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Specific Tandem Repeats Are Sufficient for Paramutation-Induced Trans-Generational Silencing

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Abstract

Paramutation is a well-studied epigenetic phenomenon in which trans communication between two different alleles leads to meiotically heritable transcriptional silencing of one of the alleles. Paramutation at the b1 locus involves RNA-mediated transcriptional silencing and requires specific tandem repeats that generate siRNAs. This study addressed three important questions: 1) are the tandem repeats sufficient for paramutation, 2) do they need to be in an allelic position to mediate paramutation, and 3) is there an association between the ability to mediate paramutation and repeat DNA methylation levels? Paramutation was achieved using multiple transgenes containing the b1 tandem repeats, including events with tandem repeats of only one half of the repeat unit (413 bp), demonstrating that these sequences are sufficient for paramutation and an allelic position is not required for the repeats to communicate. Furthermore, the transgenic tandem repeats increased the expression of a reporter gene in maize, demonstrating the repeats contain transcriptional regulatory sequences. Transgene-mediated paramutation required the mediator of paramutation1 gene, which is necessary for endogenous paramutation, suggesting endogenous and transgene-mediated paramutation both require an RNA-mediated transcriptional silencing pathway. While all tested repeat transgenes produced small interfering RNAs (siRNAs), not all transgenes induced paramutation suggesting that, as with endogenous alleles, siRNA production is not sufficient for paramutation. The repeat transgene-induced silencing was less efficiently transmitted than silencing induced by the repeats of endogenous b1 alleles, which is always 100% efficient. The variability in the strength of the repeat transgene-induced silencing enabled testing whether the extent of DNA methylation within the repeats correlated with differences in efficiency of paramutation. Transgene-induced paramutation does not require extensive DNA methylation within the transgene. However, increased DNA methylation within the endogenous b1 repeats after transgene-induced paramutation was associated with stronger silencing of the endogenous allele.

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Introduction

Paramutation is a trans-interaction between specific alleles or transgenes that leads to a meiotically heritable change in the expression of one of the participating alleles or transgenes. Originally described for the maize (Zea mays L.) v1 (red1) [1] and b1 (booster1) [2] genes, paramutation has since been reported for several other genes in plants (see e.g. [3–9]). Paramutation-like interactions have also been described in other species, including Drosophila [10], mammals and humans (for review see [11]).

Paramutation at the b1 locus provides a powerful system for dissecting the underlying mechanism of paramutation (reviewed in [12]). The b1 gene encodes a transcription factor that activates the purple anthocyanin biosynthesis pathway. Alterations of b1 expression lead to a visual change in plant pigmentation, and the amount of pigment is a read-out of the b1 transcription level [3]. The two b1 alleles that participate in paramutation are B-I (B-Intense) and B′; B-I is highly expressed and specifies dark purple pigmentation of the husk, sheath and tassel of the maize plant, while B′ is expressed at a much lower level and specifies light streaky pigmentation in the same plant tissues as B-I [3,13]. The high expressing B-I allele is unstable and can spontaneously change to B′ at variable frequencies (can be up to 10%; [13]). In contrast, B′ is very stable and does not change to B-I in wild-type genetic backgrounds [13,14]. Paramutation occurs when B′ and B-I alleles are combined in one nucleus by crossing. The “paramutagenic” B′ allele turns the “paramutable” B-I allele into B′ at a 100% frequency. The new B′ allele (B′I in the previous generation) is as heritable and paramutagenic as the original B′ allele [13]. Alleles that do not participate in paramutation are referred to as neutral [14].
Author Summary

Paramutation is a fascinating process in which genes communicate to efficiently establish changes in their expression that are stably transmitted to future generations without any changes in DNA sequences. While paramutation was first described in the 1950s and extensively studied through the 1960s, its underlying mechanism remained mysterious for many years. Over the past ten years paramutation at the b1 locus in maize was shown to require transcribed, non-coding tandem repeats located 100 kb upstream of b1. These repeats generate small RNAs, and mutations in multiple genes mediating small RNA silencing at the transcriptional level prevent paramutation. While underlying mechanisms are shared, current models for RNA-mediated transcriptional silencing that are based on experiments with S. pombe and Arabidopsis do not explain many aspects of paramutation. In this manuscript we used a transgenic approach to demonstrate that the b1 non-coding tandem repeats are sufficient to send and respond to the paramutation signals and that this occurs even when the repeats are not at their normal chromosomal location.

Genetic screens in maize have uncovered a number of genes required for paramutation (reviewed in [12,15,16]). All but one gene [17] identified to date share homology with genes involved in the RNA-directed transcriptional silencing pathway in Arabidopsis [18], strongly indicating a requirement of this pathway for paramutation.

A necessary step towards further dissecting the mechanism of paramutation is knowledge of the key sequences mediating paramutation, the subject of this work. Previous fine structure recombination studies between B' or B-I and neutral b1 alleles revealed that paramutation requires a region spanning ~6 kb located ~100 kb upstream of the b1 transcription start site [19,20]. This region was also required for high b1 expression. In B' and B-I, this region contains seven tandem repeats of an 853-bp sequence that is unique to this location within the maize genome. Notably, an allelic series in which alleles differed only by the number of repeats revealed that multiple repeats are required for paramutation. Alleles with seven and five repeats were fully paramutagenic, alleles with three repeats had reduced paramutation. Alleles with seven and five repeats were fully paramutagenic, alleles with three repeats had reduced paramutation, and alleles with a single repeat were neutral to paramutation [19].

The B' and B-I alleles are epialleles as they have identical DNA sequences [20]. Consistent with epigenetic regulatory mechanisms defining the B' and B-I states, the hepta-repeats have distinct chromatin structures in B' and B-I [19,21]. The epigenetic mark that correlates best with paramutation ability is DNA methylation. The B' repeats have extensive DNA methylation, while the B-I repeats have low levels of DNA methylation [21]. There are differences between the alleles in histone modifications and the extent of chromosomal looping between the repeats and the b1 promoter, but these differences correlate mainly with tissue-specific expression, not the heritable silencing associated with paramutation [21,22].

The b1 tandem repeats are transcribed [23] and generate siRNAs [24], yet repeat siRNAs are produced even from alleles that do not participate in paramutation, suggesting b1 siRNAs are not sufficient for paramutation in the tissues analyzed [24]. However, when the repeat sequence is expressed as a hairpin RNA from a transgene, which generates much higher levels of siRNAs than the endogenous alleles, heritable silencing and paramutation can be reconstructed [24]. This contrasts with two other examples of siRNAs generated from hairpin RNA producing transgenes in maize. These siRNAs effectively silenced homologous promoters, yet that silencing was not heritable [24]. Similar studies using hairpin RNAs to silence promoters in Arabidopsis did not report on heritability (e.g. [25]).

We hypothesize that the tandem repeats of the B-I and B' epialleles have special properties, which confer the ability to establish and heritably transmit the silenced paramutagenic state of B'. In this study, we test this hypothesis by asking whether the tandem repeats themselves are sufficient to send and respond to trans-acting paramutation signals, using a series of transgenes containing b1 tandem repeats. Our results are consistent with the above hypothesis. While paramutation was effectively reconstituted, the repeat transgene-induced silencing of B-I was less frequent and showed reduced stability in the next generation relative to endogenous paramutation, which occurs 100% of the time and is always stably transmitted.

