

Chloroplastic photorespiratory bypass increases photosynthesis and biomass production in *Arabidopsis thaliana*

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We introduced the *Escherichia coli* glycolate catabolic pathway into *Arabidopsis thaliana* chloroplasts to reduce the loss of fixed carbon and nitrogen that occurs in C₃ plants when phosphoglycolate, an inevitable by-product of photosynthesis, is recycled by photorespiration. Using step-wise nuclear transformation with five chloroplast-targeted bacterial genes encoding glycolate dehydrogenase, glyoxylate carboligase and tartronic semialdehyde reductase, we generated plants in which chloroplastic glycolate is converted directly to glycerate. This reduces, but does not eliminate, flux of photorespiratory metabolites through peroxisomes and mitochondria. Transgenic plants grew faster, produced more shoot and root biomass, and contained more soluble sugars, reflecting reduced photorespiration and enhanced photosynthesis that correlated with an increased chloroplastic CO₂ concentration in the vicinity of ribulose-1,5-bisphosphate carboxylase/oxygenase. These effects are evident after overexpression of the three subunits of glycolate dehydrogenase, but enhanced by introducing the complete bacterial glycolate catabolic pathway. Diverting chloroplastic glycolate from photorespiration may improve the productivity of crops with C₃ photosynthesis.

Many important crops are C₃ plants, in which primary CO₂ fixation is catalyzed by the enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (rubisco). Although this chloroplastic enzyme is the world's most abundant protein, it is widely regarded as being particularly inefficient owing to its capacity to catalyze both the carboxylation and oxygenation of ribulose-1,5-bisphosphate¹. The balance between these two activities depends mainly on the CO₂/O₂ ratio in the leaves². Each carboxylation reaction produces two molecules of phosphoglycerate that enter the Calvin cycle, ultimately to form starch and sucrose and to regenerate ribulose-1,5-bisphosphate. The oxygenation reaction produces single molecules of phosphoglycerate and phosphoglycolate. In C₃ plants, which include crops such as rice and wheat, the latter is recycled into phosphoglycerate by photorespiration^{3,4} (Fig. 1). One molecule of CO₂ is released for every two molecules of phosphoglycolate produced, a net loss of fixed carbon that reduces the production of sugars and biomass. Ammonia is also lost in this reaction, and needs to be refixed through energy-consuming reactions in the chloroplast.

The negative impact of photorespiration on plant growth and yield has been demonstrated by doubling the CO₂ concentration in a glasshouse environment, dramatically increasing the performance of several crops^{5,6}. However, such a strategy cannot be implemented in the field, where photorespiratory losses are also exacerbated by high temperatures and suboptimal water supplies. Under these conditions, the stomata close and the intercellular oxygen

concentration increases through the release of O₂ from the light reactions of photosynthesis⁷.

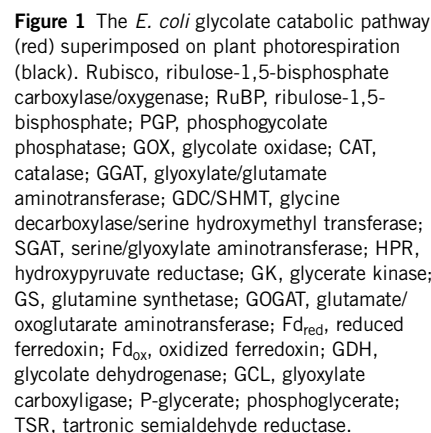
Despite these disadvantages, photorespiration is important because it recovers 75% of the carbon from phosphoglycolate and efficiently removes potent inhibitors of photosynthesis^{8,9}. Photorespiration mutants are therefore incapable of growing at ambient CO₂ concentrations^{10–12}. Moreover, photorespiration dissipates excess photochemical energy under high light intensities, thus protecting the chloroplast from over-reduction^{7,13}.

Many bacteria can metabolize glycolate, and *E. coli* can use glycolate as a sole carbon source^{14,15} (Fig. 1). Like plant photorespiration, the first reaction is the oxidation of glycolate to form glyoxylate. However, the bacterial glycolate dehydrogenase (GDH) comprises three subunits and unknown organic cofactors, whereas plant glycolate oxidase is a single polypeptide that uses oxygen as a cofactor and produces peroxide. In the bacterial pathway, two molecules of glyoxylate are ligated by glyoxylate carboligase (GCL) to form one molecule of tartronic semialdehyde, and one molecule of CO₂ is released. Tartronic semialdehyde is further converted to glycerate by tartronic semialdehyde reductase (TSR). This pathway coexists and cooperates with the glycine decarboxylase pathway in the photosynthetic cyanobacterium *Synechocystis*¹⁶.

