate predictions for the evolution

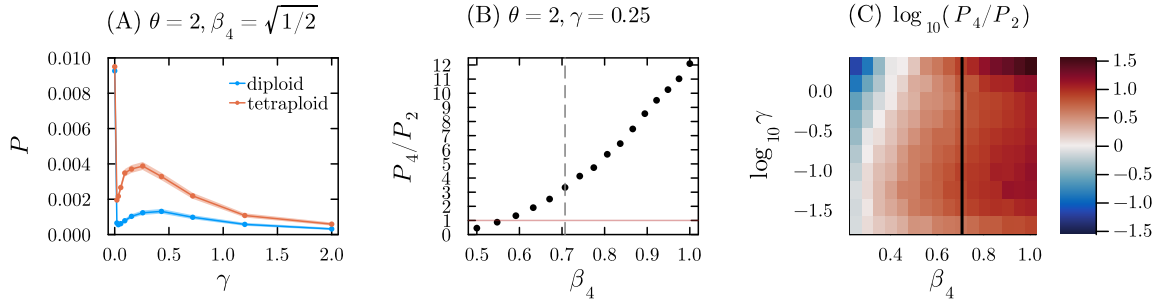


Figure 2: (A) Probability of establishment from a single diploid or tetraploid individual with trait value $z = 0$ for increasing selection intensity γ . We assume $m = 0$ and $u = 0$, i.e. there is no migration, and no unreduced gametes are produced. The trait is scaled in tetraploids so as to yield the same genetic variance at HWLE ($\beta_4 = \sqrt{1/2}$) (B) Probability of a tetraploid individual with trait value $z = 0$ successfully founding a population (P_4), relative to the probability for a diploid individual with the same trait value (P_2). The vertical dashed line marks $\beta_4 = \sqrt{1/2}$, for which the variance at HWLE is identical between diploids and autotetraploids. (C) Probability of tetraploid establishment relative to the probability of diploid establishment (on a \log_{10} scale) across a range of values for γ and β_4 . The vertical line again marks $\beta_4 = \sqrt{1/2}$. All results are estimated from 500,000 replicate simulations and assume $\theta = 2$. Establishment is defined as reaching $N = 100$.

of the genetic variance when the number of loci is sufficiently large ($L \geq 100$, say, figs. 1 and S1). Furthermore, we confirm that, in the absence of double reduction, the decay in genetic variance due to inbreeding after a time t is well-predicted by $e^{-t/4N}$ (fig. 1A), as expected from the results of Arnold et al. (2012). As predicted, double reduction (i.e. $\alpha_4 > 0$) leads to an immediate increase in genetic variance (as it increases the segregation variance), but leads to accelerated inbreeding, causing faster loss of ~~genetic variance-variation~~ in the long term (figs. 1 and S1). Simulations for the mixed-ploidy model further confirm the correctness of our infinitesimal approximation (fig. S2).

It is worth noting that, although inbreeding is slower in autotetraploids than in diploids for the same population size, the tetraploid fraction of a diploid-dominated mixed-ploidy population will have an equal or higher average inbreeding coefficient (fig. S3). This is because in such a population, triploid and tetraploid individuals mostly arise from gametes formed by diploid individuals, or by polyploid individuals with very recent diploid ancestry (on average $1 + u + 2v$ generations ago for tetraploids, and $1 + \frac{2}{3}(u + 2v)$ generations ago for triploids, see section S2.3). A nonzero probability of producing IBD diploid gametes ($\alpha_k > 0$) will then further increase the inbreeding coefficient in the tetraploid and triploid fraction of the population relative to their diploid progenitors (fig. S3). Therefore, as long as diploids dominate, harboring some fraction of the gene pool in polyploid individuals has a negligible effect on the rate of inbreeding in the mixed-ploidy population as a whole, and we find that the evolution of the inbreeding coefficient over time is well predicted by $1 - e^{-t/2N_e}$, where the inbreeding-effective population size is, to first order in u , given by $(1 - 2u)N$ (section S2.4). This is just the expected number of diploid individuals (to first order in u), highlighting that when diploids dominate, polyploids ~~have low fitness and~~ do not contribute to the effective population size.

Establishment from a single individual

Having established the validity of the mixed-ploidy infinitesimal model, we now use it to study the establishment of polyploids in a marginal habitat to which migrants from a mixed-ploidy source population are maladapted.

We first consider the establishment of a population from a single migrant individual with trait value $z_0 = 0$. We assume $u = 0$ (i.e. there are no unreduced gametes, and hence no newly formed polyploids) and compare the probability of establishment when the migrant is diploid vs. tetraploid (fig. 2). As noted by Barton and Etheridge (2018), the establishment probability (for a given cytotype) depends essentially on two dimensionless parameters, $\gamma\sqrt{2V}$ and $\theta/\sqrt{2V}$, corresponding to the intensity of selection and the degree of maladaptation, respectively. We shall scale our results accordingly, assuming $2V = 1$ throughout, and shall assume $\theta = 2$, so that the average trait value has to increase by two standard deviations to achieve a positive growth rate. The *relative* establishment probability for different cytotypes will of course also depend on how allelic effects scale across ploidy levels (β_4).

We find that reduced inbreeding in tetraploids substantially increases the establishment probability of tetraploids relative to diploids across a large part of the parameter space (fig. 2). Indeed, in the case where allelic effects are scaled across ploidy levels to yield the same equilibrium genetic variance ($\beta_4 = \sqrt{1/2}$, ~~so that polyploid migrants are not more likely to have high fitness than diploid migrants~~), the establishment probability for tetraploids can be almost five times as high as ~~in for~~ diploids depending on the selection gradient (fig. 2A). As the segregation variance and initial trait value are the same across these simulations, this is a consequence only of the reduced rate of inbreeding, which slows down the exhaustion of the genetic variance carried by the initial migrant individual.