Results

Transgenes carrying b1 upstream regulatory sequences encompassing the tandem repeats can silence B-I from non-allelic genomic locations

To test whether the b1 sequences upstream of the transcription start site (TSS) could induce silencing of the B-I allele from a non-allelic position, two constructs carrying the b1 repeats and surrounding sequences were used to generate transgenic maize lines: pB, containing the 5' part of the b1 transcription unit and 106.2 kb of sequences upstream of the ATG (Figure 1A, [19,20]) and pBA, which had 91.6 kb deleted between the tandem repeats and the proximal promoter of the b1 transcription unit relative to pB (Figure 1A). These constructs allowed us to also address if, in addition to the tandem repeats, other sequences upstream of the TSS were required for paramutation. For example, the observed transcription of the repeats [23,24] is likely to be required for paramutation and the promoter sequences driving this transcription might be located outside of the repeats.

The H-II maize stock used for transformation carried recessive neutral b1 alleles (designated as b-N) that do not participate in paramutation and do not confer anthocyanin plant pigment (N. Chandler, unpublished data), enabling the monitoring of silencing activity of the transgenes after crossing the regenerated transgenic plants to B-I. To test whether the sequences within either construct could mediate B-I silencing, the primary transgenic plants were crossed with plants carrying the paramutable B-I allele and a neutral b-N allele (Figure 2A). The presence of the neutral allele provided a means to propagate the transgenes in the absence of B-I (Figure 2A), which was done for multiple generations by crossing with b-N testers (Figure S1). To test the ability of transgenes to induce silencing, transgenic plants at different generations of propagation were crossed with B-I (Figure S1, Table S1). Scoring of plant pigment of the B-I/b-N progeny carrying transgene loci (TG/-) revealed that four out of ten pB, and five out of nine pBA transgene loci induced silencing of B-I (Figure 2B). In the transgenic events with silencing, the frequencies of silencing varied across multiple generations, ranging from 17 to 100% (Figure 2B, Table S2). The phenotypes of plants showing transgene-induced silencing of B-I were very similar to those showing b'-induced paramutation of B-I (Figure 2A and data not shown). In this paper, the transgene-induced silenced state of B-I is noted as B-I# to signify the transgenic origin of this state, in contrast to paramutation induced by the endogenous B' allele. Non-transgenic sibling plants (B-I/b-N) served as controls for sponta-
neous paramutation of $B$-I to $B'$, which can happen frequently [14]. Data from families showing spontaneous paramutation in non-transgenic siblings were not included in this paper.

Our results indicate that silencing of $B$-I can be mediated by sequences in ectopic, i.e. non-allelic, locations, paving the way for using a transgenic approach to further dissect the minimal sequences required for paramutation. Furthermore, these results demonstrate that a sub-fragment of the $b1$ locus, containing primarily the tandem repeats and the 5' part of the $b1$ transcription unit, is sufficient to establish $B$-I silencing.

Tandem repeats of a 413 bp sub-fragment of the 853 bp repeat unit are sufficient to induce silencing of $B$-I

The most prominent feature within the 16.3 kb sequence contained in the pBΔ construct are the seven 853 bp tandem repeats, and as paramutation strength correlates with the number of repeats [19], they were strong candidates for the minimal sequences mediating paramutation. To determine which part of the repeat sequence is needed to induce silencing, the 853 bp tandem repeat unit was dissected into two halves based on their different GC content; one half (hereafter referred to as FA) is 48% AT-rich, while the other half (hereafter referred to as FB) is 68% AT-rich [19] (Figure 1B). PCR-amplified sub-fragments (FA or FB halves) were ligated in head-to-tail orientation to form seven tandem repeats (Figure 1B). Constructs carrying the FA and FB hepta-repeats, pFA and pFB, were then transformed into maize and the resulting twelve transgenic events were tested for their ability to induce $B$-I silencing, similar to the approach used for pB and pBΔ transgenic loci (Figure 2A). Results revealed that all four pFA transgenic events induced $B$-I silencing at 100% frequency, indicating the pFA transgene contains all sequences sufficient for trans-silencing (Figure 2B, Table S2). None of the eight pFB transgenic events induced $B$-I silencing (Figure 2B, Table S2), suggesting the FB sequences were not sufficient for trans-silencing. Because pFB transgenic events do not induce silencing they serve as controls demonstrating that specific repeated sequences mediate silencing of $B$-I.

The $B^\#$ state is heritable and paramutagenic

One of the defining features of $b1$ paramutation is that $B'$ is fully paramutagenic to $B$-I and the silencing is heritable [13]. To assay whether the transgene-induced $B^\#$ silenced state was heritable and paramutagenic, plants carrying $B'$# alleles, induced by three independent pBΔ and two independent pFA transgenic loci, were crossed with plants heterozygous for the paramutable $B$-I and a neutral $b$-N allele (Figure S2A). Assaying the phenotype of the resulting non-transgenic $B^\#$/b-N progeny revealed that the silenced $B^\#$ phenotype was heritable in the majority (78–100%) of the non-transgenic plants (Table 1b). Assaying the $B^\#$/B-1 non-transgenic progeny revealed that the $B^\#$ states were often paramutagenic (41–100%; Table 1h). To distinguish the various epigenetic states, we use $B^\#$ to signify a $B$-I allele silenced by $B^\#$. 

Figure 1. Transgenic constructs used for maize transformation. A. Schematic drawing of the upstream $b1$ region and the two BAC clones used for plant transformation, pB and pBΔ. The scale at the top shows positions in kilobases (kb) relative to the ATG of the $b1$ gene. The 107.8 kb insert in pB contains the $b1$ repeats, the first two exons of $b1$, and all the sequences in between. The pBΔ clone is a deletion derivative of the pB clone that lacks 91.6 kb of internal sequences as indicated. The tandem repeats are indicated by arrowheads. B. Schematic representation of the pFA and pFB tandem repeat constructs. FA corresponds to one half of the repeat sequence and FB corresponds to the other half. The pFA and pFB tandem repeat constructs contain seven tandem copies of either FA or FB, respectively.

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Together, our results demonstrate that pBD and pFA-induced silencing of B-I to B' can recapitulate the two key characteristics of paramutation; the silenced B' state can be transmitted to progeny and it can be paramutagenic, inducing the B' silenced state in the absence of the inducing transgene.

Unlike the state induced by the B' allele, the heritability and paramutagenicity of the B' state was not fully penetrant and the frequency varied between the different pBD transgenic events. To test whether prolonged exposure to the pBD transgenes would increase the heritability and paramutagenicity of B' , B'/b-N; TG/- plants carrying B' alleles that had been exposed to the transgenes for two subsequent generations were crossed with either b-N or B-I (Figure S2B). For all three pBD transgenic events tested, subsequent generation in the presence of the transgene increased the heritability and paramutagenicity of B' state to 100% (Table 1ce). This could be because of prolonged in trans interactions between the transgene and B'. Spontaneous paramutation of B-I can, however, not be completely ruled out.