In this study, we demonstrate reduced photorespiration in *A. thaliana* after transfer of the *E. coli* glycolate catabolic pathway to chloroplasts. This increased biomass production in the transgenic plants concomitant with improved photosynthesis.

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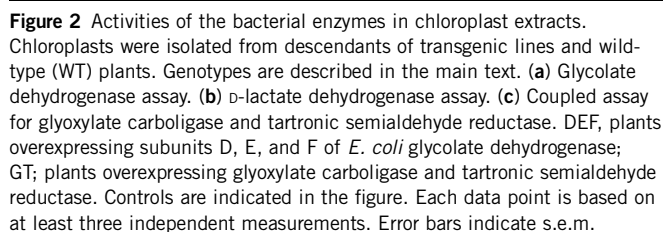
Establishment of the pathway in *A. thaliana* chloroplasts

For activity assays, chloroplasts were partially purified from *A. thaliana* line DEF5, which expressed all three GDH subunits. The unique properties of the plant and bacterial enzymes were exploited to distinguish the introduced activity from contaminating peroxisomal glycolate oxidase. The bacterial enzyme uses organic cofactors, is sensitive to cyanide ions and accepts D-lactate as an alternative substrate. DEF plants produced substantially more glyoxylate from glycolate compared to the wild-type plants, and this activity was inhibited by cyanide (**Fig. 2a**). Similar results were obtained in D-lactate dehydrogenase assays—DEF plants showed enhanced activity that was also sensitive to cyanide (**Fig. 2b**). This suggests that all three bacterially derived subunits are targeted to chloroplasts and assemble to form a functional GDH.

coupled assay. NAD⁺ generation by chloroplastic extracts from GT plants depended on the availability of glyoxylate (**Fig. 2c**). This suggests that GCL produces tartronic semialdehyde as a substrate for the TSR reaction, which in turn uses NADH as a cofactor. No substrate-dependent activity was observed in control extracts from wild-type plants. The data indicate that both GCL and TSR are active inside the chloroplast.

The full pathway was assembled by crossing GT and DEF plants. Plants containing all constructs were selected by multiplex PCR (**Supplementary Fig. 1** online) and expression levels were verified by real-time RT-PCR (data not shown). We were not able to generate lines homozygous for all constructs because transgene expression was strongly reduced in these plants, probably owing to homology-dependent gene silencing¹⁷. Thus, all further experiments were performed with lines that were hemizygous for some of the transgenes. Unless specified, descendants from the lines DEF5 and GT-DEF12 were selected on suitable antibiotics and used for physiological and growth assays without further evaluation of gene expression levels.

Representative photographs of wild-type, DEF and GT-DEF plants are shown in **Figure 3a**. Both classes of transgenics show a substantial increase in rosette diameter. This effect is not observed in plants overexpressing incomplete glycolate dehydrogenase (DE, F) or in GT



