

Deleterious Mutations Accumulate Faster in Allopolyploid Than Diploid Cotton (*Gossypium*) and Unequally between Subgenomes

Justin L. Conover  and Jonathan F. Wendel 

Department of Ecology, Evolution, and Organismal Biology, Iowa State University, Ames, IA, USA

*Corresponding author: E-mail: jfw@iastate.edu.

Associate editor: Michael Purugganan

Abstract

Whole-genome duplication (polyploidization) is among the most dramatic mutational processes in nature, so understanding how natural selection differs in polyploids relative to diploids is an important goal. Population genetics theory predicts that recessive deleterious mutations accumulate faster in allopolyploids than diploids due to the masking effect of redundant gene copies, but this prediction is hitherto unconfirmed. Here, we use the cotton genus (*Gossypium*), which contains seven allopolyploids derived from a single polyploidization event 1–2 Million years ago, to investigate deleterious mutation accumulation. We use two methods of identifying deleterious mutations at the nucleotide and amino acid level, along with whole-genome resequencing of 43 individuals spanning six allopolyploid species and their two diploid progenitors, to demonstrate that deleterious mutations accumulate faster in allopolyploids than in their diploid progenitors. We find that, unlike what would be expected under models of demographic changes alone, strongly deleterious mutations show the biggest difference between ploidy levels, and this effect diminishes for moderately and mildly deleterious mutations. We further show that the proportion of nonsynonymous mutations that are deleterious differs between the two coresident subgenomes in the allopolyploids, suggesting that homoeologous masking acts unequally between subgenomes. Our results provide a genome-wide perspective on classic notions of the significance of gene duplication that likely are broadly applicable to allopolyploids, with implications for our understanding of the evolutionary fate of deleterious mutations. Finally, we note that some measures of selection (e.g., dN/dS , π_N/π_S) may be biased when species of different ploidy levels are compared.

Key words: polyploidy, deleterious mutations, purifying selection, molecular evolution.

Introduction

Genome duplication (polyploidy) is among the most dramatic mutational processes in nature, causing myriad saltational changes at the cellular and organismal levels (Doyle and Coate 2019; Bomblies 2020; Fernandes Gyorfy et al. 2021), and is associated with consequential phenomena ranging from crop domestication (Renny-Byfield and Wendel 2014; Qi et al. 2021) to cancer progression (Matsumoto et al. 2021). Polyploidy is especially common in the angiosperms, with all extant species having experienced at least one or more polyploidy events during their evolutionary history (Jiao et al. 2011), and at least 30% of currently recognized species having a polyploidy event in the recent past (One Thousand Plant Transcriptomes Initiative 2019).

Novel evolutionary patterns created by polyploidy at the genic (e.g., neofunctionalization, subfunctionalization, and loss; Kuzmin et al. 2021) and genomic (e.g., homoeologous recombination; Mason and Wendel 2020) levels have been well documented across taxa, including the frequent asymmetry of these responses with respect to coresident genomes in a polyploid nucleus. Nonetheless, many questions remain

regarding the effects of natural selection on polyploid relative to diploid genomes (Baduel et al. 2019; Monnahan et al. 2019) and the interplay between these novel evolutionary patterns and the long-term trajectories of genome evolution (Qi et al. 2021) following polyploidization (e.g., biased fractionation).

One of the earliest predictions about natural selection in polyploids relative to diploids is that putatively deleterious mutations may accumulate faster due to the masking effect of completely or partially recessive deleterious mutations in duplicated genes (Haldane 1932; Hill 1970; Bever and Felber 1992). Only recently, however, have these predictions begun to be evaluated in young allopolyploids such as *Arabidopsis kamchatica* (Paape et al. 2018) and *Capsella bursa-pastoris* (Douglas et al. 2015; Kryvokhyzha, Milesi, et al. 2019; Kryvokhyzha, Salcedo, et al. 2019), and autotetraploid *Arabidopsis arenosa* (Monnahan et al. 2019). Because the number of deleterious mutations is strongly influenced by shifts in demography and mating system (Brandvain and Wright 2016), which may coincide with polyploid formation (Grant 1981; Barringer 2007), a clear link between ploidy level and the accumulation of deleterious mutations is challenging to demonstrate in natural polyploid populations.

The cotton genus (*Gossypium*) represents one of the best studied allopolyploid systems (Wendel and Grover 2015; Hu et al. 2021). The genus includes approximately 45 currently recognized diploid species classified into eight genome groups (A–G, and K), and seven allopolyploid species resulting from a single (Grover et al. 2012) allopolyploidization event approximately 1–2 million years ago (Mya) between members of the A and D genome groups (Wendel 1989). Although the most closely related extant species of these two progenitor diploids are found in southern Africa and Northern Peru, respectively, the polyploids are only found in the Americas (fig. 1). Most wild populations, including those of the two independently domesticated species *G. hirsutum* (AD₁) and *G. barbadense* (AD₂), occur in small, isolated populations on islands or in coastal regions. Subsequent to their initial domestication 4,000–8,000 years ago in the Yucatan Peninsula (AD₁) and NW S. America (AD₂), respectively, the ranges of the two domesticated species rapidly expanded to encompass much of the American tropics and subtropics and then spread globally with the rise of the international cotton fiber trade (Yuan et al. 2021).

Here, we describe the evolutionary trajectory of deleterious mutations in two wild diploid and six wild allopolyploid cotton species (all descended from a single allopolyploidization event), with a focus on how allopolyploidization and speciation have shaped the number and genomic distribution of deleterious mutations. We use two methods to estimate the

strength of selection at the amino acid and nucleotide level and show support for a nearly century-old hypothesis that polyploids accumulate mutations faster than their diploid progenitors. We demonstrate that, in agreement with this hypothesis, polyploidy has the greatest influence on strongly, rather than moderately or mildly, deleterious mutations. We also find that deleterious mutations accumulate asymmetrically between the two coresident subgenomes in the allopolyploid nucleus, indicating that these masking effects may act unequally between the subgenomes. In total, our results support theoretical predictions that allopolyploidy can lead to a faster rate of deleterious mutation accumulation through masking of recessive deleterious variants, and that the relationship of the rate of deleterious mutation accumulation between subgenomes and their progenitor diploids is complex, even when comparing identical pairs of single-copy homoeologs among lineages.

Results

Patterns of Synonymous and Nonsynonymous Mutations

To investigate patterns of deleterious mutations, we viewed our data at three phylogenetic depths: single nucleotide mutations that occurred anywhere on the global phylogenetic tree (fig. 2A–D), mutations that emerged since the divergence of each subgenome from its respective diploid progenitor

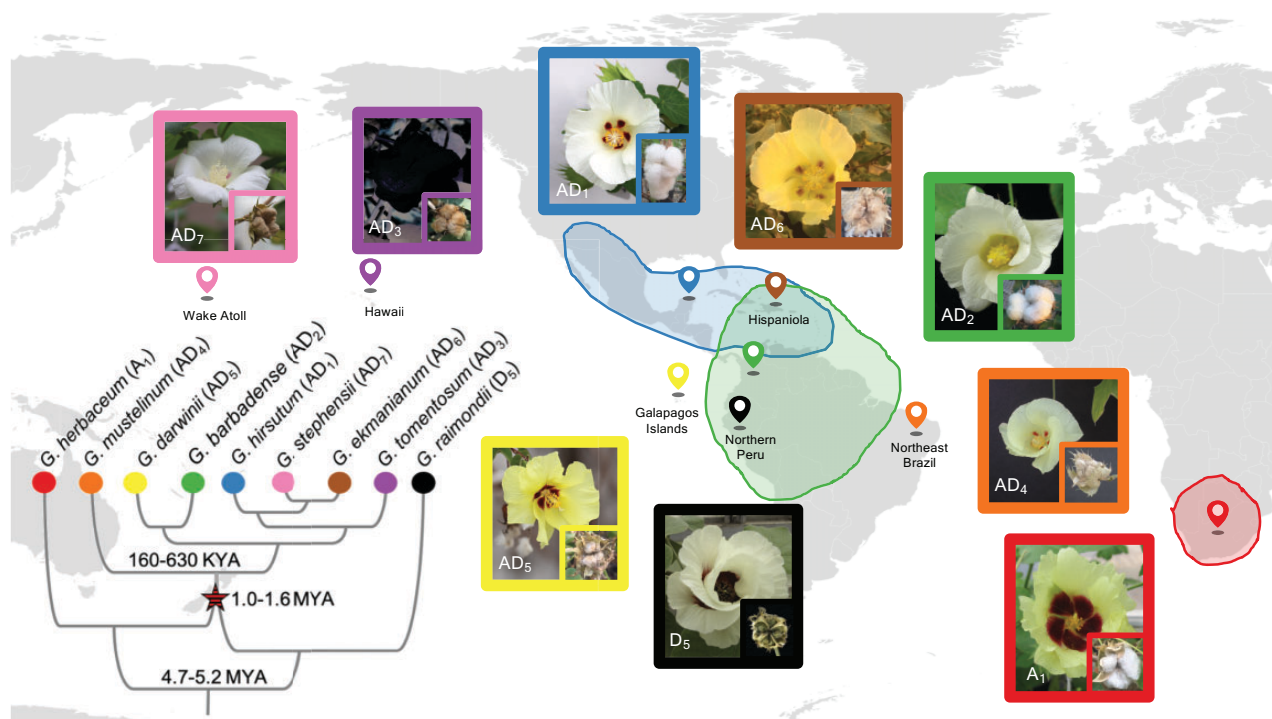


FIG. 1. Phylogeny and biogeography of *Gossypium* allopolyploids and progenitor diploids. Diploid *Gossypium* species are classified into eight diploid genome groups. The A (represented by *G. herbaceum*) and D (represented by *G. raimondii*) genome groups diverged approximately 5 Mya, with ranges in different hemispheres. Allopolyploids formed approximately 1–1.6 Mya following transoceanic dispersal of an A genome ancestor (modeled by *G. herbaceum* [A₁]) to the Americas and hybridization with a native D genome species (modeled by *G. raimondii* [D₅]). Subsequent diversification of the new allopolyploid (AD genome) lineage led to the evolution of seven currently recognized species with a broad geographic range in the Americas and the Pacific islands. Flower and fruit morphology for each species are shown, and the island location and geographic range are indicated. Branch lengths on the phylogeny are not to scale but notable divergence times are labeled.