Figure 2. Silencing of the B-I allele by transgenes carrying tandem repeat sequences integrated in non-allelic locations. A. Crossing strategy for testing the ability of transgenes to induce silencing of the endogenous B-I allele. Regenerated transgenic plants, b-N/b-N; TG/-, were crossed with plants carrying the paramutable B-I allele and a neutral b-N allele. Silencing of the B-I allele was assessed by analyzing the pigmentation of the B-I/b-N progeny plants. If B-I is silenced by the transgene, indicated by B', transgenic plants should be light. If a transgene is not able to silence B-I, all plants, transgenic and non-transgenic, should be dark, unless spontaneous paramutation endogenous of B-I to B' occurred. Non-transgenic B-I/b-N siblings served as controls for spontaneous paramutation of B-I to B' and should remain dark if spontaneous paramutation does not occur. Any families that showed spontaneous paramutation of B-I to B' in non-transgenic siblings were removed from further analysis. B. Results from the experiments indicated in Panel A for the four constructs diagrammed in Figure 1. Detailed information on each transgenic event is in Table S1 and Table S2. The indicated frequencies of transgenic plants with a light phenotype are a compilation of the data obtained for transgenic loci maintained up to six generations in the presence of a neutral b1 allele (outlined in Figure S1). Frequency of light plants was calculated by dividing the number of light transgenic plants over the total number of transgenic plants. The designation b-N is used to represent the neutral alleles used in the crosses; b-N alleles carry a single 853 bp repeat unit, do not participate in paramutation and produce no plant pigment.

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Table 1. Heritability and paramutagenicity of transgene-induced B'^ silencing.

| Transgenic construct | Transgenic event | Heritability of B'^ as determined by phenotype of non-transgenic B'^/b-N plants | Paramutagenicity of B'^ as determined by phenotype of non-transgenic (B'^ or B-I)/B'^ plants |
|----------------------|------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
|                      |                  | One generation with transgene | Two generations with transgene | One generation with transgene | Two generations with transgene |
|                      |                  | Total Plants | Frequency of light plants | Total Plants | Frequency of light plants | Total Plants | Frequency of light plants |
| pFA                  | 60-05            | 77          | 100%                     | Nt           | 19           | 100%                     | Nt           |
|                      | 60-11            | 51          | 100%                     | Nt           | 14           | 100%                     | Nt           |
| pFB                  | 3-33             | 52          | 84%                      | 92           | 19           | 73%                      | 46           |
|                      | 3-39             | 51          | 78%                      | 36           | 24           | 41%                      | 73           |
|                      | 3-57             | 85          | 96%                      | 55           | 24           | 91%                      | 84           |
|                      | 60-05            | 77          | 100%                     | Nt           | 19           | 100%                     | Nt           |
|                      | 60-11            | 51          | 100%                     | Nt           | 14           | 100%                     | Nt           |

*aCrossing scheme to test B'^ heritability and paramutagenicity is shown in Figure S2; the data are summarized in this table.

*bHeritability of B'^ after one generation in the presence of the transgene.

*cHeritability of B'^ after two generations in the presence of the transgene.

*dParamutagenicity of B'^ after one generation in the presence of the transgene.

*eParamutagenicity of B'^ after two generations in the presence of the transgene.

Nt, not tested because paramutation was already 100% after one generation with the transgene.

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events (see previous section for definitions). As is typical for biolistic transformation, the DNA blot analysis revealed that the pB and pB\textsuperscript{D} transgenic plants contained multiple copies of the transgenes, including complete and truncated fragments (Figure 3A), which segregated as a single locus in each independent event. Six of the paramutagenic transgene loci carried an intact hepta-repeat fragment (Figure 3A, black arrow, 7 kb) and three paramutagenic events did not. None of the paramutable or neutral events carried an intact hepta-repeat. Thus, an intact hepta-repeat fragment was associated with paramutagenicity but was not absolutely necessary for an event to be paramutagenic or paramutable. As all of the insertions are complex we cannot rule out that one or more of the transgenic lines also contain repeats in an inverted orientation, a sequence arrangement known to mediate silencing [25,26]. We favour our hypothesis that it is the tandem repeats mediating paramutation because it is unambiguous from the fine structure mapping that tandem repeats mediate endogenous paramutation [19] and all the transgenic events with an intact tandem hepta-repeat were paramutagenic.

The number of repeat units present within each event was estimated by normalizing to an endogenous fragment containing a single repeat unit (Materials and Methods). In each functional category, paramutagenic, paramutable or neutral, there are examples of transgenic events that have relatively high or low numbers of repeat units (Figure 3A). All transgenic events, except one neutral event (4–12), carried more than one copy of the 853 bp repeat unit. There was not an absolute correlation between the number of the repeats and paramutation activity in the transgenic events (Figure 3A), although all intact hepta-repeat events were paramutagenic. A similar lack of correlation was observed with the pFA and pFB transgenic events (Figure 3B). The pFA transgenic events, which were all highly paramutagenic, had lower copy numbers (6–9 repeat units) than most of the pFB events (seven out of eight events had 16 or more repeat copies), which showed no paramutation ability. In addition, most of the pFB events had an intact fragment containing seven repeats, while none of the pFA events did (Figure 3B). These results confirm that the pFA sequences are sufficient for paramutation, while the pFB sequences are not.

Paramutation does not require extensive DNA methylation within the transgene repeats

Relative to \textit{B-I}, the paramutagenic \textit{B'} allele has high levels of cytosine methylation within the tandem repeats [21]. To determine if there was a correlation between the frequency of paramutation and DNA methylation levels at the transgenic repeats, two pB\textsuperscript{D} transgenic events, 3-39 and 3-46, were selected for DNA blot analysis. These two events have relatively simple transgene integrations; one intact hepta-repeat fragment and only a few other, truncated repeat-containing fragments (Figure 3A), enabling the interpretation of the DNA blot results. Representative examples of the 3-39 and 3-46 transgenic loci that were in the presence of neutral \textit{b-N} alleles (in the immediate progeny of regenerated transgenic plants) and had not been exposed to \textit{B-I} or \textit{B'}, are shown in Figure 4A. The transgenic repeats were mostly unmethylated within the assayed restriction sites (Figure 4A, open and grey arrows; a total of four 3-39 and seven 3-46 plants were examined). The repeat DNA methylation levels were not only lower than those previously observed for \textit{B'}, and for plants undergoing spontaneous paramutation of \textit{B-I} to \textit{B'}, but were also lower than those observed for \textit{B-I} (Figure 4B and 4D; Figure S4) [19,21]. These results indicate that paramutation can be mediated
by transgenic repeats that do not have the DNA methylation levels typical of B'.

To test if the methylation levels of the transgene increased after it had mediated paramutation, we examined the 3-39 transgene after it had segregated from the F1 between the primary 3-39 transgenic plant and B-I [In this F1, paramutation occurred at a frequency of 90%, (Table S1)]. The segregating 3-39 repeat transgene was extensively methylated, equivalent to B′ [Figure 4B; three plants examined]. Thus, after paramutation and segregation the transgene was extensively methylated. This could be due to spontaneous increases in DNA methylation or due to interactions between the transgene and the endogenous allele (resulting in paramutation of B-I to B′), or both. To test for spontaneous DNA methylation within the repeats, we examined the 3-39 transgene maintained in the presence of neutral b1 alleles for four generations (never exposed to B-I or B'). We observed a spontaneous increase in the DNA methylation levels in the transgenic repeats (Figure 4C, black arrows, four plants tested) up to the levels observed for the endogenous B′ repeats (Figure 4B and 4D). Thus, the increased methylation observed within the 3-39 transgenic repeats after encountering B-I could be due to spontaneous events.

The 3-46 transgenic event had very low levels of DNA methylation (Figure 4A) in the immediate progeny of the primary transgenic event, and when crossed with B-I plants, paramutation occurred at a frequency of 66% (Table S1). After crossing the 3-46 transgenic with B′ and then outcrossing to B-I, 100% paramutation was observed. With this one event, we saw that after crossing with B′, both the transgene and B′ had acquired extensive DNA methylation (summarized in Figure 4D and data not shown; a total of six B′ TG/- plants, and 11 B′ TG/- plants were tested). This result indicates that transgenic repeats with low levels of DNA methylation can acquire higher DNA methylation, but more events and individuals need to be examined to determine if increased paramutagenicity correlates with DNA methylation.

