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Assessment of Gene Flow Between *Gossypium hirsutum* and *G. herbaceum*: Evidence of Unreduced Gametes in the Diploid Progenitor

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ABSTRACT In the framework of a gene flow assessment, we investigated the natural hybridization rate between *Gossypium hirsutum* (AADD genome) and *G. herbaceum* (AA genome). The latter species, a diploid progenitor of *G. hirsutum*, is spontaneously present in South Africa. Reciprocal crosses were performed without emasculation between *G. herbaceum* and *G. hirsutum*. Neither examination of the morphological characteristics nor flow cytometry analysis of the 335 plants resulting from the *G. hirsutum* × *G. herbaceum* cross showed any hybrid features. Of the 148 plants produced from the *G. herbaceum* × *G. hirsutum* cross, three showed a hybrid phenotype, and their hybrid status was confirmed by SSR markers. Analysis of DNA content by flow cytometry and morphological traits clearly showed that two of these plants were triploid (AAD). The third plant had a flow cytometry DNA content slightly higher than *G. hirsutum*. In addition, its morphological characteristics (plant architecture, presence and size of petal spots, leaf shape) led us to conclude that this plant was AAAAD thus resulting from fertilization with an unreduced AA gamete of the female *G. herbaceum* parent. Fluorescent *In Situ* Hybridization (FISH) and meiotic behavior confirmed this hypothesis. To the best of our knowledge, this is the first description of such gametes in *G. herbaceum*, and it opens new avenues in breeding programs. Furthermore, this plant material could provide a useful tool for studying the expression of genes duplicated in the A and D cotton genome.

KEYWORDS

Gene flow
natural
hybridization
unreduced
gamete
Gossypium hirsutum
Gossypium herbaceum

Assessment of gene flow from a crop to a wild relative is particularly relevant in the case of allopolyploid species, which are formed by

hybridization between related species, when one of its progenitors is present in cultivated areas. In certain geographical areas, this may be the case for the cultivated tetraploid cotton (*Gossypium hirsutum*, AADD, $2n = 4x = 52$) and a wild diploid species (*Gossypium herbaceum*, AA, $2n = 2x = 26$). Cultivated cotton, the most important source of natural fiber, has been the long-standing subject of a number of taxonomical studies (Watt 1907; Hutchinson *et al.* 1947; Saunders 1961; cited in Wendel *et al.* 2010; Fryxell 1979; Fryxell *et al.* 1992). The cotton genus (*Gossypium* L.) includes 50 diploid species ($2n = 2x = 26$) that can be differentiated cytogenetically into eight genome groups (A–G and K), and seven allotetraploid species ($2n = 4x = 52$) (Fryxell 1979; Fryxell *et al.* 1992; Stewart 1995; Wendel and Cronn 2003; Grover *et al.* 2015; Gallagher *et al.* 2017). Remarkably, among the four domesticated species, there are two allotetraploids (the New World tetraploids *G. hirsutum* and *G. barbadense*) and two diploids (the Old World diploids *G. arboreum* and *G. herbaceum*). The tetraploid species originated from a single polyploidization

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event between an A-genome diploid species and a D-genome diploid species (Wendel and Cronn 2003). The two African-Asian A-genome cottons, *G. arboreum* and *G. herbaceum*, are the equivalent of the maternal genome donor to polyploid cotton (Wendel 1989), although some evidence suggests that *G. herbaceum* may more closely resemble the A-genome donor than *G. arboreum* (Wendel *et al.* 2010). Recent results have suggested an independent domestication of these two Old World cotton species (Renny-Byfield *et al.* 2016). Grover *et al.* (2015) demonstrated that this combination of a D-genome progenitor, resembling modern *G. raimondii*, and an A-genome progenitor, much like modern *G. arboreum* and *G. herbaceum*, occurred as a single hybridization event (genomic merger and doubling) that gave rise to all polyploid cottons. Interspecific hybridizations have been used extensively to improve yield, fiber quality, or other agronomic traits, and numerous studies have focused on the introgression of traits of interest from wild diploid cotton into cultivated cotton *G. hirsutum* (Meyer 1974; Stewart 1995; Mergeai 2003; Chee *et al.* 2016). Colchicine doubling is an essential step in producing an improved cultivar through interspecific crossing, as the recovered triploid hybrids are sterile. Unreduced gametes have proven useful in enabling crosses between plants of different ploidy levels, which otherwise often fail due to unbalanced parental contributions in the developing seed (Barcaccia *et al.* 2003; Carputo *et al.* 2003). If the plant of the lower ploidy level can be induced to produce unreduced gametes, such limitations can be overcome. This strategy has been successfully used in various species such as potato, alfalfa, and manioc (reviewed in Brownfield and Kohler 2011; Dewitte *et al.* 2012).

The large-scale development of transgenic insect-resistant and/or herbicide-tolerant cotton has promoted studies about the ability of native diploid A or D species to produce fertile hybrids with tetraploid cotton (Stewart 1995; Brubaker *et al.* 1999). In South Africa, and particularly in the KwaZulu Natal Province, where the commercialization of transgenic Bt cotton began in 1998, a wild species (*G. herbaceum*), one of the progenitors of *G. hirsutum*, is found in areas neighboring the cultivated cotton fields. Consequently, we have undertaken a study to evaluate the likelihood of gene flow between the allotetraploid cultivated cotton (*G. hirsutum*) and its wild diploid relative (*G. herbaceum*). Transgene escape depends on the generation of fertile hybrids, and the possible selective advantage that would result in the development of weedy derivatives. In this paper, we present our analysis of natural cotton gene flow in South Africa, which furthermore provides evidence for unreduced gametes in the species *G. herbaceum*.

MATERIALS AND METHODS

Plant material

Reciprocal crosses were performed without emasculation between *G. herbaceum* Indian accession Boumi Aria (A_1A_1 , $2n = 26$) and *G. hirsutum* ($A_tA_tD_tD_t$, $2n = 52$; lower case letter “t” referring to the “tetraploid” genome) Delta Opal RR from Deltapine, South Africa. Forty plants from each accession were maintained in individual pots in a greenhouse at Pretoria University and divided into two batches: donor plants for pollen harvest and recipient plants for hybrid production. To simulate both pollination occurring in the field and regular visits by pollinators to plants, pollen harvested from newly opened flowers was spread on the recipient flowers without emasculation two or three times between 9 and 11 AM. All the subsequently produced seeds were sown (one seed per pot) in greenhouses at the Versailles Centre of the French

National Institute of Agricultural Research (INRA) to screen for hybrids.

Seeds with a thick seed coat harvested from *G. herbaceum* were scraped with sandpaper to facilitate germination, and then placed on wet paper at 24°. Germinating seeds were planted in soil in a greenhouse following radicle emergence.

