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MSH1 Is a Plant Organellar DNA Binding and Thylakoid Protein under Precise Spatial Regulation to Alter Development

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ABSTRACT

As metabolic centers, plant organelles participate in maintenance, defense, and signaling. MSH1 is a plant-specific protein involved in organellar genome stability in mitochondria and plastids. Plastid depletion of MSH1 causes heritable, non-genetic changes in development and DNA methylation. We investigated the msh1 phenotype using hemi-complementation mutants and transgene-null segregants from RNAi suppression lines to sub-compartmentalize MSH1 effects. We show that MSH1 expression is spatially regulated, specifically localizing to plastids within the epidermis and vascular parenchyma. The protein binds DNA and localizes to plastid and mitochondrial nucleoids, but fractionation and protein–protein interactions data indicate that MSH1 also associates with the thylakoid membrane. Plastid MSH1 depletion results in variegation, abiotic stress tolerance, variable growth rate, and delayed maturity. Depletion from mitochondria results in 7%–10% of plants altered in leaf morphology, heat tolerance, and mitochondrial genome stability. MSH1 does not localize within the nucleus directly, but plastid depletion produces non-genetic changes in flowering time, maturation, and growth rate that are heritable independent of MSH1. MSH1 depletion alters non-photoactive redox behavior in plastids and a sub-set of mitochondrially altered lines. Ectopic expression produces deleterious effects, underlining its strict expression control. Unraveling the complexity of the MSH1 effect offers insight into triggers of plant-specific, transgenerational adaptation behaviors.

Key words: Thylakoid protein, Organellar DNA binding, MSH1, Epigenetic variation

INTRODUCTION

Environmental stress elicits rapid and profound responses in plants designed for protection, avoidance, or progeny survival through changes in conditions. Many of the pathways that participate in these adaptive responses are influenced or controlled by epigenetic variations in the cell, involving small RNA, chromatin modification, and cytosine methylation changes (Eichten et al., 2014). Genes encoding DNA methylation machinery in plants are influenced in their expression by environmental cues (Boyko et al., 2010; Pecinka et al., 2010; Bilichak et al., 2012). Moreover, small RNAs can be transmitted systemically, permitting dissemination of these changes throughout the plant (Melnyk et al., 2011; Shivaprasad et al., 2012; Bond and...
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Baulcombe, 2014). Reprogramming of the methyleome can produce changes that are transmitted through the gamete, perhaps a key capacity to predispose the next generation for enhanced stress response.

Many of the metabolic and developmental pathways that participate in plant adaptation intersect within the plastid (Rolland et al., 2012). This includes phytohormone and lipid metabolic processes, light- and daylength-responsive flower induction processes, plant biotic defense, and redox response. Likewise, heat tolerance (Kim et al., 2012), cytoplasmic male sterility (facultative gynodioesy; Hu et al., 2014), and oxidative stress response (Jacoby et al., 2012) are controlled by the mitochondrion. Because both epigenetic and organellar changes are often maternally transmitted, it is difficult to dissect their relative contributions to adaptive behaviors or to investigate their possible interrelationship. Yet there exists compelling evidence that organelles serve as key environmental sensors (Pfalz et al., 2012; Schwarzländer and Finkemeier, 2013), suggesting that they could participate directly in the signaling of programmed epigenetic responses.

**MSH1** represents an unusual system that interlinks both organellar and heritable, non-genetic effects. The **MSH1** gene is unique to plants, encoding a protein that is dually targeted to both mitochondria and plastids (Abdelnoor et al., 2003; Xu et al., 2011). The MSH1 protein sequence is composed of at least six conserved domains, three presumably involved in DNA binding and regulation of recombination (Abdelnoor et al., 2006; Davila et al., 2011). Disruption or suppression of **MSH1** expression results in altered organellar genome stability (Davila et al., 2011; Xu et al., 2011), together with a process of developmental reprogramming that includes changes in numerous pathways affecting growth rate, flowering time, transition from juvenility, and abiotic stress responses (Xu et al., 2012).

Genome-wide methylome changes that characterize the **msh1** mutant are indicative of broader epigenetic effects (Virdi et al., 2015). While loss of **MSH1** in the plant produces developmental reprogramming, reciprocal crossing of the reprogrammed plant to wild-type and selection of restored **MSH1**/**MSH1** genotype produces plant lineages with novel DNA methylome profiles and markedly enhanced and heritable growth vigor over wild-type (Virdi et al., 2015). Recent experiments demonstrate that these enhanced-growth effects are reproducibly transmitted through grafting (Virdi et al., 2015), implying that methylome reprogramming is mediated, at least in part, by small RNAs. These growth effects are recapitulated in other plant species by **MSH1** RNAi suppression (Santamaria et al., 2014; Yang et al., 2015), reinforcing the argument that organellar and epigenetic effects of **MSH1** manipulation are conserved in plants.

Hemi-complementation experiments designed to effect mitochondrial versus plastid complementation of **MSH1** function in the mutant reveal distinct organellar contributions to the phenotype (Xu et al., 2012). Coupled with RNAi suppression experiments, the **MSH1** effect can be dissected to its relative plastid, mitochondrial, and epigenetic contributions to developmental reprogramming. Here we describe the relationship of mitochondrial, plastid, and nuclear epigenetic changes following loss of **MSH1** expression.

We show that **MSH1** localizes to the nucleoid and thylakoid membrane of a specialized plastid type, appearing to associate with particular photosynthesis/stress-related components. **MSH1** perturbation or overexpression in the plastid produces redox changes in the plant that may be important in triggering the epigenetic response. **MSH1** depletion in the mitochondrion leads to mitochondrial genome alteration and, at low frequency, combined heat tolerance, reduced seed germination, and altered leaf morphology. The epigenetic effects in **msh1** are separable from organellar effects, and integrate into the final **msh1** phenotype. Specialized localization and expression features of **MSH1**, coupled with mutation and gene-suppression behaviors, implicate **MSH1** as a novel organellar component of environmental sensing and stress signal transmission in the plant.