A key difference between transgene-mediated and endogenous allele-mediated paramutation is that the resulting silencing of B-I to B′ is less stable when induced by the transgenes than by B′ (Table 1). To determine whether this difference in silencing, as measured by plant phenotypes, might correlate with the extent of repeat DNA methylation in the endogenous allele, non-transgenic progeny plants segregating B-I and B′ were tested. This was observed. With this one event, we saw that after crossing with B′, both the transgene and B′ had acquired extensive DNA methylation (summarized in Figure 4D and data not shown; a total of six B′ TG/- plants, and 11 B′ TG/- plants were tested). This result indicates that transgenic repeats with low levels of DNA methylation can acquire higher DNA methylation, but more events and individuals need to be examined to determine if increased paramutagenicity correlates with DNA methylation.

MOP1 is required for transgene-induced b1 paramutation

Paramutation by the endogenous B′ allele requires the Mop1 gene [23], which encodes a protein with high similarity to RDR2, a putative RNA-dependent RNA polymerase required for RNA-directed transcriptional silencing in Arabidopsis [27]. To test whether MOP1 is required for the transgene-induced paramutation, the appropriate crosses were done to assay the ability of three pBα transgenes to paramutate B-I in the presence of the mop1-1
Figure 4. DNA methylation patterns in transgenic and endogenous \( \beta_1 \) repeats. Fragment sizes are indicated by numbers and are in kb. All DNA blots were hybridized with the full \( \beta_1 \) repeat probe (Figure 3A). For all blots, genomic leaf DNA was cut with the methylation insensitive enzyme EcoRI to release the ~7 kb fragment within which DNA methylation was assayed, and with the methylation sensitive enzymes indicated above each blot. Fragments resulting from complete digestion are indicated by open arrows, bands resulting from partial digestion (indicating partial DNA methylation) are indicated by filled arrows. The DNA methylation pattern for each enzyme combination is shown in Figure 4D. The DNA methylation pattern for each enzyme combination is shown in Figure 4D.

\[ \text{DNA methylation patterns in transgenic and endogenous } \beta_1 \text{ repeats.} \]

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mutation (Figure S5). If paramutation was prevented, the segregating progeny should have the B-I phenotype, whereas if paramutation occurred, most progeny should have the B' phenotype. Analysis of the segregating non-transgenic progeny revealed that the majority of the plants had a B-I phenotype (Table 3), indicating that the mop1-1 mutation prevented the pB\textsubscript{A} transgenes from paramutating B-I to B'. A few light B' plants were observed in three out of twelve testcross families. These could be the result of spontaneous paramutation of B-I to B', or because paramutation was not fully prevented in all plants. The observation that MOP1 is required for the transgenes to silence B-I demonstrates RNA-mediated mechanisms are involved in transgene-induced paramutation of B-I.

**b1 tandem repeats can mediate high expression of a reporter gene**

In addition to mediating silencing, multiple \(b1\) tandem repeats are required for high B-I expression [19]. It is, however, not known if the repeats are sufficient to mediate high expression or whether additional sequences are needed. To test if the repeats can mediate high expression a construct was produced in which the seven tandem repeats of \(B'\), B-I (b1TR) were fused to the minimal \(-90\) bp Cauliflower Mosaic Virus 35S promoter (35S) [28] and the GUS (beta-glucuronidase, [29]) reporter gene to generate the pb1TR::GUS transgene (Figure 5A, Materials and Methods). As a negative control, a construct was made that carried only the minimal \(-90\) bp 35S promoter fused to GUS (p35S::GUS). Both constructs were used to generate transgenic maize lines; only lines carrying intact GUS reporter genes were examined for GUS activity (Materials and Methods). Sleahe and husk tissues were stained for GUS activity and scored using a graded scale shown in Figure 5B. High GUS activity was observed in pb1TR::GUS events 36-7, 36-21 and 36-31, but not in the event 36-11 (Figure 5C). Southern blot analysis (not shown) revealed that the GUS transgenes in events showing high GUS activity carried about \(\sim 7\) repeats (36-7, 1 transgene copy), 6 and 1.5 repeats (36-21, 2 copies), and 4 and 3 repeats (36-31, 2 copies), while the transgenes in the event showing weak GUS activity carried about 3.5 and 2.5 repeats (35-11, 2 copies). Three p35S::GUS control events that contained no repeats showed low GUS activity, while one had high GUS activity (34-10, Figure 5D).

The high GUS activity in the p35S::GUS event 34-10 was unexpected and was hypothesized to be caused by integration of the transgene near an endogenous transcriptional regulatory element. If this hypothesis was correct, the expectation was that the GUS activity should not be silenced by \(B'\). In contrast, if the high expression in the pb1TR::GUS events 36-7, 36-21 and 36-31 was mediated by the repeats, \(B'\) should silence that expression. To test these hypotheses, the p35S::GUS event (34-10) and the three pb1TR::GUS transgenic events strongly expressing GUS (36-7, 36-21 and 36-31) were crossed with the paramutagenic \(B'\) allele. The three pb1TR::GUS transgenic events were also crossed with two highly paramutagenic p\(B\) transgenic events. Results shown in Figure 5E revealed that the expression of p35S::GUS event 34-10 was not affected by \(B'\); consistent with the hypothesis that its high expression is caused by integration near an endogenous regulatory element that is insensitive to \(B'\). In contrast, all three pb1TR::GUS transgenic events exhibited a significant reduction in GUS activity after exposure to \(B'\) (Figure 5F) or the paramutagenic p\(B\) transgenes (Figure 5G), providing additional support that the high expression was not simply due to insertion next to an endogenous enhancer. The silencing of the pb1TR::GUS transgenic loci in the presence of the paramutagenic p\(B\) transgenes was not due to spontaneous paramutation, because for all three pb1TR::GUS loci control transgenic siblings segregating only the pb1TR::GUS transgenes showed higher GUS activity (Figure 5G). Together, these data suggest that the \(b1\) tandem repeats are sufficient to trigger expression of a heterologous gene and that this expression is sensitive to paramutation.

To determine if the transcriptional regulatory activity within the repeats could be further delineated, transgenic lines containing seven FA or seven FB tandem repeats fused to the minimal p35S::GUS reporter gene were generated (Figure S6). GUS expression was observed in all the four intact p\(F\)A::GUS events and the one intact p\(F\)B::GUS event. However, because there was only one intact p\(F\)B::GUS event available, more experiments will be required to delineate where the transcripational regulatory activity maps.