Morphological examinations

Morphological examinations were made both at the vegetative stage (six leaves) and at the reproductive stage. Details of flower morphology were recorded. In plants that exhibited hybrid characteristics, particular attention was paid to flower size and color, and especially to the presence and intensity of red petal spots, as *G. hirsutum* has no spot, and *G. herbaceum* shows large, bright red spots.

Pollen viability

Pollen viability was assessed after Alexander dye staining (Alexander 1969) with a 3-hr incubation period at 50°. Several samples were taken in the greenhouse between 10 and 11 AM on several distinct days.

Estimation of nuclear DNA amount by flow cytometry

Flow cytometry analyses (Partec ploidy analyzer, Munster, Germany) were performed for all progeny on leaf tissue to assess their nuclear DNA amount, as described by Eber *et al.* (1997). Barley leaves served as the internal reference with set value of 100. Preliminary experiments confirmed that the measure was not affected neither by leaf age or conservation delay (5–20 min) of shredded leaves in the buffer (Kit Partec, Munster, Germany). Three measurements with independent leaf samples were performed for each control and potentially hybrid plant. Twenty plants were analyzed for the *G. hirsutum* and *G. herbaceum* parents. The twofold size difference between the two genomes A and D was taken into account to determine chromosome numbers.

Meiotic behavior and chromosome counting

Young squares (flower buds) were sampled in the greenhouse from the two parental lines and for deemed hybrid plants according to flow cytometric analysis and morphological observations. They were fixed in Carnoy's solution (ethanol:chloroform:acetic acid, 6:3:1) for 24 hr, and preserved in 70% ethanol until characterized. For the observation of pollen mother cells (PMCs), anthers were squashed in 1% acetocarmine, and cells inspected with a light microscope. PMCs were observed at metaphase I to establish the meiotic behavior of the hybrids.

SSR marker analysis

Microsatellite (SSR) markers were used to verify the hybrid status of progenies obtained from the different hybridizations. Six SSRs (BNL 3264, BNL 3563, BNL 409, BNL 4049, NAU 0915, and NAU 1246) that demonstrated clear polymorphisms between *G. hirsutum* and *G. herbaceum* were selected, based on prior screens of diploid and tetraploid accessions (J.M. Lacape, unpublished data). Their primer sequences are available from CottonGen (<https://www.cottongen.org/>). Sixty-six DNAs were analyzed, including 64 progenies from the two reciprocal crosses (46 for *G. hirsutum* × *G. herbaceum*, and 18 for *G. herbaceum* × *G. hirsutum*), and from control DNAs of each parental species. Polymorphic markers between the two species were kept for hybrid characterization. DNA extraction, PCR amplification and electrophoresis-based allele separation were performed according to Lacape *et al.* (2007). The progenies were assigned an allelic “hybrid” coding when alleles of both *G. hirsutum* (could be one or two amplicons) and *G. herbaceum* (an additional unique amplicon) were detected.

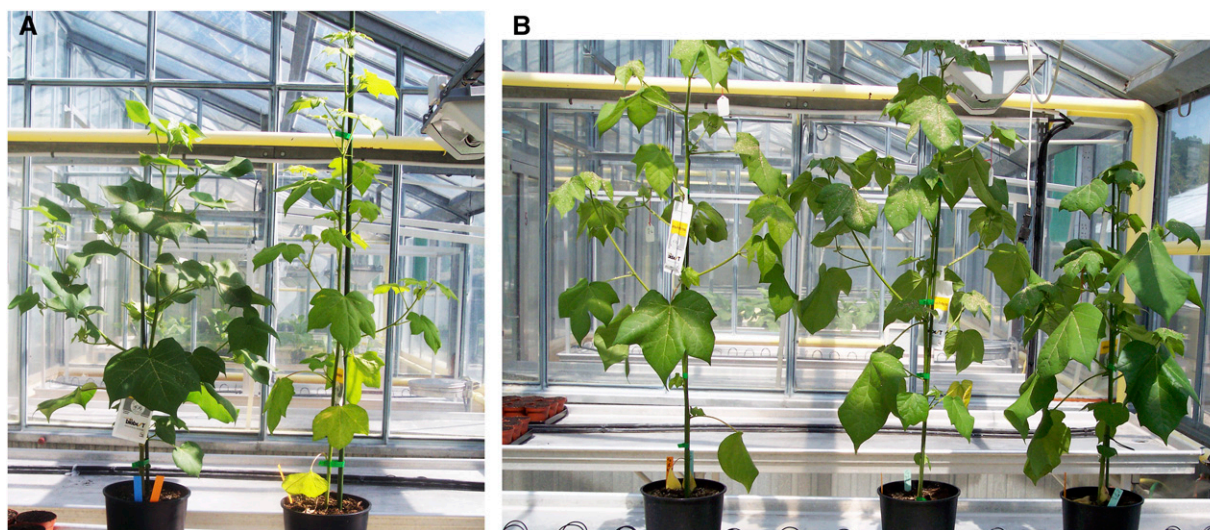


Figure 1 Plants at 70 d of culture. (A) Left to right *G. hirsutum*, *G. herbaceum*, (B) left to right, hybrid H1, hybrid H2, and hybrid H3.

Fluorescence in situ hybridization (FISH)

Mitotic chromosomal squashes were prepared with standard techniques. FISH experiments were carried out with two DNA probes: the 45S rDNA probe (pTa 71) is a cloned 9-kb *EcoRI* fragment of a rDNA repeat unit (18S-5.8S-26S genes and spacers) isolated from *Triticum aestivum* (Gerlach and Bedbrook 1979) and the pTa 794 probe is a 410 bp *BamHI* fragment of the 5S rDNA from wheat (Gerlach and Dyer 1980). The two probes were labeled by random priming with Alexa-488 dUTP (Invitrogen, Life Technologies) and Alexa 594 (Invitrogen, Life Technologies) respectively. Genomic *in situ* hybridization (GISH) was performed with probe DNAs from the progenitors of the allotetraploids. Total genomic DNA from *G. herbaceum* (A-genome) was labeled by nick translation with biotin-16-dUTP (Roche Diagnostics, Indianapolis, IN). Total genomic DNAs from *G. raimondi* (D-genome) were auto-claved to yield fragments of 100–300 bp and used as a blocking DNA. A series of test assessments determined the amount of blocking DNA that was required to discriminate between the two genomes. Optimum results were obtained with a ratio of 1:50 for A genome probe and D genome blocking DNA in the hybridization mixture. Biotinylated probes were immunodetected by Texas-red-conjugated with avidin antibodies (Vector Laboratories, Burlingame, CA). The chromosomes were mounted and counterstained in Vectashield (Vector Laboratories) containing 2.5 $\mu\text{g/ml}$ 4,6-diamidino-2-phenylindole (DAPI). Fluorescence images were captured using a CoolSnap HQ camera (Photometrics, Tucson, AZ) on an Axioplan 2 microscope (Zeiss, Oberkochen, Germany), and analyzed with the MetaVue_{TM} software (Universal Imaging Corporation, Downingtown, PA).