**RESULTS**

**MSH1-Associated Developmental Reprogramming Represents a Complex, Inter-organellar Integration Phenotype**

We reported earlier (Xu et al., 2012) that hemi-complementation of plastid function in the **msh1** mutant (mitochondrial depletion of **MSH1**) produces normal-appearing plants showing little or no altered growth phenotype. In approximately 7%–10% of the plants, however, two unusual phenotypes occur. The first, termed “curly leaf,” is characterized by plants with downward curling of leaves showing a smooth surface, as shown in Figure 1A. Progeny of a curly leaf type display 100% penetrance of the phenotype in subsequent generations (Supplemental Tables 1 and 2).

The second phenotype is termed “wrinkled leaf,” and displays an unevenly ridged, bumpy leaf surface and dramatically altered leaf shape (Figure 1A). The wrinkled leaf phenotype ranges in intensity, with plants that display the most intense alterations producing few or no progeny. The phenotype is incompletely penetrant in subsequent generations (37.50%–89.47%), sometimes giving rise to curly leaf types as well (Supplemental Tables 1 and 2). In both curly and wrinkled leaf types, reciprocal crossing to wild-type demonstrates maternal transmission of the altered phenotypes (Supplemental Figure 1), and both show evidence of plastid-localized **MSH1** (Figure 1B) and mitochondrial genome rearrangements (Figure 1C), confirming that the phenotypes arise as mitochondrial genetic effects. Both types also display evidence of enhanced heat tolerance (Figure 2A–2C), with reduced seed germination in the curly types (Figure 2D and 2E). Both curly and wrinkled leaf phenotypes are evident in the **msh1** mutant, and are not a consequence of the hemi-complementation process (Supplemental Figure 2).

Hemi-complementation of mitochondrial function in the **msh1** mutant (plastid depletion of **MSH1**) produces plants that are developmentally reprogrammed and display a range in intensity for leaf variegation, dwarfing, delay in juvenility–maturity transition (marked by rounded, juvenile leaf shape), and delay in flowering, similar to what was described in the earlier study of **msh1** (Supplemental Figure 3; Xu et al., 2012). This plastid-specific depletion of **MSH1** also affects abiotic stress response, so that
hemi-complementation lines are, perhaps by their slower growth, more drought tolerant (Figure 3) and, by virtue of their variegation, more tolerant to high light stress (Xu et al., 2011). These observations are consistent with the \( msh1 \) developmental reprogramming phenotype as an integration of both mitochondrial- and plastid-mediated behaviors.

**Plastid and Low-Frequency Mitochondrial Disruption by MSH1 Depletion Alter Redox-Regulating Metabolite Physiology**

While profound changes in plastid behavior were observed with depletion of MSH1, no significant differences between wild-type and the \( msh1 \) mutant were apparent in amounts, oxidation rates, and reduction rates of the cytochrome \( b_6/f \) complex or P700, and no major defects were observed in O-J-I-P fluorescence induction curves for assessing efficiency of photosystem II (PSII) closure (Methods as described by Roose et al., 2014). The \( msh1 \) mutant produces a variegated phenotype. Dissected yellow sectors show increased levels of non-photoactive plastoquinone in reduced form (Xu et al., 2012), a feature that is generally characteristic of plants undergoing senescence (Besagni and Kessler, 2013). Furthermore, variegated tissues of the \( msh1 \) mutant show an unusually high level of the demethylated precursor to phylloquinone (Xu et al., 2012), which distinguishes it from other variegation mutants in \textit{Arabidopsis}.

For extended our analysis of physiological changes in \( msh1 \) and hemi-complementation lines.

In green tissues, \( msh1 \) mutants displayed elevated, more highly reduced plastoquinone levels than in wild-type (Figure 4A), with the effect more pronounced in the stem than the leaf (Figure 4D). Similarly, plastochromanol-8 and \( \alpha \)-tocopherol levels were higher in the stem of \( msh1 \) plants relative to...
An MSH1 overexpression line was developed by stable transformation of Col-0 wild-type plants with an MSH1 native promoter::MSH1 full-length gene::GFP (green fluorescent protein) construction. Overexpression of MSH1 results in an unusual leaf-yellowing phenotype, delayed flowering, MSH1 accumulation in mesophyll plastids, and altered plastid morphologies including enhanced plastoglobule accumulation and size as a likely sign of plastid stress (Figure 4G–4J). Overexpression of MSH1 results in physiological effects strikingly similar to those of the msh1 mutant for plastoquinone, plastochromanol-8, and α-tocopherol levels in the stem, together with exaggerated levels of these metabolites in the leaf (Figure 4A–4F). Overexpression studies with CaMV3SS::MSH1::GFP introduced to Col-0 wild-type plants produced high-frequency gene co-suppression and the msh1 mutant phenotype (Supplemental Figure 5). Thus we conclude that high-level, ectopic MSH1 expression is not tolerated by the system, and even mild overexpression under native promoter produces deleterious growth effects. The observation of MSH1 co-suppression may also be indication of endogenous epigenetic regulation of MSH1.

Hemi-complementation tests showed that the altered redox behavior in msh1 was conditioned by plastid perturbation (Supplemental Figure 6A). Plastid-complemented msh1 mutants showed no alteration in redox-associated metabolite behavior, while mitochondrially targeted MSH1 (plastid depletion) showed effects similar to those described for the msh1 mutant. However, assays of the low-frequency curly and wrinkled leaf hemi-complementation lines, depleted in mitochondrial MSH1, produced plastid metabolite changes similar to those in msh1, indicating that mitochondrial dysfunction can also lead to plastid redox stress response (Supplemental Figure 6A). These results show that msh1 organellar perturbation in either plastid (high frequency) or mitochondrion (at lower frequency) creates a similar stress state that we suspect to be relevant to epigenetic reprogramming.

