Ancient duons may underpin spatial patterning of gene expression in C_4 leaves

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If the highly efficient C_4 photosynthesis pathway could be transferred to crops with the C_3 pathway there could be yield gains of up to 50%. It has been proposed that the multiple metabolic and developmental modifications associated with C_4 photosynthesis are underpinned by relatively few master regulators that have allowed the evolution of C_4 photosynthesis more than 60 times in flowering plants. Here we identify a component of one such regulator that consists of a pair of *cis*-elements located in coding sequence of multiple genes that are preferentially expressed in bundle sheath cells of C_4 leaves. These motifs represent duons as they play a dual role in coding for amino acids as well as controlling the spatial patterning of gene expression associated with the C_4 leaf. They act to repress transcription of C_4 photosynthesis genes in mesophyll cells. These duons are also present in the C_3 model *Arabidopsis thaliana*, and, in fact, are conserved in all land plants and even some algae that use C_3 photosynthesis. C_4 photosynthesis therefore appears to have coopted an ancient regulatory code to generate the spatial patterning of gene expression that is a hallmark of C_4 photosynthesis. This intragenic transcriptional regulatory sequence could be exploited in the engineering of efficient photosynthesis of crops.

C_4 photosynthesis | evolution | duons | gene regulation

Photosynthesis forms the basis of life on earth. When plants moved onto land they inherited a photosynthetic system developed by bacteria in which ribulose bisphosphate carboxylase oxygenase (RuBisCO) generates phosphoglyceric acid (PGA) (1). As PGA contains three carbon atoms, this is referred to as C_3 photosynthesis. A side reaction of RuBisCO fixes O_2 rather than CO_2 and generates the toxic compound phosphoglycolate. Although plants use photorespiration to remove phosphoglycolate, both carbon and energy are lost in the process (2). Around 30 Mya, some species evolved a system in which CO_2 is concentrated around RuBisCO such that oxygenation is minimized, and photosynthetic efficiency increases by around 50% (3, 4). These species now represent the most productive vegetation on the planet (5, 6), and because they initially generate a C_4 acid in the photosynthetic process, are known as C_4 plants.

The C_4 mechanism depends on spatial separation of photosynthetic reactions, most commonly between mesophyll (M) and bundle sheath (BS) cells. How this complex process has evolved in over 66 independent lineages remains a mystery. The finding that expression of multiple *NAD-dependent MALIC ENZYME (NAD-ME)* genes in the BS of C_4 *Gynandropsis gynandra* is dependent on coding sequence (7) hinted at the importance of exons in this process, which are more highly conserved than intragenic sequences and therefore a potential hotspot underpinning repeated evolution. Although genome-wide studies commonly report transcription factor binding within genes (8, 9), there is little functional validation to support these findings and their general importance remains unclear.

Results

To better understand mechanisms responsible for generating preferential expression in BS cells of C_4 plants, analysis was focused on the coding region of *GgNAD-ME1*. Although a 240-nucleotide fragment under control of the constitutive CaMV35S promoter confers BS accumulation in *G. gynandra* (Fig. 1 *A* and *B* and Figs. S1 and S2) it was unclear whether this was due to transcriptional and posttranscriptional mechanisms. These can be distinguished using an antisense construct that maintains DNA sequence, but when transcribed generates a complementary mRNA. An antisense construct under the constitutive CaMV35S promoter maintained preferential accumulation in the BS (Fig. 1 *A* and *B*), indicating that DNA sequence is recognized by *trans*-acting factors regardless of the orientation of the sequence. The preferential rather than exclusive accumulation of GUS in BS cells reported here is consistent with quantification of transcripts encoding components of the C_4 cycle in BS and M cells of C_4 leaves (7, 10) and also previous analysis of elements controlling gene expression (11–13). Thus, the coding sequence of *GgNAD-ME1* controls transcription, and as it suppresses activity of the constitutive 35SCaMV promoter in M cells, the simplest explanation is that this region interacts with a repressive transcription factor.