(fig. 2E–H), and mutations that are still variable within the polyploids (fig. 2I–L). Each group is a subset of the previously described group. We restricted our analyses to a set of 8,884 single-copy, syntenically conserved homoeologous pairs of genes (17,768 genes in total) that showed no evidence of gene loss, gene copy variation, tandem duplication, ambiguous read mapping, homoeologous exchange, or homoeologous gene conversion (see Materials and Methods; [supplementary fig. 1, Supplementary Material online](#)). Notably, the patterns described below are largely reflected in genome-wide patterns as well ([supplementary fig. 2, Supplementary Material online](#)), indicating that filtering criteria did not bias overall results, and that, in cotton, homoeologous interactions have minimal effects on subgenome-specific mutation patterns ([supplementary fig. 1, Supplementary Material online](#)).

Using the curated set of 8,884 pairs of homoeologous genes, we found no evidence for differences in the rate of synonymous

mutation accumulation in diploids versus polyploids at any phylogenetic depth (fig. 2A and E), although differences can be found within the polyploid species (fig. 2I), with *G. mustelinum* (AD₄, Orange) and *G. darwinii* (AD₅, Yellow) having consistently lower rates than the rest of the clade, and in both subgenomes. When viewing mutations that have accumulated since the divergence of the earliest polyploid lineage (fig. 2A–I), there is an asymmetry between subgenomes in the rate of synonymous site changes, with the Dt (“t” denoting “tetraploid”) subgenome containing a moderately higher number of synonymous mutations than the At subgenome for all species. This difference potentially indicates a higher mutation rate or relaxed background selection in genic regions of the Dt subgenome compared with homoeologous genic regions of the At subgenome, and is consistent with previous analysis finding that genes in the Dt subgenome are evolving faster than genes in the At subgenome in five allopolyploid cottons ([Chen et al. 2020](#)).

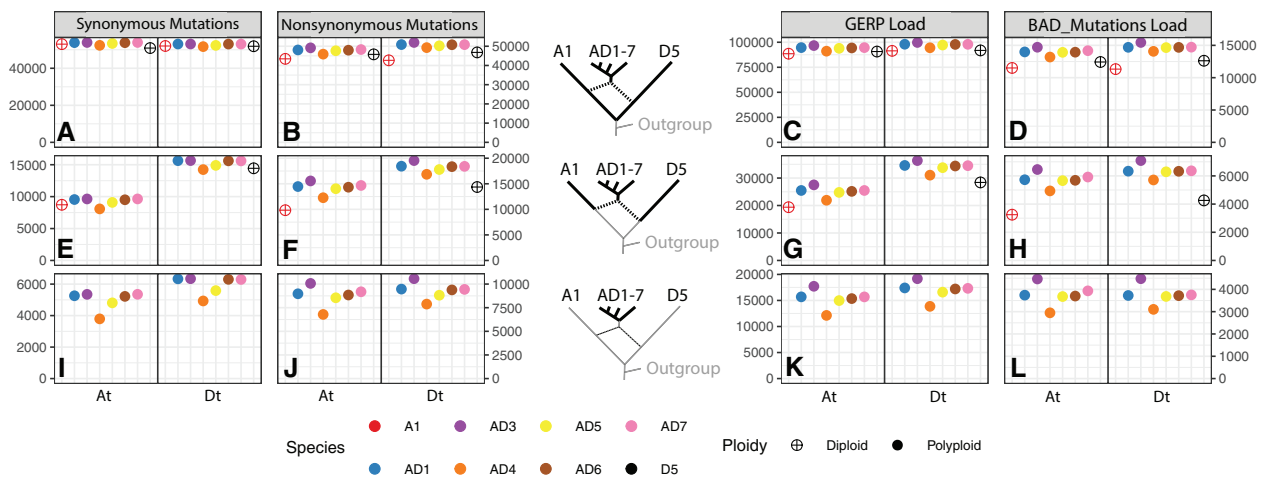


FIG. 2. Derived mutations and deleterious loads at three phylogenetic depths. Number of derived synonymous, nonsynonymous, and deleterious mutations in the CDS regions of 8,884 pairs of homoeologs (17,768 genes in total) in eight cotton species at three phylogenetic depths (indicated by bold branches in phylogeny in middle). For all panels, the ancestral state of each mutation was determined using three Australian cotton species as an outgroup (see Materials and Methods). The left portion of every panel indicates the At subgenome, and the right portion indicates the Dt subgenome. The deepest phylogenetic depth (top row: panels A–D) includes all derived mutations that originated since the divergence of the A and D diploid progenitors. For example, in panel (A), the blue solid circles represent the number of derived synonymous mutations that have occurred in the At subgenome (left half of panel) of AD1 (*Gossypium hirsutum*) since its divergence from the D5 diploid (*G. raimondii*), and in the Dt subgenome (right half of panel) since its divergence from A1 (*G. arboreum*). In this row, the diploids *G. arboreum* (A1, open red circle) and *G. raimondii* (D5, open black circle) are represented twice to show that reads mapped to either subgenome resulted in similar estimates of the number of derived mutations, indicating no genome reference bias in SNP calling. The middle row (panels E–H) shows mutations that are variable within each subgenome and its associated progenitor diploid species. For example, in panel (F), the yellow solid circles indicate the number of derived nonsynonymous mutations in the At subgenome of AD5 (*G. darwinii*) that have occurred since its divergence from the A1 diploid (left half of panel), and in the Dt subgenome of AD5 (*G. darwinii*) that have occurred since its divergence from the D5 diploid (right half of panel). The bottom row (panels I–L) shows mutations that originated postpolyploidy and are variable within the polyploids; for example, in panel (L), the purple solid circles indicated the number of derived deleterious mutations identified by BAD_Mutations that have occurred in the At subgenome of AD3 (*G. tomentosum*) since its divergence from the At subgenome of AD4 (*G. mustelinum*; left half of panel), and in the Dt subgenome of AD3 (*G. tomentosum*) since its divergence from the Dt subgenome of AD4 (*G. mustelinum*; right half of panel). Panels (A), (B), (E), (F), (I), (J): the y axis for both synonymous and nonsynonymous represents the sum of the derived allele frequencies, interpreted as the average number of derived mutations in that category in each species. Panels (C), (G), and (K): the y axis indicates the GERP Load of each species, calculated as the sum of (derived allele frequency $\times$ GERP Score) for all variant positions with GERP > 0 . Panels (D), (H), and (L): the y axis shows the total number of deleterious mutations in each species, calculated by BAD_Mutations with Bonferroni-corrected significance (see Materials and Methods) and indicates the average number of deleterious mutations in each species at a given phylogenetic depth. For panels (E–H), comparisons between subgenomes cannot be made because the D₅ diploid is more distantly related to the D subgenome than the A₁ diploid is related to the A subgenome. Therefore, we would expect a larger number of derived mutations in D than A simply due to evolutionary history rather than to polyploidization per se.

In contrast to the relative homogeneity in rates of synonymous substitution among diploids and polyploids, rates of nonsynonymous mutation accumulation differed significantly at all phylogenetic depths. Notably, at the deepest phylogenetic depth (fig. 2B), estimates for the number of derived nonsynonymous mutations in the diploids *G. herbaceum* (A₁, Red) and *G. raimondii* (D₅, Black) did not differ between subgenomes, indicating that any mapping biases or erroneous SNP calls in these samples were removed by our variant filtering criteria. *Gossypium raimondii* (D₅) contained more derived nonsynonymous mutations than did *G. herbaceum* (A₁), and this lineage-specific difference was reflected in the Dt and At subgenomes as well. When lineage-specific effects that arose from the long, shared ancestry between the subgenomes and their progenitor diploids were removed (fig. 2F), a clear distinction between the rates of nonsynonymous mutations between diploids and their respective subgenomes in the allopolyploids becomes apparent. In all polyploids, the At subgenome contained between 25% and 58% more nonsynonymous mutations than *G. herbaceum* (A₁, Red), and the Dt subgenome contained 17–36% more than *G. raimondii* (D₅, Black). These results demonstrate that even though the rates of synonymous mutation accumulation did not differ significantly between the diploids and polyploids, polyploidy significantly increases the rate of nonsynonymous substitution accumulation. Finally, when restricting our attention to only those mutations that have arisen following polyploid formation (fig. 2J), the lineage-specific patterns observed for nonsynonymous mutations were largely identical to the patterns of synonymous mutations. For example, *G. mustelinum*, (AD₄, Orange) consistently had the lowest number of derived mutations in both subgenomes. Notably, however, the Hawaiian Island endemic *G. tomentosum* (AD₃, Purple) has a higher number of derived nonsynonymous mutations than expected based on the patterns of synonymous mutations, potentially reflecting the population bottleneck associated with its origin following long-distance dispersal to the Hawaiian Islands (see Discussion). In summary, polyploidy significantly enhances the rate of nonsynonymous mutation accumulation in all *Gossypium* allopolyploids, and does so asymmetrically across coresident genomes.