MSH1 Expression Is Spatially Regulated

The more pronounced redox metabolite modulation in the stem than leaves of msh1 suggests that MSH1 is spatially regulated in its expression. To examine expression timing, the MSH1 promoter was fused to β-glucuronidase (uidA) and stably transformed to Arabidopsis ecotype Col-0. While signal was detected in nearly all plant tissues throughout development, the spatial pattern of expression was restricted to epidermal cells, vascular parenchyma, meristems, and reproductive tissues (Figure 5). This expression pattern was confirmed with gene constructions that included the MSH1 promoter and full-length gene fused to GFP (Figure 6). Homozygous msh1-hemi-complemented lines (Xu et al., 2011) were used for this study to ensure proper functional localization. These experiments show that the unusual spatial pattern of MSH1 accumulation is promoter driven.

Analysis by laser scanning confocal microscopy in the leaf lamina region showed GFP signal positioned on the upper layer of cells. However, near the midrib, the signal was detected in nearly all cell layers (Figure 6A–6D). At higher magnification, one is able to observe GFP as punctate signals within plastid structures visibly smaller than mesophyll chloroplasts (Figure 6A and 6C). These plastid structures showed only muted autofluorescence relative to mesophyll chloroplasts, implying lower chlorophyll levels. To unambiguously distinguish the small plastids from mitochondria, we confirmed that a plastid hemi-complemented line, in which native promoter-driven MSH1 targets only to plastids, produced the same expression pattern.

MSH1 Is Localized to a Special Plastid Type

The size of MSH1-containing plastids is more readily estimated by electron microscopy, whereby the smaller plastids are approximately 30% the size of mesophyll chloroplasts in neighboring cells (Figure 7). The smaller, MSH1-associated plastids display less extensive thylakoid membrane and granal stacking, and contain fewer visible plastoglobules than do mesophyll chloroplasts (Figure 7A–7D). While their autofluorescence signal is lower than that of mesophyll chloroplasts, they contain visible starch. Epidermal plastids have the capacity to synthesize starch from imported carbohydrates rather than by their own photosynthetic activity (Tsai et al., 2009).

wild-type (Figure 4E and 4F). The msh1 mutant showed enhanced non-photochemical quenching rates in the light, followed by slower decay rates in the dark (Supplemental Figure 4).

Figure 3. Response of Plastid-Perturbed Plants to Moisture Depletion.

(A) Hemi-complementation line containing a mitochondrially targeted form of MSH1 grown 28 days at 12-h photoperiod and 22°C in controlled growth room.
(B) Plants subjected to 14 days without watering in the same growth room.
(C) Plants recovered following watering.
(D) Percent survival following watering. Data from three replications, 12 plants each.
To learn whether these organelles, and their unusual association with MSH1, can be generalized to other plant species, we stably transformed the *Arabidopsis* MSH1::GFP gene construct into tobacco (*Nicotiana tabacum* L). Confocal microscopy in tobacco revealed a similar pattern of smaller organelles in epidermal and vascular parenchyma cells, as well as association of MSH1 to these organelles in punctate patterns (Figure 7E and 7F). In both *Arabidopsis* and tobacco, crude plastid preparations were analyzed by fluorescence-activated cell sorting (FACS) to estimate the fraction of plastids that contain the protein. Results from these experiments indicate that MSH1-expressing plastids comprise approximately 2%–3% of total intact plastids isolated from leaves, and 12%–14% in stems (Supplemental Figure 7). These observations would account for the predominance of redox-associated effects detected in the *msh1* stem.

**MSH1 Appears to Be a DNA Binding Protein**

The punctate GFP signal observed within the MSH1-associated plastids indicates that at least some portion of MSH1 is sub-compartamentalized within these organelles. GFP-punctate structures within the plastids may be nucleoids (Terasawa and Sato, 2005) or plastoglobules (Vidi et al., 2006). We previously showed that punctate MSH1::GFP signals in plastids co-localized with DAPI staining in a few cells (Xu et al., 2011). DNA binding feature predictions within the protein sequence and MSH1 association with mitochondrial DNA recombination activity (Davila et al.,...
imply nucleoid association. We therefore conducted transient co-infiltration and genetic complementation experiments. Co-infiltration and laser scanning confocal microscopy showed co-localization of MSH1::RFP (red fluorescent protein) with three confirmed nucleoid proteins, pTAC2, PEND and MFP1, each carboxy-tagged with GFP and displaying very similar punctate localization patterns (Figure 8A).

Locating to the nucleoid implies MSH1 association with the plastid genome, which was supported both by site-directed mutagenesis and chromatin immunoprecipitation (ChIP). The ChIP assay showed that selective pull-down of MSH1-GFP with anti-GFP antibodies was followed by successful amplification of three plastid genome encoded genes, consistent with MSH1 binding to plastid DNA (Figure 8E). Site-directed mutations were introduced to a putative FYE DNA binding motif present within MSH1 domain I for functional assay by genetic complementation (Figure 8B; Supplemental Table 3).

Substitution of the highly conserved phenylalanine alone (FYE/LCYE) produced a protein unable to complement the plastid-associated variegation phenotype as well as mitochondrial DNA recombination, reinforcing the model of MSH1 function within the nucleoid and in DNA binding in both organelles (Figure 8C; 8D, and 8F). The phenylalanine substitution in MSH1 still produced punctate signals within the sensory plastid (Figure 8G), suggesting that DNA binding is not required for nucleoid localization. Also, the phenylalanine substitution appeared to be sufficient to condition the full complexity of msh1 phenotype, implying that DNA binding, or the protein conformation stemming from this binding, is essential to the protein’s function.