Without definition of the motifs within *NAD-ME* genes specifying expression in the BS, it was not possible to determine whether they control expression of additional genes, or to understand whether the same elements are used in other species. To identify specific nucleotides responsible for BS expression, a deletion series was generated (Fig. 1*A*). Deletion of 24 or 78 nucleotides from the 3′ end did not affect preferential accumulation in BS cells (Fig. 1 *A* and *B*) but removal of 90 nucleotides did (Fig. 1). Similarly, deletion of the first 63 nucleotides from the 5′ end did not abolish preferential accumulation of

Significance

We describe an ancient regulatory code that patterns the gene expression required for the efficient C_4 pathway. This code is based on two regulatory elements located in exonic sequence that act cooperatively to repress transcription in specific cells. As these regulators are located in gene bodies they determine amino acid sequence as well as gene expression and so are known as duons. They are found in multiple genes and are not restricted to C_4 species, but rather found in all land plants and even some algae. The prevalence of these motifs has likely facilitated the repeated evolution of the complex C_4 system, and they also provide a mechanism that could be used to engineer photosynthesis.

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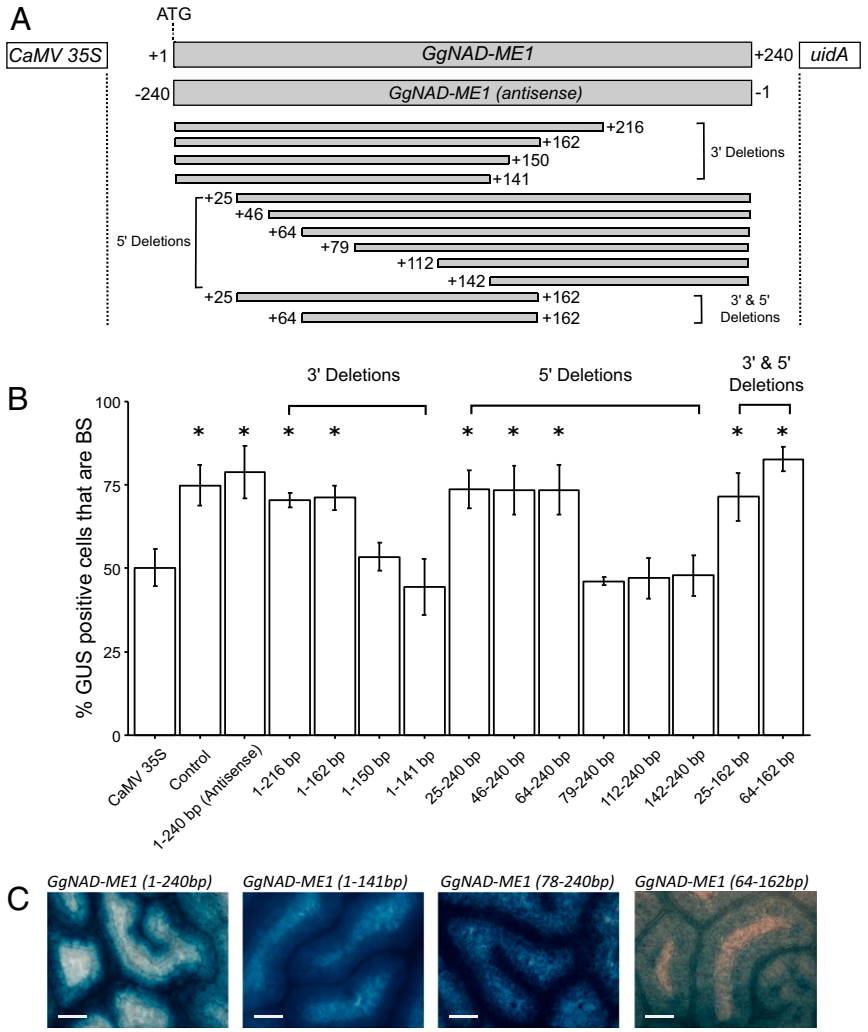

Fig. 1. Two regions within the coding sequence of *GgNAD-ME1* are necessary for preferential gene expression in the bundle sheath (BS). An antisense construct, as well as a deletion series from the 5′ and 3′ ends of *GgNAD-ME1* coding sequence were translationally fused to the *uidA* reporter under the control of the CaMV35S promoter (*A*). Percentage of cells containing GUS in the BS after microprojectile bombardment of *G. gynandra* leaves. Bars represent the percentage of stained cells in BS cells, error bars denote the SE. Statistically significant differences with **P* values <0.05 and CI = 95% determined by a one-tailed *t* test (*B*). GUS in *G. gynandra* transformants containing *uidA* fused to 1–240, 1–141, 79–240, and 64–162 base pairs from the translational start site of *GgNAD-ME1* (*C*). (Scale bars, 100 μm.)