Polyploidy Increases Rate of Deleterious Mutation Accumulation

Because the fitness effects of most nonsynonymous mutations can vary widely, from neutral to lethal, we asked if the elevated rate of nonsynonymous mutations observed in polyploid *Gossypium* reflects an increase in neutral or nearly neutral nonsynonymous mutations, or if instead this elevation is attributable to a greater accumulation of deleterious mutations. To address this, we used two approaches to estimate whether a mutation was deleterious: BAD_Mutations and GERP++. BAD_Mutations performs a likelihood ratio test from a gene-specific multispecies alignment to determine if a mutation at a particular nonsynonymous site is potentially deleterious, whereas GERP++ uses a genome-wide multiple sequence alignment (i.e., agnostic to genic regions) to

estimate the degree of conservation at a particular site in the genome (including noncoding and synonymous sites). Notably, because one of the hallmark long-term processes following polyploidy is pseudogenization (Wendel 2015), recently pseudogenized sequences may still display some degree of conservation across the multiple sequence alignment, but may not be inherently deleterious. Therefore, to avoid inflating estimates of deleterious mutations in polyploids compared with diploids, we used GERP only within the exonic regions of the 8,884 homoeologs. Additionally, although GERP can score the degree of deleteriousness of a mutation, BAD_Mutations can only classify variants into deleterious or not deleterious. Therefore, the values shown in figure 2D, H, and L represent the sum of the allele frequencies of derived deleterious mutations, similar to the values for figure 2A, E, and I and figure 2B, F, and J. For analysis with GERP, we used the GERP load, which incorporates the deleteriousness of each variant into the score, summing the frequency of each derived allele multiplied by its GERP score (see Rodgers-Melnick et al. [2015] and Wang et al. [2017]).

As shown in figure 2, both of the foregoing analyses demonstrate that deleterious mutations accumulate in polyploids in a manner similar to nonsynonymous mutations, suggesting that the difference in nonsynonymous sites cannot be wholly attributed to putatively neutral or nearly neutral alleles. For example, there is remarkable consistency in the patterns of deleterious mutations that have accumulated since the divergence of the diploid from its respective diploid progenitor in both the count of nonsynonymous substitutions (fig. 2F), the GERP load (fig. 2G), and the number of deleterious mutations (fig. 2H). In all three columns, the diploids show fewer accumulated alleles than the polyploids, *G. tomentosum* (AD₃, Purple) shows the highest number of all the polyploids, and *G. mustelinum* (AD₄, Orange) shows the fewest of all the polyploids.

An interesting pattern arises when comparing estimates of the GERP load (fig. 2G) and number of deleterious mutations (fig. 2H) between diploids and their closely related subgenomes: Although the total number of deleterious mutations in the At subgenomes was 52–99% higher in the polyploids than the diploids (fig. 2H), the GERP load in the polyploids was only 13–42% higher (fig. 2G). Similar patterns were found in the Dt subgenome, with 34–66% more deleterious mutations in the polyploids than the diploid, but only a 9–13% increase in GERP load. This discrepancy could reflect inherent differences in the types of sequences used and how deleteriousness is quantified between the two methods, suggesting that the use of multiple analytical tools for detection of genetic load may yield more nuanced insights than either method on its own (See Discussion).

Asymmetries in the Rate of Deleterious Mutation Accumulation

Although deleterious mutations are accumulating faster in polyploids relative to diploids, it is not obvious whether this increased rate is different from the increased rate of accumulation of nonsynonymous mutations. To test this, we compared, among ploidy levels, the total proportion of

nonsynonymous mutations that were considered deleterious by BAD_Mutations (fig. 3). For mutations that originated since the divergence of the A and D diploids (fig. 3A), the proportion of nonsynonymous sites that are deleterious is roughly 2% higher in polyploids than in diploids, despite the shared evolutionary history of more than 4 My between each subgenome and their respective diploid progenitors. Notably, as similarly shown in figure 2, the proportion of nonsynonymous mutations that are inferred to be deleterious in both diploids is equivalent when mapped to either subgenome, indicating that our filtering criteria did not differentially exclude deleterious or nondeleterious mutations with respect to which subgenome the diploid reads were mapped.

At shallower phylogenetic depths (fig. 3B), the difference between diploids and polyploids becomes even clearer, with polyploids exhibiting 3–4% higher proportions of deleterious mutations in the Dt subgenome and 5–12% higher in the At subgenome than their respective diploid progenitors. The most unbiased and straightforward comparison of the asymmetry in strength of the masking effect of duplicate genomes between the two subgenomes of allopolyploid cottons is provided by mutations that have occurred following polyploidization (fig. 3C). Here, the At subgenome of all species contain

a 2–3% high proportion of deleterious mutations than the Dt subgenome, indicating that differences exist in the strength of the masking effect between the two homoeologous subgenomes that have resided in the same nucleus for over a million years. This pattern is also observed when deleterious mutations are mapped onto the phylogeny (supplementary fig. 3, Supplementary Material online). Additionally, there is more variation among species in the At subgenome than in the Dt subgenome, although the patterns in this respect are not simple. The amount of subgenomic asymmetry is smallest in *G. darwinii* (AD₅, Yellow) from the Galapagos Islands, and largest in the Brazilian endemic and inland species *G. mustelinum* (AD₄, Orange), indicating that asymmetries between subgenomes of the same species may vary within a single clade of allopolyploids.

Disentangling Demography and Selection from Effects of Ploidy

Demography is a potential confounding factor in estimating the rate of deleterious mutation accumulation. Shifts in demography are known to complicate inferences of the strength of selection and genetic load (Brandvain and Wright 2016); for example, even in one of the best studied demographic shifts, the Out of Africa migration in humans, several papers (Lohmueller et al. 2008; Gazave et al. 2013; Simons et al. 2014; Henn et al. 2016; Simons and Sella 2016) have reached seemingly contradictory conclusions on whether genetic load has increased as a result of these shifts in demography (but see Lohmueller [2014]). The pattern of deleterious mutation accumulation has also been well-documented in bottlenecks and population growth associated with domestication in crops such as maize (Wang et al. 2017), soybean and barley (Kono et al. 2016), sorghum (Lozano et al. 2021), cassava (Ramu et al. 2017), and rice (Liu et al. 2017).

Polyploidy is typically associated with a population bottleneck (Grant 1981; Barringer 2007), but because the genetic diversity of both the diploid and polyploid species in this study is low (table 1), demographic modeling of the depth or duration of population bottlenecks and range expansion following polyploid formation is not straightforward. Generalized patterns of the effects of demography on deleterious mutations, however, can serve as a null expectation to test if our data follow the same trends observed under varying demographic scenarios, as explained in the following.

Demographic shifts, including population bottlenecks and expansions, have a large influence on the accumulation of deleterious mutations. According to the nearly neutral theory (Ohta 1992), the fate of deleterious mutations is determined by genetic drift instead of selection when the selection coefficient (s) of deleterious mutations is less than or equal to $1/(2N_e)$, where N_e is the effective population size. The reduction of N_e during a population bottleneck would therefore allow weakly deleterious mutations to escape purifying selection (i.e., to behave as if they were neutral), whereas strongly deleterious mutations with a selective coefficient greater than $1/(2N_e)$ would still be removed by purifying selection. On the

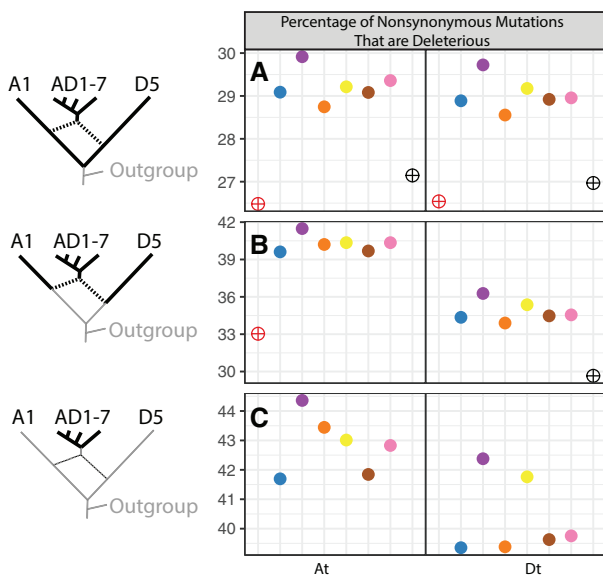


FIG. 3. Proportions of all nonsynonymous mutations that are deleterious. Rows (A), (B), and (C) summarize mutations segregating within the entire clade, within each subgenome and its respective progenitor diploid, and within each subgenome, as indicated by the bolded branches along the phylogeny at left (similar to fig. 2). Values indicate the proportion of nonsynonymous mutations that are deleterious within 8,884 homoeologous pairs (17,768 total genes) that are syntetically conserved between the two subgenomes of AD1 (*Gossypium hirsutum*; see Materials and Methods for filtering criteria). For example, the values in row (A) are calculated by dividing the values in figure 2D by the values in figure 2B for each species. Similar to figure 2, comparisons between subgenomes in row (B) reflect differing phylogenetic distances, not asymmetries between the subgenomes and/or their diploid progenitors.

