Analysis of the mutational effects of the COP/DET/FUS loci on genome expression profiles reveals their overlapping yet not identical roles in regulating Arabidopsis seedling development

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INTRODUCTION

Arabidopsis seedlings follow two distinct development pathways: skotomorphogenesis in the dark and photomorphogenesis in the light. Dark-grown seedlings develop with long hypocotyls, an apical hook, closed cotyledons and undeveloped chloroplast precursors called etioplasts; whereas light-grown seedlings have short hypocotyls, opened cotyledons and developed chloroplasts (Kendrick and Kronenberg, 1994; Deng and Quail, 1999; Neff et al., 2000). Genetic screens for Arabidopsis mutant seedlings exhibiting a light-grown phenotype when grown in darkness have resulted in the identification of both pleiotropic and partially photomorphogenic mutations (Chory et al., 1989; Deng et al., 1991; Hou et al., 1993; von Arnim and Deng, 1996). The pleiotropic constitutive photomorphogenic (COP) or de-etiolated (DET) mutants were also defined in a FUSCA (FUS) mutant screen (Misera et al., 1994; Wei and Deng, 1999). Together ten pleiotropic COP/DET/FUS mutant loci have been defined, including cop1, det1, cop8, cop9, cop10, fus5, fus6/cop11, fus11, fus12 and cop16 (Schwechheimer and Deng, 2000). Recent biochemical characterizations of these 10 loci define four biochemical entities: seven of the loci are required for the COP9 signalosome (CSN) biogenesis and three others, COP1, DET1 and COP10 are not (Wei and Deng, 1999; Serino et al., 1999; Deng et al., 2000). Mutations in these 10 loci result in almost complete photomorphogenic development in darkness, suggesting that their gene products act as light-inactivatable repressors of photomorphogenesis (Wei and Deng, 1999; Osterlund et al., 1999). Recently, it was hypothesized that in darkness all of these four defined functional entities are involved in promoting ubiquitination and proteasome-mediated degradation of photomorphogenesis-promoting transcription factors (Osterlund et al., 2000; Holm et al., 2002). Among them, COP1 and COP10 may constitute E3 and E2 activities and act together with the COP9 signalosome in targeting transcription factors for...
ubiquitination and subsequent degradation (Suzuki et al., 2002). Intriguingly, defects in a peroxisome protein were recently reported to suppress weak mutations of both COP1 and DET1 (Hu et al., 2002).

It has been generally assumed that the photoreceptors perceive and interpret incident light and transduce the signals to modulate light-responsive nuclear genes, which, in turn, direct appropriate developmental responses during photomorphogenesis (Terzaghi and Cashmore, 1995; Puente et al., 1996; Ma et al., 2001; Tepperman et al., 2001). In our previous reports, we verified that the contrasting developmental patterns are mediated primarily by coordinated changes in genome expression (Ma et al., 2001) and that a large proportion of light-controlled genome expression can be achieved by regulating nuclear COP1 activity (Ma et al., 2002). Thus logical questions to ask are whether all these pleiotropic COP/DET/FUS loci are acting together to mediate the light control of genome expression and whether they also have additional and/or distinct roles in regulating plant development and genome expression.

The less pleiotropic or partially photomorphogenic mutants included those with short hypocotyls and/or partially open and developed cotyledons. They included mutations in COP2, COP3 and COP4 that result in partial photomorphogenic cotyledon development (Hou et al., 1993) and mutations in DET2 and DET3 that result in partial photomorphogenic hypocotyls as well as cotyledon development in darkness (Chory et al., 1991; Cabrera y Poch et al., 1993). DET2 has been shown to encode an enzyme in the biosynthetic pathway of the plant hormone brassinosteroid (Li and Chory, 1996). Interestingly, mutants defective in response to the plant hormone auxin have also been reported to have a partial photomorphogenic phenotype (Dharmasiri and Estelle, 2002). It is not clear exactly how these genes contribute to the light regulation of seedling development and whether they can be considered part of the light signaling pathway. It seems feasible that an analysis of their effect on genome expression may provide some insight into their contribution to photomorphogenesis.

However, we also found that the COP9 signalosome was involved in multifaceted developmental processes besides photomorphogenesis (Peng et al., 2001a; Peng et al., 2001b; Schwechheimer et al., 2001; Schwechheimer et al., 2002). The COP9 signalosome directly interacts with SCF type E3 ubiquitin ligases and regulates their activity in tagging substrates for proteasome-mediated degradation (Schwechheimer et al., 2001; Schwechheimer et al., 2002). Clearly, the COP9 signalosome has a role beyond modulating the hypothesized COP1 (E3) and COP10 (E2) pair in controlling photomorphogenesis, but also in regulating other E3 and E2 pairs and, thus, many additional cellular and developmental processes. An E2 also probably associates with more than one E3 (Hellmann and Estelle, 2002), thus COP10 and COP1 may not necessarily work together exclusively in controlling photomorphogenesis. Therefore a systematic comparison of the genome expression profiles controlled by each of these pleiotropic COP/DET/FUS activities may reveal the extent of overlapping, as well as unique roles, in light regulated and other developmental processes.