GUS in BS cells, but removing 78 nucleotides did (Fig. 1). A fragment incorporating bases 64–162 was sufficient for preferential accumulation in the BS after microprojectile bombardment (Fig. 1*B*) and stable transformation (Fig. 1*C* and Fig. S2). We conclude that one region composed of nucleotides TTGGGTGAA (64–79 downstream of the translational start codon) and another of GATCCTTG (141–162 nucleotides downstream of the translational start codon) are necessary for preferential accumulation of *GgNAD-ME1* in BS cells of C_4 *G. gynandra*. These two regions are separated by 75 nucleotides and will hereafter be referred to as Bundle Sheath Motif 1a (BSM1a) and Bundle Sheath Motif 1b (BSM1b).

To refine efforts to identify the presence of this *cis*-regulatory logic in other genes, each motif was subjected to site-directed mutagenesis and the spacer separating BSM1a and BSM1b was replaced with exogenous sequence (Fig. S3). This showed that both regions are necessary but that the intervening sequence is not required for preferential accumulation of GUS in BS cells (Fig. S3). The fact that BSM1a and BSM1b alone are sufficient to repress transcription in M cells indicates that they do not function as promoters for long antisense mRNAs. Although the exact sequence separating BSM1a and BSM1b does not impact on their function, the distance separating them does. BSM1a and BSM1b do not generate preferential accumulation in BS cells when fused together directly, or when separated by 999 nucleotides (Fig. S4). However, when the intervening sequence was between 240 and 550 nucleotides, preferential accumulation in BS cells occurred (Fig. S4). We conclude that in the coding region of *NAD-ME1,* two sequences separated by a spacer are necessary and sufficient to generate strong expression in BS cells.

Although thousands of genes are differentially expressed between M and BS cells of C_4 plants (11–14), to our knowledge no DNA motifs that determine the patterning of more than one gene in BS cells have been identified. To test whether BSM1a and BSM1b operate more widely to generate preferential expression in BS cells, coding sequence of other genes relevant to C_4 photosynthesis was scanned. Sequences similar to BSM1a and BSM1b were identified in two such genes encoding mitochondrial MALATE DEHYDROGENASE (mMDH) and GLYCOLATE OXIDASE 1 (GOX1). Fragments from *mMDH* and *GOX1* containing each motif were sufficient to drive BS accumulation of GUS (Fig. 2*A*), and when either was deleted preferential accumulation in BS cells was lost (Fig. 2*A*). The identification of BSM1a and BSM1b in these additional genes allowed consensus sequences to be defined (Fig. 2*B*). These data suggest that multiple gene families involved in C_4 photosynthesis and photorespiration have been recruited into BS expression using a regulatory network based on these two motifs.

Sequences similar to BSM1a and BSM1b were identified near the predicted translational start sites of *GgNAD-ME2*, but also in the orthologs *AtNAD-ME1* and *AtNAD-ME2* from C_3 *Arabidopsis thaliana* (Fig. 3*A*). In these additional genes, BSM1a is located in the mitochondrial transit peptide and its position varies relative to the translational start site. BSM1b is located in the mature processed protein and its position appears invariant (Fig. 3*A*). When either motif was removed preferential accumulation in BS cells

was lost (Fig. 3*B*). Thus, sequences defined by BSM1a and BSM1b from eight genes (Fig. 3*C* and Fig. S6*A*) are necessary and sufficient to generate BS expression in the C_4 leaf. Although synonymous substitutions to the BSM1a and BSM1b sequences from *GgNAD-ME1* failed to abolish preferential expression in BS cells (Fig. S5) amino acid sequence encoded by BSM1a and BSM1b vary considerably for two reasons. First, because BSM1a is found on either DNA strand (Fig. S6). Second, in the eight genes studied, amino acids encoded by each motif differ because codons are not in identical frames (Fig. S6). Combined with the fact that both BSM1a and BSM1b are functional when present in antisense orientation, this variation in amino acid sequence supports the notion that these motifs do not act posttranslationally through amino acid sequence, but rather function transcriptionally via transcription factor binding.