Table 1. Nucleotide Diversity (π) in 8,884 Homoeologs in Eight *Gossypium* Species, by Subgenome.

Species	Species Code	At Subgenome	Dt Subgenome
<i>Gossypium herbaceum</i>	A1	7.41E-04	
<i>Gossypium raimondii</i>	D5		2.36E-04
<i>Gossypium hirsutum</i>	AD1	6.69E-04	7.06E-04
<i>Gossypium tomentosum</i>	AD3	1.75E-04	1.67E-04
<i>Gossypium mustelinum</i>	AD4	2.64E-04	3.15E-04
<i>Gossypium darwinii</i>	AD5	1.71E-04	1.60E-04
<i>Gossypium ekmanianum</i>	AD6	7.75E-04	7.67E-04
<i>Gossypium stephensii</i>	AD7	4.94E-05	5.59E-05

other hand, as N_e increases during population expansion, mutations that are mildly deleterious are expected to be more efficiently purged from the population.

In both demographic scenarios, we expect that mildly or moderately deleterious mutations would be most differentially affected, whereas strongly deleterious mutations would consistently be removed by purifying selection. Based on this theory, if the differences in the number of deleterious mutations we see between diploids and polyploids are due to demography, then we would expect to see most of that difference reflected in mildly, rather than strongly, deleterious mutations. In contrast, if masking of deleterious alleles in polyploids is driving a higher rate of accumulation relative to diploids, this pattern will not be observed.

To test if our data were consistent with changes in demography, we first asked if there was a correlation between the degree of deleteriousness of a mutation (as measured by GERP) and its relative increase in the polyploids compared with the diploids. To answer this question, we plotted the relative change of deleterious mutations in each subgenome relative to its most closely related diploid progenitor. We plotted this relative change for three different degrees of deleteriousness—strongly deleterious mutations ($4 < \text{GERP} \leq 6$), moderately deleteriousness ($2 < \text{GERP} \leq 4$), and mildly deleteriousness ($0 < \text{GERP} \leq 2$) deleterious (fig. 4). We found that in both subgenomes of all six polyploids, when comparing mutations that had originated after the divergence of the diploid from its respective subgenome in the allopolyploids, strongly deleterious mutations accumulated at a faster rate relative to diploids than did moderately or mildly deleterious mutations, which is inconsistent with expectations under a demographic change model alone. We also observed this change under both an additive and recessive model of dominance (supplementary fig. 5, Supplementary Material online), and also when evaluating deleteriousness using the “masked constraint” estimates generated by BAD_Mutations (supplementary fig. 6, Supplementary Material online, but see Kono et al. [2018] and Chun and Fay [2009] for cautions on interpreting this value as deleteriousness). In total, the rate of accumulation among mutations with different inferred degrees of deleteriousness do not suggest that the patterns we see can be explained solely by demographic changes, but that the masking effect of duplicated genes may play an important role in the determining the fate of deleterious mutations in allopolyploids.

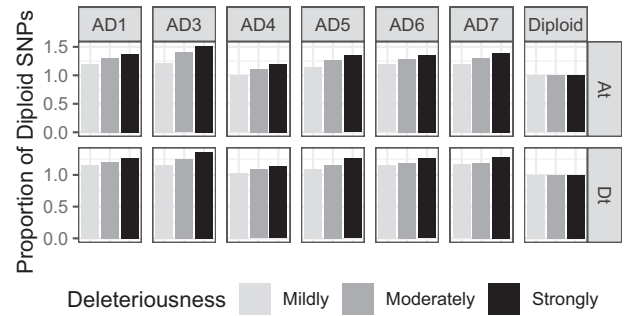


Fig. 4. Relative increase of deleterious mutations among GERP categories in polyploids compared with diploids. For mutations that originated since the divergence of each subgenome from its diploid progenitor, we plotted the relative increase in deleterious alleles across three GERP load categories: mildly deleterious ($0 < \text{GERP} \leq 2$; light gray), moderately deleterious ($2 < \text{GERP} \leq 4$; gray), and strongly deleterious ($4 < \text{GERP} \leq 6$; black). We used the diploid as the reference population, meaning that the relative increase of GERP load in the diploid is always equal to one for all categories. In both subgenomes of all polyploids, strongly deleterious mutations had the greatest relative increase compared with the diploids, followed by the moderately deleterious mutations, and finally, mildly deleterious mutations. This pattern does not fit the expected patterns under demographic models alone, where most of the changes between two populations should be seen in mildly or moderately deleterious mutations. However, under a model where recessive deleterious mutations are masked by their homoeologs, we would expect that strongly deleterious mutations would accumulate faster than moderately or mildly mutations (i.e., the pattern we see here) due to the correlation between the recessivity of a mutation (h) and its selection coefficient (s).

Discussion

Effects of Polyploidy on Deleterious Mutation Accumulation

One of the earliest hypotheses regarding mutation accumulation in allopolyploids dates back to Haldane (Haldane 1932) where he posits that in allopolyploids, “one gene may be altered without disadvantage, provided its functions can be performed by a gene in one of the other sets of chromosomes.” Allopolyploids are therefore predicted to be able to tolerate a higher mutational load than their diploid relatives, and putatively deleterious mutations may accumulate faster in polyploids than in their diploid relatives due to the masking effect of recessive or incompletely dominant deleterious alleles. Here, we demonstrate that these predictions are true in allopolyploid cottons. All polyploids in *Gossypium* harbor more mutations at phylogenetically conserved sites than do their closest diploid progenitors, as determined by two different methods of detecting deleterious mutations. We also find that the proportion of all nonsynonymous mutations that are inferred to be deleterious is higher in polyploids than in their diploid progenitors and that polyploidy has the greatest effect on strongly deleterious (and, inferentially, more recessive; Eyre-Walker and Keightley 2007; Huber et al. 2018) mutations. Thus, using the power of comparative phylogenetics and genomics combined with analytical methods for detection of deleterious mutations, we

demonstrate confirmation of a nearly century-old hypothesis regarding natural selection in allopolyploid organisms.

Demography Alone Cannot Explain Patterns of Deleterious Mutations in Polyploids

Estimating the strength of natural selection and genetic load is notoriously challenging (Lohmueller 2014) and is complicated by shifts in effective population size (including bottlenecks and expansions), mating systems, and effective recombination rates, among other life-history and demographic factors (Brandvain and Wright 2016). Here, we illuminate an additional relevant consideration, that is, whole-genome duplication. Yet many of the considerations for populations that are not in demographic equilibrium also apply to *Gossypium*. Diversification in the cotton tribe (*Gossypieae*) has been characterized by numerous long-distance dispersal events (Grover et al. 2017), including the one from Africa to the Americas 1–2 Mya that led to the evolution of allopolyploid *Gossypium*. We note that in the Hawaiian Islands endemic *G. tomentosum*, the total number of synonymous substitutions is not significantly different from the rest of the polyploids, but the number of nonsynonymous and deleterious mutations is significantly increased, suggesting that the genetic bottleneck associated with island dispersal has elevated the number of deleterious mutations compared with the rest of the polyploids.

Although demographic changes upon polyploid formation have been shown to change the number and frequency of deleterious mutations in other systems (Douglas et al. 2015; Paape et al. 2018; Baduel et al. 2019; Kryvokhyzha, Milesi, et al. 2019; Kryvokhyzha, Salcedo, et al. 2019), we show here that the patterns of mutation accumulation in *Gossypium* cannot be explained by demography alone, and that the data are more consistent with the nearly century-old hypothesis that recessive deleterious mutations can accumulate faster in allopolyploids due to the masking effect of duplicated genes and lack of recombination between subgenomes (Haldane 1932). Specifically, we show that strongly (and, hence, more recessive; Morton et al. 1956; Mukai et al. 1972; Eyre-Walker and Keightley 2007; Agrawal and Whitlock 2011; Huber et al. 2018) deleterious mutations accumulate faster in polyploids compared with diploids than moderately or mildly deleterious mutations, and that this pattern is inconsistent with demographic shifts or long-term change in population size (fig. 4 and supplementary fig. 5, Supplementary Material online).

Asymmetry in Subgenomes in the Distribution of Deleterious Mutations

One of the elegant attributes of a clade of allopolyploid genomes derived from a single polyploidization event is that they offer a remarkable natural experiment for comparing subgenomes that have resided within the same nucleus for, in the case of *Gossypium*, approximately 1.5 My. Once an allopolyploid is established, each subgenome is subjected to identical external or population-level factors, including demography, mating systems, and environmental and ecological conditions, as well as internal cellular processes, including

identical DNA replication and recombination machinery. These features remove many of the confounding factors that may influence the genetic load and provide a simple comparative context for revealing evolutionary forces that might differentially affect coresident genomes or homoeologs.