**Repeat transgenes produce siRNAs**

Previous studies have shown that the tandem repeats in B-I and B' produce siRNAs [24]. Therefore various repeat transgenes were tested for the production of \(b1\) repeat siRNAs from their ectopic locations. As \(b1\) alleles that have a single copy of the repeat unit, and do not participate in paramutation, also produce \(b1\) repeat siRNAs [24], non-transgenic siblings with the same \(b1\) genotype as their transgenic counterparts were tested alongside (Figure 6). Transgenic p\(B\) 3-39 plants with the full length repeats showed slightly increased levels (\(\sim 2–3\) fold) of \(b1\) repeat siRNAs relative to their non-transgenic siblings, suggesting that either the transgenic locus was producing \(b1\) repeat siRNAs and/or it triggered an increase in the production of \(b1\) repeat siRNAs from the endogenous alleles. Similar increases in \(b1\) repeat siRNAs were seen with p\(F\)A::GUS and p\(F\)B::GUS transgenes (Figure 6 and Figure S6A). Notably, the \(b1\) oligonucleotide used in this experiment hybridizes to the FA part of the repeats, indicating that, at least in the p\(F\)B::GUS event, the \(b1\) siRNAs detected are derived from the endogenous \(b1\) repeat sequences. In spite of similar siRNA levels, the p\(B\) 3-39 and p\(F\)A::GUS transgenic events were paramutagenic, while the p\(F\)B::GUS transgenic event was not (Figure 2 and data not shown), suggesting that the increased production of siRNAs was not sufficient to establish paramutation. A similar lack of correlation with paramutagenic ability and production of siRNAs was previously reported for endogenous \(b1\) alleles [24].
Table 3. The mop1-1 mutation prevents pBΔ-induced paramutation of B-1.

| Transgenic event | Family 1 | Family 2 | Family 3 | Family 4 |
|------------------|---------|---------|---------|---------|
| 3-39             | 12/13 (92%) | 5/5 (100%) | 7/7 (100%) | 1/1 (100%) |
| 3-46             | 8/8 (100%) | 11/18 (61%) | 21/26 (80%) | 7/7 (100%) |
| 3-57             | 13/13 (100%) | 13/13 (100%) | 18/18 (100%) | 10/10 (100%) |

*Four families, representing the progeny of four individual mop1-1 homozygotes, were examined for each transgenic event. The families were derived from outcrossing homozygous mop1-1 plants carrying B-1 and a paramutagenic B1 repeat transgene to B-1 plants (details of the crosses performed are shown in Figure S5). The number of purple plants is shown before the slash, with the total number of plants scored indicated after the slash. The frequency of dark plants is shown in parenthesis.

The maize b1 tandem repeats do not display transcriptional regulatory activity in Arabidopsis

The observation that the b1 tandem repeats are sufficient to recapitulate paramutation with a heterologous reporter gene in maize suggested that it might be possible to transfer the maize b1 paramutation system to Arabidopsis thaliana. For Arabidopsis, a large set of well-characterized mutations affecting epigenetic regulation exist that could be tested for their involvement in paramutation. The first step was to generate transgenic loci in Arabidopsis that would be dependent on the b1 tandem repeats for their expression. Constructs were generated with three to seven b1 tandem repeats fused to the minimal −90 35S promoter and luciferase reporter gene (Figure 7A). As a control, sequences upstream of the repeats (Figure 7A) or b1 proximal promoter sequences (not shown) were used. Extensive analysis of the transgenic Arabidopsis plants containing intact transgenes revealed that all transgenic events carrying the b1 repeats exhibited a low level of luciferase activity similar to that displayed by control events with no b1 sequences (Figure 7A and Table S3). One possibility was that the transgenes integrated into a B'-like epigenetic state, which is associated with DNA methylation [19,21]. Analyses of methylation using DNA blot analyses (Figure 7B and 7C, Figure S7A) revealed low levels of DNA methylation within the repeats and no detectable methylation in sequences upstream or downstream of the tandem repeats. All 7-repeat-containing transgenic events analyzed (pEN-MS1 and pEN-MS2) showed similar DNA methylation patterns compared to each other and also to that of the maize transgenes with seven repeats (Figure 4A). Such uniformity among transgenic events is unusual as methylation patterns between independent transgenic events are typically more variable [30–33]. The transgenic events carrying four and three b1 repeats (pEN-MS3 and pEN-MS4) showed low methylation levels within the repeats, but there was more variation between the different independent transgenic events (Figure 7B and 7C, and data not shown), similar to that seen for the endogenous maize three-repeat allele [19]. Together, these results demonstrate that, in the primary transgenic plants, the transgenic repeat sequence acquired similar sparse DNA methylation in maize and Arabidopsis.

During the Arabidopsis transformation process de novo DNA methylation occurs [34,35]. We hypothesized that preventing any DNA methylation from occurring may enable the detection of the transcriptional regulatory function of the b1 repeats. To investigate this hypothesis, an Arabidopsis line in which the de novo DNA methyltransferases dm1 and dm2 (DOMAIN REARRANGED DNA METHYLASE 1 and 2; [34]) were mutated, was transformed with pb1::GFP constructs carrying b1 repeat- or b1 proximal promoter sequences fused to the minimal 35S promoter and GFP (Green Fluorescent Protein) coding region (Figure S7B). As a positive control, the 35S enhancer was fused to the GFP reporter gene (p35S::GFP). None of the pb1::GFP transgenic events showed GFP expression, while all of the p35S::GFP events did (Figure S7B and S7C, and Table S4). DNA blot analyses revealed that the dm1 dm2 double mutant background did prevent DNA methylation within the b1-repeats (Figure S7D), indicating that the lack of GFP expression was not due to DNA methylation.

Two other possible explanations for a lack of GFP expression, RNA-directed transcriptional or post-transcriptional silencing, were tested using the appropriate Arabidopsis mutants. Constructs with either seven or three b1 repeats (Figure S7B) were introduced into the rdr2-1 [35] and sg2-1/rdr6 [36] mutants. RDR2 mediates RNA-directed transcriptional gene silencing, and RDR6 post-transcriptional gene silencing. None of the transgenic plants showed GFP expression (Figure S7B, Table S4), suggesting that neither RNA-directed transcriptional or post-transcriptional silencing is responsible for the lack of GFP expression. Taken together these data suggest that the maize b1 repeats do not have transcriptional regulatory activity in Arabidopsis. As one needs transcription to study transcriptional silencing this approach is not viable to study paramutation in Arabidopsis.

Discussion

Results of the transgenic analysis presented in this paper demonstrate that specific tandem repeats are sufficient to both send and respond to the paramutation signal and that the repeat sequences need not be in an allelic position to communicate. The Mop1 gene, necessary for endogenous paramutation, is also required for transgene-induced paramutation, suggesting common mechanisms. The sequences required and sufficient for paramutation are localized in the first half of the b1 repeat unit. The tandem repeats are furthermore sufficient to enhance the expression of a heterologous reporter gene in maize, but not Arabidopsis. While transgenes are capable of inducing paramutation, several key differences exist between endogenous- and transgene-induced paramutation. Endogenous b1 paramutation is stable, fully penetrant and associated with dense DNA methylation within the b1 repeats, while transgene-induced paramutation displays variation in stability, penetration and DNA methylation levels within the transgenic and endogenous b1 repeats.

Repeats have been implicated in multiple examples of paramutation [5,19,37,38] and other silencing phenomena (e.g. [39–41]), but detailed mechanisms for why multiple copies are quantitatively required is not known in any system. Multiple models postulating which properties of the repeats are being counted have been discussed (reviewed in [42]). Models include a quantitative increase in a repeat product such as siRNAs [43], the
quantitative binding of regulatory proteins to the repeats [44], the extent of DNA methylation within the repeats [21], or the creation and amplification of a unique junction fragment [21]. The transgenes were able to slightly elevate the production of siRNAs in immature ears but as we previously observed [24] there was no correlation between levels of siRNAs and the ability to participate in paramutation. These results do not exclude the possibility of a correlation between repeat siRNA levels and paramutation in other tissue types and/or developmental time-points. Our results that tandem repeats of either the full repeat unit or the FA half are both strongly paramutagenic, yet they have distinct junctions, argues against a critical role for the junction regions. Furthermore, our observation that multiple repeats of FB have no paramutation activity strongly suggests tandem repeats of a specific sequence within FA are being counted during paramutation.