Substitution of the less-conserved tyrosine (FYE/QYCE) had no obvious effect on mitochondrial and plastid functions, and the mutation permitted complementation of msh1 phenotypes with three confirmed nucleoid proteins, pTAC2, PEND and MFP1, each carboxy-tagged with GFP and displaying very similar punctate localization patterns (Figure 8A). Substitution of the highly conserved glutamate (FYE/FYE) led to unexpected results. The mutant protein produced no detectable signal in plastids (Supplemental Figure 8), and negative complementation results. The mutation did not affect mitochondrial DNA stability, indicating that DNA binding and mitochondrial-targeting features of the protein remained intact. Thus, mutation of the glutamate does not appear to affect DNA binding, but is apparently essential for either targeting or protein stability within the plastid (Supplemental Figure 8). As further confirmation, the triple mutant FYE/LCA showed loss of MSH1 plastid localization, non-complementation of msh1 phenotype, and increased mitochondrial DNA recombination (Supplemental Figure 8).

Mutant phenotypes produced by substitution of phenylalanine, which affects DNA binding but allows nucleoid localization of the protein, and glutamate, which prevents targeting or protein stability in the plastid altogether, were indistinguishable. This result argues for the essential nature of DNA binding not only in genome stability but also in developmental, stress, and epigenetic features of the MSH1 effect.

A series of MSH1 nested deletions was developed to delimit, beyond domain I, the protein interval necessary for nucleoid targeting and protein function. These experiments, summarized in Supplemental Figure 9, showed that in addition to domain I, domain II and the hydrophobic interval of domain III appear to be essential for protein localization to the nucleoid. Likewise, deletion analysis showed that domains I–V and domains II–VI are not sufficient for partial protein function; the full-length protein is required.

MSH1 Also Associates with the Thylakoid Membrane

Because MSH1 is in low abundance, we carried out cell fractionation experiments in an Arabidopsis stable MSH1-GFP transformant under control of its native promoter. In silico analysis of the MSH1 protein predicted three hydrophobic intervals (Supplemental Table 4), and plastid fractionations showed MSH1 co-purifying with the thylakoid membrane (Figure 9A). This association persisted with mild detergent, salt washes, or DNase treatments, implying that the protein is membrane-attached and

Figure 5. MSH1 Expression with GUS Reporter.
(A) Seedling of stable Col-0 transformant containing a gene construction comprising MSH1 native promoter fused to β-glucuronidase.
(B) Seedling sectioned to expose meristem.
(C) Expression in veins and trichomes of young rosette leaf.
(D) Leaf midrib cross section showing MSH1 expression in the vascular parenchyma.
(E and F) Expression in vascular bundle of root (E) and root tip (F).
(G–J) Ovules within silique (G), ovule (H), pollen within anthers (I), and pollen (J).
not simply a component of the nucleoid (Figure 9B, 9C, and 9F). Although protein topology has not yet been fully elucidated, MSH1 co-fractionated with a high molecular weight complex (Figure 9D) believed to comprise the PSII–light-harvesting complex II supercomplex under protein non-denaturing conditions (Fristedt et al., 2015).

Yeast two-hybrid and co-immunoprecipitation (coIP) experiments identified putative MSH1 protein partners within the plastid. Initial yeast two-hybrid assays, with full-length MSH1 as bait and a cDNA library prepared from whole above-ground plant tissue at flowering, identified at least 12 gene products as putative interaction partners (see Supplemental Table 5 for partial listing). We have focused on one of these, PPD3, for the present study. PPD3 is a 27.5-kDa PsbP domain-containing protein thought to reside in the thylakoid membrane and/or lumen (Friso et al., 2004; Bricker et al., 2013; Ifuku, 2014). CoIP experiments with MSH1 also produced PPD3 as a putative interaction partner (Figure 10).

MSH1 sub-divides into six conserved intervals based on cross-species protein alignments (Abdelnoor et al., 2006), with domain 1 containing the DNA binding/mismatch recognition domain, domain 5 an ATPase domain, and domain 6 a GIY-YIG endonuclease domain. Sub-cloning MSH1 in accordance with these intervals, we conducted yeast two-hybrid matings with each MSH1 domain as bait. From these experiments, positive interaction occurred with PPD3 at domains 2, 3, and 6. The nature of MSH1 association with the thylakoid membrane is not yet defined, although domain 3–4 is bordered on both sides by short hydrophobic intervals (Supplemental Table 4).

MSH1 and PPD3 Are Co-expressed and Appear to Be Functional Interaction Partners

Native promoter::PPD3::GFP fusion constructs were developed to test PPD3 expression and localization behavior. PPD3 produced punctate signals within small sized plastids in the epidermal layer and the vascular parenchyma similarly to MSH1, with no detected signal in mesophyll chloroplasts (Figure 10E and 10F). This was in contrast to PsbO1 and PsbO2, two control proteins that also reside within the PSII oxygen-evolving complex and produced signal in all plastids including mesophyll.

Experiments by others have suggested that some PSBO1 protein may reside within the plastoglobule (Vidi et al., 2006; Ytterberg et al., 2006), and this could perhaps be the case, though unconfirmed, for PPD3. The observed spatial expression pattern of PPD3 would preclude its detection in plastoglobule preparations from whole leaf tissues. PPD3 expression appears to be suppressed by redox signals (Fey et al., 2005), similarly to MSH1, and there is some indication that PPD3 may be part of a stress response in the plant (Ifuku, 2014). Confocal microscopy of contrasting fluor-tagged MSH1 and PPD3 show overlap in their diffuse (membrane) signal, but not their punctate signal patterns (Figure 10H). We interpret this result to reflect the localization of MSH1, but not PPD3, within the nucleoid, and PPD3 and MSH1 interaction on or within the thylakoid membrane.