In a systematic effort to examine the overlapping and distinct roles of these pleiotropic and partially photomorphogenic genes, we utilized a previously described Arabidopsis cDNA microarray with 6126 unique genes (Ma et al., 2001; Ma et al., 2002). A comparison of their genome expression profiles to that of light-regulated genome expression revealed the overlapping as well as distinct roles of the pleiotropic COP/DET/FUS proteins. Furthermore, new insights into the contribution of the partially pleiotropic photomorphogenic loci in overall photomorphogenesis, as well as their specific function, can be derived from this genomic analysis.

MATERIALS AND METHODS

Experimental materials

Unless otherwise indicated, the wild-type Arabidopsis thaliana used in this study was in the Arabidopsis thaliana Columbia and Wassileskija ecotypes. The cop1-1, cop1-6, det1-1, cop4 and tir1-1 mutants used in this study were in the Columbia ecotype (Deng et al., 1991; Deng et al., 1992; Deng and Quail, 1992; McNellis et al., 1994; Chory et al., 1989; Hou et al., 1993; Ruegger et al., 1998). cop1-5, det1-6, fus6-1, cop9-1, cop10-1 and det2 mutants and the CRY1 overexpression line were in the Wassileskija ecotype (Wei and Deng, 1992; Wei et al., 1994; McNellis et al., 1994; Chory et al., 1991; Pepper et al., 1994; Lin et al., 1996). cop1-8 was in the Landsberg erecta ecotype (McNellis et al., 1994). Surface sterilization and cold treatment of the seeds have been described previously (Ang and Deng, 1994). The N282 overexpression line was in No-0 ecotype (McNellis et al., 1996), and the wild-type No-0 was used for its control. Arabidopsis seedlings were grown on plates of growth medium agar containing 1% sucrose. The seedlings were grown in continuous white light or darkness for 6 days. The white-light intensity used was 150 µmol/m²/second unless otherwise indicated. The wild-type Arabidopsis used in the different light intensity experiments was Columbia ecotype. Low light intensity was obtained by putting various layers of kimwipe tissue papers on top of the plate. High-intensity light was obtained by putting the plate under high-intensity fluorescent light in the greenhouse, with the heat filtered out by a 2 cm deep layer of water between the light and the seedlings. The colored-light growth chamber (Percival Scientific E-30LED2/3) had intensities of 16.2 µmol/m²/second for blue light (470 nm).

The microarray slide used in this study was described previously (Ma et al., 2001; Ma et al., 2002). Each array contains 9,216 EST clones that represented about 6,126 unique genes. For more information, please see our web sites (http://plantgenomics.biology.yale.edu or http://info.med.yale.edu/wmkeck/dna_arrays.htm).

RNA preparation, fluorescent labeling of probe, slide hybridization, washing and scanning

Total RNA was extracted from the whole seedlings using the Qiagen RNeasy Plant Mini Prep kit. For each treatment, at least two independent biological samples were used for RNA preparations and probe synthesis. 50 µg total RNA was first labeled with aminoallyl-dUTP (aa-dUTP; Sigma, St. Louis, Missouri) by direct incorporation of aa-dUTP during reverse transcription as described previously (Ma et al., 2002). After 3-4 hours of incubation at 42°C, the reaction was stopped by adding 5 µl of 0.5 M EDTA and incubating at 94°C for 3 minutes. The RNA in the mix was hydrolyzed by adding 10 µl of 1 M NaOH and incubating at 65°C for 20 minutes. The reaction was neutralized by adding 6 µl of 1 M HCl and 2 µl of 1 M HCl-Tris (pH 7.5). The aa-dUTP-labeled cDNA was purified from the unincorporated aa-dUTP molecules by adding 450 µl of water and spinning through a Microcon YM-30 filter (Millipore, Bedford, MA) for 9 minutes at 11000 g. The flow-through cDNA solution was spun through the same Microcon filter once more. The purified, labeled
probe was concentrated to a final volume of 5-7 μl. Then, the cDNA probe was further labeled with fluorescent dye by conjugating aa-dUTP and monofunctional Cy-3 or Cy-5 dye (Amersham Pharmacia Biotech, Piscataway, NJ) as follows: 1 μl cDNA solution added to 0.1 volume 1 M sodium bicarbonate (Sigma, St. Louis, Missouri) and 1 μl Cy3 or Cy-5 dye (solved in DMSO). The mixture was incubated at room temperature in the dark for 60 minutes. After incubation, the labeling reaction was stopped by adding 1 μl 2 M ethanolamine (Sigma, St. Louis, Missouri) and further incubated at room temperature for 5 minutes. The dye-labeled probe was purified from the unicorporated dye molecules by washing through a Microcon YM-30 filter (Millipore, Bedford, MA) three times, as mentioned above. The probes from the designated sample pairs were combined at the last washing. The purified, labeled probe was concentrated to a final volume of 7 μl.

The protocols for hybridization to the Arabidopsis microarray, microarray slide washing and scanning were as described previously (Ma et al., 2001; Ma et al., 2002).