An unexpected finding of our analyses is the striking asymmetry in the proportion of all nonsynonymous mutations that are inferred to be deleterious between the two subgenomes of all allopolyploid species in *Gossypium*. We found that the At subgenome of all species contains 2–3% more nonsynonymous mutations that are inferred to be deleterious (fig. 3) even when only considering mutations that have arisen following the earliest allopolyploid diversification events, and correcting for removing the biases of unequal phylogenetic distances to each subgenome's model progenitor diploid. Our work adds to a growing recognition that the two coresident subgenomes in cotton allopolyploids may be shaped asymmetrically by evolutionary processes, including interspecific introgression and selection under domestication (Fang, Guan, et al. 2017; Fang, Wang, et al. 2017; Chen et al. 2020; Yuan et al. 2021), and that this phenomenon also extends to other important allopolyploid crop plants, including wheat (Pont and Salse 2017; Jiao et al. 2018) and *Brassica* (Tong et al. 2020).

Teasing apart the genesis of differential subgenomic responses to selection is rendered challenging by several factors independent of phylogeny. We note, for example, the relevant example of the recently formed allopolyploid *Capsella bursa-pastoris* and its diploid progenitors, where consistent asymmetries in genetic load are reported between the subgenomes (Kryvokhyzha, Milesi, et al. 2019; Kryvokhyzha, Salcedo, et al. 2019) the differences likely reflect the dramatically different mating systems of the progenitors, in which the subgenome with the higher genetic load originated from an obligate outcrosser, *C. grandiflora* ($N_e = 800,000$), whereas the subgenome with the lower genetic load derives from the predominantly selfing *C. orientalis* ($N_e = 5,000$) (Douglas et al. 2015). In another recently formed (20–250 ka) allopolyploid, *Arabidopsis kamchatica*, no asymmetry in the distribution of fitness effects between subgenomes was found, although it was observed that each subgenome of the allopolyploid contained more neutral and fewer deleterious alleles than either of the diploid progenitors (Paape et al. 2018). It is unclear, however, whether this shift was due to allopolyploidy per se or if it reflects the transition from an obligate outcrossing to a mating system with some degree of inbreeding, with a concomitant purging of partially or completely recessive deleterious alleles, as shown in several other systems (Arun Kumar et al. 2015; Roessler et al. 2019). In *Gossypium*, all species have similar mating systems and a canonical outcrossing floral morphology including highly exerted styles and stigmas. Population sizes often are small, however, likely leading to relatively high levels of generalized inbreeding. At present, however, no data exist that address these considerations.

Polyploidy, Redundancy, and Fitness Effects

One possible interpretation of our results is that *Gossypium* polyploids are less fit than their closely related diploid

progenitors because they harbor more deleterious mutations in their genomes, especially mutations that have already been driven to fixation. We note, however, that the fitness effects of a mutation may change as a result of the genetic (e.g., epistasis) or environmental (e.g., local adaptation, conditional neutrality) context in which it occurs (Huang et al. 2021). Comparative genomics techniques used to infer deleterious mutations at phylogenetically conserved sites, as employed here, cannot identify these shifts in fitness effects (Huber et al. 2018), and also frequently incorrectly identify beneficial mutations as deleterious (Chen et al. 2020). Therefore, an additional possibility is that mutations in polyploids that occur at phylogenetically conserved sites may not actually have a deleterious effect on fitness as they do in diploids. Inferring the genetic load of a population simply by counting the number of deleterious variants also assumes that all alleles contribute independently to the total genetic load of a population. However, because of the functional overlap of duplicated genes and, in most cases, absence of recombination between homoeologous chromosomes in an allopolyploid, a recessive deleterious mutation can never be present in all four copies of a gene and thus may be invisible to selection because of the masking effect of its homoeologous partner.

An important takeaway from this study is that recessive deleterious mutations in allopolyploids, at least at some loci, may actually accumulate in a manner more similar to neutral mutations, presumably because of the lack of recombination between subgenomes and, hence, the inability of purifying selection to “see” the negative effects of these mutations. Because these recessive deleterious mutations escape the effects of purifying selection, many traditional tests for detecting positive and negative selection (e.g., dN/dS , π_N/π_S) may be biased when comparing a polyploid to diploid because the polyploid would be expected to accumulate putatively deleterious sites more quickly (and maintain a higher genetic diversity at nonsynonymous sites) than their diploid relatives. This increased dN/dS value in allopolyploids compared with diploid progenitors was recently shown in five allopolyploid systems in addition to *Gossypium* (Sharbrough et al. 2022), and duplicated genes associated with an ancient polyploid event in *Brassica rapa* were shown to contain higher amounts of genetic variation than nonduplicated genes (Qi et al. 2021), indicating this phenomenon is likely not restricted to *Gossypium* and should be taken into consideration for other allopolyploid/diploid comparisons. Additionally, although this bias will be most notable in genome-wide comparisons, it may also be evident at the individual gene level, given that both homoeologs are still present and retain some degree of functional overlap (although the robustness of attributing this bias to a ploidy effect acting on a single gene is expected to be low).

Another important implication of this finding is that allopolyploidy (or gene duplication in general) may play an important and underrecognized role in determining how selection acts on new mutations, notwithstanding the burgeoning literature on fates of duplicate gene evolution (Conant et al. 2014; Shi et al. 2020; Veitia and Birchler 2022). The evolutionary trajectory of new mutations will

largely be dependent on the selection coefficient (s) acting on that locus, and the dominance coefficient (h), defined as the proportion of the fitness cost that a mutation harbors when in a heterozygous state. In allopolyploids, however, the evolutionary fate of new mutations may be determined not only by allelic dominance at that locus, but also by the interaction arising from the coexistence of its homoeologous locus, a term we call “homoeologous epistatic dominance.” The relationships between this homoeologous epistatic dominance, allelic dominance, and the selection coefficient are likely complicated and potentially heavily influenced by other biological considerations such as biased expression of homoeologs, sub- or neofunctionalization, and homoeologous recombination, among others. Moreover, notwithstanding these polyploidy-specific effects, even the genome-wide relationships between two of these factors, allelic dominance and the selection coefficient, have only been modeled using genomic data in the past few years (Huber et al. 2018).

Nonetheless, understanding how this homoeologous epistatic dominance impacts the fitness effects of new mutations is an unexplored aspect of polyploid genome evolution, and it is not yet clear whether this will equally affect advantageous and deleterious variants. How homoeologous epistatic dominance operates with respect to functional properties arising from considerations such as gene balance (Veitia and Birchler 2022), dosage effects (Conant et al. 2014), structural and functional entanglement (Kuzmin et al. 2020, 2021), and intersubgenomic *cis*- and *trans*-effects (Bottani et al. 2018; Hu and Wendel 2019) would seem to represent important avenues for understanding how natural selection operates differently in polyploids compared with diploids. From an applied perspective, these insights could be important in agriculture, particularly because so many of our most important crop plants have a recent history that includes polyploidy (Renny-Byfield and Wendel 2014), and segregating patterns of genome fractionation have the potential to serve as targets of selection in crop improvement (Hufford et al. 2021).

Materials and Methods

Plant Materials and Sequencing

We used whole-genome sequencing data from 46 individuals in *Gossypium*, including between two and ten individuals from each of eight species. Included in our sampling was six polyploid species originating from a single polyploidization event 1–2 Mya (Wendel 1989; Hu et al. 2021), two diploid species representing models of the genome donors to the allopolyploids (A and D), and three species from Australia that served as outgroups for polarizing mutations into ancestral and derived states. These sequences were previously described (Yuan et al. 2021), and SRA codes for all 46 resequenced individuals are listed in [supplementary table 1, Supplementary Material online](#). For *G. hirsutum*, we randomly chose ten accessions that were classified in the “Wild” population from Yuan et al. (Yuan et al. 2021), and for the other species, we chose all accessions available that did not show evidence of being mislabeled, as determined by a PCA plot.

After the data were downloaded from NCBI, adapter sequence removal and quality score filtering of FASTQ reads were performed using Trimmomatic v0.36 (Bolger et al. 2014) using the parameters “LEADING:28 TRAILING:28 SLIDINGWINDOW:8:28 SLIDINGWINDOW:1:10 MINLEN:65 TOPHRED33.” Trimmed reads from each polyploid sample were mapped to the 26 chromosomes of the *G. hirsutum* reference genome (Saski et al. 2017), and reads from each diploid sample were mapped to each subgenome separately to avoid competitive mapping of the diploid reads against a tetraploid reference genome. Reads from the three outgroup species were separately mapped to both subgenomes to ensure that reads were not filtered out for mapping to multiple parts of the genome. All mapping was done using bwa-mem v0.7.17 (Li and Durbin 2009) and only uniquely mapping paired reads (-F 260 flag) that were mapped in their proper orientation (-f 2 flag) were retained using Samtools v1.9 (Li et al. 2009) before the files were sorted and converted to bam files. Using the Sentieon (Kendig et al. 2019) SNP Calling program, gVCF files were generated, and joint genotyping was performed using the GVCFTyper algorithm (see Github repository for full scripts). Variant filtering was performed using GATK v4.0.4.0 using the filter expression “QD < 2.0 || FS > 60.0 || MQ < 40.0 || SOR > 4.0 || MQRankSum < -12.5 || ReadPosRankSum < -8.0.” For each species (excluding the outgroup species, and treating *G. stephensii*, and *G. ekmanianum* as a single species), we nullified any variant call in which all individuals were heterozygous to remove any collapsed genomic region in the reference genome or paralogous regions that were not present in the reference genome. We treated *G. stephensii* and *G. ekmanianum* as a single species because we only sampled two individuals of *G. stephensii*, so removing any sites in which both individuals were heterozygous errantly removed real variants that were not due to paralogy mapping issues. All scripts for generating and filtering variant calls are located on our Github repository (<https://github.com/conJUSTover/Deleterious-Mutations-Polyploidy>).