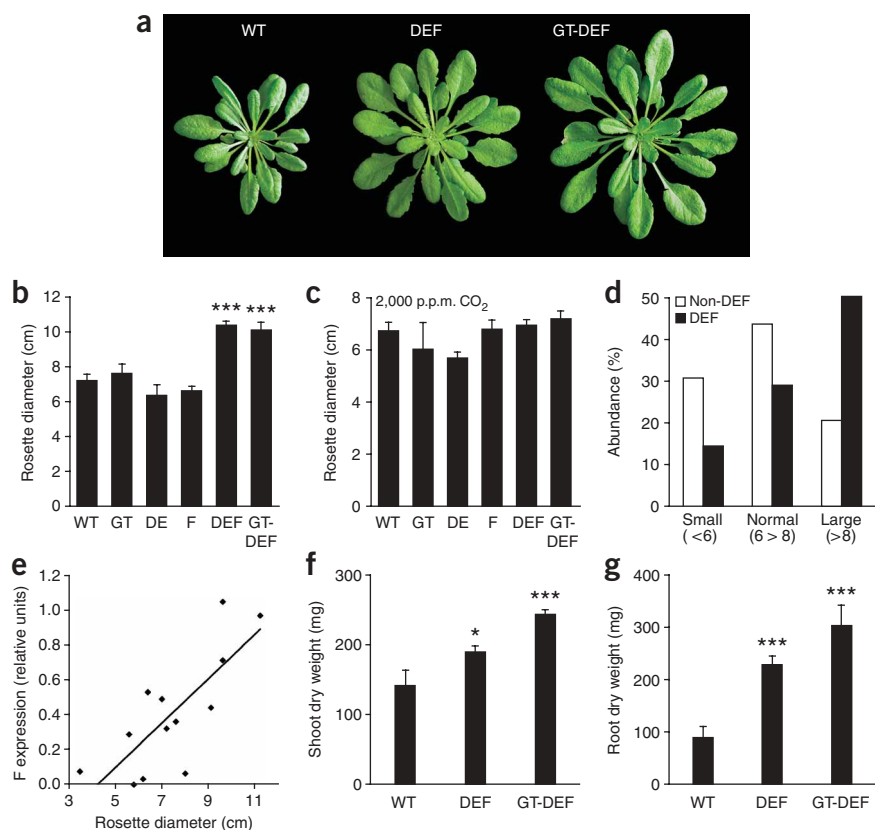


Figure 3 Growth parameters of transgenic (DEF, GT-DEF) and wild-type (WT) lines. (a) Representative photographs of selected transgenic plants. (b) Rosette diameters of plants grown at ambient conditions. (c) Rosette diameters of plants grown at elevated CO₂ (2,000 p.p.m.). (d) Abundances of small (<6 cm rosette diameter), normal (6–8 cm) and large (>8 cm) plants in a segregating population dependent on the genotype. DEF, plants containing the DE and F transgenes; non-DEF, all other genotypes. (e) Correlation of abundance of transcript encoding the F subunit of GDH with rosette diameter in descendants from a segregating population. (f) Shoot dry weights of plants grown under ambient conditions. (g) Root dry weights of plants grown under ambient conditions. DEF, plants overexpressing subunits D, E, and F of *E. coli* glycolate dehydrogenase; GT-DEF, plants overexpressing the complete *E. coli* glycolate catabolic pathway as shown in Figure 1. Each data point represents at least five independent plants. Error bars indicate s.e.m.; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$ according to Student's *t*-test. Plants were selected on appropriate antibiotics for 2 weeks and then grown in soil for 6 weeks. Plants analyzed in d and e were directly grown in soil without antibiotic selection.

conditions such as high temperature or strong light, when photorespiration is increased (Supplementary Fig. 2 online).

Next, we determined the contents of representative carbohydrates in leaves. GT-DEF plants showed higher contents of glucose, fructose and sucrose per unit leaf area, an increase not evident in DEF plants (Table 1). Similar contents of starch were observed in all genotypes.

The growth data indicate that plants overexpressing the bacterial glycolate catabolic pathway in their chloroplasts have greater biomass. This effect was obtained in part by the establishment of glycolate dehydrogenase activity.

Reduced photorespiration in DEF and GT-DEF plants

Expression of the bacterial glycolate catabolic pathway in chloroplasts should divert glycolate from photorespiration. We therefore used two different assays to quantify photorespiration. First, we determined the ratio of glycine and serine in leaves (Gly/Ser ratio)¹⁸. Under ambient conditions, the Gly/Ser ratio was similar for all genotypes (Fig. 4a), but after incubating plants at 100 p.p.m. CO₂ for 4 h, the Gly/Ser ratio increased by a factor of 10 for the wild type. This increase was much lower in the transgenic lines. GT-DEF plants showed final ratios <50% compared to wild type, and DEF plants showed intermediate values. These differences predominantly reflect the different glycine

plants (Fig. 3b). In addition, the leaf blades of DEF and GT-DEF plants are flatter than those of wild-type plants and the petiole seems elongated. These phenotypic effects were reproducible over at least three generations for the two DEF lines tested (DEF5 and DEF7) and for three GT-DEF lines derived from them (Supplementary Note). However, when grown at elevated CO₂ concentrations, no size differences were observed among the tested genotypes (Fig. 3c).