Data analysis

The general approaches were as described in our previous work (Ma et al., 2001; Ma et al., 2002) with minor modifications. Briefly, spot intensities were quantified using Axon GenePix image analysis software (GenePix Pro 3.0). The channel ratio was measured with the GenePix median of ratios method and was then normalized using the GenePix default normalization factor. In order to merge the replicated GenePix output data files in a reasonable way, we developed a computer program called GPMERGE (http://bioinformatics.med.yale.edu/software.html). With this program we pooled the four or more replicated data sets of each experiment. Different quality control procedures were also conducted before data points were averaged from the replicates. First, all spots that were flagged Bad or Not Found by GenePix software, were not included in the final data analysis. Second, a very simple outlier searching algorithm was incorporated in GPMERGE; those spots that led to a large difference between the ratio mean and the ratio median were defined as outliers and eliminated from the analysis. Third, only those spots that met both of the following two conditions were considered in further data analysis: (1) signals were higher than the backgrounds for both channels; (2) the signal was twofold higher than the background at least for one channel. For those unique genes that have more than one EST clone, we developed a custom computer program to extract a ratio for the gene as described previously (Ma et al., 2002).

Different kinds of expression pattern identification and pattern matching were conducted within or across these experiment groups. Within each group a hierarchical clustering analysis was performed as described by Eisen et al. (Eisen et al., 1998). Only those genes that had more than twofold changes in expression in at least one of the experimental sets were used in the cluster analysis shown in the figures.

RESULTS

Experimental strategy

To reveal the functional relationship among the selected group of genes, we took advantage of an available EST-based microarray (Ma et al., 2001; Ma et al., 2002) and used the expression profiles of the 6126 unique genes in the microarray as molecular markers to examine the effect of their loss-of-function mutations on genome expression during Arabidopsis seedling development. The pleiotropic COP/DET/FUS loci belong to four biochemical entities: COP1, DET1, COP10 or the COP9 signalosome (Wei and Deng, 1999; Suzuki et al., 2002). We selected fus6-1 (for CSN1) and cop9-1 (for CSN8) mutants to represent the COP9 signalosome defect, and the cop10-1 mutant to represent COP10. For COP1 and DET1, we selected both viable (cop1-1, cop1-6 and det1-1) and lethal (cop1-5, cop1-8 and det1-6) mutants, respectively. To provide insights into the role of the mutants that display partial photomorphogenesis in darkness, we selected cop4-1 (Hou et al., 1993), det2-1 (Chory et al., 1991) and tir1-1 (Ruegger et al., 1998) mutants for a comparative analysis. Appropriate ecotypes of wild type (Col-O, WS and Ler) were used as controls.

As in our previous studies (Ma et al., 2001; Ma et al., 2002), at least two independent biological samples for each treatment (6-day old dark or light-grown seedlings, Fig. 1A and 1B) were used for RNA preparations. Each RNA preparation was used to generate probes for hybridization to at least two arrays. In this way we ensured that there were at least four quality data sets for each experimental test. The average of the mean value for each gene expression ratio was used for further analysis and comparison. A commonly used clustering analysis (Eisen et al., 1998) was employed to reveal the relatedness of distinct mutant genome expression, and, thus, to extrapolate the functional relationship of the loci defined by the mutations.

The mutations in pleiotropic COP/DET/FUS genes have a similar influence over genome expression as light, but with clear distinctions

We first analyzed the genome expression profile changes caused by the selected mutations in darkness (Fig. 1A) and compared those to the light effect on genome expression in wild-type seedling. All the genes that displayed a differential expression of twofold or more in at least one experimental test were selected to undergo clustering and relatedness analysis. Fig. 1C shows the relatedness of the genome expression changes across these selected mutants and wild types for each experimental test based on the calculation of distance matrices. The light-induced genome expression profiles of the two most frequently used wild-type ecotypes (Col-O and WS) were quite similar to each other (Fig. 1C). The genome expression patterns induced by the pleiotropic cop/det/fus mutations were also similar. However, there were clear differences conferred by the distinct pleiotropic loci and even the nature of the mutations (viable versus lethal) from the same locus. Among the representative pleiotropic cop/det/fus mutants, genome expression profiles in darkness were most similar between those affected by the cop1 and det1 mutations (Fig. 1C). Both the viable (weaker) mutants (cop1-1 and det1-1) and lethal mutants (cop1-5, cop1-8 and det1-6) of COP1 and DET1 showed very similar genome expression patterns. However, the viable cop1 and det1 mutant patterns clustered much closer to each other and exhibited significant differences from their respective lethal mutant cluster. Consistent with our previous studies (Ma et al., 2002), the viable cop1 and det1 alleles triggered genome expression profiles most closely resembling those of the white light-grown wild-type seedlings. In contrast, the genome expression profiles caused by the three representative lethal mutations in COP1 and DET1 in darkness were more diverged from those of the wild type in white light.

The genome expression profiles of the csn mutants (fus6-1 or cop9-1) and cop10-1, each representing one of the other two functional units, exhibited distinct expression patterns from
either the viable or lethal alleles of the COP1 and DET1 clusters. Both cop9-1 and fus6-1, which are lethal mutants in subunits 8 and 1 of the COP9 signalosome, induced similar genome expression patterns in darkness and light (data not shown). Thus, only one of them was used to represent lethal csn mutants in most of the data analysis. Among the representative lethal cop/det/fus mutants for the four functional units, the lethal csn mutant genome expression in darkness was most similar to that of white-light induction in wild-type seedlings (Fig. 1C). However, the csn1/fus6-1 genome expression profile in darkness is slightly more diverged from the white-light control of genome expression than the clade for the viable cop1 and det1 mutations. The genome expression profile of the lethal mutation in COP10 (cop10-1) in darkness was the most diverged from that of the white light control (Fig. 1C).