Data availability

The authors state that all data necessary for confirming the conclusions presented in the article are represented fully within the article.

RESULTS

Interspecific F1 hybrid production

G. hirsutum ($A_1A_1D_1D_1$) \times *G. herbaceum* (A_1A_1): After pollination, moderate boll shedding was observed, as 60 mature bolls were obtained from 68 pollinated flowers. A total of 335 plants was obtained from 504 sown seeds. Flow cytometry analysis revealed that all of them were identical to the female allotetraploid parent, *G. hirsutum*. This observation

was confirmed by their morphological characteristics including plant architecture, leaf shape as well as flower size, shape, and color. No interspecific hybrid was obtained.

G. herbaceum (A_1A_1) \times *G. hirsutum* ($A_1A_1D_1D_1$): Significant boll abscission was observed from the hybridizations involving *G. herbaceum* as the female (29 mature bolls out of 146 pollinated flowers). Similarly, a large number of aborted seeds were harvested (163 aborted seeds out of a total 498 harvested). Out of 335 seeds sown, 148 developed into plants: among these, three interspecific hybrids were detected. Flow cytometric analysis showed that two of them (namely H1 and H2) had an intermediate value possibly corresponding to $A_1A_1D_1$ hybrids. The third hybrid (H3) exhibited a slightly higher DNA content than *G. hirsutum*.

Our results indicate a hybridization rate of 0.02 hybrid seed per pollinated flower, compared to ~ 30 seeds per boll observed after selfing of *G. hirsutum*. Among the 148 plants observed, the interspecific hybridization rate detected was 0.02.

Characterization of interspecific F1 hybrids

Morphological traits: Among the 148 plants obtained with *G. herbaceum* as the female parent, observations 20 d after sowing (at the three-leaf stage) led to the morphological identification of the three hybrids. Already at a young stage (three-leaf, 20 d after sowing), three plants exhibited general morphological traits similar to *G. hirsutum*. Several weeks later, two types of plants could be distinguished. Among the

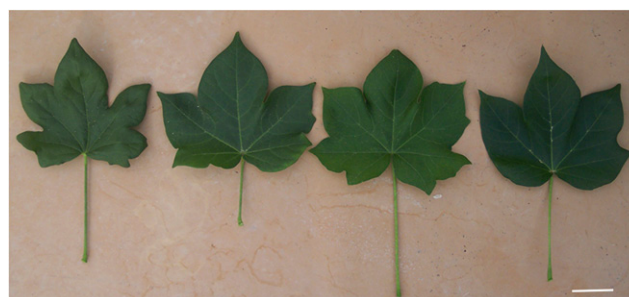


Figure 2 Leaf shapes. Left to right *G. herbaceum*, hybrid H1, hybrid H3, and *G. hirsutum*. Bar, 1 cm.



Figure 3 Flower characteristics: Left to right: *G. herbaceum*, hybrid H1, hybrid H3, and *G. hirsutum*. Bar, 1 cm.

three hybrids, H1 and H2 displayed identical morphological characteristics, and exhibited the phenotype typical of a triploid hybrid ($A_1A_tD_t$), with traits intermediate between the two parents (Figure 1). For the third hybrid (H3), the overall plant phenotype was intermediate between *G. hirsutum* and the triploid (Figure 1), with individual plant parts varying between the triploid and *G. herbaceum*. Hybrid H3 leaves had less marked serrations, but more lobes, and were intermediate between *G. herbaceum* and the triploid (Figure 2). In its first stages of development, the hybrid H3 displayed density of stem hairs and gossypol glands similar to those of *G. herbaceum*. The two types of hybrid phenotypes were also differentiated by flower characteristics: corolla size, petal red spot intensity and size, and stamen color and size (Figure 3). The corollas of the H1 and H2 hybrid flowers had the same size as *G. hirsutum*, but they exhibited light red spots (Figure 3). H3 had larger, brighter red spots, intermediate

between $A_1A_tD_t$ and *G. herbaceum* (Figure 3), and its corolla size was slightly smaller than those of H1 and H2. These observations can support the hypothesis that the H3 hybrid carries more genome A than the *G. herbaceum* parent. Moreover, it has been reported that spot presence is controlled by a single gene carried by the A genome (Stephens 1974).

Microsatellite-based allelic status of the interspecific hybrids: One of the six SSRs tested was not exploited because of ambiguous allele assignment. For the five remaining SSRs (BNL3563, BNL409, BNL4049, NAU0915, and NAU1246), the hybrid status of hybrids H1, H2, and H3 was confirmed (Figure 4). The three hybrids exhibited the alleles from *G. hirsutum* as well as from *G. herbaceum*. However, the amplification profiles did not reveal any quantitative difference between these hybrids.

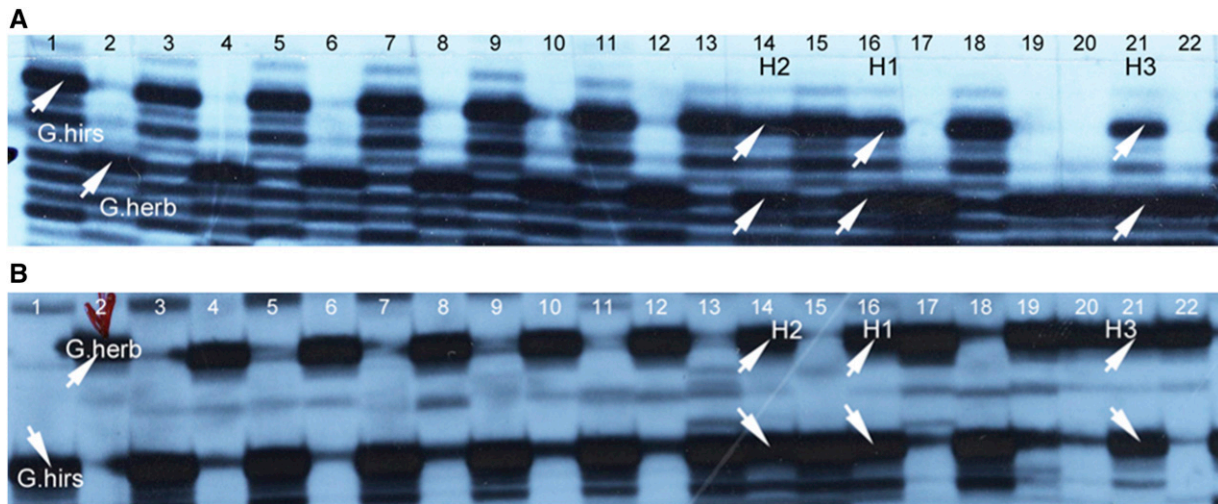


Figure 4 Molecular profiles of parents *G. hirsutum*, *G. herbaceum*, and 20 progenies showing the hybrid profile of H1, H2, and H3. (A) Marker BNL409, (B): marker NAU1246.