**Figure 5.** *b1* tandem repeats are sufficient to mediate transcriptional activation in maize. A. Drawing of the transgenic constructs used to assay transcriptional regulatory activity of the *b1* repeats. The pb1TR::GUS construct carries the seven tandem *b1* repeats (b1TR). The promoter is the minimal ~90 bp Cauliflower Mosaic Virus 35S promoter (35S), which contains no enhancer sequences [28]. GUS is the beta-glucuronidase gene from *E. coli* [29]. PinII is the 3′ untranslated region from the potato proteinase II gene [61]. The p35S::GUS construct, in which GUS expression is driven by the minimal ~90 35S promoter, was used as a control. B. The scoring scale used to evaluate GUS expression levels in sheath and husk tissues of transgenic plants. Panels C–G show the percentage of transgenic plants with specific levels of GUS staining. The shades of blue correspond to the levels of GUS staining indicated in panel B; white signifies no staining. Sheath and husk tissues are denoted as S and H, respectively. The number of plants assayed is shown on the top while the transgenic events are shown below each pair of columns. Panels C and D show GUS staining levels for pb1TR::GUS and p35S::GUS in a neutral *b1* background. Panels E and F show GUS staining levels for p35S::GUS and pb1TR::GUS transgene loci in the presence of the paramutagenic *B′* allele. Panel G shows GUS staining levels in two classes of progeny derived from crosses between GUS expressing pb1TR::GUS transgenic events and paramutagenic pBΔ events. One class carries both a pb1TR::GUS and pBΔ transgene, the second class carries only a pb1TR::GUS transgene. All transgenic loci shown in panels C–G were in a hemizygous state.
Two broad classes of models have been proposed for the allelic interaction that mediates endogenous paramutation, diffusible trans-acting signals or pairing between the repeats - these models are not mutually exclusive. Our observation that many different transgenic loci, located at distinct genomic sites, efficiently induce paramutation is most consistent with a diffusible trans-acting signal mediating the initial communication establishing paramutation. Consistent with this hypothesis, mutations in multiple genes involved in the RNA-directed transcriptional silencing pathway prevent the establishment of paramutation (reviewed in [42]), suggesting RNA may be the signal. However, our transgene experiments do not eliminate repeat pairing, as there are examples of pairing between homologous sequences in non-allelic positions in other systems [46–48]. Future experiments employing cytological methods may be able to shed light on whether there is a role for DNA pairing in paramutation.

Fine structure recombination mapping and chromosome conformation capture studies demonstrated that the b1 tandem repeats are also required for transcriptional activation of b1p1 [19,22], but those studies could not distinguish between a direct role, i.e. the repeats carry transcriptional regulatory sequences, versus an indirect role, i.e. they mediate the ability of regulatory sequences located elsewhere to activate b1. Our maize transgenic results demonstrate that the b1 repeats do carry sequences that can mediate transcriptional activation of heterologous reporter genes, most consistent with a direct role of the repeats in transcriptional activation. Previous chromatin immunoprecipitation experiments demonstrated that upon transcriptional activation of B-I, the repeats are relatively depleted for nucleosomes and those that remain are enriched for H3ac histone marks [21]. These two properties, which strongly correlate with active transcriptional regulatory sequences [49,50], are observed in both the FA and FB halves [21].

There is only one other paramutation system (p1, popcorn color) in which the sequence mediating paramutation has been defined [5], and that sequence also contains transcriptional regulatory activity [51,52]. However, simply having a transcriptional regulatory element is not sufficient for paramutation as there are two transcriptional regulatory elements at p1 and only one of them can induce paramutation [5]. In contrast to the observations in maize, the b1 tandem repeats did not function as a transcriptional activator in Arabidopsis, suggesting that the transcription factors recognizing this sequence are not conserved between maize and Arabidopsis.

When B-I is paramutated by the repeat transgenes, the resulting transgene-induced B'++ state, while heritable, often induced paramutation at a lower frequency and was less stable relative to the endogenous B' allele-induced B' state, in spite of the sequences being identical. The fact that after the transgenes are crossed to B', they induced a much more stable B'++ state, indicates that their non-allelic positions or the structure of the transgenic loci cannot be responsible for the original reduced penetrance and heritability. Furthermore, the observation that a generation together with B' increased the transgenes’ paramutagenicity, relative to carrying the transgenes over neutral alleles, suggests some type of heritable epigenetic mark is accumulating. Precedence for a role for DNA methylation has been reported in Arabidopsis where the RNA-directed transcriptional silencing machinery requires the presence of pre-existing DNA methylation on the endogenous FWA locus for effective silencing of an incoming FWA transgene [40]. This may not be the case with paramutation in maize, as two transgenes with very low DNA methylation levels could induce paramutation of the endogenous allele. Our results do indicate that specific sequences within the FA region of the repeat are a critical
Figure 7. DNA methylation of maize \( b1 \) repeats in Arabidopsis. A. Drawings of constructs used to transform Arabidopsis. The indicated \( b1 \) fragments were fused to the minimal 35S promoter, the luciferase reporter gene and nopaline synthase (nos) polyadenylation signal. The numbers above the diagrams indicate the genomic location from where the \( b1 \) sequences are derived relative to the \( b1 \) transcription start site in kb. Every independent transgenic event with an intact insertion was tested for luciferase activity; the numbers are indicated. The number of these events also tested for DNA methylation is indicated as well. B. DNA methylation analyses of \( b1 \) repeats in primary Arabidopsis transgenic plants. Genomic DNA was digested with \( \text{EcoRI} \), which cuts on both sides of the repeats, and one of three methylation sensitive enzymes, \( \text{Sau3AI} \), \( \text{Sau96I} \) or \( \text{AluI} \). Representative examples are shown for each enzyme combination. Additional examples are shown in Figure S7A. Open arrows indicate fragments derived from complete digestion (no DNA methylation), while gray arrows indicate fragments containing one or more undigested, cytosine methylated restriction sites. Fragment sizes are indicated on the right of the blots. C. Summary of the DNA methylation pattern of the \( b1 \) tandem repeats in transgenic events, and \( B' \) and \( B-I \) for comparison [21]. The single repeat shown represents all repeats present in each transgenic event or allele; the \( \text{Sau3A} \), \( \text{Sau96A} \), and \( \text{AluI} \) restriction sites are indicated. Subscripts indicate individual recognition sites present more than once in each repeat. The methylation levels at each site are indicated by the gray-scale shown. The multiple independent pEN-MS1/2 transgenic events had similar levels of DNA methylation (solid shading). The pEN-MS3/4 transgenic events showed different DNA methylation levels at some sites in independent transgenic events (hatched shading). Figure S7 shows additional DNA blots and summarizes reporter gene assays for \( b1 \) repeat transgenes in different Arabidopsis mutant backgrounds.

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component and given that most of the DNA methylation marks are within this region, it remains possible that DNA methylation marks contribute to the strength of paramutation. Further studies of multiple transgenic events will be required to test this hypothesis.

Materials and Methods

Maize seed stocks

The b1 stocks were initially acquired from a variety of sources and have been maintained in the Chandler laboratory for a number of years. The B', B-I and neutral b1 alleles were obtained from E.H. Coe, Jr. (University of Missouri, Columbia) and B-P was obtained from M.G. Neuffer (University of Missouri). All maize plant stocks used in this study carry functional alleles for all biosynthetic genes and the other regulatory genes required for anthocyanin biosynthesis, unless otherwise indicated. All genetic tests were conducted in the irrigated field conditions in Tucson, Arizona.