TDNA insertion mutants were obtained for PPD3 in Arabidopsis. The insertions were located at two sites in the gene, one in the promoter (ppd3-sail) and one in an exon (ppd3-gabi) (Supplemental Figure 10). TDNA insertion mutants produced no readily detectable changes in growth behavior of the plants grown under normal conditions. A small proportion (~10%) of ppd3-gabi plants, and their progeny, displayed a perennial-like growth behavior with aerial rosettes, similar to what is observed in Arabidopsis.
**Figure 7. Morphology of the MSH1-Containing Plastid.**
(A) Electron microscopy of leaf epidermal and mesophyll plastids from Arabidopsis wild-type Col-0. Epidermal plastids measure approximately 30% the size of mesophyll chloroplasts.
(B) Number of plastoglobules per electron microscopy section from 20–25 different fields of two independent samples. *P* ≤ 0.05.
(C and D) Vascular bundle (C) and mesophyll surrounding bundle (D) from Col-0.
(E and F) Plastids from tobacco wild-type expressing MSH1::GFP under the MSH1 native promoter (E), with localization to epidermal plastids. Electron microscopy section from wild-type tobacco (F) displaying a similar size disparity between epidermal and mesophyll plastids.
Scale bars, 2 μm.

in the msh1 mutant (Supplemental Figure 10D). Nonphotochemical quenching level and redox status were also altered in ppd3-gabi lines similarly to msh1 (Figure 4; Supplemental Figure 4). However, no mutant lines displayed a full msh1-like phenotype.

**MSH1 Does Not Appear to Be a Nuclear Protein but Effects a Heritable, Epigenetic Phenotype**

Earlier studies showed that MSH1 disruption or suppression is accompanied by heritable changes in nuclear cytosine methylation patterns (Virdi et al., 2015). These observations raise the possibility that MSH1 might also function within the nucleus of the cell. MSH1 hemi-complementation experiments that target the protein to the plastid and appear to fully complement msh1 (Xu et al., 2012) show no evidence of MSH1 nuclear localization by confocal microscopy. An MSH1::GFP construction, encoding native promoter and substituting an ATG start codon in place of the MSH1 targeting presequence (Supplemental Figure 11A), produced a cytosolic protein (Supplemental Figure 11E). These experiments revealed no evidence of functional complementation for the msh1 phenotype (Supplemental Figure 11B–11D). This was also the case when the CaMV 35S promoter was substituted for native promoter in a similar experiment.

Introduction of a nuclear localization signal (NLS) to the MSH1 gene construction in place of the presequence produced nuclear-targeting MSH1 (Supplemental Figure 11F). However, this construction also produced no functional complementation (Supplemental Figure 11G). These results do not definitively rule out MSH1 function in the nucleus but, together with hemi-complementation data (Xu et al., 2011), suggest that any MSH1 nuclear association would likely occur via the plastid.

To dissect the epigenetic component of the msh1 phenotype, we developed MSH1 RNAi suppression lines in Arabidopsis and, following the T1 generation, derived RNAi transgene-plus and -minus lines for further analysis. Lines containing the RNAi transgene displayed 50%–80% suppression of MSH1 transcripts and the full msh1 phenotype, including variegation and mitochondrial DNA rearrangement (Figure 11). Transgene-null lines displayed normal levels of MSH1 transcript, and no longer displayed leaf variegation, a plastid genetic phenotype, or the curly leaf/wrinkled leaf types that derive at low frequency from mitochondrially perturbed lines (Figure 11A). These traits appear to constitute the epigenetic component of the msh1 phenotype.

The msh1 mutant is altered not only in phenotype but in crossing behavior. Crossing msh1 reciprocally to wild-type Col-0 produces enhanced vigor phenotypes in a proportion of the MSH1/MSH1 progeny, an effect that is particularly pronounced by the F3 and F4 generations (Virdi et al., 2015). Genome-wide cytosine methylation analysis of F3 enhanced-growth selections, termed epif3, shows non-random changes in methylation pattern that are distinctive (Virdi et al., 2015).

The enhanced-growth effects from crossing an msh1 mutant with wild-type are observed in reciprocal crosses, and so are non-organellar (Virdi et al., 2015). Earlier studies showed these growth effects to emanate from crossing plastid-perturbed lines (Virdi et al., 2015). However, similar growth effects may arise from crossing the curly/wrinkled leaf types that derive at low frequency from mitochondrially perturbed lines (Supplemental Figure 6C), implying that the redox metabolite changes may serve as a predictor of this enhanced-growth phenomenon. To further investigate the possibility of cytoplasmic influence on this MSH1 effect, we carried out two independent experiments. The first involved reciprocal crosses between first- and second-generation msh1 mutants with the
Figure 8. MSH1 Appears to Be a Plastid DNA Binding Protein and Phenylalanine is Essential for Its Function.
(A) Co-localization of MSH1 with nucleoid proteins by laser scanning confocal microscopy. Fluor-tagged gene constructs are indicated to the left of each panel at distinct wavelengths to allow resolution of RFP (red), GFP (green), and merged images. This experiment tests for co-localization of MSH1 and three known nucleoid proteins.
(B) Diagram of MSH1 protein consisting of six domains, three hydrophobic/transmembrane stretches (red bars), and FYE motif within DNA binding domain.
(C and D) Genetic complementation assay with FYE/LYE and FYE/FCE point mutations within MSH1 DNA binding domain, early stage (C) and days to flowering (D). The complementation assay involves introduction of the test MSH1 transgene construction to an MSH1/msh1 heterozygote, followed by selection of the msh1/msh1 progeny segregant containing the transgene.
(E) Plastid ChIP assay. DNA immunoprecipitation was carried out with anti-GFP beads, and PCR was run with primers specific for three plastid genome-specific genes. msh1 indicates that a MSH1::GFP complemented line was used.
(F) PCR-based mitochondrial DNA recombination assay results for the two DNA binding domain mutants. The double band pattern indicates that illegitimate recombination is occurring, an indication that the transgene does not complement the msh1 phenotype.
(G and H) Confocal microscopy of stable transgenic lines containing FYE/LYE (G) or FYE/FCE (H) transgene to confirm that the altered MSH1::GFP constructs are targeted to the epidermal plastids.
phenotypically normal MSH1/msh1 heterozygote. In these experiments, crosses with the heterozygote as female, and either first- or second-generation msh1/msh1 mutants as pollen donors, resulted in normal and enhanced-growth progeny. However, the reciprocal crosses, with the heterozygote as male, consistently resulted in a proportion (~10%–25%) of the progeny displaying a range of variegation, dwarfing, and delayed flowering similar to the msh1 mutant (Figure 12). The frequency of msh1-like plants from crossing was far lower than would be expected by self-pollination of the msh1 mutant. These results are consistent with our hypothesis that the msh1 effect is an integrated organellar–epigenetic behavior.