We tested the correlation between rosette diameter and the presence of particular transgenes. Progenies of a hemizygous GT-DEF plant formed a segregating population containing the transgenes in different combinations. Grouping the descendants into three size classes and analyzing the individual genotypes by multiplex PCR (Supplementary Fig. 1 online) revealed that DEF progenies were noticeably enriched among the largest plants. All other genotypes (e.g. DE plants, F plants or plants containing no transgene) showed a normal distribution among the three groups (Fig. 3d). To determine whether the phenotypic effect depended on transgene expression, we quantified the accumulation of the corresponding transcripts in individual DEF lines. We found a linear correlation ($R^2 = 0.76$, $P = 0.002$) between the expression of subunit F and the rosette diameter (Fig. 3e). No correlation between rosette diameter and the abundances of transcripts encoding subunits D and E was observed (data not shown). Transcripts encoding the D and E subunits are tenfold more abundant than those encoding the F subunit (data not shown), suggesting that the relative scarcity of the F subunit of GDH might limit the assembly of complete DEF complexes.

The dry weights of shoots and roots at the end of the vegetative period were also significantly ($P < 0.05$ and $P < 0.001$, respectively) enhanced in DEF plants compared to the wild type, but a further increase was observed in GT-DEF plants (Figs. 3f,g). This positive effect on biomass was also evident when plants were shifted to stress

Table 1 Contents of carbohydrates in wild-type and transgenic plants

Parameter ^a	WT	DEF	GT-DEF
Starch	1,510 (±203)	1,320 (±43)	1,522 (±114)
Glucose	188 (±16)	180 (±19)	227 (±15)
Fructose	40 (±3)	45 (±3)	66 (±3)***
Sucrose	328 (±23)	372 (±28)	403 (±17)*

^aGiven in $\mu\text{mol m}^{-2}$; *, $P < 0.05$; ***, $P < 0.001$; $\pm$, s.e.m.

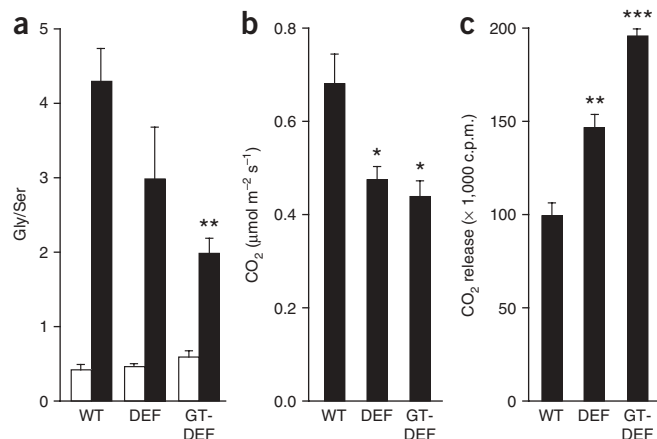


Figure 4 Reduction of the photorespiratory flow in transgenic plants (DEF, GT-DEF) compared to the wild type (WT). **(a)** Ratio of the abundances of glycine and serine in leaves of plants grown under ambient conditions (white) or shifted for 4 h to 100 p.p.m. CO₂ (black). Samples were taken 3 h after the onset of illumination. **(b)** Quantification of the postillumination CO₂ burst (PIB). **(c)** CO₂ release from glycolate in chloroplast extracts. ¹⁴C-glycolate was added to chloroplast extracts and the evolving radioactive CO₂ was captured in a NaOH trap. c.p.m., counts per minute. DEF, plants overexpressing subunits D, E and F of *E. coli* glycolate dehydrogenase; GT-DEF, plants overexpressing the complete *E. coli* glycolate catabolic pathway as shown in **Figure 1**. Each data point represents at least four independent plants. Error bars indicate s.e.m.; *, *P* < 0.05; **, *P* < 0.01; ***, *P* < 0.001 according to Student's *t*-test.

contents, as the serine levels are similar in the transgenic and wild-type lines (**Supplementary Fig. 3** online).

Second, we measured the postillumination CO₂ burst (PIB) as an indicator of CO₂ release in the mitochondrial glycine decarboxylase reaction. A typical PIB profile is described in **Supplementary Fig. 4** online. DEF and GT-DEF plants showed a reduction in PIB levels of ~30% compared to the wild type (**Fig. 4b**). This confirms reduced photorespiratory flux in transgenic lines.