~~While As expected,~~ the probability of establishment ~~becomes lower as decreases when~~ the strength of selection becomes large, ~~the establishment probability does not decrease monotonically with as the fitness of the initial migrant individual decreases with increasing γ , i.e. as~~ (fig. 2A). ~~However, when~~ selection becomes very weak, the establishment probability also decreases. This happens because, although the probability of surviving the first couple of generations becomes higher when selection is weaker, adaptation (i.e. increase in the trait mean) will be slower, increasing the risk that genetic variation is exhausted due to inbreeding before the population is able to reach a consistently positive growth rate. Note that when $\gamma = 0$, each individual has fitness 1 and we have a critical branching process with a Poisson offspring distribution, so that the probability to reach $N = 100$ is ~~1/100~~ $\sim 1/100$ (Barton and Etheridge, 2018).

Evidently, the scaling of the genetic variance across ploidy levels has a profound effect on the establishment probability, but only when β_4 is close to 0.5 (i.e. individual alleles have almost half the effect size in tetraploids compared to diploids) is the benefit of the slower rate of inbreeding in tetraploids canceled (fig. 2B,C).

Establishment with recurrent migration

We next consider establishment in the new habitat when there is a continuous influx of migrants (m migrants per generation on average) coming from a large, noninbred and predominantly diploid source population at cytotype equilibrium. In this setting, establishment is certain to happen eventually, and we are interested in the probability that a tetraploid population establishes before a diploid one does.

We hypothesized that two counteracting processes affect the probability of autotetraploid establishment in this scenario. On the one hand, increased migration will increase the probability that an otherwise likely successful tetraploid migrant suffers from MCE in the early generations while the population size is low, because migrants are likely

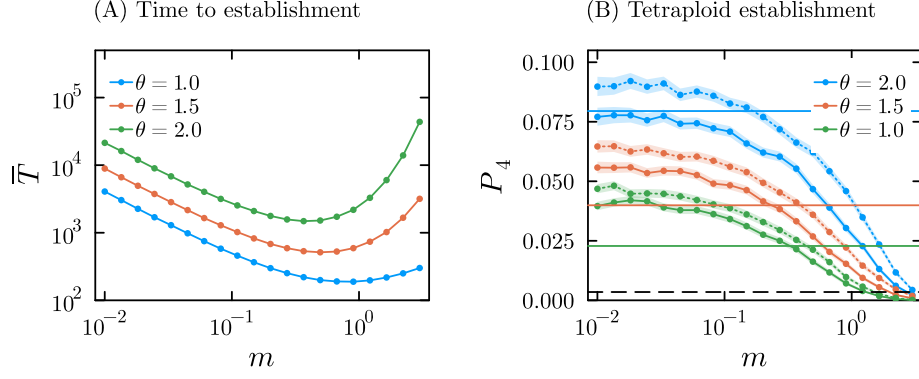


Figure 3: Establishment with recurrent migration. (A) Expected time until a population is established in the marginal habitat for increasing rates of migration and different degrees of maladaptation (θ). Results are shown for the case with $\alpha_k = 0$ for $k = 2, 3, 4$. (B) Proportion of simulation replicates in which tetraploids established. The dots connected by solid lines show simulation results with $\alpha_k = 0$, whereas the dots connected by dashed lines show simulation results with $\alpha_2 = 1/2, \alpha_3 = 1/4$ and $\alpha_4 = 1/6$ (i.e. maximum α). The solid horizontal lines mark $\frac{p_4\pi_4}{(p_4\pi_4 + p_2\pi_2)}$, where p_2 and p_4 are the establishment probabilities for a single diploid and a single tetraploid individual in the absence of migration (as in fig. 2, but with unreduced gamete formation included). The dashed horizontal line marks the proportion of tetraploid migrants (i.e. the proportion of tetraploids at equilibrium in the source population, $\approx 0.3\%$). The baseline predictions (horizontal lines) are based on 5×10^6 simulation replicates. All other results are based on 50.000 replicate simulations. We assume $\gamma = 0.25$ and $u = v = 0.05$.

to be diploid. On the other hand, tetraploids are more strongly reproductively isolated from a typical migrant, so that a tetraploid subpopulation should be less prone to maladaptive gene flow. Hence, conditional on evading MCE, they should be able to adapt to the new habitat at a rate which is not strongly affected by the migration rate. This contrasts with diploids, which interbreed freely with maladapted migrants, resulting in a pulling back of the trait mean towards that of the source population. Lastly, as the mean trait value on the island increases in diploids during adaptation, tetraploid offspring will have more extreme phenotypes on average than diploid offspring when $\beta_4 > 1/2$, which may also aid their establishment (irrespective of m).