The second experiment involved reciprocal crosses with an msh1 mutant hemi-complemented with a mitochondrial-targeting form of MSH1. This line continues to express the msh1 developmentally altered phenotype as a consequence of MSH1 depletion from the plastid (Supplemental Figure 12). The hemi-complemented line was crossed reciprocally to Col-0 wild-type, again showing a low and variable frequency of the msh1 mutant phenotype when the hemi-complementation line was used as female, but no evidence of the mutant phenotype when used as pollen parent (Supplemental Figure 12B–12D). These data indicate that these reciprocal differences are the consequence of plastid influence.

DISCUSSION

The MSH1 effect, characterized by dramatic changes in development and stress response, as well as enhanced growth upon...
crossing and grafting, is conserved among angiosperms (Xu et al., 2012; Santamaria et al., 2014; Virdi et al., 2015; Yang et al., 2015). The system serves as an excellent model for dissecting coordinate stress response networks within the plant. Gene expression changes in the msh1 mutant integrate across a range of processes involving flowering time/vernalization, gibberellic acid catabolism, leaf morphology, maturity transition, cell cycle and growth rate, and abiotic stress responses (Shedge et al., 2010; Xu et al., 2011, 2012). Many of the processes perturbed in the msh1 mutant are epigenetically modulated (reviewed by Bloomfield et al., 2014). Results here, and from previous studies, suggest that the msh1 reprogramming process is a plastid-driven phenomenon accompanied by mitochondrial genomic and epigenetic changes. The msh1 phenotype integrates mitochondrial genome recombination which, at relatively low frequency, leads to altered leaf morphology and seed germination, heat tolerance, and male sterility (Sandhu et al., 2007), with plastid changes producing variegation, redox changes, variability in growth rate, and drought and light tolerance, together with epigenetic effects of uniform dwarfing, flowering delay, maturity delay, and a perennial growth behavior in short-day conditions.

Hemi-complementation and RNAi suppression studies show that these various phenotypes are a complex amalgamation resulting from depletion of a single multitargeting gene product. More importantly, the unusual range of msh1 phenotypes, under conditions of chronic environmental stress, could represent a heritable adaptive response. While the relationship of organelle behavior with plant stress response is well documented, the integration of epigenetic effects with organelar perturbation is less so. Mammalian systems show interesting interplay of mitochondrial and nuclear epigenetic behavior (Figueroa et al., 2010; Castegna et al., 2015), but little if anything is known in plants of organelar triggers for non-stochastic epigenetic change.

The precise sub-compartmentation of MSH1 is elusive. Data are convincing for MSH1 as a nucleoid protein, and previous and present reports show MSH1 to influence both mitochondrial and plastid genome stability (Davila et al., 2011; Xu et al., 2011). We show that MSH1 function is affected by substitution of the signature phenylalanine (Phe-39) that characterizes the mismatch recognition motif of MutS homolog proteins (Malkov et al., 1997).

Protein–protein interaction data and physiological changes measured in the mutant argue for influence of MSH1 on redox regulation and stress response in the cell. Consistent with this interpretation, MSH1 associates with the plastid thylakoid membrane, and MSH1 transcript levels are markedly reduced in plants under abiotic stress conditions (Shedge et al., 2010; Xu et al., 2011), a response that makes little sense when viewed in the context of organellar genome stability but is consistent with a role in environmental adaptation. Plastid nucleoid functions have been shown to be modulated by redox changes, leading to wider effects on gene expression (reviewed in Powikrowska et al., 2014). Consequently, we suggest that the MSH1-containing organelles behave as “sensory” plastids. Several studies have shown that vascular parenchyma and/or bundle-sheath plastids serve a signaling function to regulate mesophyll plastid behavior (Lundquist et al., 2014), consistent with our view that these unusual small plastids function as regulators.

Multifunctionality is relatively common in organellar proteins (Gancedo and Flores, 2008), particularly in nucleoid proteins (Kucej and Butow, 2007; Krupinska et al., 2013). One explanation for our observations is that MSH1 carries out two primary functions in the cell. In the meristem, MSH1 associates with the plastid thylakoid membrane, and MSH1 transcript levels are markedly reduced in plants under abiotic stress conditions (Shedge et al., 2010; Xu et al., 2011), a response that makes little sense when viewed in the context of organellar genome stability but is consistent with a role in environmental adaptation. Plastid nucleoid functions have been shown to be modulated by redox changes, leading to wider effects on gene expression (reviewed in Powikrowska et al., 2014). Consequently, we suggest that the MSH1-containing organelles behave as “sensory” plastids. Several studies have shown that vascular parenchyma and/or bundle-sheath plastids serve a signaling function to regulate mesophyll plastid behavior (Lundquist et al., 2014), consistent with our view that these unusual small plastids function as regulators.

The MSH1 gene displays evidence of multifunctionalization during its evolution. The high degree of alignment of DNA binding and mismatch recognition motifs within domain I and the
ATPase of domain V suggest that MSH1 originated as a MutS homolog that, during its evolution, underwent fusion with a GIY-YIG class of homing endonuclease to enhance the protein’s capacity for regulating recombination (Malik and Henikoff, 2000). MSH1 likely originated from the mitochondrion (Abdelnoor et al., 2006). Subsequent retargeting of the protein to the plastid may have facilitated acquisition of domains II, III, and IV, which encompass two hydrophobic intervals and potential sites of interaction with other thylakoid-localized proteins including PPD3. While PPD3 function has not been elucidated, it also appears to be associated with stress responses (Fey et al., 2005; Ifuku, 2014). Furthermore, ectopic expression of MSH1 within mesophyll cells is not tolerated, further underlining the specialized properties of the protein.