Arabidopsis seed stocks

The seed stocks used were wild type Arabidopsis thaliana (ecotype WS) and the previously described mutants drm1 drm2 (ecotype Ws-2; [34]), rdr2 (ecotype Col-0, SAIL_1277108; [35]) and rdr6 (syg2, Col-0 [36]). All Arabidopsis plants were grown under standard greenhouse conditions.

Maize plasmid and BAC clone construction

The pB clone (Figure 1A) contains 106.6 kb of sequences upstream of the b1 transcription start site plus exon one, two and part of exon three (also named pBACB1 in [20]; accession AY078063). The pBA clone was produced by digesting pB with the Ncol restriction enzyme, removing 91.6 kb of internal sequences and religation of the remaining sequences [20]. To produce the pFA and pFB transgenes, the two halves of the repeat were PCR amplified and inserted one by one in the BamHI/HindIII digested P1.0b::GUS plasmid [51]. The p35S::GUS construct (Figure 5A) was the same as ~90 35S::GUS described in [53] and contained the minimal ~90 bp Cauliflower Mosaic Virus 35S promoter (35S), the maize adh1 gene intron 1, the omega leader, the beta-glucuronidase (GUS) coding region, and the potato PnII terminator. To produce the pFA::GUS construct, the sequence 853 bp repeat array was inserted in the p35S::GUS construct upstream of the 35S promoter. To produce the pFA::GUS and pFB::GUS constructs, the FA and FB tandem repeats were ligated upstream of the 35S promoter of the p35S::GUS construct, respectively. Primer information and detailed information on cloning and vectors used for plasmid construction is presented in the Methods S1.

Maize transformation

Transgenic maize plants were generated at the Iowa State University Plant Transformation Facility using biolistic particle bombardment of Hi-II immature embryos, which carry a neutral b1 allele (b-N) [54,55]. The plasmid pBAR184 carrying the BAR gene, which confers resistance to the herbicide bialaphos, was co-bombarded with each construct [55]. Herbicide resistant calli were screened for DNA of interest using DNA blot analysis. Transformation events carrying transgene copies of the b1 repeat DNA were regenerated from calli.

Arabidopsis plasmid construction

The first set of plasmids used for Arabidopsis transformation carried the luciferase reporter gene (Figure 7A). These plasmids were made by inserting fragments of the maize b1 gene in front of a ~90 35S promoter fused to the omega leader, luciferase coding region and nopaline synthase (nos) polyadenylation signal. The second set of the plasmids contained a GFP reporter gene (Figure S7). These plasmids were produced either by replacing the luciferase reporter gene by a GFP reporter gene from the pFLUAR100 plasmid [56] or by transferring the b1 sequences to an intermediate plasmid containing the 90 bp-35S promoter-GFP-nos gene cassette. A detailed description of the cloning steps and vectors used for plasmid construction is provided in the Methods S1.

Arabidopsis transformation and expression analysis

Arabidopsis plants were transformed as described by [57] using 5% sucrose, 0.05% Silwet L-77, 0.5× Murashige & Skoog basal salts (micro and macro elements; Duchefa). The dipped plants were covered with Saran wrap, placed in the dark the first night and then grown in the greenhouse to maturity. To screen for transgenic plants, depending on the binary vector used, fluorescent seeds were either selected using the Leica MZ FL III stereo fluorescence microscope with a dsRed filter or seedlings were sprayed with 0.5% BASTA (Glufosinate) twice, two and three weeks after sowing in soil, and surviving plants were transferred to individual pots. Transgenic plants were examined for reporter gene expression. Luciferase activity was evaluated using the Luciferase Assay System (Promega) and GFP activity was examined using the Leica MZ FLIII stereo fluorescence microscope with a GFP2 and GFP3 filter.

DNA extraction and DNA blot analysis

Transgenic maize calli were ground in liquid nitrogen and incubated with extraction buffer (200 mM Tris-HCl pH 7.5; 250 mM NaCl; 25 mM EDTA pH 8.0; 0.5% SDS) for 10 minutes, followed by phenol/chloroform (1:1) and chloroform extraction. DNA was precipitated with 1/10 of the volume of 3 M NaOAc and an equal volume of isopropanol. Pelleted DNA pellet was washed with 70% ethanol and resuspended in TE (10 mM Tris-HCl pH 8.0; 1 mM EDTA). DNA extraction from maize leaves and Arabidopsis flower heads was performed according to [58,59], respectively. For DNA blot analysis 4–5 μg of maize and 0.5–2.5 μg of Arabidopsis genomic DNA was digested with the appropriate restriction enzyme(s) following the manufacturer’s specifications, size-fractionated by electrophoresis in 0.5× TBE 0.8–1.5% agarose gels, transferred to positively charged nylon membranes, fixed by UV fixation and hybridized with 32P labeled DNA probes as described [26]. All blots that contained samples digested with DNA methylation sensitive enzymes were probed with a fragment (Probe A [19]) that recognizes sequences that are not methylated in maize to confirm all restriction enzymes cut the DNA to completion [19] followed by hybridization to the b1 repeat probe. Details describing probe fragments and restriction enzymes used for DNA blot analysis of maize and Arabidopsis transgenes are in Methods S1. Copy number of b1 repeat units in maize transgenic plants was estimated using the software packages Quantity One (Biorad) for pB and pBA, and ImageJ [60] for pFA and pFB. Copy number was calculated and normalized to the intensity of a single copy band of one of the endogenous b1 allele present in each lane. Description of PCR-based genotyping of the endogenous b1 alleles and the mop1-1 mutation is presented in Methods S1.

RNA extraction and Northern blot analyses

Small RNA fractions were extracted from young, immature (~5 cm) maize ears as described by [24]. RNA was separated on
denaturing polyacrylamide gels, hybridized with \(^{32}\)P end-labeled DNA/LNA b1 repeat [VC1657F, [24]) and U6 (5'-GGTGTCATCCTTGCGCAGGGGCCATGCTAATCTTCTCTGTATGCT-3') oligos. Results were analysed similarly to described previously [24].

Analysis of GUS expression in maize transgenic plants

Tissues from transgenic plants (Figure 5 and Figure S6) were collected between ~30–60 days after germination and incubated with 1 ml of 0.1% X-GLUC solution (β-bromo-3-chloro-2-indolyld-D-glucuronic acid, Sigma) in the dark at 37°C for 24 hours [52]. Chlorophyll pigment was removed by repeated incubations in 70% ethanol. Stained tissues were analyzed under a binocular microscope and categorized according to the staining levels shown in Figure 5B and Figure S6B.