As expected, we find that the time to establishment (of a population of either ploidy level) first decreases with increasing migration as a result of a larger influx of potentially successful migrants, but later increases with increasing migration due to swamping by gene flow (fig. 3A). Importantly, the tetraploid establishment probability is considerably larger than the expected proportion of tetraploid migrants over a large part of the parameter range (fig. 3B, black dashed line). Furthermore, we find that for small migration rates, the probability that tetraploids establish rather than diploids can be larger than expected based on the establishment probabilities in the absence of migration (colored lines in fig. 3), depending on how maladapted migrant individuals are. This suggests that maladaptive gene flow in diploids can increase the probability of tetraploid establishment. However, at the same time we find that the tetraploid establishment probability declines monotonically with m , which highlights the negative effects of MCE. ~~Together, these results confirm the view that, while cytotype differences are an effective barrier to maladaptive gene flow, this advantage to establishment is outweighed by the negative effects of MCE.~~

Our simulations further show that the mechanism of unreduced gamete formation (as determined by the α_2 parameter) can affect the establishment probability (fig. 3B, dashed lines). This is mainly because the phenotypic variance of a newly formed tetraploid is

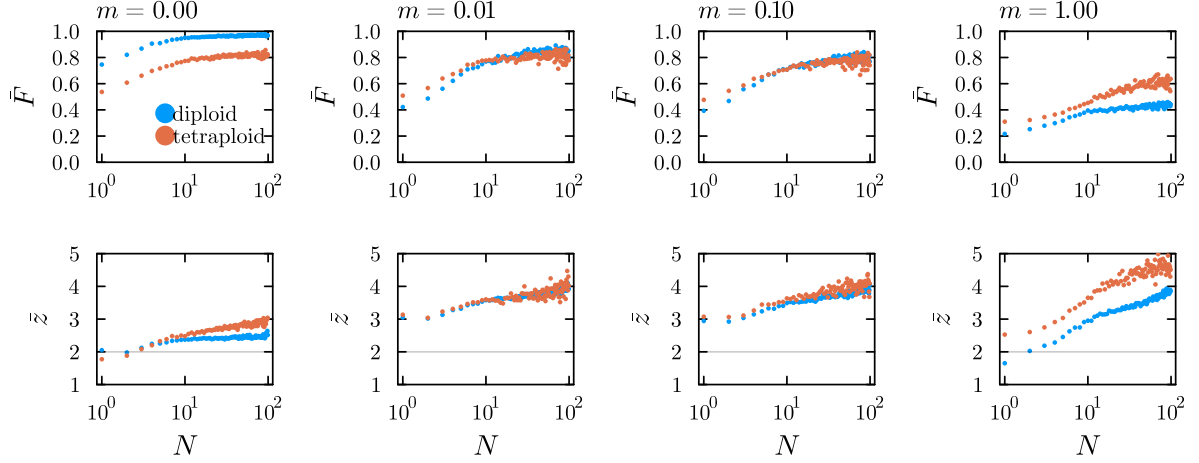


Figure 4: Evolution of the mean inbreeding coefficient and trait value across simulation replicates where diploids (blue) or tetraploids (orange) established eventually. Average F and z by population size are shown for increasing rates of migration (m) from the predominantly diploid source population. All results are based on 1000 successful establishment replicates. We assume equal equilibrium variance across ploidy levels and $\gamma = 0.25, \theta = 2, 2V = 1$ and $u = v = 0.05$. The $m = 0$ simulations are seeded with a single diploid or tetraploid individual with trait value 0, and assume $u = v = 0$.

increased by a factor $(1 + \alpha_2)$, thereby increasing the chance that a tetraploid migrant is well-adapted to the marginal habitat. The rate of double reduction (α_4) has a more limited effect (fig. S4).

Established diploid populations are more inbred on average than established tetraploids when migration is weak, but the difference is slight except when there is no migration at all (fig. 4, top row). For stronger migration ($m > 0.1$), the opposite holds. This is a result of two interacting processes. On the one hand, inbreeding is slower in tetraploids, so that during adaptation and establishment from a single or limited number of outbred individuals, the inbreeding coefficient is expected to increase less rapidly conditional on the event of tetraploid establishment. On the other hand, migration mostly introduces unrelated diploids, which cross more readily with diploids than tetraploids, reducing the average relatedness more strongly in established diploid than in tetraploid populations.

Conditional on establishment, tetraploids have a higher trait mean both in the absence of migration and for moderate to strong migration, but not when migration is weak (fig. 4, bottom row). In the absence of migration, this is a consequence of the reduced rate of inbreeding and the resulting increased adaptive potential of tetraploids. Another consequence of this is that the average trait value in tetraploids at low population size (conditional on eventual establishment) is lower than that in diploids. This is because, in order to adapt before genetic variation is exhausted, tetraploids need not increase the trait mean as much as diploids do in the first couple of generations. The similar trait means for weak migration suggest that establishment depends mostly on the chance pick of a well-adapted migrant (note that the $m = 0$ simulations in fig. 4 assume the initial migrant has $z = 0$, whereas the $m = 0.01$ simulations assume the initial trait value to be Gaussian). When migration is strong, tetraploids have markedly larger trait values than diploids ($m = 1$ in fig. 4), showing that diploids suffer strongly from maladaptive gene flow when the population size is low, while tetraploids enjoy some reproductive isolation. Furthermore, in these replicates, tetraploids tend to emerge and rise in frequency at larger population sizes on the island, and hence tend to derive from diploids that already

experienced several generations of selection. These neotetraploids, deriving from diploid parents with $z > 0$, will have more extreme phenotypes on average (see methods) and hence be better adapted.