To provide orthogonal evidence that BSM1a and BSM1b are indeed the targets for transcription factors binding in vivo, two additional approaches were pursued. First, the consensus motifs for BSM1a and BSM1b were used to search databases that document transcription factor binding specificities (15–17). Six members of the MYOBLASTOMA (MYB) family have been reported to bind sequences that are similar but not identical to the BSM1a motif ($P < e^{-3}$, Dataset S6) but there were no clear matches for BSM1b. It is therefore possible that a member of the MYB family binds BSM1a, but the cognate factor binding BSM1b remains unclear. Second, DNaseI sequencing of *G. gynandra* was used to define regions of chromatin that are accessible for transcription factor binding. Genome-wide DNaseI sequencing has previously been used to define the landscape of DNaseI hypersensitive sites (DHSs) as well as digital genomic footprints (DGFs) that mark sequence motifs subject to transcription factor binding (9, 16, 18–20). Consistent with the reporter analysis described above, DNaseI analysis showed that BSM1a and BSM1b from *GgNAD-ME1*, *GgNAD-ME2*, *GgmMDH*, and *GgGOX1* were associated with DHSs and so accessible to *trans*-acting factors (Fig. S7). For *GgNAD-ME1*, *GgmMDH*, and *GgGOX1*, these DHSs were present in germinating seedlings grown in the dark, while for *GgNAD-ME2*, the DHS appeared within 4 h of transfer from dark to light. The four DHSs remained in adult leaf tissue (Fig. S7). Moreover, BSM1a and BSM1b either overlapped with or were adjacent to DGFs present in these DHSs (Fig. S7). While DNA sequence bound by a transcription factor can be found in the center of a DGF, variation in how individual transcription factors bind and contort DNA and thus make sequence available for DNaseI digestion result in different cleavage profiles (21–24). The similarity of BSM1a to a MYB binding site, the location of both BSM1a and BSM1b in DNA accessible for transcription factor binding, and the presence of DGFs in close proximity to each sequence, support the contention that these motifs function as duons and recruit transcription factors that lead to preferential expression in the BS of C_4 *G. gynandra*.

In contrast, analysis of publicly available DNaseI data for *Arabidopsis* (9, 21) indicated that for *AtNAD-ME1*, *AtNAD-ME2*, or *AtGOX1*, BSM1a and BSM1b are not located within DHSs (Fig. S8). These data are consistent with a model in which BSM1a and BSM1b are present in the ancestral C_3 state, but their relative inaccessibility inhibits binding by cognate transcription factors, and so cell-specific gene expression is not achieved. In contrast, in the C_4 leaf, BSM1a and BSM1b are accessible to transcription factor binding and this leads to preferential gene expression in BS compared with M cells.

To determine the extent to which BSM1a and BSM1b could control gene expression more widely, their distribution across the genome was quantified. More than 4,000 genes contained both motifs in *G. gynandra*, but fewer than half of these genes were separated by 35–550 nucleotides required to repress expression in M cells (Dataset S5). Compared with randomly generated hits of the same size, both BSM1a and BSM1b were overrepresented in coding sequence DHSs (Fig. S9), supporting the notion that they carry out a specialized role in transcription factor binding within gene bodies. Of the genes containing BSM1a and BSM1b separated by 35–550 nucleotides, 250 are found in genes that are preferentially expressed in BS cells of *G. gynandra*. We therefore estimate that these duons control BS expression of between four and 250 genes in the C_4 leaf. It was noticeable that BSM1a and BSM1b were also widespread in C_3 *A. thaliana* (Dataset S5). The simplest explanation for the presence of BSM1a and BSM1b in genes that are not preferentially expressed in BS cells may be that they contain additional *cis*-elements that override their function. The highly combinatorial nature of transcription factor binding and impact that this has on cell-specific gene expression in the root has previously been documented (25). It is also possible that chromatin environment also influences the function of these motifs and that this can repress their role in restricting expression to BS cells.

We next investigated the extent to which BSM1a and BSM1b are conserved across 1,135 wild inbred *A. thaliana* accessions (26). No single nucleotide polymorphisms (SNPs) were detected within either BSM1a or BSM1b (Fig. 4 *A* and *B*). Despite the lack of chromatin accessibility observed in the orthologs from *A. thaliana* (Fig. S7), the BSM1a and BSM1b motifs and sequence around them are highly conserved, suggesting a role for these duons in C_3 *A. thaliana* that is independent of cell preferential expression in the leaf. To determine whether these motifs are also found more widely in *NAD-ME* genes, homologs were retrieved from all sequenced land plants (Fig. S10). All dicotyledons contained at least one *NAD-ME* gene carrying sequences that define BSM1a and BSM1b (Fig. 4*C*). In monocotyledons, BSM1a was completely conserved in rice, *Brachypodium*, and *Panicum*. Although BSM1b showed one nucleotide substitution in all monocotyledonous genomes available, its conservation in spikemoss and moss argues for its being ancient (Fig. 4*C* and Fig. S10). Both BSM1a and BSM1b are highly conserved in *GOX1* and *MDH* genes of land plants, but BSM1b appears more ancient, as it is found in *GOX1* genes from all land plants and even chlorophyte algae.