Physiological changes in msh1 are characteristic of altered redox state and plastoglobule response (Zbierzak et al., 2009; Piller et al., 2014). Measurable enhancement of these effects within the stem tissues, where MSH1 expression is more concentrated, is consistent with localization to sensory plastids. The vascular tissue association of MSH1 may also account for the graft transmissibility of effects arising from its depletion (Virdi et al., 2015). The plastoglobule, where much of the msh1-associated physiological response occurs, is a suborganellar compartment that participates in stress signaling and senescence (Kessler and Vidi, 2007; Singh and McNellis, 2011; Besagni and Kessler, 2013). Our working model involves marked changes within the plastoglobule during MSH1 depletion that trigger the signal for nuclear epigenetic response. Recently, plastidial redox signals were shown to participate in epigenetic control (Dietzel et al., 2015) and in generating mobile signals in vasculature (Petrillo et al., 2014).

Although the msh1 cellular behavior collectively resembles a plant undergoing senescence (Besagni and Kessler, 2013), the msh1 mutant is green and completes successful flowering and formation of viable seed. It is, perhaps, this mistimed condition of senescence-like physiological behavior under conditions of continued plant growth that leads to programmed epigenetic changes.

Evidence of heritable, non-genetic changes in the plant (Santamaria et al., 2014; Virdi et al., 2015; Yang et al., 2015), following MSH1 depletion, reflects either direct or indirect influence of the protein on nuclear genome behavior. We have no direct evidence for interaction of MSH1 in the nuclear genome, but we have not formally eliminated the possibility of plastid–nuclear interaction. Unusual intracellular plastid–nuclear behavior has been suggested to occur for WHIRLY1 protein (Grabowski et al., 2008), also a nucleoid, multitargeting, and multifunctional organellar protein, and plastid stromules have been demonstrated to participate in cellular plant stress behavior, perhaps constituting a direct conduit of plastid–nuclear communication (Caplan et al., 2015).

We previously showed in several plant species that MSH1 depletion produces a complex and programmed alteration in plant phenotype. The present study dissects this developmental reprogramming phenotype into its mitochondrial, plastidial, and epigenetic components, and links the effects to a specialized spatial pattern and plastid type. It is unclear how initial cellular perturbations arising with MSH1 depletion are transformed into heritable epigenetic changes, although we show that these processes are largely directed via the plastid and, remarkably, that the epigenetic component of the reprogramming process is...
subsequently separable from the organellar one. This advancement should now allow us to test for a small RNA component sufficient to condition these dissected epigenetic changes, and to begin to understand how organellar and epigenetic behaviors integrate to affect growth.

METHODS

Plant Materials

Arabidopsis thaliana Col-0 was obtained from Lehle Seed Company. Heterozygous plants for complementation experiments were generated by conventional crossing using Col-0 as a female (Col-0 × chm1-1). MSH1 fully and hemi-complemented Arabidopsis transgenic lines were advanced from the Xu et al. (2011) study. The TDNA mutants were obtained from TAIR (http://www.arabidopsis.org/): msh1 (SAIL-877-F01), ppd3-sail (SAIL-641-C02), and ppd3-gabi (GK-121C07). Genotyping primers are listed in Supplemental Table 6. Plants were grown in standard growth conditions at 22 °C under long-day (16 h light/8 h dark) or short-day (12 h light/12 h dark) photoperiods in a walk-in chamber. MSH1 RNA materials were developed as described by Virdi et al. (2015).

Plasmid Construction for Arabidopsis Transgenic Plants and Tobacco Infiltration Experiments

For GUS (β-glucuronidase) fusion expression constructs, MSH1 full-length genomic DNA (gDNA) with its native promoter was ligated to pBI101 promoter-less binary vector. MSH1 DNA binding mutant constructs were created by serial cloning. Full-length MSH1 gDNA with native promoter was ligated to intermediate vector pBlueScript (KS+). Site-directed mutagenesis was carried out with primers specific for FYE/LYE, FYE/FCA, FYE/FYA, and triple mutation FYE/LCA with the QuiChange Site-Directed Mutagenesis Kit (Stratagene) according to the manufacturer’s instructions. Mutated fragments from the intermediate vector were transferred to plant binary vector pCambia1302C lacking 35S promoter. For reporter clones, the first 88 amino acids of PEND and full-length gDNA of pTAC2, MPF1, PPD3, PSBO1, PSBO2, PetC, and Tic55 were ligated to mGFP and mRFP versions of pCambia1302C. Full-length gDNA MSH1 was also ligated to the pFAST::eYFP vector for some of the co-localization experiments. Truncated versions of MSH1 were ligated to the mGFP version of pCambia1302C. For the construction of the nuclear targeted MSH1 clone, NLS sequence was derived from the class 5 plant-specific NLS sequence (b54) (Kosugi et al., 2009) and cloned into an intermediate vector pBlueScript (SK+) carrying MSH1 native promoter and the gene in-frame. This was then moved into the binary vector pCambia1302C::GFP for plant experiments.

Transmission Microscopy

Leaves for transmission electron microscopy were prepared as follows. Leaf samples from green lamina and midrib of 3-week-old chm1-1 mutant and wild-type plants were dissected and fixed in 2.5% glutaraldehyde in 0.05 M sodium cacodylate (pH 7.4) and postfixed in 1% osmium tetroxide in 0.05 M sodium cacodylate (pH 7.4) for 2 h. Samples were dehydrated in a graduated ethanol series and embedded in Epon 812 (Electron Microscopic Sciences). Thin sections (80 nm) were stained by uranyl acetate and lead citrate, and observed under a transmission electron microscope (Hitachi H7500-I) at the University of Nebraska Center for Biotechnology Microscopy Facility.