Loss of self-incompatibility, selfing and assortative mating

When polyploidization disrupts an existing SI system (see e.g. Robertson et al. (2011); Zenil-Ferguson et al. (2019); Novikova et al. (2023)), we expect that tetraploids suffer less from MCE, as some portion of their ovules are now assured to be fertilized by diploid gametes, irrespective of the composition of the population. At the same time, we expect that accelerated inbreeding in selfing tetraploids diminishes the adaptive advantage of tetraploids. We find that when polyploidization is associated with the loss of a SI system (i.e. when diploids are self-incompatible, but tetraploids are not), tetraploids have a strongly increased establishment probability (fig. 5). This is the case even when the selfing rate σ in tetraploids is zero (in which case, under our modeling assumptions, there is only random selfing, i.e. the *realized* selfing rate in tetraploids is $1/N$). Furthermore, we find that when the selfing rate is sufficiently high (≥ 0.4 in fig. 5A), the relative establishment probability of tetraploids increases with increasing migration rate. In this regime, the increased strength of MCE due to increased migration and increased reproductive assurance in diploids is compensated by the stronger maladaptive gene flow experienced by diploids.

Self-incompatibility is clearly a strong disadvantage when colonizing a novel habitat, as a self-incompatible population of size one can never reproduce. However, even when diploids are self-compatible, polyploids may still have increased rates of self-fertilization (for instance due to altered flower morphology). For the sake of comparison, fig. 5A also shows results where diploids are assumed to be self-compatible with $\sigma_2 = 0$ (i.e. random selfing, dashed transparent lines). The tetraploid establishment probability is still markedly increased when $\sigma_4 \geq 0.4$, and as for the simulations with self-incompatibility, migration still promotes the probability of tetraploid establishment when the selfing rate in polyploids is sufficiently large compared to the diploid selfing rate.

Another prezygotic isolating mechanism that has often been considered relevant for explaining tetraploid establishment is assortative mating by ploidy level, where ovules from a tetraploid are more likely to be fertilized by pollen coming from a tetraploid – irrespective of the trait values of these individuals. Clearly, assortative mating increases the probability of tetraploid establishment (fig. 5B), although not as strongly as the loss of an SI system does. Again, we find that for some parameter values (roughly $\rho \geq 0.4$), assortative mating may be strong enough so that tetraploid establishment increases with increasing migration rates, suggesting that tetraploids evade maladaptive gene flow sufficiently to overcome MCE. Note that the case $\rho = 1$ amounts to complete prezygotic isolation.

Discussion

The observation that polyploid populations tend to inhabit more extreme habitats or occur at the edge of the range of their conspecific diploids has spurred considerable interest among botanists and evolutionary biologists (~~Rice et al., 2015; Kolář et al., 2017; Van de Peer et al., 2017~~ (Kolář et al., 2017; Rice et al., 2019; Van de Peer et al., 2021; Griswold, 2021; Mortier et al., 2024)). An important question is whether such patterns emerge because polyploids are somehow

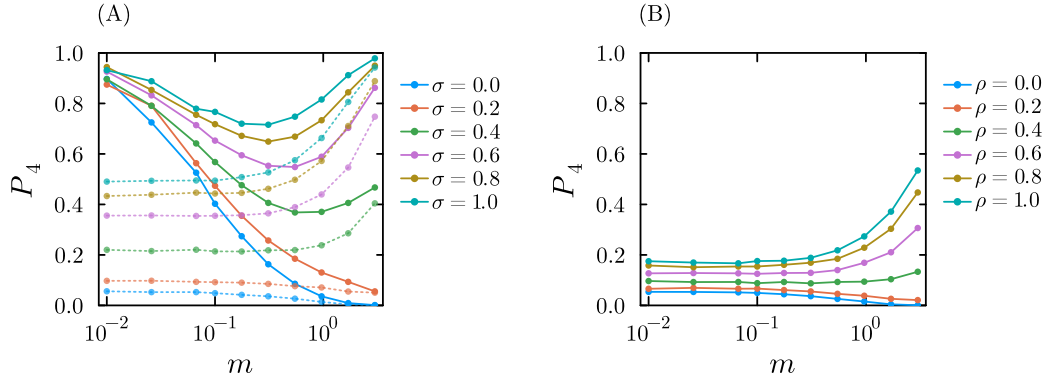


Figure 5: (A) Establishment with recurrent migration and selfing in polyploids. The solid lines show the case where diploids are self-incompatible. The dashed transparent lines show the case where diploids do random self-fertilization (i.e. self-fertilization occurs with probability $1/N$). Triploids and tetraploids have the same selfing rate. $\sigma = 0.0$ refers to random self-fertilization. (B) Establishment with recurrent migration and assortative mating by cytotype. The rate of assortative mating is determined by $\rho_k = \rho$ for $k = 2, 3, 4$, where ρ_k is the probability that an ovule from a k -ploid mother is pollinated by a k -ploid father. All results are based on 25,000 replicate simulations. We assume $\gamma = 0.25, \theta = 1.5$ and $u = v = 0.05$.

more tolerant to extreme environmental conditions (i.e. they somehow are intrinsically more fit than diploids in marginal habitats), or whether other aspects of the population dynamics of mixed-ploidy populations may favor the establishment of polyploid subpopulations.

In this study, we worked out the infinitesimal model for an additive polygenic trait in autotetraploids and mixed-ploidy populations and used it to study the establishment of tetraploids in a marginal habitat by means of individual-based simulations. Assuming the trait to be under directional selection in the marginal habitat, and migration of maladapted individuals from a predominantly diploid source, we sought to determine the conditions under which tetraploids are more likely to establish a stable population.

Throughout, we have assumed a relatively high and constant rate of unreduced gamete formation u and triploid fertility v in all our simulations (5%), whereas these are known to be variable across the population, and at least in part genetically determined (Kreiner et al., 2017a; Clo et al., 2022). We ignore such complications, and hence do not take the actual establishment probabilities very seriously, focusing instead on how migration load and prezygotic isolation affect the tetraploid establishment probability.