In view of the importance of exonic sequences in regulating BS accumulation of *NAD-ME*, *MDH*, and *GOX1*, the wider importance of exonic regulation in controlling C_4 gene expression was investigated. Seven of 12 core C_4 cycle genes contained regulatory elements located in transcribed sequence that were sufficient to generate preferential accumulation in M or BS cells (Fig. 5). Except for *PPCk1*, which encodes the kinase that posttranslationally modifies PEPC in M cells of C_4 plants, coding sequences from orthologs of these C_4 genes in C_3 *A. thaliana* led to preferential expression in either M or BS cells of the C_4 leaf (Fig. 5). Overall, these data indicate that spatial patterning of gene expression in the C_4 leaf is largely derived from *cis*-regulatory elements present in genes found in the ancestral C_3 state.

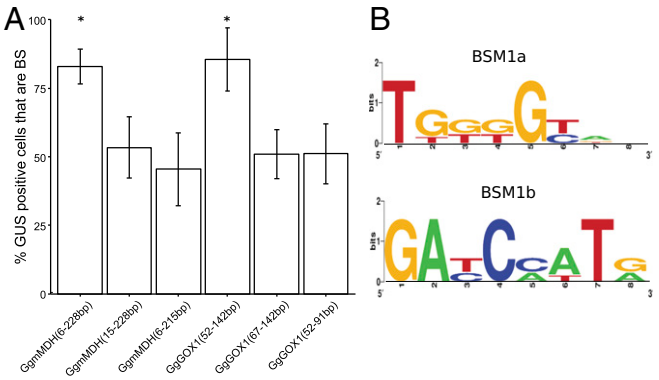

Fig. 2. BSM1a and BSM1b drive the expression of additional genes in C_4 photosynthesis and photorespiration. Sequences similar to BSM1a and BSM1b were identified in coding sequences of *mMDH* and *GOX1* genes of *G. gynandra*. Deleting the motifs resulted in the loss of preferential accumulation of GUS in the bundle sheath (BS) (*A*). Consensus sequences were defined from motifs operational in *NAD-ME1*, *mMDH*, and *GOX1* (*B*). Error bars denote the SE. Statistically significant differences with **P* values <0.05 and CI = 95% determined by a one-tailed *t* test.

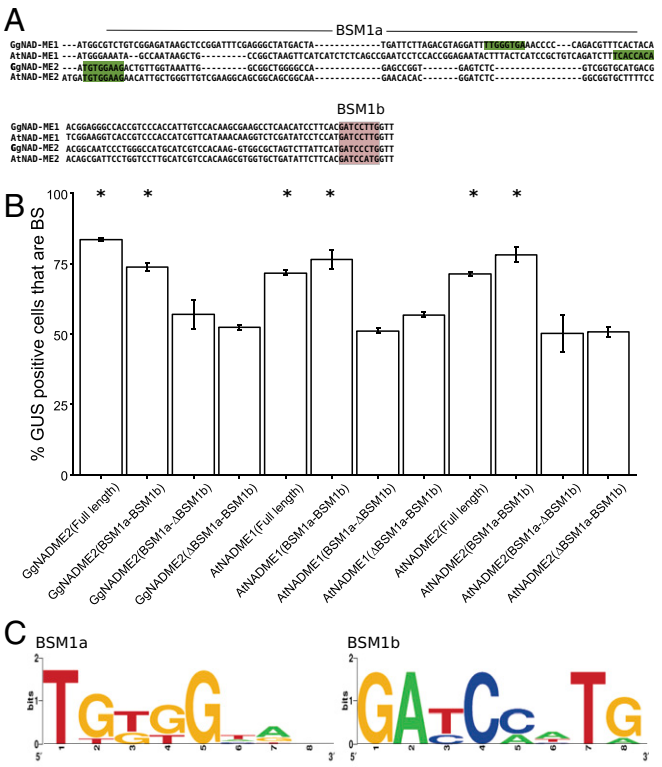

Fig. 3. Functional versions of BSM1a and BSM1b are present in additional *NAD-MEs.* BSM1a and BSM1b are found in *GgNAD-ME2* and in orthologs of *GgNAD-ME1* and *2* from the C_3 species *A. thaliana* (*A*). Translational fusions carrying these fragments confer bundle sheath (BS) preferential expression in *G. gynandra* leaves. When BSM1a or BSM1b were removed this pattern of GUS was lost (*B*). Consensus sequences derived from all versions of BSM1a and BSM1b tested experimentally (*C*). Error bars denote the SE. Statistically significant differences with **P* values <0.05 and CI = 95% determined by a one-tailed *t* test.