Identification of the genomic structure of hybrids: Results of the FISH analysis at mitosis showed that *G. hirsutum* ($A_tA_tD_tD_t$) carried six 45S loci with two loci on A_t genome (Figure 5, A and B), in accordance with previous reports (Hanson *et al.* 1996; Gan *et al.* 2013). However, six 45S loci were also observed on the A genome of *G. herbaceum* (A_1A_1) (Figure 5C). The structure of H1 and H2 hybrids was confirmed with 39 chromosomes, and we found the expected number of 45S loci for an $A_1A_tD_t$ genomic structure, *i.e.*, six in total with three from *G. herbaceum* and three from *G. hirsutum* (Figure 5D). Analysis of H3 resulted in a count of 52 chromosomes carrying nine 45S loci six from *G. herbaceum*, plus three from *G. hirsutum* thus compatible with the genome structure $A_1A_1A_tD_t$ (Figure 5E).

Therefore, this hybrid was formed from a female unreduced gamete of *G. herbaceum* and a reduced gamete of *G. hirsutum* (Table 1). According to the genomic composition ($A_1A_tD_t$) of H1 and H2 plants, the expected meiotic behavior is 13 univalents corresponding to the D genome and 13 bivalents between the homologous chromosomes of the A genomes. Of the 26 analyzed PMCs, 35% matched this configuration, but 57.7% revealed the presence of multivalents, trivalents, or quadrivalents (Figure 6A and Table 2). In the third H3 hybrid, all the 15 PMCs observed indicated the presence of multivalents, likely due to the presence of three homologous A genomes (Figure 6B and Table 2). Tetrads harboring 3–7 microspores have been observed from young flowers of the triploid hybrids H1 and H2.

Fertility of interspecific hybrids: As expected, pollen grains from the parental lines had a high viability (Figure 7). In contrast, very few pollen grains (<5%) from hybrids H1 and H2 were stained by Alexander dye (Figure 7). Pollen grains from the hybrid H3 exhibited a range of viability, up to 20%. Sampling was performed on all the plants at the same time, and the fertility of *G. herbaceum* was observed to be lower than that of *G. hirsutum*. This difference in the viability of the pollen grains from *G. hirsutum* and *G. herbaceum* could be explained by the time of the sampling. Flowers were collected at the same time in the morning, which might not have been optimal for the sampling of *G. herbaceum* pollen.

None of the three hybrids produced any seed, either through open or self-pollination. In order to save the hybrid materials, the plants were reproduced through cutting when they became too large.

DISCUSSION

The results showed a relatively high hybridization rate (three hybrids among 148 progeny) between *G. herbaceum* and *G. hirsutum* without emasculation of the female parent, and when the plant with the lower ploidy level was the female. This result is similar to those observed with *Brassica napus*, which is also an allotetraploid species; when one of its progenitors, *B. rapa* was used as female, the spontaneous interspecific hybridization ranged from 3 to 8% (Warwick *et al.* 2003). When the diploid parent *G. herbaceum* was used as male, no hybrids were obtained. These results are not in accordance with those of Brubaker *et al.* (1999), working on the improvement of cultivated cotton by crosses with diploid Australian species (genomes C, G, and K). They found that it was more difficult to obtain triploid hybrids when the female parent was diploid. Similarly, Beasley (1940) concluded that the likelihood of successful hybridization is higher if the female parent has the higher ploidy level, reflecting the traditional recommendations concerning the critical role of ploidy ratio of endosperm and zygote for successful embryo development (Beasley 1942; Stephens 1942 cited in Ahoton *et al.* 2003). Similarly, it has been observed among *Brassicaceae* species that the production of interspecific hybrids using *B. napus* as female or male with different diploid species depends on the species combination (Chèvre *et al.* 2004). Our combined analyses based on cytometry, fluorescent *in situ* hybridization and chromosome counting indicated that the three hybrids obtained were of two types. Two, H1 and H2, were triploids ($A_1A_tD_t$), and, remarkably, the third one (H3) was a tetraploid carrying three A genomes and a single D genome. The meiotic behavior of triploid hybrids is close to what can be expected with a majority of pollen mother cells with 13 bivalents corresponding to homologous pairing of the 13 A chromosomes, whereas the D chromosomes remained at univalent stage with 13 univalents. However, it is important to note that several cells showed the presence of multivalents, indicating the possibility of homeologous pairing between A and D genomes, even if these exchanges were difficult to detect after a long evolution in *G. hirsutum* (Page *et al.* 2016). In the third hybrid, the presence of >2 A genomes was shown by the morphological characteristics (leaf shape, flower size, and red spots on the corolla). Its genomic structure, $A_1A_1A_tD_t$, was confirmed by observation of metaphase in mitosis, revealing the presence of the nine 45S loci expected for this genomic structure. Additionally, the high frequency of multivalents was in agreement with the presence of three A genomes.