Enhanced CO₂ release from glycolate in chloroplast extracts

To determine the metabolic fate of glycolate, we fed labeled glycolate to chloroplast extracts from wild-type and transgenic lines. Unexpectedly, no clear spots other than the glycolate signal were observed when metabolites were separated by thin-layer chromatography (data not shown). Instead, CO₂ release from glycolate in chloroplast extracts from DEF and GT-DEF plants increased in comparison with that from the wild type (**Fig. 4c**). This suggests that the oxidation product glyoxylate is decarboxylated by GCL in GT-DEF chloroplasts. Glyoxylate decarboxylation also appears to occur in DEF plants, albeit with lower efficiency. The background activity in wild-type chloroplast extracts was not due to contamination with peroxisomal glycolate oxidase, because the peroxisomal marker enzyme catalase could not be detected in these extracts. This implies the presence of an endogenous glycolate-oxidizing enzyme in plant chloroplasts, as suggested previously¹⁹.

Improved photosynthetic performance of DEF and GT-DEF plants

We next analyzed gas exchange and chlorophyll fluorescence parameters in wild-type and transgenic plants (**Table 2**). The apparent rate of CO₂ assimilation (*A*) under ambient conditions was clearly enhanced in GT-DEF plants compared to that of the wild type. DEF plants showed intermediate values. However, the maximum CO₂ fixation at saturating CO₂ concentrations was not affected. CO₂ release from glycolate in the chloroplast could be responsible for this effect and we therefore tested several parameters reflecting the CO₂/O₂ balance in the vicinity of rubisco. As anticipated, the increase in *A* correlated with a reduction in the oxygen inhibition of CO₂ assimilation when assimilatory rates were compared at normal (21%) and enhanced (40%) atmospheric oxygen concentrations. A similar trend was observed for the apparent CO₂ compensation point (Γ^*), but deviations from wild-type data were not significant. To exclude any possible indirect impact of the transgenes on CO₂ release from other metabolic pathways, for example, dark respiration in the light (*R_d*), we calculated the CO₂ compensation point Γ^* . For this, we determined the crossing point of several *A*/leaf internal CO₂ concentration curves

(*A/C_i*) measured at different low light intensities (**Supplementary Fig. 5** online). The *C_i* at this point represents Γ^* and the CO₂ release by the leaf corresponds to *R_d*^{20,21}. Also, Γ^* was significantly (*P* < 0.05) reduced in DEF plants and the effect was enhanced for GT-DEF plants with a reduction of more than 10%. However, transgene overexpression did not affect the maximum quantum efficiency of photosystem II (*F_v/F_m*), suggesting that differences in growth are not accounted for by differences in photoinhibition or photochemistry.

Together, these data suggest that expression of a bacterial glycolate catabolic pathway in *A. thaliana* chloroplasts enhances carbon assimilation by increasing the chloroplastic CO₂ concentration.

DISCUSSION

We established a strategy to reduce photorespiratory losses in a C₃ plant by introducing a bacterial glycolate catabolic pathway into chloroplasts. Theoretical considerations predict that the most efficient approach to reduce photorespiration may be to increase the specificity of rubisco for CO₂ through the overexpression of algal enzymes with high specificity factors²². Increased specificity tends to correlate with reduced catalytic rates in such enzymes²³. Other attempts to enhance CO₂ fixation have involved introducing a C₄-like CO₂-concentrating mechanism into C₃ plants^{24–26}. These strategies aim at concentrating CO₂ in the vicinity of rubisco and thus reducing the oxygenase activity of the enzyme. In our approach, the oxygenase activity is tolerated, but we divert the products of this reaction into a pathway that consumes less energy. Formally, the bacterial glycolate catabolic pathway inside the chloroplast is also a photorespiratory pathway because it involves CO₂ release and depends on O₂ fixation by rubisco.

Table 2 Chlorophyll fluorescence and gas exchange parameters of wild-type and transgenic lines

	WT	DEF	GT-DEF
<i>A</i> (μmol m ⁻² s ⁻¹) (at <i>C_a</i> = 400 p.p.m.)	5.5 (±0.4)	6.7 (±0.4)*	8.2 (±0.4)***
<i>A</i> (μmol m ⁻² s ⁻¹) (at <i>C_a</i> = 2,000 p.p.m.)	19.7 (±0.8)	19.8 (±0.6)	20.2 (±0.3)
O ₂ inhibition of <i>A</i> (%)	36.0 (±2.9)	31.3 (±1.5)	26.2 (±0.7)*
Γ (p.p.m. CO ₂)	76.3 (±2.4)	70.0 (±0.6)	67.5 (±5.4)
Γ^* (p.p.m. CO ₂)	50.4 (±1.0)	46.3 (±1.2)*	44.0 (±1.5)**
<i>R_d</i> (μmol m ⁻² s ⁻¹)	0.83 (±0.06)	0.81 (±0.04)	0.79 (±0.08)
<i>F_v/F_m</i>	0.69 (±0.03)	0.65 (±0.04)	0.70 (±0.03)