Yeast Two-Hybrid Experiments

MSH1 full-length gene from cDNA was cloned in the pGBK7 two-hybrid DNA BD vector. For the library, total RNA was isolated from floral tissues of Arabidopsis Col-0, and purified mRNA was obtained using the NucleoTrap mRNA kit from Clontech. The yeast two-hybrid library was made in pGADT7 AD vector using the Matchmaker library construction and screening kit according to protocols provided by the manufacturer (Clontech). Positive interaction partners were isolated and identified by sequencing. Further testing of interaction was done by one-to-one mating with MSH1 on rich media and transferred to synthetic dropout plates, first plated on SD-Leu-Trp to confirm the presence of both bait and fish and then on SD-Leu-Trp-His-Ade X-alpha-gal plates for blue color development for positive interactions. The second more stringent screen was done by developing a yeast two-hybrid library from A. thaliana ecotype Col-0 stem tissue using the Make Your Own “Mate & Plate” Library System (Clontech cat. #630490). This library was screened with MSH1 as bait using the more stringent yeast two-hybrid screen Matchmaker Gold Yeast Two-Hybrid System (Clontech cat. #630489).

Mass Spectrometry

Tandem mass spectrometry was performed at the University of Nebraska Mass Spectrometry Core Facility using a Waters Q-TOF Ultima mass spectrometer.
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spectrometer (Waters; formally Micromass). Results were analyzed using the Mascot software package (Matrix Science).

Plastid and Thylakoid Preparation, and Nuclease Treatment for MSH1 Topology Experiments

Crude plastids were prepared as described by Hall et al. (2011). In brief, 4-week-old plants were ground in chloroplast extraction buffer (20 mM Tricine–NaOH [pH 8.0], 300 mM sorbitol, 10 mM KCl, 10 mM EDTA, 0.25% BSA, 4.5 mM sodium ascorbate, 5 mM L-cysteine) centrifuged at 3000 g for 10 min at 4°C. Pellet was washed twice with wash buffer (20 mM HEPES–NaOH [pH 7.8], 300 mM sorbitol, 10 mM KCl, 2.5 mM EDTA, and 5 mM MgCl2) resuspended in the same buffer at 1 mg/ml chlorophyll concentration, and stored at −80°C. For thylakoid preparation, fresh resuspended plastids were lysed osmotically with osmotic shock buffer (10 mM sodium pyrophosphate–NaOH [pH 7.8], 1× Sigma protease inhibitor cocktail) and kept for 30 min at 4°C. Stomatal proteins were separated at 100 000 g for 1 h, and the thylakoid pellet was washed with thylakoid wash buffer (2 mM Tricine–HCl [pH 7.8], 300 mM sucrose) and buffer II (2 mM Tricine–HCl [pH 7.8], 100 mM sucrose, 50 mM NaCl, 5 mM MgCl2, 1 mM EDTA) resuspended in wash buffer II, and aliquoted at 1 mg/ml chlorophyll concentration. Isolated thylakoids were treated with micrococcal nuclease (Sigma) in digestion buffer (25 mM HEPES [pH 8.0], 5 mM MgCl2, 20 mM NaCl, 1× Sigma protease inhibitor cocktail without EDTA) at specified time and concentrations, and washed with thylakoid wash buffer II. Nucleoids were precipitated from nuclease-treated and -untreated plastids with the chloroform/phenol DNA extraction method. For SDS–PAGE, crude plastids or thylakoids were lysed with resuspension buffer containing 1% Triton for 1 h and centrifuged at 20 000 g for 1 h at 4°C. Cleared lysate was used for further analysis.

Chloroplast Chromatin Immunoprecipitation Assay

Chloroplast ChiP assay was performed as described by Yagi et al. (2012). In brief, crude plastids were cross-linked with formaldehyde 1% (v/v) in chloroplast isolation buffer and incubated at 25°C for 10 min. Cross-linking reaction was stopped with 150 μl of 1 M glycine for 25°C for 5 min and washed with chloroplast isolation buffer. Cross-linked plastids were lysed and incubated with GFP-Trap beads, and DNA–protein complex was eluted, reverse cross-linked with 8 μl of 5 M NaCl and 2 μl of 10 mg/ml Proteinase K in elution fraction, and incubated at 65°C overnight. Immunoprecipitated DNA was purified with a PCR purification kit according to the manufacturer’s instructions. Detailed protocol and buffers are as described by Yagi et al. (2012). PCR was performed with 1 μl of DNA and run in 1% agarose gel.

Protein Preparation, Co-immunoprecipitation, and ImmunobLOTS

Leaves were ground in liquid nitrogen and total proteins were extracted with lysis buffer (50 mM sodium phosphate buffer [pH 7.0], 10 mM EDTA, 1% Triton, 0.1% sodium lauryl sarcosine, 1× protease inhibitor, and freshly added 7 μl of β-mercaptoethanol/10 ml) for 1 h at 4°C and centrifuged at 20 000 g for 1 h. Cleared supernatant was used for immunoblot assay. Plastid proteins were prepared as described above. For coIP, anti-MSH1 beads were prepared with Pierce NHS activated agarose and GlycoLink purified MSH1 antibody. Anti-GFP (ab69314) agarose beads was purchased from Abcam, while GFP-Trap A (gta-10) and RFP-Trap A (rta-10) beads were purchased from ChromoTek. Total protein was extracted with buffer (100 mM Tris–HCl [pH 7.8], 100 mM NaCl, 0.1% NP-40, 1 mM MgCl2, 1 mM CaCl2, and 1× protease inhibitor cocktail without EDTA). Antibody beads were incubated with protein lysate overnight, washed three times with wash buffer (100 mM Tris–HCl [pH 7.8], 50 mM NaCl, 0.05% NP-40, 1 mM MgCl2, 1 mM CaCl2, and 1× protease inhibitor cocktail without EDTA), and proteins were eluted with 2× SDS loading buffer.

Fluorescence-Activated Cell Sorting Analysis

Crude plastids from leaves and inflorescence stems were prepared as described above. Resuspended plastids were cleared through 5-ml poly-
REFERENCES


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