Discussion

The data presented here, combined with previous reports (7, 27, 28), portray an overview of the contribution that untranslated regions (UTRs) and coding sequences make to the generation of cell-specific gene expression in leaves of C_4 *G. gynandra*. Seven of the 12 core C_4 cycle genes possess regulatory elements in their transcript sequences that are sufficient for preferential accumulation in either M or BS cells of the C_4 leaf. These data strongly imply that, in addition to promoters being involved in generating cell specificity in C_4 leaves (29, 30), coding sequences and UTRs play a widespread role in the preferential accumulation of C_4 transcripts to either M or BS cells. It remains to be seen whether this high degree of regulation from genic sequence is critical for the spatial control of gene expression in other tissues and other species. However, as genome-wide studies of transcription factor recognition sites in organisms as diverse as *A. thaliana* and human cells (9, 19) have reported that significant binding occurs in genic sequence, we anticipate many more examples of spatial regulation of gene expression being associated with *cis*-elements outside of promoter sequences.

The accumulation of *GgNADME1*, *GgNADME2*, *mMDH*, and *GOX1* transcripts in BS cells is dependent on the cooperative function of two *cis*-elements that are separated by a spacer sequence, all of which are located in the first exon of these genes. There are a number of options relating to how such regulatory sequence found within genes could operate. For example, they could impact on transcription by either interacting with a transcription factor or by acting as promoters to drive expression of an antisense RNA. In addition, they could act posttranscriptionally via the RNA molecule once the gene is transcribed. As the BSM1a and BSM1b motifs without additional sequence are sufficient to restrict gene expression to BS, this excludes them acting as promoters to antisense RNA molecules. Furthermore, two pieces of evidence indicate that they do not function posttranscriptionally via the transcripts generated from the endogenous gene. First, in different genes BSM1a is found on each strand of DNA so that it would not be present in all of the mRNAs that accumulate preferentially in BS cells. Second, an antisense construct inserted as a transgene into *G. gynandra* still generates BS expression again indicating that the transcribed RNA is not involved. The simplest hypothesis is that BSM1a and BSM1b therefore act transcriptionally to suppress activity of the constitutive 35SCaMV promoter in M cells. The proposal that BSM1a and BSM1b act as duons does not exclude additional levels of regulation contributing to the cell-specific accumulation of proteins in the C_4 leaf. Indeed, it is notable that these *cis*-elements alone do not completely restrict accumulation of GUS to BS cells, and so posttranscriptional and/or posttranslational regulation may well act to reinforce their function.

BSM1a and BSM1b are conserved both in their sequences and in the number of nucleotides that separates them. In orthologous *NAD-ME* genes from C_3 *A. thaliana*, which diverged from the Cleomaceae ~38 Mya (31, 32), although these motifs are present, they are not sufficient to generate cell preferential expression in the C_3 leaf (7). This finding indicates that for *NAD-ME* genes to