Identification of Homoeologs

We used the pSONIC pipeline (Conover et al. 2021) to identify syntenically conserved homoeologs in the *G. hirsutum* reference genome, and kept only homoeologous pairs that were less than 5% different in their total annotated CDS length. To remove homoeologous pairs that may have experienced homoeologous exchange events (though there is scant evidence for this in *Gossypium*; Salmon et al. 2010; Flagel et al. 2012; Chen et al. 2020), we removed any pair in which the proportion of the reads from the two progenitor diploid genomes (termed At and Dt in the allopolyploid, the “t” indicating “tetraploid”) did not meet the expected 2:2 ratio, similar to previous analyses of homoeologous exchange events in other allotetraploids (Bird et al. 2021). Average read depth of CDS regions was determined by bedtools2 v2.27.1 (Quinlan and Hall 2010). Briefly, for a single homoeologous pair, we calculated the average read depth of the At homoeolog divided by the sum of the average read depth of both homoeologs for each individual. We removed any

homoeologous pair in which this fraction was less than 37.5 or greater than 62.5 in any individual. We expect any HEs that result in a 0:4 At: Dt copy number to contain 0% At reads/total reads; HEs that result in 1:3 At: Dt copy number should have a 25% At reads/total reads; HEs that result in a 3:1 At: Dt copy number should have a 75% At reads/total reads; HEs that result in a 4:0 At: Dt copy number should have a 100% At reads/total reads; and no HE (i.e., 2:2 At: Dt copy number) would result in a 50% At reads/total reads. We used the midpoints between the “No HE” and the 1:3 and 3:1 copy numbers as cutoff points. Because we compared the read depth for homoeologous pairs within each individual, we expect there to be no difference in read depth between homoeologs, and differing read depths among individuals should not introduce any bias in our gene filtering criteria. This filtering resulted in 8,884 homoeologous pairs (17,768 genes) being analyzed further.

Nonreciprocal homoeologous exchanges (i.e., homoeologous gene conversion) could also bias the estimates of the genetic load in a way that is not related to new mutation following polyploidization or speciation. To control for positions in these non-HE homoeologs that may be influenced by gene conversion, we linked variant positions between homoeologs in the following way. We first performed pairwise alignments of the CDS sequences using MACSEv2 (Ranwez et al. 2011, 2018), which aligns CDS sequences in accordance with their translated amino acid sequences, but allows for the possibility of frameshift mutations. We then used the aligned CDS sequences to identify where indels were present and found the corresponding genomic positions for every nucleotide in the alignment, inserting gaps where indels occurred. We then extracted the genomic positions for each SNP position as well as the genomic position for its aligned nucleotide. We retained only those homoeologous SNP positions in which both positions had a confidently called ancestral allele (described above) and in which the ancestral allele matched between the two homoeologs. Importantly, for homoeologs that were encoded in opposite orientations in the reference genome (i.e., one homoeolog was encoded on the forward strand of the reference genome, and the other homoeolog was encoded on the reverse complement), we ensured that the inferred ancestral states for the two SNP positions included both nucleotides of a purine/pyrimidine pair (e.g., the ancestral state for homoeologous SNP was “A,” whereas the ancestral state of the other homoeologous SNP was “T”). We also removed any pair of homoeologous SNPs in which more than two alleles were present (while similarly treating homoeologous pairs encoded in opposite directions as described in the previous sentence).

In total, we only used those SNP sites that: 1) did not link to an indel in its homoeologous pair, 2) were biallelic and had consistently inferred ancestral states in the two subgenomes, 3) the derived allele was found in only one of the two subgenomes or their respective diploid progenitors, and 4) the derived allele was fixed in a diploid and segregating in its respective subgenome (or vice-versa).

Quantifying Deleterious Mutations

We used GERP++ (Davydov et al. 2010) to identify regions of the genome that are evolutionarily conserved, using whole-genome alignments from 11 genomes spanning the Eudicots (supplementary table 2, Supplementary Material online). Species were chosen if they contained chromosome-level assemblies publicly available on Phytozome or NCBI, and if all documented whole-genome duplication events in each species' evolutionary history is also shared by *Gossypium* (e.g., the *Arabidopsis thaliana* genome was not chosen because it has experienced at least one independent WGD event since its divergence from *Gossypium*). Genomes were aligned to the *G. hirsutum* reference genome using the LASTZ/MULTIZ approach used by the UCSC genome browser. Briefly, genomes were masked using Repeatmasker using a custom repeat library enriched with *Gossypium* TEs (Grover et al. 2017). Each query genome was aligned to each of the *G. hirsutum* reference chromosomes separately. These alignments were chained together using axChain, and the best alignment was found using ChainNet. These alignment files were converted into fasta files using the roast program from the MULTIZ package.

Using these genome alignments, we used the gerp++ package (Davydov et al. 2010) to calculate GERP scores for every position in the genome. First, we used 4-fold degenerate sites in all genomes to calculate a neutral-rate evolutionary tree, which was calculated using RAXML (Stamatakis 2014). We then used the gerp++ package to estimate the GERP score at every position in the genome, but importantly, we excluded the *G. hirsutum* reference genome from the alignment to avoid biasing sites in the reference genome that may be deleterious. Because the gerp++ program ignores gaps in the reference genome, we used custom R scripts to enter dummy variables in the gapped regions of the GERP score so the number of GERP scores equaled the total number of nucleotide positions in each chromosome. To calculate the genetic load across linked sites, we used the GERP load (i.e., the sum of the derived allele frequency times the GERP score for each variant site) as described in Wang et al. (2017) and Rodgers-Melnick et al. (2015). All scripts for generating the multiple sequence alignments and GERP scores can be found in our GitHub repository (<https://github.com/conJUSTover/Deleterious-Mutations-Polyploidy>).

Secondly, we used the BAD_Mutations (Kono et al. 2016, 2018) pipeline to perform LRT tests on conserved amino acid substitutions sites. Nonsynonymous substitutions were identified using SNPEff (Cingolani et al. 2012) and statistical significance was determined using a Bonferroni correction with 967,155 missense mutations to correct for multiple testing. Every step of the BAD_Mutations pipeline was performed using the dev branch of the github repository (accessed July 13, 2020). Species included in the calculation of deleterious mutations are included in supplementary table 3, Supplementary Material online, with the notable absence of *Gossypium raimondii* since it was sampled as part of this project.

We used the GERP load (sum of the allele frequencies $\times$ GERP score) (Wang et al. 2017) and the

BAD_Mutations load (sum of the allele frequencies of all statistically significant deleterious mutations) as a summary of the genetic load present in each genome at different phylogenetic depths. The BAD_Mutations load may be interpreted as the average number of deleterious alleles expected in each individual of a population, but it does not differentiate between severity of deleteriousness (as does GERP load). We also used GERP to classify mutations into mildly deleterious ($0 < \text{GERP} \leq 2$), moderately deleterious ($2 < \text{GERP} \leq 4$), and strongly deleterious ($4 < \text{GERP} \leq 6$). Scripts for generating the whole-genome alignments for GERP are located on our GitHub repository (<https://github.com/conJUSTover/Deleterious-Mutations-Polyploidy>).

Rate of Deleterious Mutations along the Phylogeny of *Gossypium*

To determine if there was a bias in the rate of deleterious mutation accumulation between the two subgenomes, we used homoeologous SNPs in which the derived allele showed a parsimony-informative position between the two subgenomes of allopolyploids and the two diploid progenitors (identified by the green bars in supplementary fig. 1, Supplementary Material online).

Genetic Diversity

For each species, π for the 17,768 high-quality gene CDS sequences (8,884 homoeologous pairs) was calculated on a sitewise basis using vcftools (Danecek et al. 2011). To find the total π across all genes, we summed the total sitewise π values and divided by the total length of the concatenated CDS sequences, removing any positions which did not have a null SNP call in the VCF file.

Supplementary Material

Supplementary data are available at *Molecular Biology and Evolution* online.

Acknowledgments

The authors thank the Iowa State University ResearchIT Unit for computational support. The authors also thank Guanqing Hu for her assistance in designing figure 1, Corrinne Grover for providing the repeat database used in the initial genome alignments for GERP, and Matthew Hufford for his helpful comments and discussions on the manuscript. Additionally, they would like to thank the two reviewers for their helpful comments, which improved the clarity of this manuscript. This work was supported by funding from the National Science Foundation-Plant Genome Research Program (awarded to J.F.W.) and Cotton Inc. (awarded to J.F.W. and J.L.C.).