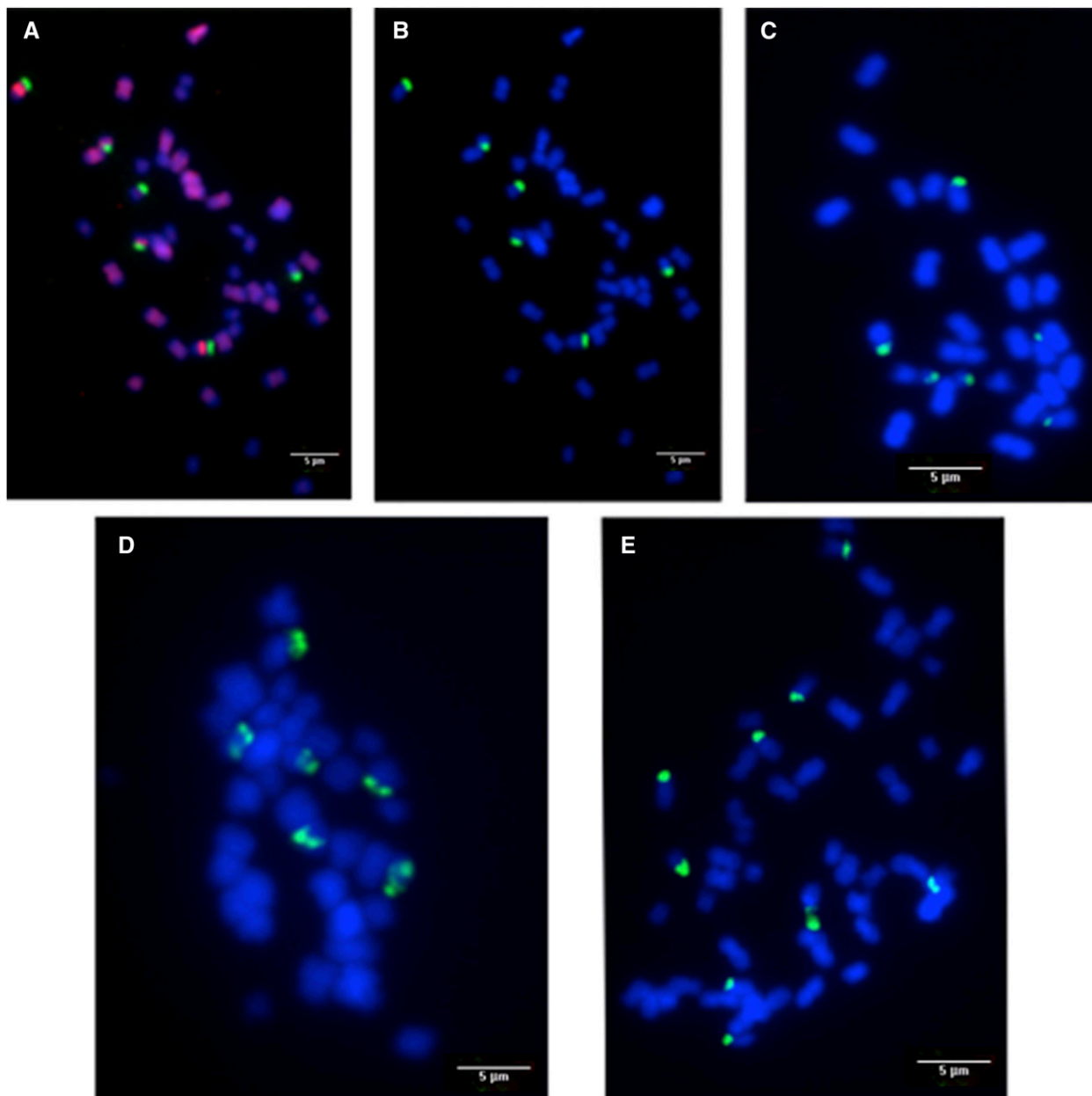


Figure 5 *In situ* hybridization analysis. (A) The GISH probe hybridized specifically to all A genome chromosomes (pink) in *G. hirsutum* ($A_t A_t D_t D_t$); 5S rDNA in red, (B–E) FISH with 45S rDNA in green. FISH analyses of somatic metaphase chromosomes from *G. hirsutum* (B), *G. herbaceum* (C), hybrid H2 (D), and hybrid H3 (E). Chromosomes were counterstained with DAPI (blue).

Our primary objective was to estimate the risk of cross-pollination between allotetraploid cultivated cotton (*G. hirsutum*) and wild diploid cotton (*G. herbaceum*), since, in the Makhathini flats area of South Africa, the diploid progenitor grows in proximity to the cultivated transgenic cotton fields. Most of published studies were concerned

either with gene flow between transgenic and nontransgenic cultivated cotton in various areas of the world (Zhang *et al.* 2005; Van Deynze *et al.* 2005; Llewellyn *et al.* 2007; Heuberger *et al.* 2010; Loureiro *et al.* 2016), or between wild and cultivated tetraploid cotton (Wegier *et al.* 2011; Pereira *et al.* 2012). Our study on the hybridization rate between

■ **Table 1** 45S rDNA signal numbers and genome structures

	Chromosomes Numbers	45srDNA Signal Numbers	Genome Structure
<i>G. hirsutum</i>	52	6: 2 ($A_t A_t$), 4 ($D_t D_t$)	$A_t A_t D_t D_t$
Hybrid H1	39	6: 3 A_1 , 1 A_t , 2 D_t	$A_1 A_t D$
Hybrid H2	39	6: 3 A_1 , 1 A_t , 2 D_t	$A_1 A_t D$
Hybrid H3	52	9: 6 ($A_1 A_1$), 1 A_t , 2 D_t	$A_1 A_1 A_t D_t$

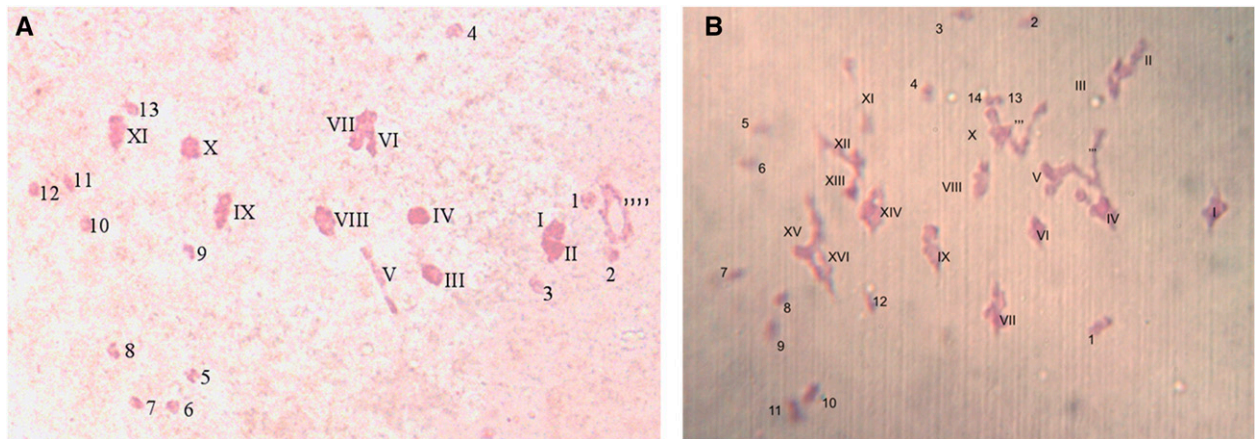


Figure 6 PMC in metaphase I. (A) from $A_1A_1D_t$ hybrid H1, 13 univalents (1–13), 11 bivalents (I–XI), and one quadrivalent; (B) from $A_1A_1A_1D_t$ hybrid H3: 14 univalents (1–14), 16 bivalents (I–XVI), and two trivalents.

diploid and tetraploid cotton, showed that the three recovered hybrids produced no seeds, and that the viability of their pollen was very low. The single seed was produced after crossing a triploid hybrid, and *G. hirsutum* developed after hand-pollination on an emasculated flower of the triploid (data not shown). It is reasonable to conclude from the present study that the probability of obtaining offspring is very low. Moreover, only the species *G. herbaceum* var. *africanum* is endemic in South Africa (van Wyk and van Wyk 1997). Entomological investigations have shown that the beetle *Astylus atromaculatus* could be an unexpected but efficient pollinator on *G. hirsutum* in South Africa (Pierre and Hofs 2010). However, *A. atromaculatus* and domestic bees are not present on *G. herbaceum* (J. L. Hofs, personal communication). In contrast, Anthophoridae are common on both *G. hirsutum* and *G. herbaceum* and have a great capacity for carrying pollen, and may thus be a potential vector for pollen transfer between the two species (J. L. Hofs, personal communication). However, in the case of trials involving interspecific hybridization, reverting to a more fertile form required several generations of backcrosses with the cultivated species (Kammacher 1966; Mergeai 2003).