Similarly, we have ignored mutation, which would reduce the rate at which genetic variation is lost through inbreeding (Barton et al., 2017), and would likely do so differently across cytotypes (i.e. μV_m is expected to differ for different ploidy levels, where μ is the mutation rate and V_m the mutational variance). The contribution of new mutation to the genetic variance on the timescales we consider should however be very limited. Indeed, any individual at the time of establishment derives from a completely outbred migrant individual a relatively short time in the past, so that the opportunity for mutation to contribute to differences in establishment probability between diploids and tetraploids is negligible for realistic μV_m .

Importantly, we assume no intrinsic advantage or disadvantage of polyploids in the marginal habitat, i.e. the expected fitness of a migrant individual is the same regardless of the ploidy level. Differences in establishment probabilities the likelihood

of polyploid establishment are hence caused solely by aspects of autopolyploid genetics and the barrier to gene flow between subpopulations of different ploidy levels. This is undoubtedly unrealistic, as both trait values and fitness will often differ systematically across ploidy levels (Porturas et al., 2019). For instance, neopolyploids are likely to suffer intrinsic fertility issues due to meiotic irregularities associated with multivalent formation (Bomblies et al., 2016; Novikova et al., 2023). Furthermore, in our simulations, we have focused on the case where the, and triploids may be inviable due to issues with endosperm development (Bretagnolle and Thompson, 1995).

Similarly implausible is the assumption of a constant equilibrium genetic variance is constant across cytotypes ($\beta_4 = \sqrt{1/2}$ in our model). It would be very interesting to experimentally assess whether typical quantitative traits in mixed-ploidy populations follow approximately the mixed-ploidy infinitesimal model we outlined in this paper, and to actually estimate how the, which we used in most of our results (but see fig. 2). Empirical data on how the genetic variance scales across ploidy levels. In addition, we have assumed a relatively high and constant rate of unreduced gamete formation u and triploid fertility v in all our simulations (5%), whereas these are known to be variable across the population, and at least in part genetically determined (Kreiner et al., 2017a; Clo et al., 2022). We ignore such complications, and hence do not take the actual establishment probabilities very serious, focusing instead on how migration load and prezygotic isolation affect the tetraploid establishment probability is scant and suggests that there is no general rule (Gallais, 2003; Porturas et al., 2019). The meta-analysis performed by Porturas et al. (2019) does indicate that trait variance across ploidy levels may often be fairly constant, so our assumption may not yield too bad an approximation. It should be noted that other authors have made different assumptions on how allelic effects (and hence genetic variance) scale across ploidy levels (in particular Griswold (2021), who scaled allelic effects in a way that is equivalent to $\beta_4 = 1/2$ in our model). Such assumptions evidently impact the likelihood of polyploid establishment (fig. 2). More empirical data on quantitative traits in experimental or natural mixed-ploidy populations is needed to assess whether the mixed-ploidy infinitesimal model can adequately describe the genetics of quantitative traits across cytotypes, and to suggest plausible values for the relevant parameters (α, β).

When migration is weak, succesful establishment is not affected by maladaptive gene flow and we can treat establishment in the marginal habitat as independent trials of founding a population from a single individual. In order to avoid extinction, the population has to increase the trait mean by a sufficient amount before the genetic variation carried by the initial migrant individual is exhausted. The probability that the population manages to do so depends on the degree of maladaptation, the intensity of selection and the rate of inbreeding. We find that the decreased rate of inbreeding in autotetraploids gives a rare tetraploid migrant a larger adaptive potential than a diploid migrant, even if the genetic variance carried by the founding individual is the same.

In the presence of maladaptive gene flow, a nascent tetraploid subpopulation suffers from MCE, and although polyploids are more reproductively isolated from a typical migrant (and hence suffer less maladaptive gene flow), MCE will increasingly hamper the establishment of tetraploids as the rate of migration grows. Nevertheless, it is important to remark that despite MCE, the probability of tetraploid establishment in the marginal habitat can be an order of magnitude higher than expected based on the frequency of tetraploid migrants (i.e. is roughly $\Theta(u)$ instead of $\Theta(u^2)$ of order u instead of u^2) when migration is sufficiently weak and maladaptation sufficiently high.

Additional sources of prezygotic isolation such as selfing and assortative mating by cytotype may further boost the probability of tetraploid establishment. These processes interact with the rate of migration, so that when selfing/assortative mating occurs above some threshold rate, the tetraploid establishment probability increases with increasing migration rates, whereas below the threshold it decreases with increasing migration pressure. In the latter case, the advantage that tetraploids have when it comes to avoiding maladaptive gene flow is not strong enough to overcome the effects of MCE, whereas in the former case it is.

A major weakness of the present work, and an important caveat, is that we have ignored inbreeding depression and dominance throughout. Including dominance in the infinitesimal framework is already challenging for diploids (requiring the tracking of four-way identity coefficients; Barton et al. (2023)), and appears intractable for higher ploidy levels. However, autopolyploidy has important consequences whenever dominance is relevant, as in the case of inbreeding depression (Ronfort, 1999) (Ronfort, 1999; Gallais, 2003; Husband et al. 2004). Indeed, when inbreeding depression is due to recessive deleterious variation, it is expected to be less expressed in neotetraploids because homozygous genotypes should be much rarer than in their diploid parents. — When there is indeed deleterious recessive variation, inbreeding (the ‘masking’ effect; Husband and Schemske (1997); Otto and Whitton (2000)). Inbreeding during the establishment process should therefore incur a higher fitness cost in diploids relative to tetraploids, and hence further increase the probability of tetraploid establishment. How this plays out depends however on the rate of inbreeding at which populations become inbred, which will differ between cytotypes and will depend strongly on the mating system. In outcrossing populations, inbreeding occurs at a slower rate in tetraploids, further decreasing inbreeding depression and aiding tetraploid establishment. However, when polyploidization is associated with increased selfing (as when it disrupts an existing SI system), increased inbreeding depression in autotetraploids may prevent their establishment.