References

- Agrawal AF, Whitlock MC. 2011. Inferences about the distribution of dominance drawn from yeast gene knockout data. *Genetics* 187(2):553–566.
- Arunkumar R, Ness RW, Wright SI, Barrett SCH. 2015. The evolution of selfing is accompanied by reduced efficacy of selection and purging of deleterious mutations. *Genetics* 199(3):817–829.

- Baduel P, Quadrana L, Hunter B, Bomblies K, Colot V. 2019. Relaxed purifying selection in autopolyploids drives transposable element over-accumulation which provides variants for local adaptation. *Nat Commun.* 10(1):5818.
- Barringer BC. 2007. Polyploidy and self-fertilization in flowering plants. *Am J Bot.* 94(9):1527–1533.
- Bever JD, Felber F. 1992. The theoretical population genetics of autopolyploidy. Futuyma D, Antonovics J, editors. *Oxford surveys in evolutionary biology*. Vol. 8. New York: Oxford University Press. p. 185–185.
- Bolger AM, Lohse M, Usadel B. 2014. Trimmomatic: a flexible trimmer for Illumina sequence data. *Bioinformatics* 30(15):2114–2120.
- Bomblies K. 2020. When everything changes at once: finding a new normal after genome duplication. *Proc Biol Sci.* 287(1939):20202154.
- Bottani S, Zabet NR, Wendel JF, Veitia RA. 2018. Gene expression dominance in allopolyploids: hypotheses and models. *Trends Plant Sci.* 23(5):393–402.
- Brandvain Y, Wright SI. 2016. The limits of natural selection in a non-equilibrium world. *Trends Genet.* 32(4):201–210.
- Chen ZJ, Sreedasyam A, Ando A, Song Q, De Santiago LM, Hulse-Kemp AM, Ding M, Ye W, Kirkbride RC, Jenkins J, et al. 2020. Genomic diversifications of five *Gossypium* allopolyploid species and their impact on cotton improvement. *Nat Genet.* 52:525–533.
- Chun S, Fay JC. 2009. Identification of deleterious mutations within three human genomes. *Genome Res.* 19(9):1553–1561.
- Cingolani P, Platts A, Wang LL, Coon M, Nguyen T, Wang L, Land SJ, Lu X, Ruden DM. 2012. A program for annotating and predicting the effects of single nucleotide polymorphisms, SnpEff: SNPs in the genome of *Drosophila melanogaster* strain w1118. *Fly (Austin)* 6(2):80–92.
- Conant GC, Birchler JA, Pires JC. 2014. Dosage, duplication, and diploidization: clarifying the interplay of multiple models for duplicate gene evolution over time. *Curr Opin Plant Biol.* 19:91–98.
- Conover JL, Sharbrough J, Wendel JF. 2021. pSONIC: ploidy-aware syntenic orthologous networks identified via collinearity. G3 11(8). Available from: <http://dx.doi.org/10.1093/g3journal/jkab170>.
- Danecek P, Auton A, Abecasis G, Albers CA, Banks E, DePristo MA, Handsaker RE, Lunter G, Marth GT, Sherry ST, et al. 2011. The variant call format and VCFtools. *Bioinformatics* 27(15):2156–2158.
- Davydov EV, Goode DL, Sirota M, Cooper GM, Sidow A, Batzoglou S. 2010. Identifying a high fraction of the human genome to be under selective constraint using GERP++. *PLoS Comput Biol.* 6(12):e1001025.
- Douglas GM, Gos G, Steige KA, Salcedo A, Holm K, Josephs EB, Arunkumar R, Ågren JA, Hazzouri KM, Wang W, et al. 2015. Hybrid origins and the earliest stages of diploidization in the highly successful recent polyploid *Capsella bursa-pastoris*. *Proc Natl Acad Sci U S A.* 112(9):2806–2811.
- Doyle JJ, Coate JE. 2019. Polyploidy, the nucleotype, and novelty: the impact of genome doubling on the biology of the cell. *Int J Plant Sci.* 180(1):1–52.
- Eyre-Walker A, Keightley PD. 2007. The distribution of fitness effects of new mutations. *Nat Rev Genet.* 8(8):610–618.
- Fang L, Guan X, Zhang T. 2017. Asymmetric evolution and domestication in allotetraploid cotton (*Gossypium hirsutum* L.). *Crop J.* 5(2):159–165.
- Fang L, Wang Q, Hu Y, Jia Y, Chen J, Liu B, Zhang Z, Guan X, Chen S, Zhou B, et al. 2017. Genomic analyses in cotton identify signatures of selection and loci associated with fiber quality and yield traits. *Nat Genet.* 49(7):1089–1098.
- Fernandes Gyorffy M, Miller ER, Conover JL, Grover CE, Wendel JF, Sloan DB, Sharbrough J. 2021. Nuclear-cytoplasmic balance: whole genome duplications induce elevated organellar genome copy number. *Plant J.* 108(1):219–230.
- Flagel LE, Wendel JF, Udall JA. 2012. Duplicate gene evolution, homoeologous recombination, and transcriptome characterization in allopolyploid cotton. *BMC Genomics* 13:302.
- Gazave E, Chang D, Clark AG, Keinan A. 2013. Population growth inflates the per-individual number of deleterious mutations and reduces their mean effect. *Genetics* 195(3):969–978.
- Grant V. 1981. Plant speciation. New York : Columbia University Press.
- Grover CE, Arick MA, 2nd, Conover JL, Thrash A, Hu G, Sanders WS, Hsu C-Y, Naqvi RZ, Farooq M, Li X, et al. 2017. Comparative genomics of an unusual biogeographic disjunction in the cotton tribe (Gossypieae) yields insights into genome downsizing. *Genome Biol Evol.* 9(12):3328–3344.
- Grover CE, Grupp KK, Wanzek RJ, Wendel JF. 2012. Assessing the monophyly of polyploid *Gossypium* species. *Plant Syst Evol.* 298(6):1177–1183.
- Haldane JBS. 1932. The causes of evolution. New York: Longmans, Green and Co.
- Henn BM, Botigué LR, Peischl S, Dupanloup I, Lipatov M, Maples BK, Martin AR, Musharoff S, Cann H, Snyder MP, et al. 2016. Distance from sub-Saharan Africa predicts mutational load in diverse human genomes. *Proc Natl Acad Sci U S A.* 113(4):E440–E449.
- Hill RR Jr. 1970. Selection in autotetraploids. *Theor Appl Genet.* 41(4):181–186.
- Hu G, Grover CE, Yuan D, Dong Y, Miller E, Conover JL, Wendel JF. 2021. Evolution and diversity of the cotton genome. In: Rahman MU, Zafar Y, Zhang T, editors. Cotton precision breeding. Cham (Switzerland): Springer International Publishing. p. 25–78.
- Hu G, Wendel JF. 2019. Cis-trans controls and regulatory novelty accompanying allopolyploidization. *New Phytol.* 221(4):1691–1700.
- Huang X, Fortier AL, Coffman AJ, Struck TJ, Irby MN, James JE, León-Burguete JE, Ragsdale AP, Gutenkunst RN. 2021. Inferring Genome-Wide Correlations of Mutation Fitness Effects between Populations. *Mol Biol Evol.* 38(10):4588–4602.
- Huber CD, Durvasula A, Hancock AM, Lohmueller KE. 2018. Gene expression drives the evolution of dominance. *Nat Commun.* 9(1):2750.
- Hufford MB, Seetharam AS, Woodhouse MR, Chougule KM, Ou S, Liu J, Ricci WA, Guo T, Olson A, Qiu Y, et al. 2021. De novo assembly, annotation, and comparative analysis of 26 diverse maize genomes. *Science* 373(6555):655–662.
- Jiao W, Yuan J, Jiang S, Liu Y, Wang L, Liu M, Zheng D, Ye W, Wang X, Chen ZJ. 2018. Asymmetrical changes of gene expression, small RNAs and chromatin in two resynthesized wheat allotetraploids. *Plant J.* 93(5):828–842.
- Jiao Y, Wickett NJ, Ayyampalayam S, Chanderbali AS, Landherr L, Ralph PE, Tomsho LP, Hu Y, Liang H, Soltis PS, et al. 2011. Ancestral polyploidy in seed plants and angiosperms. *Nature* 473(7345):97–100.
- Kendig KI, Baheti S, Bockol MA, Drucker TM, Hart SN, Heldenbrand JR, Hernaez M, Hudson ME, Kalmbach MT, Klee EW, et al. 2019. Sentieon DNaseq variant calling workflow demonstrates strong computational performance and accuracy. *Front Genet.* 10:736.
- Kono TJY, Fu F, Mohammadi M, Hoffman PJ, Liu C, Stupar RM, Smith KP, Tiffin P, Fay JC, Morrell PL. 2016. The role of deleterious substitutions in crop genomes. *Mol Biol Evol.* 33(9):2307–2317.
- Kono TJY, Lei L, Shih C-H, Hoffman PJ, Morrell PL, Fay JC. 2018. Comparative genomics approaches accurately predict deleterious variants in plants. G3 (Bethesda). 8(10):3321–3329.
- Kryvokhyzha D, Milesi P, Duan T, Orsucci M, Wright SI, Glémin S, Lascoux M. 2019. Towards the new normal: transcriptomic convergence and genomic legacy of the two subgenomes of an allopolyploid weed (*Capsella bursa-pastoris*). *PLoS Genet.* 15(5):e1008131.
- Kryvokhyzha D, Salcedo A, Eriksson MC, Duan T, Tawari N, Chen J, Guerrina M, Kreiner JM, Kent TV, Lagercrantz U, et al. 2019. Parental legacy, demography, and admixture influenced the evolution of the two subgenomes of the tetraploid *Capsella bursa-pastoris* (Brassicaceae). *PLoS Genet.* 15(2):e1007949.
- Kuzmin E, Taylor JS, Boone C. 2021. Retention of duplicated genes in evolution. *Trends Genet.* 38:59–72.
- Kuzmin E, VanderSluis B, Nguyen Ba AN, Wang W, Koch EN, Usaj M, Khmelinskii A, Usaj MM, van Leeuwen J, Kraus O, et al. 2020. Exploring whole-genome duplicate gene retention with complex genetic interaction analysis. *Science* 368(6498):1–11.
- Li H, Durbin R. 2009. Fast and accurate short read alignment with Burrows-Wheeler transform. *Bioinformatics* 25(14):1754–1760.
- Li H, Handsaker B, Wysoker A, Fennell T, Ruan J, Homer N, Marth G, Abecasis G, Durbin R. 2009. Genome Project Data Processing