Our results have demonstrated the possibility of the formation of unreduced gametes. To our knowledge, this phenomenon has been poorly documented in cotton, while it is prevalent in diverse plant species, and considered to be an important mechanism for polyploidization (reviewed in Mason and Pires 2015). The formation of unreduced gametes in *Gossypium* interspecific hybrids has been reported in crosses between *G. hirsutum* and Australian K-genome diploids *G. exiguum* or *G. nobile* (Brubaker *et al.* 1999). Observations of meiosis in these hybrids suggested that some may have derived from unreduced gametes arising from dysfunctions during M2; hence, the duplication of the segregating chromosomes. Furthermore, Skovsted (1934), working on the production of hybrids between diploid Asiatic and tetraploid New World cotton, obtained a hybrid with 52 chromosomes, and hypothesized the production of $2n$ gametes in the diploid parent. Likewise, in cytogenetic studies of cotton cultivars grown in Iran, the occurrence of

large pollen grains was assumed to be potential unreduced gametes (Sheidai 2008; Noormohammadi *et al.* 2012), although other methods are considered to be necessary to confirm the correlation between size and ploidy in pollen (Dewitte *et al.* 2012). For the same type of sterile hybrids (triploids $2n = 39$, one tetraploid $2n = 52$) obtained by crossing A-genome Asiatic cottons with tetraploid New World cottons, Amin (1940) reported that backcrossing to New World cottons gave occasional success in boll setting on the F1s. Such bolls contained very few seeds, and the plants developed from them had varying degrees of fertility. In this context, by crossing one of our triploid hybrid (H1) as female with *G. hirsutum* (25 flowers emasculated and hand pollinated with *G. hirsutum* pollen) we obtained a single large seed. Its germination gave rise to a plant with $2n = 65$ chromosomes and a putative $A_1A_1A_1D_t$ structure (data not shown). The structure may be the result of unreduced gametes from the triploid hybrid. This ability of *Gossypium* to produce such gametes from diploid parents and from F1 hybrids might point to an alternative explanation for the formation of the allotetraploid cultivated species, *G. hirsutum*. In fact, it has been hypothesized the formation of unreduced gametes offers the possibility to generate a triploid bridge, which can be at the origin of polyploid species (reviewed in Mason and Pires 2015). Interspecific hybridization has often been carried out to provide new sources of germplasm for incorporation into breeding programs (Chee *et al.* 2016). However, it is not possible to obtain fertile hybrids from crosses between cultivated tetraploid *G. hirsutum* and wild diploids species without treating the floral bud at the time of fertilization with growth substances in order to prevent boll abscission (Meyer 1974; Altman 1988). Brubaker *et al.* (1999) have shown that, in the best case, the natural crossing of diploid wild Australian species with tetraploid cotton cultivars resulted only in the production of sterile hybrids. However, fertility can be restored by doubling the number of chromosomes using colchicine to produce hexaploid plants ($2n = 78$ chromosomes). This approach has been widely used in interspecific hybridization to improve cotton plants, but such a doubling has never been observed occurring spontaneously in nature

Table 2 Meiotic behavior of hybrids H1, H2, and H3

	$2n$	PMC	Univ.	Bival.	Trival.	Quadrival.
Hybrid H1–H2	39	26	12.61 ^a (9–14) ^b	11.81 (7–14)	0.31 (0–2)	0.17 (0–2)
Hybrid H3	52	15	14.67 (12–17)	16.8 (14–20)	1.07 (0–4)	0.13 (0–1)

^a Average per cell.
^b Range.

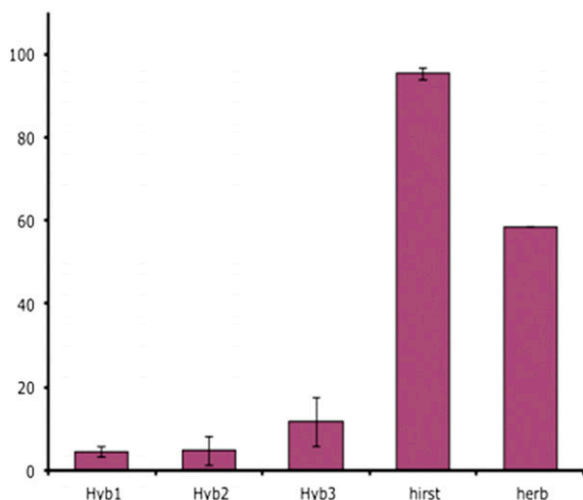


Figure 7 Pollen viability (percentage). Seven repetitions (40 to >1000 pollen grains per sampling) for *G. hirsutum*. and H1, H2, and H3. One observation on 120 pollen grains for *G. herbaceum*.

(Mergeai 2003, 2006). $2n$ gametes have already been exploited to create new cultivars at higher ploidy levels, but, more interestingly, they have also been used in various species to create a bridge for the transfer of desirable genes from wild diploid species into the cultivated polyploid gene pool in various species (reviewed in Dewitte *et al.* (2012)). This approach is particularly relevant for cultivated cotton, as the wild diploid species of *Gossypium* are rich in rare desirable attributes that are not available in the germplasm of cultivated species (Stewart 1995; Mergeai 2006). This methodology has been used to transfer genetic diversity from diploids through $2n$ gametes to polyploid crop varieties, as demonstrated for example in potato and alfalfa (Peloquin *et al.* 1999; Ramanna and Jacobsen 2003). The production of autopolyploids to overcome the difficulty of transferring desirable traits from wild or cultivated diploids to *G. hirsutum* was investigated by Mehetre *et al.* (2003). The use of unreduced gametes would facilitate the direct production of such AAAD hybrids either by direct crosses (H3 hybrid) or by crossing an AAD hybrid with *G. hirsutum*. Even though the production of unreduced gametes has rarely been described in cotton, various methods have been tested in other species to increase their occurrence (Brownfield and Kohler, 2011; Dewitte *et al.* 2012; Younis *et al.* 2014). New strategies (Ravi *et al.* 2008; Chan 2010; Ravi and Chan 2010) developed on the model plant *Arabidopsis thaliana* (reviewed in Crismani *et al.* 2013) are considered by the authors to be possibly applicable to crops.