Supporting Information

**Figure S1** Crossing scheme used to maintain transgenes in a neutral b-N background and to test transgene-induced silencing of B-I. Regenerated transgenic plants were crossed with non-transgenic B-I/b-N tester lines. Progeny carrying the B-I allele and transgene, which had been in the presence of a neutral b1 allele for one generation, was assayed for transgene-induced silencing. Transgenic progeny plants carrying only neutral alleles (b-N) were outcrossed to plants carrying b-N for further maintenance in a neutral b-I/b-N background and to B-I for testing transgene-induced silencing. Summaries of the B-I silencing tests are shown in Figure 2B and Table S2. Detailed data on transgene-induced silencing over multiple generations of propagation with neutral b1 alleles is shown in Table S1. (TIFF)

**Figure S2** Crossing scheme to test for the heritability and paramutagenicity of the B-I state induced by pBΔ and pFA transgenes. In all testcrosses, genotyping was used to distinguish segregating b1 alleles and to identify the presence/absence of a transgene. A. To assay heritability and paramutagenicity of the silenced B-I state after one generation of exposure to a transgene, transgenic plants displaying a B-I silencing phenotype were crossed with a plant heterozygous for the paramutable B-I and a neutral b-N allele. The phenotypic data for the informative progeny classes are presented in Table 1b and 1d. B-N is used to indicate a B-I allele silenced by B-I. B. To assay heritability and paramutagenicity of B-I after two generations of exposure to a transgene, transgenic B-I/b-N plants from the first testcross were crossed with plants carrying either b-N (heritability test) or B-I (paramutagenicity test). Phenotypic data on informative progeny classes are presented in Table 1c and 1e. (TIFF)

**Figure S3** Crossing scheme to test whether exposure to B-I increases the silencing potential of weakly paramutagenic or non-paramutagenic pB, pBΔ and pFB transgenic events. The b-N/b-N; Tg/ Tg (indicated in Figure 2A) of fourteen independent transgenic events that were initially not paramutagenic and four events that were weakly paramutagenic were crossed to B-I plants. Transgenic progeny plants derived from these crosses were crossed with B-I to segregate the transgene from B-I and to assay paramutagenicity of the transgenic events. The data are summarized in Table 2. (TIFF)

**Figure S4** Developmental profile of b1 repeat DNA methylation pattern in a plant in which B-I is spontaneously changing to B-I. A. Map of restriction sites and probe used for DNA blot analysis; EoRI (E), Alul (A), and Sma961 (S). Subscripts indicate specific recognition sites present more than once each repeat. B. Seeds were planted from a family showing a high frequency of spontaneous paramutation. Leaves were taken from plants at different stages of development. Representative examples of some developmental stages are shown in the diagram. C. DNA methylation was assayed in leaves collected at different stages of plant development (see panel B). Leaf DNA was digested with the methylation insensitive enzyme EcoRI and the cytosine methylation sensitive enzymes Alul or Sma961. DNA blots were probed with the b1 repeat probe indicated in panel A. As a control, the B-I and B' DNA methylation profile is shown for each enzyme. Open arrows indicate completely digested DNA. Gray arrows indicate fragments in which the S2 and S3 sites are methylated, while black arrows indicate fragments in which all sites are methylated. The fragments in between the open and black arrows are the result of DNA methylation at one or more of the assayed sites within the b1 repeats. (TIFF)

**Figure S5** Crossing scheme for testing whether the mop1-1 mutation can prevent the pBΔ transgenes from paramutating B-I. The plus sign denotes the wild-type Mop1 allele. Transgenic b-N mop1-1/B-P plants were crossed to homozygous B-I mop1-1 plants and the colorless seeds planted. B-P is a neutral b1 allele and provides purple seed color that was used to identify seeds carrying this allele. Because mop1-1 was linked to b-N in the transgenic plants, the majority of the progeny plants were homozygous for the mop1-1 mutation (parental, non-recombinant classes, 77%) and a minority was heterozygous for the mutation (recombinant classes, 23%). Molecular genotyping was used to distinguish between the segregating progeny classes. In mop1-1 homozygotes, B' expression is up-regulated resulting in dark plant phenotypes [62]. To determine whether paramutation of B-I occurred in these plants, testcrosses were done with a neutral b1 allele (b-N) that specifies no plant pigment. The resulting progeny were genotyped for transgene presence and assayed for plant pigment. The data on the informative progeny class is shown in Table 3. (TIFF)

**Figure S6** GUS staining in leaves and sheath of pFA::GUS and pFB::GUS transgenic events. A. Drawing of the pFA::GUS and pFB::GUS constructs with the sequence component indicated on the top. All components, except the b1 sequences, were the same as those described for the constructs shown in Figure 5 (see also Materials and Methods). B. The scoring scale used to evaluate GUS expression levels in leaves and sheath tissue of transgenic plants. C. Chart showing percentages of transgenic plants with the GUS staining levels indicated in panel B. Leaf and sheath tissues are denoted as L and S, respectively. The number of plants assayed is shown on top of each pair of columns. (TIFF)

**Figure S7** Arabidopsis b1-repeat::lacZ transgenes carrying seven tandem repeats display low levels of DNA methylation. A. DNA blot analyses for the pEN-MS1 and pEN-MS2 transgenes. Genomic DNA was cut with the methylation insensitive enzyme EcoRI (E) and one of three methylation sensitive enzymes, Sph3AI (U), Suv961 (S) and Alul (A). Open arrows indicate fragments derived from complete digestion of genomic DNA, while grey arrows indicate fragments consistent with the presence of cytosine DNA methylation in one or more restriction sites within the b1 repeats. Each lane contains DNA of an independent transgenic line. B. The indicated b1
fragments were fused to the minimal 35S promoter and the GFP reporter gene. The numbers above the diagrams indicate the location (in kilobases) from which the sequences are derived relative to the bI transcription start site. The minimal ~90 bp 35S promoter region contained no enhancer sequences [63]. The pRB7 plasmid was used to verify the functionality of the GFP reporter gene and carried 747 bp of the 35S enhancer sequence. The number of independent transgenic events that were tested for GFP expression is indicated. C. Representative photos of pRB7 and pRB1 transgenic events. The greenish color of the pRB7 inflorescence is characteristic for GFP expression. There was no detectable green fluorescence in the pRB1 inflorescence. The observed reddish color is due to chlorophyll autofluorescence. D. DNA methylation analyses of pRB1 transgenic drm1 drm2 plants. Genomic DNA was cut with EcoRI and AluI and the resulting blot hybridized with the bI repeat and a GFP probe. A few representative samples are shown. The complete digestion observed with the bI repeat probe indicates that the drm1 drm2 double mutation prevented DNA methylation of the AluI sites. The hybridization with a GFP probe demonstrates that the DNA was digested to completion. (TIFF)

Methods S1 The Methods S1 describe the construction of plasmids used for maize and Arabidopsis transformation, restriction enzymes and probes used for Southern blot analyses of Arabidopsis and maize plants, and genotyping assays used in experiments that tested the requirement of MOP1 for transgene-induced paramutation. (DOCX)

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Table S1 Frequency of pB and pBA-induced B-I silencing. (DOCX)

Table S2 Frequency of transgene-induced B-I silencing after propagation with a neutral bI allele. (DOCX)

Table S3 DNA blot analysis of the Arabidopsis transgenes. (DOCX)

Table S4 Analysis of effect of bI repeats on expression of GFP reporter gene in Arabidopsis mutants. (DOCX)

Author Contributions
We thank Rosa Jamie-Frias and Samira Arabi-Bean for technical and maize field assistance and Vishwas Sheshadri for generating the pFA and pFB constructs. We thank Mara de Sain, Gerben Marsman, Michael Ignarski and Pegah Poorafar for their work on the Arabidopsis project. We thank Jim Carrington (Danforth Center, United States) and Hervé Vacheret (INRA, France) for providing the rdr2 (SAIL_1277H08) and rde6 (sg2-t) mutants, respectively; Toon Stuitje and Kees Spelt (Vrije Universiteit, The Netherlands) for providing the vectors pAR121, pFLUAR100 (Stuitje) and pHS-LUC (Spelt); and Carol M. Hamilton (Cornell University, United States) for providing pH20.

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