As anticipated, the less pleiotropic constitutive photomorphogenic loci, such as cop4 and det2 in darkness, triggered more diverged genome expression profiles than any of the pleiotropic cop/det/fus mutations when compared to the expression profile in white light [WT/WL vs. WT/D (WT, wild type; WL, white light; D, dark grown)]. Among the three examined, the mutation in COP4 resulted in an expression profile that was most similar, followed by det2, and tir1-1 produced the most divergent profile (Fig. 1C).

Functional relationship among pleiotropic COP/DET/FUS in light-grown seedlings

We also carried out a similar genome expression relatedness analysis for the pleiotropic cop/det/fus mutants in light and compared them with the light control of genome expression (WT/WL vs. WT/D). As shown in Fig. 1D, it was apparent that both the representative lethal pleiotropic cop/det/fus mutations have similar genome expression profiles and fall into one general clade. Within this clade, the specific relationship of the genes representing the four biochemical entities (Fig. 1D) is similar to that revealed by their dark genome expression profiles (Fig. 1C), e.g., det1-6 and cop1-8 were the most similar to each other, then the COP9 signalosome representative cop9-1, and lastly the cop10-1 mutant. However, the viable mutants of cop1 and det1 showed similar genome expression profiles and were significantly diverged from those of the lethal cop/det/fus mutants. In fact, the genome expression profiles triggered by viable cop1 and det1 mutations in the light (mutant/WL vs. WT/WL) are closely related to those of white-light regulation (WT/WL vs. WT/D). This implies that in light-grown plants, the viable cop1 and det1 mutants may simply enhance the control of genome expression by light.

Fig. 1. A summary of the seedling phenotypes of the photomorphogenic mutants and their genome expression profile relatedness. (A) Morphological comparison of dark-grown Arabidopsis wild-type (WT), pleiotropic cop/det/fus and partial photomorphogenic mutant seedlings. All seedlings were 6-day-old. Scale bars: (in cop1-1 panel for top row) 1 mm. (B) Morphological comparison of continuous white light-grown wild-type (WT) and pleiotropic cop/det/fus mutant seedlings. All seedlings were 6-day-old and photographed at the same magnification. Some of the mutants shown in A and B were used in studies reported in subsequent Figures. (C) Hierarchical clustering analysis of overall relatedness for expression ratios from wild-type seedlings grown under normal white light (WL) versus dark-grown (D) siblings, and dark-grown pleiotropic cop/det/fus and partial photomorphogenic mutants versus dark-grown wild-type seedlings of the same ecotype. An expression profile from dark-grown tir1-1 versus dark-grown wild-type seedlings is also included for comparison. Only those genes that exhibited twofold or more differential expression in at least one sample pair of the 13 tested were included. There are 3057 genes included in the cluster analysis (see supplementary data at http://dev.biologists.org/supplemental/ or http://plantgenomics.biology.yale.edu/ for more information). Asterisks denote the ecotype of wild-type Arabidopsis: * for Col-0 and ** for WS. (D), Hierarchical clustering analysis of overall relatedness for expression ratios from wild-type seedlings grown under normal white light (WL) versus dark-grown (D) siblings, and high intensity light-grown (H WL) pleiotropic cop/det/fus mutants versus normal white light-grown wild-type seedlings of the same ecotype. Only those genes that exhibited twofold or more differential expression at least in one sample pair of the nine tested were included for comparison. There are 2608 genes included in the cluster (see supplementary data at http://dev.biologists.org/supplemental/ or http://plantgenomics.biology.yale.edu/ for more information). Asterisks denote the ecotype of wild-type Arabidopsis as in A.
The lethal mutations of pleiotropic COP/DET/FUS genes confer distinct effects on different subgroups of light-regulated genes

To reveal what changes in genome expression are responsible for the divergence between the lethal cop/det/fus mutations in darkness and white-light control of genome expression (Fig. 1C) and viable cop1 mutations (Ma et al., 2002), we examined genes belonging to 24 previously defined metabolic pathways that are coordinately up- or down-regulated by light (Ma et al., 2001). As summarized in Table 1, there are clear differential effects of the lethal cop/det/fus mutations on the expression of the genes in these pathways. For all pathways directly linked to photosynthesis, including dark and light reactions, starch and sucrose biosynthesis pathways, photosynthesis and chlorophyll synthesis, their gene expression in dark-grown lethal cop/det/fus mutants are much less activated or even down-regulated, as compared to light activation in wild-type seedlings. However, some pathways, such as phenylpropanoid biosynthesis, cytoplasmic protein synthesis, and water transport across tonoplast and plasma membranes, were more strongly regulated by the lethal cop/det/fus mutations in darkness than by white light in wild-type seedlings. For the remaining half of the pathways that are regulated by light, their associated genes seem to be similarly regulated by the lethal cop/det/fus mutations in darkness and by light.