The possibility of obtaining an interspecific hybrid between tetraploid cultivated and diploid wild cotton through fertilization with an unreduced gamete raises the question of its evolution in natural populations. We have shown that this hybrid produced no seeds and its pollen has very low viability. In conclusion, the likelihood of natural transfer of chromosomal material from cultivated cotton to the diploid *G. herbaceum* is very low; even though one hybrid with a particular genomic structure arose via an unreduced gamete of the diploid parent, it did not produce seeds after selfing. However, the assessment of the hybrids' ability to produce a backcross progeny would require further experimentation, such as cultivating hybrids in the presence of *G. herbaceum*. Furthermore, the hybrid materials obtained in this study, with different genome dosages (triploids AAD and unreduced gamete-derived hybrid AAAD), could provide useful tools for the study of the expression of duplicated genes and the effects of allele dosage from A and D cotton genomes.

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LITERATURE CITED

- Ahton, L., J. M. Lacape, J. P. Baudoin, and G. Mergeai, 2003 Introduction of Australian diploid cotton genetic variation into upland cotton. *Crop Sci.* 43: 1999–2005.
- Alexander, M. P., 1969 Differential staining of aborted and nonaborted pollen. *Stain Technol.* 44: 117–122.
- Altman, D. W., 1988 Exogenous hormone applications at pollination for in vitro and in vivo production of cotton interspecific hybrids. *Plant Cell Rep.* 7: 257–261.
- Amin, K. C., 1940 Interspecific hybridization between Asiatic and new world cottons. *Indian J. Agric. Sci.* 10: 404–413.
- Barcaccia, G., S. Tavoletti, A. Mariani, and F. Veronesi, 2003 Occurrence, inheritance and use of reproductive mutants in alfalfa improvement. *Euphytica* 133: 37–56.
- Beasley, J. O., 1940 The production of polyploids in *Gossypium*. *J. Hered.* 31: 39–48.
- Beasley, J. O., 1942 Meiotic chromosome behavior in species, species hybrids, haploids and induced polyploids of *Gossypium*. *Genetics* 27: 25–54.
- Brownfield, L., and C. Kohler, 2011 Unreduced gamete formation in plants: mechanisms and prospects. *J. Exp. Bot.* 62: 1659–1668.
- Brubaker, C. L., A. H. D. Brown, J. M. Stewart, M. J. Kilby, and J. P. Grace, 1999 Production of fertile hybrid germplasm with diploid Australian *Gossypium* species for cotton improvement. *Euphytica* 108: 199–213.
- Carpato, D., L. Frusciante, and S. J. Peloquin, 2003 The role of $2n$ gametes and endosperm balance number in the origin and evolution of polyploids in the tuber-bearing solanums. *Genetics* 163: 287–294.
- Chan, S. W. L., 2010 Chromosome engineering: power tools for plant genetics. *Trends Biotechnol.* 28: 605–610.
- Chee, P. W., A. H. Paterson, J. A. Udall, and J. F. Wendel, 2016 Interspecific hybridization for upland cotton improvement, pp. 1–20 in *Polyploidy and Interspecific Hybridization for Crop Improvement*, edited by Mason, A. S. CRC Press, Boca Raton, FL.
- Chèvre, A.-M., H. Ammitzbøll, B. Breckling, A. Dietz-Pfeilstetter, F. Eber *et al.*, 2004 A review on interspecific gene flow from oilseed rape to wild relatives, pp. 235–251 in *Introgression from Genetically Modified Plants into wild relatives*, edited by Den Nijs, H. C. M., D. Bartsch, and J. Sweet. CABI Publishing, Cambridge.
- Crismani, W., C. Girard, and R. Mercier, 2013 Tinkering with meiosis. *J. Exp. Bot.* 64: 55–65.
- Dewitte, A., K. Van Laere, and J. Van Huylenbroeck, 2012 Use of $2n$ gametes in plant breeding. *Plant Breed.* 69: 59–86.
- Eber, F., J. C. Letanneur, and A.-M. Chèvre, 1997 Chromosome number of oilseed rape (*Brassica napus* L.) - wild radish (*Raphanus raphanistrum*) spontaneous hybrids and of their progeny estimated by flow cytometry. *Cruciferae Newsletter* 19: 17–18.
- Fryxell, P. A., 1979 *The Natural History of Cotton Tribe*, Texas A&M University Press, College Station, TX.
- Fryxell, P. A., L. A. Craven, and J. M. Stewart, 1992 A revision of gossypium sect. Grandicalyx (Malvaceae), including the description of 6 new species. *Syst. Bot.* 17: 91–114.
- Gallagher, J. P., C. E. Grover, K. Rex, M. Moran, and J. F. Wendel, 2017 A new species of cotton from Wake Atoll, *Gossypium stephensii* (Malvaceae). *Syst. Bot.* 42: 115–123.
- Gan, Y. M., F. Liu, R. H. Peng, C. Y. Wang, S. H. Li *et al.*, 2012 Individual chromosome identification, chromosomal collinearity and genetic-physical