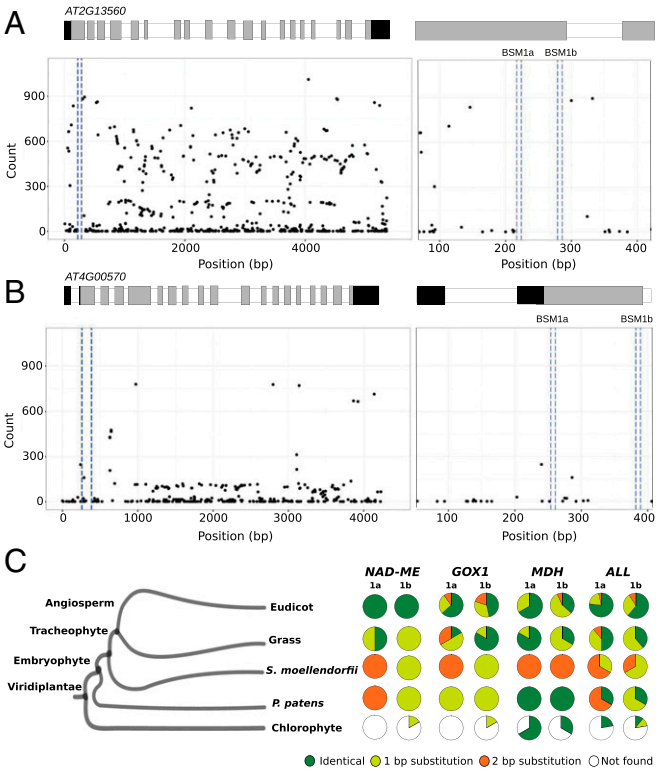

Fig. 4. BSM1a and BSM1b are highly conserved in land plants. Single nucleotide polymorphisms (SNPs) in *AtNAD-ME1* (*A*) and *AtNAD-ME2* (*B*) genes from 1,135 wild inbred *A. thaliana* accessions. (*Left*) Positions of BSM1a and BSM1b are highlighted by dashed blue lines; UTRs, exons, and introns are denoted by black, gray, and white bars, respectively, on the *x* axis. (*Right*) Expanded area representing exon 1, intron 1, and exon 2 is shown, with BSM1a and BSM1b marked within the blue dashed lines. For both genes, no SNPs were detected in either motif. (*C*) The presence of each motif was investigated in gene sequences of *NAD-ME1*, *mMDH*, and *GOX1* retrieved from 44 species in Phytozome (v10.1) (51). Each pie chart shows the percentage of motif instances that were identical (green), or had one base pair (yellow), two base pair (orange) substitutions, or no similarity (white) detected.

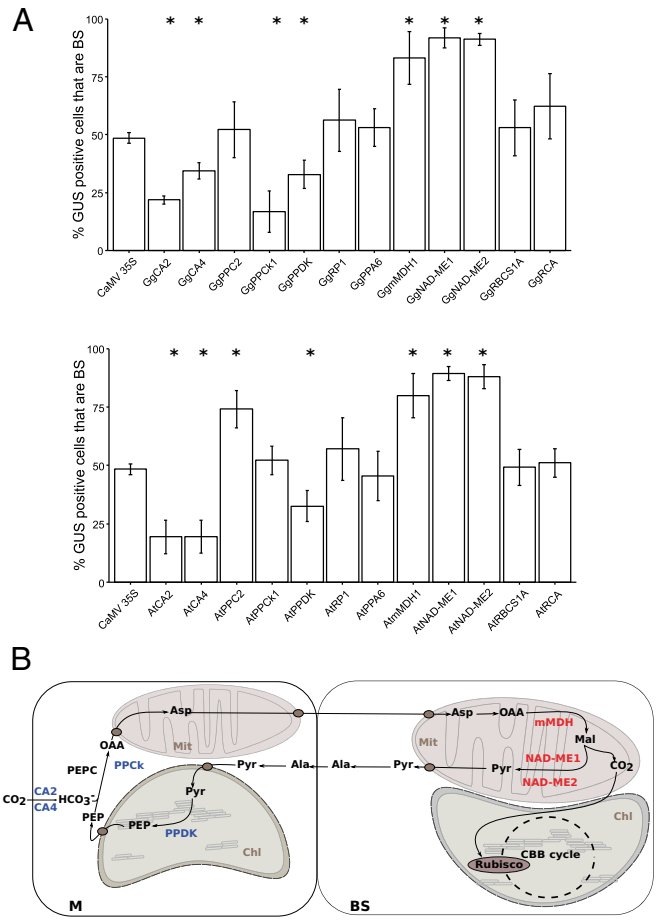

Fig. 5. Intragenic regulatory sequences play a major role controlling C_4 photosynthesis genes. Coding sequences encoding core proteins of the C_4 pathway from *G. gynandra* together with orthologs from *A. thaliana* were translationally fused to *uidA* and placed under control of the CaMV35S promoter. After introduction into *G. gynandra* leaves by microprojectile bombardment, mesophyll preferential expression of *CA2*, *CA4*, *PPDK*, and *PPCk1*, together with bundle sheath (BS) preferential expression of *mMDH*, *NAD-ME1*, and *NAD-ME2* were observed (*A*). With the exception of *PPCk*, these regulatory elements are conserved in orthologues from *A. thaliana* (*B*). The contribution of intragenic sequences controlling gene regulation of the C_4 pathway is summarized in *C*, *CA2*, *CA4*, *PPDK*, and *PPCk1* (blue) and *mMDH*, and *NAD-ME1* and *-2* (red) denote genes where intragenic sequences control cell preferential gene expression. Error bars denote the SE. Statistically significant differences with $^*P$ values <0.05 and CI = 95% determined by a one-tailed *t* test.

be preferentially expressed in BS cells of C_4 plants, a change in the behavior of one or more *trans*-factors was a fundamental event. At least in *G. gynandra*, evolution appears to have repeatedly made use of *cis*-elements that exist in genes of C_3 species that are orthologous to those recruited into C_4 photosynthesis (7, 27, 28, 33). The alteration in *trans*-factors such that they recognize ancestral elements in *cis* in the M or BS therefore appears to be an important and common mechanism associated with evolution of the highly complex C_4 system.