The lethal mutations of pleiotropic COP/DET/FUS genes mimic a high-intensity light stress effect on light regulated genes

To further examine the effect of the pleiotropic COP/DET/FUS group of genes on light regulation of gene expression, we selected 15 genes involved in photosynthetic light reactions and examined their expression levels in various cop1 or det1 mutants. Fig. 2A illustrates the expression of 15 genes in the dark-grown viable (weak) mutants of COP1 (cop1-6), DET1 (det1-1), a strong cop1 mutant (cop1-8), lethal mutants of COP1 (cop1-8) and DET1 (det1-6). All these 15 genes were induced to a certain extent in the dark-grown weak and strong mutants of COP1 or DET1 when compared to the dark-grown wild-type seedlings (lanes 2, 3 and 5), but were repressed in both cop1 and det1 lethal mutants (lanes 4 and 6).

It has been shown previously that light can exert a quantitative control on photomorphogenesis by proportionally inhibiting nuclear COP1 activity (Osterlund et al., 2000). As the lethal mutant seedlings accumulated high levels of pigments and resembled Arabidopsis subjected to high light intensity stress, it is reasonable to hypothesize that the null mutations of COP1 may mimic the effect of an excess high intensity light environment even when mutants are grown in darkness. To test this hypothesis, we examined whether extremely high light intensity or excess light signaling can cause genome expression profiles in wild-type similar to those of the lethal mutants.

To this end, we employed two experimental approaches. First, we grew wild-type seedlings under normal intensity of white light for 5.5 days, then transferred them to high-intensity white light (H WL: 2500 μmol/m²/second) for another 12 hours; the resulting genome expression pattern was analyzed. Indeed, the genome expression profile triggered by the high light intensity (WT/HWL vs. WT/D) is closely related to those of the dark-grown lethal mutants, falling between that of the fus6-1 mutant and those of the lethal mutants in COP1 or DET1 (data not shown). The genome expression profile triggered by high intensity white light (2500 μmol/m²/second) in wild type (WT/HWL vs. WT/WL) is also similar to those caused by the lethal cop/det/fus mutations in the light (Fig. 1D). This can be best illustrated by the expression profiles of the 15 selected photosynthetic genes, as their expression levels are all down-regulated by the high-intensity light compared to that of normal light-grown siblings (Fig. 2A, lane 8).

Second, we compared the effect of CRY1 over-expression (CRY1 OE) to that of the lethal cop/det/fus mutations on blue-light regulation of genome expression (Ma et al., 2001). In general, the genome expression profile triggered by CRY1 over-expression is somewhat similar to that of the lethal cop/det/fus mutations in darkness. In fact, all of the 15 selected photosynthetic genes also exhibited a down-regulation as a result of CRY1 over-expression when compared to wild-type siblings grown under the same blue-light condition (Fig. 2A, lane 7).

We also analyzed the expression profiles of the 15 selected photosynthetic genes in cop1 or det1 mutants grown in normal white light. As shown in Fig. 2B, the light-grown cop1-6 mutants (the weakest allele) exhibited a slight enhancement of the light activation of all these genes. In the light-grown cop1-1 and det1-1 mutants (two other viable mutations), the expression for some genes was slightly enhanced, but most exhibited a slight decrease in light activation. In the lethal

Table 1. Comparison of metabolic pathways regulated by light or the lethal cop/det/fus mutations in dark

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<tr>
<th>Strongly activated by light</th>
<th>No obvious difference between light and COP/DET/FUS regulation</th>
<th>Stronger regulation by COP/DET/FUS</th>
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<tr>
<td>Photosynthetic light reactions</td>
<td>Fatty acid biosynthesis</td>
<td>Phenylpropanoid biosynthesis</td>
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<tr>
<td>Photosynthetic carbon assimilation</td>
<td>Fatty acid β oxidation</td>
<td>Protein synthesis in cytoplasm</td>
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<tr>
<td>Starch biosynthesis</td>
<td>Glyoxylate cycle</td>
<td>Water transport across tonoplast</td>
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<td>Sucrose biosynthesis</td>
<td>Sulfate assimilation</td>
<td>Water transport across plasma membrane</td>
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<td>Photospiration</td>
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<td>Chlorophyll synthesis</td>
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<td>Starch degradation</td>
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**cop1-8 and det1-6 mutants, the light activation of all 15 genes was completely reversed in these mutants (Fig. 2B, lanes 4 and 6), an effect also caused by the high-intensity light treatment of the normal light-grown wild-type seedlings (Fig. 2B, lane 7).**

**Lethal cop1 or det1 mutations induce a new set of genes in both darkness and light**

Analysis of the genome expression profiles of light-grown...
lethal cop/det mutants revealed a significant fraction of genes whose expressions were oppositely regulated in comparison to that by light. For example, the regulation of more than 250 genes in light-grown lethal cop1 or det1 mutants (mutant/WL vs. WT/WL) was found to be opposite that of the same genes from light grown wild-type plants (Fig. 3). Again, the similarity among the pleiotropic COP/DET/FUS mutations reflected their relatedness as defined by their genome expression profiles (Fig. 1). The genes that are oppositely regulated in light-grown lethal cop1 and det1 mutants are essentially identical. Only a small fraction of genes exhibited opposite regulation by either viable det1 or cop1 mutations in light.