Dominance and inbreeding depression may strongly affect the complicated relationship between selfing, migration load and tetraploid establishment probability interaction between selfing and migration load in determining tetraploid establishment. Griswold (2021) studied the case where local fitness is determined by a single biallelic locus, and investigated the interaction between inbreeding depression and migration load (where inbreeding depression is modeled as a fixed fitness reduction in offspring produced by selfing). In his model, inbreeding depression is different between cytotypes (assuming stronger inbreeding depression in diploids), so that tetraploids are able to produce more offspring through selfing relative to diploids, who have to rely more on outcrossing. However, outcrossing incurs maladaptive gene flow, and thereby puts the diploids at a disadvantage. He found that autotetraploids can establish when adaptation in the peripheral habitat is conferred by recessive alleles (so that migration load is expressed when migrant alleles are rare) and when inbreeding depression in tetraploids is lower than in diploids. It would be very interesting to combine the infinitesimal framework with some form of inbreeding depression to investigate in a more realistic model whether the combination of maladaptive migration and differential inbreeding depression could explain the prevalence of polyploid subpopulations at range edges.

In the long term, polyploids are expected to accumulate a larger mutation load when deleterious variation is recessive due to less efficient purging, and this may yield increased inbreeding depression (Vlček et al., 2025). These effects have been studied in the context of range expansions (Booker and Schrider, 2024). However, this applies only to polyploids

that have been established for a long time. In our case, polyploids are always recently descended from diploid ancestors, and they will not have accumulated more deleterious mutations than their diploid counterparts, so that polyploidy ~~leads~~ should lead to reduced rather than increased inbreeding depression when selfing rates are similar (as discussed above). Interestingly, the interplay between the effects of polyploidy on different timescales could yield an equilibrium situation that may characterize many mixed-ploidy populations in nature: although sometimes polyploids could enjoy enhanced establishment probabilities in peripheral habitats, the accumulation of mutational load may in the long-term limit further range expansion or even lead to competitive exclusion by diploids. Further modeling efforts could provide more insights into the plausibility of such a model.

While in this study we focused on polyploid establishment in a peripheral habitat and how this is affected by migration from a diploid source, the mixed-ploidy infinitesimal framework could be used to address many other eco-evolutionary questions that arise in the study of mixed-ploidy populations. For instance, it could be of interest to develop a complicated individual-based model along the lines of Oswald and Nuismer (2011) to study the effects of selfing, assortative mating and competition on establishment and coexistence of tetraploids within diploid populations, but where the focal trait that determines fitness and assortative mating is not controlled by a few large-effect loci, but many loci of small effect. Similarly, our model could be straightforwardly extended to include population regulation and stabilizing selection, which would allow us to study polyploid establishment along an environmental gradient and the potential of polyploidization to promote range expansions (Polechová and Barton, 2015).

References

- B. Arnold, K. Bomblies, and J. Wakeley. Extending coalescent theory to autotetraploids. *Genetics*, 192(1):195–204, 2012.
- E. Baack. To succeed globally, disperse locally: effects of local pollen and seed dispersal on tetraploid establishment. *Heredity*, 94(5):538–546, 2005.
- N. Barghi, J. Hermisson, and C. Schlötterer. Polygenic adaptation: a unifying framework to understand positive selection. *Nature Reviews Genetics*, 21(12):769–781, 2020.
- N. H. Barton and A. Etheridge. Establishment in a new habitat by polygenic adaptation. *Theoretical Population Biology*, 122:110–127, 2018.
- N. H. Barton, A. M. Etheridge, and A. Véber. The infinitesimal model: Definition, derivation, and implications. *Theoretical population biology*, 118:50–73, 2017.
- N. H. Barton, A. M. Etheridge, and A. Véber. The infinitesimal model with dominance. *Genetics*, 225(2):iyad133, 2023.
- J. Bezanson, A. Edelman, S. Karpinski, and V. B. Shah. Julia: A fresh approach to numerical computing. *SIAM review*, 59(1):65–98, 2017.
- M. Bohutínská, J. Vlček, S. Yair, B. Laenen, V. Konečná, M. Fracassetti, T. Slotte, and F. Kolář. Genomic basis of parallel adaptation varies with divergence in arabidopsis and

its relatives. *Proceedings of the National Academy of Sciences*, 118(21):e2022713118, 2021.

K. Bomblies and C. L. Peichel. Genetics of adaptation. *Proceedings of the National Academy of Sciences*, 119(30):e2122152119, 2022.

K. Bomblies, G. Jones, C. Franklin, D. Zickler, and N. Kleckner. The challenge of evolving stable polyploidy: could an increase in “crossover interference distance” play a central role? *Chromosoma*, 125:287–300, 2016.

W. W. Booker and D. R. Schrider. The genetic consequences of range expansion and its influence on diploidization in polyploids. *The American Naturalist*, 0(ja):null, 2024. doi: 10.1086/733334. URL <https://doi.org/10.1086/733334>.

F. Bretagnolle and J. D. Thompson. Gametes with the somatic chromosome number: mechanisms of their formation and role in the evolution of autopolyploid plants. *New Phytologist*, 129(1):1–22, 1995.