The dual role of exons in protein coding as well as the regulation of gene expression has received significant attention in vertebrates (19, 34–37). Although 11% of transcription factor binding sites are located in exonic sequence in *A. thaliana* (9), to our knowledge, the identification of BSM1a and BSM1b represents the first functional evidence for *cis*-elements in plant exons. The fact that these motifs are present in C_3 *A. thaliana*, and, in fact, also found in the genomes of many land plants and some chlorophyte algae, indicates that these duons play ancient and conserved roles in photosynthetic organisms. The role of such regulatory elements within coding sequences has previously been proposed to be associated with constraints on both protein coding function and codon bias. For example, mutation to these *cis*-elements could be deleterious to both the correct function of the protein, but also to codon usage and so translational efficiency (38–40). If this is the case, BSM1a and BSM1b could be highly conserved across deep phylogeny because of strong selection pressure on these elements that impact on translation, and this conservation is then coopted to also regulate transcription during the evolution of C_4 photosynthesis to generate cell-specific gene expression. Establishing the role of BSM1a and BSM1b in C_3 plants would provide insight into the extent to which their role has altered during the transition from C_3 to C_4 photosynthesis.

Duons under strong selection pressure may represent a rich resource of *cis*-elements upon which the C_4 pathway has evolved. Although C_4 photosynthesis is a complex trait that requires multiple changes to gene expression, the repeated evolution of C_4 species across multiple plant lineages suggests that a relatively low number of changes may be required to acquire the C_4 syndrome (41–43). A single C_4 master switch has been proposed (43) but despite multiple comparative transcriptomic studies (13, 44–46), there is as yet no evidence for it. The only transcription factor associated with photosynthesis in C_4 species is Golden-like1 (47), which controls expression of genes associated with chlorophyll biosynthesis and the light harvesting complexes in both C_3 and C_4 species (48). Given the repeated and highly convergent evolution of the C_4 pathway, as well as evidence that separate lineages can arrive at the C_4 state via different routes (49), it appears more plausible that C_4 photosynthesis made use of a number of gene subnetworks. This is now supported by a number of findings. First, just as core photosynthesis genes encoding the light harvesting complexes and the Calvin–Benson–Bassham cycle are regulated by light, the vast majority of genes that encode proteins of the C_4 cycle in C_3 *A. thaliana* are also regulated by light signaling; yet, during the evolution of C_4 photosynthesis, there was a significant gain of responsiveness to chloroplast signaling (50). Second, it has been suggested that evolution of the C_4 pathway is associated with the recruitment of developmental motifs into leaves that in C_3 species operate in roots (46). Lastly, the identification of the *cis*-element MEM2 (28), which controls preferential expression of multiple genes in C_4 M cells, and now BSM1a and BSM1b in four different genes that are strongly expressed in BS cells, indicates that C_4 evolution has made use of small-scale recruitment of gene subnetworks in both cell types.

In summary, the data indicate regulatory elements located in transcript sequences are of central importance in patterning gene expression in the C_4 leaf. Expression of multiple genes in BS cells is regulated by highly conserved duons that appear to play ancient roles in photosynthetic organisms. Our data also indicate that evolution of the highly complex C_4 trait is built upon ancient *cis*-regulatory architecture that is common to all land plants and some green algae.

Materials and Methods

G. gynandra seeds were germinated in the dark at 30 °C for 24 h. For microprojectile bombardment seedlings were then transferred to Murashige and Skoog (MS) medium with 1% (wt/vol) sucrose and 0.8% (wt/vol) agar (pH 5.8) and grown for a further 13 d in a growth room at 22 °C and 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ photon flux density (PFD) with a photoperiod of 16 h light. For DNaseI-seq, germinating seeds were placed in the dark to promote hypocotyl extension for 3 d or transferred to a growth cabinet maintained at 25 °C ± 0.5 °C, 60% relative humidity, ambient CO_2, and 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ PFD with a photoperiod of 16 h light. For DNaseI analysis, tissue was flash frozen in liquid nitrogen and stored at −80 °C before processing. After bombardment or stable transformation, plant tissue was GUS stained and then chlorophyll was removed in 70% (vol/vol) ethanol.

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