In addition to the oppositely regulated genes, there were also genes that were not regulated by light but exhibited significant variation in expression in the lethal cop/det/fus mutations. For example, about 200 genes that were not regulated by normal intensity white light in wild type, showed a twofold differential expression in light-grown lethal cop1 or det1 mutants (Fig. 3C). Interestingly, about 70% of those genes specifically affected by lethal cop/det/fus mutations in normal light are also up- or down-regulated in high-intensity white light in the wild type. This group of genes includes DREB2A (At5g05410), ADP-ribosylation factor (At5g17060) and phospholipase C (At4g38690).

Different light-regulated genes exhibit distinct light intensity dependence in their regulated expression

The clear, distinct effects of the two light intensities on the genome expression profiles described above prompted us to further examine the effects of a large range of light intensities on the genome expression profiles. For this purpose, the wild-type seedlings were grown under 1% (1.5 μmol/m²/second), 10% (15 μmol/m²/second) and normal intensity (150 μmol/m²/second) white light for 6 days. Furthermore, seedlings exposed to high-intensity white light (2500 μmol/m²/second) for 12 hours after growth in normal intensity white light for 5.5 days were also included in this analysis. The morphology of seedlings is shown in Fig. 4A, and a cluster analysis of their genome expression profiles is shown in Fig. 4B. Among the four increasing light intensities, about 7.7% (471), 15.3% (936), 30.0% (1838) and 31.4% (1922) of genes showed differential expression (≥2-fold) when compared to dark-grown siblings (Fig. 4C). Most of these genes showed the highest variation under normal intensity white light. However, many distinct patterns of light intensity dependence are evident. Twelve representative patterns, with the number of genes following each pattern, are shown in Fig. 5.

Genes involved in photosynthetic light and dark reactions, starch and sucrose synthesis, photoreirpiration and chlorophyll synthesis pathways were induced even at a very low intensity.
were affected at intermediate light intensities, and reached maximal expression under high light intensity (2500 μmol/m²/second).

Comparison of the genome expression profiles regulated by different light intensities, together with the expression profiles of two lethal cop1-8 and det1-6 mutants (Fig. 4B) revealed different subclusters or expression patterns among different light conditions and mutants. Some of the genes showed similar expression patterns in all 6 tests, such as subclusters c and j. Other genes exhibited different expression patterns between light and the lethal mutations, such as b and h.

A fraction of transcription factor genes are regulated in light intensity-dependent manners

Among the 333 putative transcription factors included in our array, 53 showed differential expression (±2-fold) in at least one light intensity treatment. As shown in Fig. 6A, the expression of the majority of these transcription factors was light intensity dependent. For example, PAP3 was induced under two low light intensities but was not affected by two higher light intensities. While the expression of two WRKY protein genes was not affected under very low light intensity, they were induced or repressed under higher light intensities. Some transcription factor genes, such as Pcmyb1, were similarly regulated by different light intensities, while other transcription factor genes (such as the zinc finger protein At5g58620) were regulated differently in different light intensities.

Interestingly, all these transcription factors also showed differential expression (±2-fold) in dark-grown cop1-6 mutant and wild-type seedlings (Ma et al., 2002). The expression pattern triggered by the cop1-6 mutation in darkness is very similar to that of normal intensity light-grown seedlings, with only two exceptions (At3g59060 and At2g01530, both of which were induced in the dark-grown cop1-6 mutant but not in normal light). We further checked the expression profiles of these transcription factor genes in different cop1 mutant alleles (N282, cop1-6, cop1-1 and cop1-5) to represent very weak, weak, strong and lethal mutations of COP1, respectively. As shown by the five representative genes in Fig. 6B, the expression patterns of most of the transcription factor genes behaved in a COP1 activity-dependent manner, and, in general, are consistent with their response to increasing light intensities in wild type. This further substantiates a previous conclusion that increasing the light intensity quantitatively inactivates more COP1 activity, thus promotes stronger photomorphogenesis.

The **COP10** mutation induces high expression of genes involved in cytosolic translation

In comparing the effect of pleiotropic cop/det/fus mutations from the four functional groups, we also observed some distinct expression patterns among these groups. As shown in Fig. 3A, the number of distinctly regulated genes in these lethal
mutant seedlings is highly variable, with those of cop1-8 and det1-6 being more similar to each other and with fus6-1 and cop10-1 diverging. cop10-1 is, by far, the most diverged in its genome expression profile (Fig. 1C). One striking example is illustrated in Fig. 7, where almost all the genes encoding 60S or 40S ribosomal proteins were much more sensitive to COP10 regulation (lane 5) than any other pleiotropic COP/DET/FUS proteins or to high intensity light. The reason for this is not clear.

The majority of COP4-controlled genes are included within light-regulated genes

The cop4 mutant belongs to the less pleiotropic or partial photomorphogenic mutants. Seedlings with mutations in the COP4 locus exhibited open and enlarged cotyledons but long hypocotyls (Hou et al., 1933) (Fig. 1A). Genome expression profile analysis revealed that 496 genes showed twofold or higher differential expression between dark-grown cop4 and wild-type seedlings, with 246 and 250 genes up- or down-regulated in the mutant, respectively. The genes induced in the cop4 mutant encode proteins involved in photosynthetic light reactions, carbon assimilation, starch synthesis, sucrose synthesis, photosynthesis, chlorophyll synthesis and the TCA cycle. Repressed genes in the cop4 mutant encoded proteins that are involved in cell wall degradation, water transport across tonoplast and plasma membranes, fatty acid β oxidation, glycogen cycle, nitrate assimilation and sulfate assimilation. Most of these COP4-regulated genes are actually light-regulated as well (Ma et al., 2001; Ma et al., 2002). However,
the number of differentially expressed genes controlled by COP4 is much fewer than those of light or pleiotropic COP/DET/FUS protein.