- integrated map in *Gossypium darwinii* and four D genome cotton species revealed by BAC-FISH. *Genes Genet. Syst.* 87: 233–241.
- Gerlach, W. L., and J. R. Bedbrook, 1979 Cloning and characterization of ribosomal RNA genes in wheat and barley. *Nucleic Acids Res.* 7: 1869–1885.
- Gerlach, W. L., and T. A. Dyer, 1980 Sequence organisation of the repeating units in the nucleus of wheat which contain 5S rRNA genes. *Nucleic Acids Res.* 8: 4851–4865.
- Grover, C. E., J. P. Gallagher, J. J. Jareczek, J. T. Page, J. A. Udall *et al.*, 2015 Re-evaluating the phylogeny of allopolyploid *Gossypium* L. *Mol. Phylogenet. Evol.* 92: 45–52.
- Hanson, R. E., M. N. IslamFaridi, E. A. Percival, C. F. Crane, Y. Ji *et al.*, 1996 Distribution of 5S and 18S–28S rDNA loci in a tetraploid cotton (*Gossypium hirsutum* L.) and its putative diploid ancestors. *Chromosoma* 105: 55–61.
- Heuberger, S., C. Ellers-Kirk, B. E. Tabashnik, and Y. Carriere, 2010 Pollen- and seed-mediated transgene flow in commercial cotton seed production fields. *PLoS One* 5: e14128.
- Kammacher, P., 1966 Etudes des relations genetiques et caryologiques entre genomes voisins du genre *Gossypium*. *Coton et Fibres Tropicales* 21: 263–290.
- Lacape, J. M., D. Dessauw, M. Rajab, J. L. Noyer, and B. Hau, 2007 Microsatellite diversity in tetraploid *Gossypium* germplasm: assembling a highly informative genotyping set of cotton SSRs. *Mol. Breed.* 19: 45–58.
- Llewellyn, D., C. Tyson, G. Constable, B. Duggan, S. Beale *et al.*, 2007 Containment of regulated genetically modified cotton in the field. *Agric. Ecosyst. Environ.* 121: 419–429.
- Mason, A. S., and J. C. Pires, 2015 Unreduced gametes: meiotic mishap or evolutionary mechanism? *Trends Genet.* 31: 5–10.
- Mehetre, S. S., A. R. Aher, V. L. Gawande, V. R. Patil, and A. S. Mokate, 2003 Induced polyploidy in *Gossypium*: a tool to overcome interspecific incompatibility of cultivated tetraploid and diploid cottons. *Curr. Sci.* 84: 1510–1512.
- Mergeai, G., 2003 Forty years of genetic improvement of cotton through interspecific hybridisation at Gembloux Agricultural University: Achievement and prospects. in *Proc. World Cotton Research Conference - 3. Cotton Production for the New Millennium*, edited by A. Swanepoel. (Cape Town, South Africa: Agricultural Research Council, Institute for Industrial Crops, Pretoria), pp. 120–133.
- Mergeai, G., 2006 Cotton improvement through interspecific hybridization. *Cah. Agric.* 15: 135–143.
- Meyer, V. G., 1974 Interspecific cotton breeding. *Econ. Bot.* 28: 56–60.
- Noormohammadi, Z., M. Sheidai, F. Shojaei, F. S. Jeshvaghani, and O. Alishah, 2012 Cytogenetic analysis of mehr cotton cultivar and its crossing progenies: a search for unreduced pollen grains. *Cytologia (Tokyo)* 77: 107–112.
- Page, J. T., Z. S. Liechty, R. H. Alexander, K. Clemons, A. M. Hulse-Kemp *et al.*, 2016 DNA sequence evolution and rare homoeologous conversion in tetraploid cotton. *PLoS Genet.* 12: e1006206 (erratum: *PLoS Genet.* 12: e1006012).
- Peloquin, S. J., L. S. Boiteux, and D. Carputo, 1999 Meiotic mutants in potato: valuable variants. *Genetics* 153: 1493–1499.
- Pereira, G. S., R. L. Sousa, R. L. Araujo, L. V. Hoffmann, E. F. Silva *et al.*, 2012 Selective fertilization in interspecific crosses of allotetraploid species of *Gossypium*. *Botany-Botanique* 90: 159–166.
- Pierre, J., and J. L. Hofs, 2010 *Astylus atramaculatus* (Coleoptera: Melyridae): abundance and role in pollen dispersal in Bt and non-Bt cotton in South Africa. *Environ. Entomol.* 39: 1523–1531.
- Ramanna, M. S., and E. Jacobsen, 2003 Relevance of sexual polyploidization for crop improvement—a review. *Euphytica* 133: 3–18.
- Ravi, M., and S. W. Chan, 2010 Haploid plants produced by centromere-mediated genome elimination. *Nature* 464: 615–618.
- Ravi, M., M. P. A. Marimuthu, and I. Siddiqi, 2008 Gamete formation without meiosis in Arabidopsis. *Nature* 451: 1121–1124.
- Renny-Byfield, S., J. T. Page, J. A. Udall, W. S. Sanders, D. G. Peterson *et al.*, 2016 Independent domestication of two old world cotton species. *Genome Biol. Evol.* 8: 1940–1947.
- Sheidai, M., 2008 Cytogenetic distinctiveness of sixty-six tetraploid cotton (*Gossypium hirsutum* L.) cultivars based on meiotic data. *Acta Botanica Croatica* 67: 209–220.
- Skovsted, A., 1934 Cytological studies in Cotton. II. Two interspecific hybrids between Asiatic and new world cottons. *J. Genet.* 28: 407–424.
- Stephens, S. G., 1942 Colchicine-produced polyploids in *Gossypium* I. And autotetraploid asiatic cotton and certain of its hybrids with wild diploid species. *J. Genet.* 44: 272–295.
- Stephens, S. G., 1974 Geographic and taxonomic distribution of anthocyanin genes in new world cottons. *J. Genet.* 61: 128–141.
- Stewart, J., 1995 Potential for crop improvement with exotic germplasm and genetic engineering. In *Challenging the Future - Proc. World Cotton Research Conf. -1; Brisbane, Australia 14–17 February 1994*. Constable GA and Forrester NW (Eds). CSIRO, Melbourne. pp 313–327
- Van Deynze, A. E., F. J. Sundstrom, and K. J. Bradford, 2005 Pollen-mediated gene flow in California cotton depends on pollinator activity. *Crop Sci.* 45: 1565–1570.
- Van Deynze, A. E., R. B. Hutmacher, and K. J. Bradford, 2005 Gene flow between *Gossypium hirsutum* L. and *Gossypium barbadense* L. is asymmetric. *Crop Sci.* 51: 298–305.
- van Wyk, B., and P. van Wyk, 1997 *Field Guide to Trees of Southern Africa*, Struik Publishers, Cape Town, South Africa.
- Warwick, S. I., M. J. Simard, A. Legere, H. J. Beckie, L. Braun *et al.*, 2003 Hybridization between transgenic *Brassica napus* L. and its wild relatives: *Brassica rapa* L., *Raphanus raphanistrum* L., *Sinapis arvensis* L., and *Erucastrum gallicum* (Willd.) O.E. Schulz. *Theor. Appl. Genet.* 107: 528–539.
- Wegier, A., A. Pineyro-Nelson, J. Alarcon, A. Galvez-Mariscal, E. R. Alvarez-Buylla *et al.* 2011 Recent long-distance transgene flow into wild populations conforms to historical patterns of gene flow in cotton (*Gossypium hirsutum*) at its centre of origin *Molecular Ecology* 20: 4182–4194.
- Wendel, J. F., 1989 New world tetraploid cottons contain old-world cytoplasm. *Proc. Natl. Acad. Sci. USA* 86: 4132–4136.
- Wendel, J. F., and R. C. Cronn, 2003 Polyploidy and the evolutionary history of cotton. *Adv. Agron.* 78(78): 139–186.
- Wendel, J. F., C. L. Brubaker, and T. Seelanan, 2010 The origin and evolution of *Gossypium*, pp. 1–18 in *Physiology of Cotton*, edited by Stewart, J. M. D., J. M. Oosterhuis, J. J. Heitholt, and J. R. Mauney. Springer, Netherlands.
- Younis, A., Y. J. Hwang, and K. B. Lim, 2014 Exploitation of induced 2n-gametes for plant breeding. *Plant Cell Rep.* 33: 215–223.
- Zhang, B. H., X. P. Pan, T. L. Guo, Q. L. Wang, and T. A. Anderson, 2005 Measuring gene flow in the cultivation of transgenic cotton (*Gossypium hirsutum* L.). *Mol. Biotechnol.* 31: 11–20.

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