M. R. Brown, R. J. Abbott, and A. D. Twyford. The emerging importance of cross-ploidy hybridisation and introgression. *Molecular Ecology*, 33(8):e17315, 2024.

J. Clo. The evolution of the additive variance of a trait under stabilizing selection after autopolyploidization. *Journal of Evolutionary Biology*, 35(6):891–897, 2022a.

J. Clo. Polyploidization: Consequences of genome doubling on the evolutionary potential of populations. *American Journal of Botany*, 109(8):1213–1220, 2022b.

J. Clo and F. Kolář. Inbreeding depression in polyploid species: a meta-analysis. *Biology Letters*, 18(12):20220477, 2022.

J. Clo, N. Padilla-García, and F. Kolář. Polyploidization as an opportunistic mutation: The role of unreduced gametes formation and genetic drift in polyploid establishment. *Journal of Evolutionary Biology*, 35(8):1099–1109, 2022.

N. De Storme and D. Geelen. Sexual polyploidization in plants—cytological mechanisms and molecular regulation. *New Phytologist*, 198(3):670–684, 2013.

F. Felber. Establishment of a tetraploid cytotype in a diploid population: effect of relative fitness of the cytotypes. *Journal of evolutionary biology*, 4(2):195–207, 1991.

F. Felber and J. D. Bever. Effect of triploid fitness on the coexistence of diploids and tetraploids. *Biological Journal of the Linnean Society*, 60(1):95–106, 1997.

A. Gallais. Quantitative genetics and breeding methods in autopolyploid plants. 2003.

C. K. Griswold. The effects of migration load, selfing, inbreeding depression, and the genetics of adaptation on autotetraploid versus diploid establishment in peripheral habitats. *Evolution*, 75(1):39–55, 2021.

L. K. Hayward and G. Sella. Polygenic adaptation after a sudden change in environment. *Elife*, 11:e66697, 2022.

- 654 T. Herben, P. Trávníček, and J. Chrtek. Reduced and unreduced gametes combine
655 almost freely in a multiploidy system. *Perspectives in Plant Ecology, Evolution and*
656 *Systematics*, 18:15–22, 2016.
- 657 B. C. Husband and H. A. Sabara. Reproductive isolation between autotetraploids and
658 their diploid progenitors in fireweed, *chamerion angustifolium* (onagraceae). *New Phy-*
659 *tologist*, 161(3):703–713, 2004.
- 660 B. C. Husband and D. W. Schemske. The effect of inbreeding in diploid and tetraploid
661 populations of *epilobium angustifolium* (onagraceae): implications for the genetic basis
662 of inbreeding depression. *Evolution*, 51(3):737–746, 1997.
- 663 B. C. Husband, B. Ozimec, S. L. Martin, and L. Pollock. Mating consequences of poly-
664 ploid evolution in flowering plants: current trends and insights from synthetic poly-
665 ploids. *International journal of plant sciences*, 169(1):195–206, 2008.
- 666 F. Kauai, Q. Bafort, F. Mortier, M. Van Montagu, D. Bonte, and Y. Van de Peer.
667 Interspecific transfer of genetic information through polyploid bridges. *Proceedings of*
668 *the National Academy of Sciences*, 121(21):e2400018121, 2024.
- 669 T. J. Kawecki. Adaptation to marginal habitats. *Annual review of ecology, evolution,*
670 *and systematics*, 39(1):321–342, 2008.
- 671 C. Köhler, O. M. Scheid, and A. Erilova. The impact of the triploid block on the origin
672 and evolution of polyploid plants. *Trends in Genetics*, 26(3):142–148, 2010.
- 673 F. Kolář, M. Čertner, J. Suda, P. Schönswetter, and B. C. Husband. Mixed-ploidy
674 species: progress and opportunities in polyploid research. *Trends in plant science*, 22
675 (12):1041–1055, 2017.
- 676 V. Konečná, S. Bray, J. Vlček, M. Bohutínská, D. Požárová, R. R. Choudhury,
677 A. Bollmann-Giolai, P. Flis, D. E. Salt, C. Parisod, et al. Parallel adaptation in au-
678 topolyploid *arabidopsis arenosa* is dominated by repeated recruitment of shared alleles.
679 *Nature Communications*, 12(1):4979, 2021.
- 680 V. Konečná, M. Šustr, D. Požárová, M. Čertner, A. Krejčová, E. Tylová, and F. Kolář.
681 Genomic basis and phenotypic manifestation of (non-) parallel serpentine adaptation
682 in *arabidopsis arenosa*. *Evolution*, 76(10):2315–2331, 2022.
- 683 J. M. Kreiner, P. Kron, and B. C. Husband. Frequency and maintenance of unreduced
684 gametes in natural plant populations: associations with reproductive mode, life history
685 and genome size. *New Phytologist*, 214(2):879–889, 2017a.
- 686 J. M. Kreiner, P. Kron, and B. C. Husband. Evolutionary dynamics of unreduced gametes.
687 *Trends in Genetics*, 33(9):583–593, 2017b.
- 688 R. Lande. The fixation of chromosomal rearrangements in a subdivided population with
689 local extinction and colonization. *Heredity*, 54(3):323–332, 1985.
- 690 D. A. Levin. Minority cytotype exclusion in local plant populations. *Taxon*, 24(1):35–43,
691 1975.