To further characterize these COP4-regulated genes, we compared gene expression patterns in cop4 with the differential gene expression patterns of light-grown wild type and dark-grown cop/det/fus mutant seedlings in a cluster analysis (Fig. 8A). The vast majority of the COP4-regulated genes showed qualitatively similar expression in white light or the pleiotropic cop/det/fus mutations. In fact, about 72% and 70% of the up-regulated genes that displayed twofold or more differential expression in the cop4 mutants were included in the white light- or det1-1-induced genes, respectively. Likewise, about 73% and 72% of the down-regulated genes displaying ≥2-fold differential expression in the cop4 mutants were included in the white light or det1-1 repressed genes, respectively. Less than 5% of COP4-regulated genes show opposite regulation in most pleiotropic cop/det/fus mutants, with only the cop10-1 mutant exhibiting a higher percentage of opposite regulation (Fig. 8C,D). These results support a hypothesis that COP4 is a locus involved in regulating a subset of photomorphogenic processes (Hou et al., 1993).

A BR synthesis mutation induces a partially overlapping set of light-regulated genes in the dark

We also examined the genome expression profile of another representative partially photomorphogenic locus, DET2, which encodes an enzyme involved in brassinosteroid biosynthesis (Li et al., 1996). Dark-grown det2 mutants had a partially photomorphogenic phenotype with short hypocotyls and small opened cotyledon without an apical hook (Chory et al., 1991) (Fig. 1A). We observed that 253 genes in our array showed twofold or higher differential expression between dark-grown det2 mutant and wild-type seedlings, while 156 and 97 genes were up- or down-regulated in dark-grown det2 mutant seedlings, respectively. A comparison of the genome expression profiles between det2 mutants and light or pleiotropic cop/det/fus mutants showed that less than half of the DET2-regulated genes exhibited the same expression pattern with light and pleiotropic COP/DET/FUS regulation. Those genes regulated by both DET2 and light included the genes for the photosynthetic light reaction, cell wall degradation, water transport across the tonoplast, sulfate assimilation and fatty acid β oxidation. Of the approximately 50% of DET2-regulated genes in darkness that were not similarly regulated by light or pleiotropic cop/det/fus mutations in the darkness, a small fraction were oppositely regulated by light and/or pleiotropic cop/det/fus mutations (Fig. 8E,F). Our result suggested that brassinosteroid also regulates the expression of other unrelated genes in addition to a small subset of light-regulated genes.

DISCUSSION

An evolutionarily conserved group of either pleiotropic or less pleiotropic COP/DET/FUS proteins was initially defined by their ability to repress photomorphogenesis in Arabidopsis. Genetic analysis of light control of Arabidopsis seedling development revealed that the COP/DET/FUS genes play a key role in integrating light signals and modulating developmental pattern formation. In this study, we have systematically investigated COP/DET/FUS-controlled genome expression during Arabidopsis seedling development using a cDNA microarray. Our results substantiate the working model build upon molecular genetic studies from the past and provide several new insights regarding the COP/DET/FUS control of gene expression and plant development patterns.

Pleiotropic COP/DET/FUS protein-regulated genome expression exhibits a large overlap with that of light

Phenotypically, all pleiotropic cop/det/fus mutants showed an almost complete light-grown response when they were grown in the dark (Wei and Deng, 1999) (Fig. 1A). In this genome expression profiling study, we also found that individual pleiotropic COP/DET/FUS proteins control a largely overlapping set genes; the majority of COP/DET/FUS-regulated genes (more than 80%) overlapped with light-regulated expression at seedling stage as judged by the gene expression profiles. The gene products of the less pleiotropic COP/DET loci also controlled variable fractions of the light-controlled genome expression. So, this genomic study provides an explanation for why mutations in these loci lead to a
The ten pleiotropic COP/DET/FUS proximity in the pathway expression profiles and may function in the close COP1 and DET1 control highly similar genome expression profiles and may function in the close proximity in the pathway

The ten pleiotropic COP/DET/FUS loci represent four biochemical entities: the COP9 signalosome, COP1, COP10 and DET1. Recently, it has been proposed that COP1 functions as a putative component of an ubiquitin protein ligase (E3) (Osterlund et al., 2000). COP10 encodes an ubiquitin-conjugating enzyme (E2) variant (Suzuki et al., 2002) and the COP9 signalosome is structurally similar to the lid of the 19S regulatory particle of the 26S proteasome (Wei and Deng, 1999). While DET1 encodes a novel nuclear-localized protein (Pepper et al., 1994), its specific biochemical function is not known. These proteins appear to work together to mediate the degradation of photomorphogenesis-promoting transcription factors (Holm et al., 2002).