- Subgroup. 2009. The sequence alignment/Map format and SAMtools. *Bioinformatics* 25(16):2078–2079.
- Liu Q, Zhou Y, Morrell PL, Gaut BS. 2017. Deleterious variants in Asian rice and the potential cost of domestication. *Mol Biol Evol*. 34(4):908–924.
- Lohmueller KE. 2014. The distribution of deleterious genetic variation in human populations. *Curr Opin Genet Dev*. 29:139–146.
- Lohmueller KE, Indap AR, Schmidt S, Boyko AR, Hernandez RD, Hubisz MJ, Sninsky JJ, White TJ, Sunyaev SR, Nielsen R, et al. 2008. Proportionally more deleterious genetic variation in European than in African populations. *Nature* 451(7181):994–997.
- Lozano R, Gazave E, dos Santos JPR, Stetter MG, Valluru R, Bandillo N, Fernandes SB, Brown PJ, Shakoob N, Mockler TC, et al. 2021. Comparative evolutionary genetics of deleterious load in sorghum and maize. *Nat Plants*. 7(1):17–24.
- Mason AS, Wendel JF. 2020. Homoeologous exchanges, segmental allopolyploidy, and polyploid genome evolution. *Front Genet*. 11:1014.
- Matsumoto T, Wakefield L, Peters A, Peto M, Spellman P, Grompe M. 2021. Proliferative polyploid cells give rise to tumors via ploidy reduction. *Nat Commun*. 12(1):646.
- Monnahan P, Kolář F, Baduel P, Sailer C, Koch J, Horvath R, Laenen B, Schmickl R, Paajanen P, Šrámková G, et al. 2019. Pervasive population genomic consequences of genome duplication in *Arabidopsis arenosa*. *Nat Ecol Evol*. 3(3):457–468.
- Morton NE, Crow JF, Muller HJ. 1956. An estimate of the mutational damage in man from data on consanguineous marriages. *Proc Natl Acad Sci U S A*. 42(11):855–863.
- Mukai T, Chigusa SI, Mettler LE, Crow JF. 1972. Mutation rate and dominance of genes affecting viability in *Drosophila melanogaster*. *Genetics* 72(2):335–355.
- Ohta T. 1992. The nearly neutral theory of molecular evolution. *Annu Rev Ecol Syst*. 23(1):263–286.
- One Thousand Plant Transcriptomes Initiative. 2019. One thousand plant transcriptomes and the phylogenomics of green plants. *Nature* 574:679–685.
- Paape T, Briskine RV, Halstead-Nussloch G, Lischer HEL, Shimizu-Inatsugi R, Hatakeyama M, Tanaka K, Nishiyama T, Sabirov R, Sese J, et al. 2018. Patterns of polymorphism and selection in the subgenomes of the allopolyploid *Arabidopsis kamchatica*. *Nat Commun*. 9:1–13.
- Pont C, Salse J. 2017. Wheat paleohistory created asymmetrical genomic evolution. *Curr Opin Plant Biol*. 36:29–37.
- Qi X, An H, Hall TE, Di C, Blischak PD, McKibben MTW, Hao Y, Conant GC, Pires JC, Barker MS. 2021. Genes derived from ancient polyploidy have higher genetic diversity and are associated with domestication in *Brassica rapa*. *New Phytol*. 230(1):372–386.
- Quinlan AR, Hall IM. 2010. BEDTools: a flexible suite of utilities for comparing genomic features. *Bioinformatics* 26(6):841–842.
- Ramu P, Esuma W, Kawuki R, Rabbi IY, Egesi C, Bredeson JV, Bart RS, Verma J, Buckler ES, Lu F. 2017. Cassava haplotype map highlights fixation of deleterious mutations during clonal propagation. *Nat Genet*. 49(6):959–963.
- Ranwez V, Douzery EJP, Cambon C, Chantret N, Delsuc F. 2018. MACSE v2: toolkit for the alignment of coding sequences accounting for frameshifts and stop codons. *Mol Biol Evol*. 35(10):2582–2584.
- Ranwez V, Harispe S, Delsuc F, Douzery EJP. 2011. MACSE: multiple Alignment of Coding SEquences accounting for frameshifts and stop codons. *PLoS One* 6(9):e22594.
- Renny-Byfield S, Wendel JF. 2014. Doubling down on genomes: polyploidy and crop plants. *Am J Bot*. 101(10):1711–1725.
- Rodgers-Melnick E, Bradbury PJ, Elshire RJ, Glaubitz JC, Acharya CB, Mitchell SE, Li C, Li Y, Buckler ES. 2015. Recombination in diverse maize is stable, predictable, and associated with genetic load. *Proc Natl Acad Sci U S A*. 112(12):3823–3828.
- Roessler K, Muyle A, Diez CM, Gaut GRJ, Bousios A, Stitzer MC, Seymour DK, Doebley JF, Liu Q, Gaut BS. 2019. The genome-wide dynamics of purging during selfing in maize. *Nat Plants*. 5(9):980–990.
- Salmon A, Flagel L, Ying B, Udall JA, Wendel JF. 2010. Homoeologous nonreciprocal recombination in polyploid cotton. *New Phytol*. 186(1):123–134.
- Saski CA, Scheffler BE, Hulse-Kemp AM, Liu B, Song Q, Ando A, Stelly DM, Scheffler JA, Grimwood J, Jones DC, et al. 2017. Sub genome anchored physical frameworks of the allotetraploid Upland cotton (*Gossypium hirsutum* L.) genome, and an approach toward reference-grade assemblies of polyploids. *Sci Rep*. 7:15274.
- Shi X, Chen C, Yang H, Hou JTT, Cheng J, Veitia RA, Birchler JA. 2020. The gene balance hypothesis: epigenetics and dosage effects in plants. In: Spillane C, McKeown P, editors. *Plant epigenetics and epigenomics: methods and protocols*. New York: Springer US. p. 161–171.
- Simons YB, Sella G. 2016. The impact of recent population history on the deleterious mutation load in humans and close evolutionary relatives. *Curr Opin Genet Dev*. 41:150–158.
- Simons YB, Turchin MC, Pritchard JK, Sella G. 2014. The deleterious mutation load is insensitive to recent population history. *Nat Genet*. 46(3):220–224.
- Stamatakis A. 2014. RAXML version 8: a tool for phylogenetic analysis and post-analysis of large phylogenies. *Bioinformatics* 30(9):1312–1313.
- Tong C, Kole C, Liu L, Cheng X, Huang J, Liu S. 2020. The asymmetrical evolution of the mesopolyploid *Brassica oleracea* genome. In: Liu S, Snowdon R, Kole C, editors. *The Brassica oleracea genome*. Cham, Switzerland: Springer Nature. p. 67.
- Veitia RA, Birchler JA. 2022. Gene-dosage issues: a recurrent theme in whole genome duplication events. *Trends Genet*. 38(1):1–3.
- Wang L, Beissinger TM, Lorant A, Ross-Ibarra C, Ross-Ibarra J, Hufford MB. 2017. The interplay of demography and selection during maize domestication and expansion. *Genome Biol*. 18(1):215.
- Wendel JF. 1989. New World tetraploid cottons contain Old World cytoplasm. *Proc Natl Acad Sci U S A*. 86(11):4132–4136.
- Wendel JF. 2015. The wondrous cycles of polyploidy in plants. *Am J Bot*. 102(11):1753–1756.
- Wendel JF, Grover CE. 2015. Taxonomy and evolution of the cotton genus, *Gossypium*. In: Fang DD, Percy RG, editors. *Cotton*. Agronomy monograph. Madison (WI): American Society of Agronomy, Inc., Crop Science Society of America, Inc., and Soil Science Society of America, Inc. p. 25–44.
- Yuan D, Grover CE, Hu G, Pan M, Miller ER, Conover JL, Hunt SP, Udall JA, Wendel JF. 2021. Parallel and intertwining threads of domestication in allopolyploid cotton. *Adv Sci*. 8(10):2003634.