- 692 D. A. Levin. *The role of chromosomal change in plant evolution*. Oxford University Press,
693 USA, 2002.
- 694 M. Lynch and B. Walsh. *Genetics and analysis of quantitative traits*, volume 1. Sinauer
695 Sunderland, MA, 1998.
- 696 M. E. Moody, L. Mueller, and D. Soltis. Genetic variation and random drift in autote-
697 traploid populations. *Genetics*, 134(2):649–657, 1993.
- 698 F. Mortier, Q. Bafort, S. Milosavljevic, F. Kauai, L. Prost Boxoen, Y. Van de Peer, and
699 D. Bonte. Understanding polyploid establishment: temporary persistence or stable
700 coexistence? *Oikos*, page e09929, 2024.
- 701 P. Y. Novikova, U. K. Kolesnikova, and A. D. Scott. Ancestral self-compatibility facilitates
702 the establishment of allopolyploids in brassicaceae. *Plant Reproduction*, 36(1):125–138,
703 2023.
- 704 B. P. Oswald and S. L. Nuismer. A unified model of autopolyploid establishment and
705 evolution. *The American Naturalist*, 178(6):687–700, 2011.
- 706 S. P. Otto and J. Whitton. Polyploid incidence and evolution. *Annual review of genetics*,
707 34(1):401–437, 2000.
- 708 J. Polechová and N. H. Barton. Limits to adaptation along environmental gradients.
709 *Proceedings of the National Academy of Sciences*, 112(20):6401–6406, 2015.
- 710 L. D. Porturas, T. J. Anneberg, A. E. Curé, S. Wang, D. M. Althoff, and K. A. Segraves.
711 A meta-analysis of whole genome duplication and the effects on flowering traits in
712 plants. *American Journal of Botany*, 106(3):469–476, 2019.
- 713 J. K. Pritchard and A. Di Rienzo. Adaptation—not by sweeps alone. *Nature Reviews*
714 *Genetics*, 11(10):665–667, 2010.
- 715 J. Ramsey and D. W. Schemske. Pathways, mechanisms, and rates of polyploid formation
716 in flowering plants. *Annual review of ecology and systematics*, 29(1):467–501, 1998.
- 717 J. H. Rausch and M. T. Morgan. The effect of self-fertilization, inbreeding depression,
718 and population size on autopolyploid establishmen. *Evolution*, 59(9):1867–1875, 2005.
- 719 A. Rice, L. Glick, S. Abadi, M. Einhorn, N. M. Kopelman, A. Salman-Minkov, J. Mayzel,
720 O. Chay, and I. Mayrose. The chromosome counts database (ccdb)—a community
721 resource of plant chromosome numbers. *New Phytologist*, 206(1):19–26, 2015.
- 722 A. Rice, P. Šmarda, M. Novosolov, M. Drori, L. Glick, N. Sabath, S. Meiri, J. Belmaker,
723 and I. Mayrose. The global biogeography of polyploid plants. *Nature ecology & evolu-*
724 *tion*, 3(2):265–273, 2019.
- 725 K. Robertson, E. E. Goldberg, and B. Igić. Comparative evidence for the correlated
726 evolution of polyploidy and self-compatibility in solanaceae. *Evolution*, 65(1):139–155,
727 2011.
- 728 J. Ronfort. The mutation load under tetrasomic inheritance and its consequences for the
729 evolution of the selfing rate in autotetraploid species. *Genetics Research*, 74(1):31–42,
730 1999.

- 731 H. Sachdeva, O. Olusanya, and N. Barton. Genetic load and extinction in peripheral
732 populations: the roles of migration, drift and demographic stochasticity. *Philosophical*
733 *Transactions of the Royal Society B*, 377(1846):20210010, 2022.
- 734 D. E. Soltis, P. S. Soltis, D. W. Schemske, J. F. Hancock, J. N. Thompson, B. C. Husband,
735 and W. S. Judd. Autopolyploidy in angiosperms: have we grossly underestimated the
736 number of species? *Taxon*, 56(1):13–30, 2007.
- 737 M. Stift, C. Berenos, P. Kuperus, and P. H. van Tienderen. Segregation models for
738 disomic, tetrasomic and intermediate inheritance in tetraploids: a general procedure
739 applied to rorippa (yellow cress) microsatellite data. *Genetics*, 179(4):2113–2123, 2008.
- 740 M. Turelli. Commentary: Fisher’s infinitesimal model: A story for the ages. *Theoretical*
741 *population biology*, 118:46–49, 2017.
- 742 Y. Van de Peer, T.-L. Ashman, P. S. Soltis, and D. E. Soltis. Polyploidy: an evolutionary
743 and ecological force in stressful times. *The Plant Cell*, 33(1):11–26, 2021.
- 744 W. E. Van Drunen and J. Friedman. Autopolyploid establishment depends on life-history
745 strategy and the mating outcomes of clonal architecture. *Evolution*, 76(9):1953–1970,
746 2022.
- 747 J. Vlček, T. Hämälä, C. V. Cobo, E. Curran, G. Šrámková, T. Slotte, R. Schmickl,
748 L. Yant, and F. Kolář. Whole-genome duplication increases genetic diversity and
749 load in outcrossing arabidopsis. *bioRxiv*, 2025. doi: 10.1101/2025.01.12.632621. URL
750 <https://www.biorxiv.org/content/early/2025/01/15/2025.01.12.632621>.
- 751 R. Zenil-Ferguson, J. G. Burleigh, W. A. Freyman, B. Igić, I. Mayrose, and E. E. Gold-
752 berg. Interaction among ploidy, breeding system and lineage diversification. *New*
753 *Phytologist*, 224(3):1252–1265, 2019.