In this study, we found that among these pleiotropic mutants, cop1 and det1 mutant seedlings have the most closely related genome expression profiles both in dark and light growth conditions (Fig. 1C,D). This is true for both the viable mutations or the lethal mutations of COP1 and DET1. This genomic evidence supports the conclusion that COP1 and DET1 work closely together as observed in a previous genetic analysis (Ang et al., 1994). COP1 and DET1 may, therefore, act very closely in repressing photomorphogenesis. Thus signals perceived by photoreceptors act to negatively regulate COP1 and DET1 and relieve their repression of photomorphogenesis.

**Light signals can quantitatively regulate the pleiotropic COP1 and DET1 proteins and, thus, the degree of photomorphogenic response**

Besides acting as signals to regulate many developmental processes, light also serves as the source of energy for plant photosynthesis. Plants adjust the structure and function of the photosynthetic apparatus in response to changes in their growth environment. The change in the size of the chlorophyll antennae associated with photosystem I and II is very sensitive to light (Niyogi, 1999). Under limiting irradiance conditions, the photosystems acquire large chlorophyll antennae and more extensive thylakoid membrane to absorb more light; while under high irradiance, especially under light stress, chlorophyll antennae sizes are reduced in order to protect the photosynthetic apparatus from damage by repressing LHC gene expression (Escoubas et al., 1995; Maxwell et al., 1995) and/or increasing LHC protein degradation (Lindahl et al., 1995). Also, under light stress, plant cells express some genes encoding specific stress proteins with possible protective functions (Dunaeva and Adamska, 2001).

COP/DET/FUS proteins act as repressors of light-controlled
Arabidopsis seedling development (Wei and Deng, 1999; Osterlund et al., 1999). We have found that light can largely achieve its control of genome expression by negatively regulating COP1 (Ma et al., 2002) and DET1 protein (this work). Therefore, complete loss of COP1 or DET1 function would mimic the action of light stress even in the dark. To provide direct evidence for this, we first checked the expression of representative genes encoding chlorophyll antennae and thylakoid membrane proteins. We found that the expression of these genes was induced by normal intensity light (and even at a very low intensity) and in a dark-grown weak mutant of cop1 or det1, but was repressed in a dark-grown null mutant of cop1 (cop1-8) or det1 (det1-6) (Fig. 2A). The expression of these genes was also dependent on a COP1 activity in weak, strong and null mutants of cop1 (Fig. 2A). In addition, all these genes were repressed under high intensity white light (light stress) (Fig. 2A). Second, a predominant portion (80%) of the genes that showed opposite regulation in dark-grown cop1 or det1 null mutants compared to normal light regulation also had a similar expression pattern to that resulting from light stress. Some of the light-stress-induced marker genes, e.g. late embryogenesis abundant protein (Dunaeva and Adamska, 2001), metallothionein (Dunaeva and Adamska, 2001), HSP70 (Schroda et al., 1999), glutathione reductase (Karpinski et al., 1997) and NAD(P)H dehydrogenases (Endo et al., 1999), were also induced in dark-grown cop1 or det1 null mutants. Third, we found that the genes encoding chlorophyll antennae and thylakoid membrane proteins began to be less induced in weak cop1 mutants, repressed in light-grown strong cop1 or weak det1 mutants, and severely repressed in cop1 or det1 null mutants (Fig. 2B). Again, more than 80% of the genes that showed opposite regulation in light-grown cop1 or det1 null mutants to normal light grown seedlings had a similar expression pattern under light stress. Fourth, comparison of the whole genome expression profiles among pleiotropic cop1/det/fus mutants and normal and high intensity light induction indicated that the genome expression pattern induced by high light intensity is similar to that of lethal mutants of pleiotropic cop1/det/fus (Fig. 1 C,D). These genomic results are consistent with the physiological observation that the very short hypocotyls and reduced cotyledon with accumulation of anthocyanin (Fig. 1A) of the cop1/det/fus mutants are also commonly observed in the plants grown under high intensity light stress. The lethal (null) mutants of COP/DET/FUS loci essentially exhibited light stress responses even when grown in the dark.

The COP/DET/FUS loci have overlapping yet non-identical roles in regulating Arabidopsis seedling development

For those genes that showed opposite regulation between light- and dark-grown cop1 or det1 null mutants to regulation by light, most of them do not show opposite regulation in dark-grown fus6-1, cop9-1 or cop10-1 mutant seedlings. While in light fus6-1, cop9-1 or cop10-1 mutant seedlings share similar oppositely-regulated genes as the cop1 and det1 null mutants or seedlings subjected to light stress, as compared to light regulation. For example, in fus6-1, cop9-1 and cop10-1 mutants, the genes encoding proteins involved in photosynthetic light reactions were induced in the dark-grown mutant seedlings, whereas they were repressed in dark-grown cop1-5, cop1-8 and det1-6. However, the expression of these representative genes was repressed in all light-grown lethal pleiotropic cop1/det/fus mutant seedlings. All these characteristics that fus6-1, cop9-1 or cop10-1 mutants exhibited were similar to some viable cop1 or det1 mutants.

In addition, we found that individual pleiotropic COP/DET/FUS proteins also regulated distinct sets of genes. For example, cop10-1 mutants induced higher expression of cytosolic ribosomal proteins than other pleiotropic cop1/det/fus mutants (Fig. 6). These results suggest that the pleiotropic COP/DET/FUS proteins, especially the COP9 signalosome and COP10, also function in other developmental processes besides seedling photomorphogenesis.

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COP/Det/Fus control of genome expression