A, apparent CO₂ assimilation; *C_a*, CO₂ concentration in the measuring cuvette; Γ , apparent CO₂ compensation point; Γ^* , CO₂ compensation point in the absence of dark respiration in the light; *R_d*, dark respiration in the light; *F_v/F_m*, maximum quantum efficiency of photosystem II. *, *P* < 0.05; **, *P* < 0.01; ***, *P* < 0.001 according to Student's *t*-test; ±, s.e.m.

Even so, this technology has two major potential benefits compared to the endogenous photorespiratory pathway. First, the plastidal glycolate pathway does not release ammonia that needs to be refixed, consuming energy and reducing equivalents during conventional photorespiration²⁷. Instead, the pathway produces reducing equivalents. Second, the pathway does not consume ATP, an advantage compared to C₄-like pathways where ATP is used to regenerate the CO₂ acceptor molecule. These advantages are probably most relevant under low-light conditions when energy for photosynthesis is limited. In addition, overexpression of the plastidal glycolate pathway may also improve the rescavenging of CO₂, because photorespiratory CO₂ release is shifted from the mitochondrion to the chloroplast. The PIB data indicate that there is an ~30% decrease in the abundances of precursors for the reaction catalyzed by GDH. The Gly/Ser ratio, another independent parameter that shows a linear correlation with the photorespiratory rate¹⁸, is reduced to a similar extent. Moreover, plastidal extracts of transgenic lines release significantly ($P < 0.001$) more CO₂ from glycolate compared to those of the wild type. Such CO₂ release might improve carbon assimilation by reducing the relative oxygenase activity and by saturating the CO₂ binding site of rubisco²⁸. The positive effects of CO₂ release in the chloroplasts of C₃ plants have been questioned, because this organelle has a low resistance to CO₂ diffusion²⁹. Our gas exchange measurements provide several independent arguments suggesting that plastidal CO₂ concentration can be enhanced to a certain extent. First, the PIB is reduced in transgenic lines, which would not be expected when photorespiratory CO₂ release is simply shifted from one organelle to the other. Second, the oxygen inhibition of photosynthesis, a parameter that shows a strong negative correlation with the CO₂/O₂ ratio in the vicinity of rubisco³⁰, decreased in GT-DEF plants. Third, the CO₂ compensation point Γ^* , which provides an independent measure for the CO₂/O₂ ratio in the chloroplast, indicates that augmentation of CO₂ concentration in the chloroplast is possible.

Increased CO₂ availability is not necessarily translated directly into enhanced growth. A meta-analysis of the empirical relation between plant growth and leaf photosynthesis under laboratory conditions revealed a good correlation between these parameters³¹. Recent data from free-air CO₂ enrichment studies indicate that crop yields increase at higher CO₂ concentrations, albeit less than expected³². This limitation is probably due to the complex regulation of photosynthesis by, among others, the availability of nutrients³³, the negative feedback regulation of photosynthetic products on the expression and activity of photosynthetic enzymes^{28,33}, and the regenerative capacity of the Calvin cycle^{34,35}. Such restrictions might also apply in GT-DEF plants as exemplified by the increased contents of soluble sugars, but protein gel analysis did not reveal any differences in rubisco protein content (data not shown).

The greater root and shoot biomass of GT-DEF plants indicates that they overcome at least one growth-limiting bottleneck. This effect might even be enhanced by higher expression levels of the transgenes, because transgene expression shows a positive linear correlation with biomass production and no saturation of this correlation curve was observed thus far. DEF plants performed similarly to GT-DEF plants in this experiment, but they showed effects intermediate between those of the wild-type and GT-DEF plants in most other growth and physiological assays.

There is no obvious scenario for the further conversion of glyoxylate in the chloroplast of DEF plants. Although glyoxylate could be reconverted to glycolate by the plastidal glyoxylate reductase^{9,36}, no net advantage would be expected from such a futile cycle. Alternatively, glyoxylate could undergo a nonenzymatic oxidative

decarboxylation to formate in the presence of peroxides. Chloroplast extracts can decarboxylate externally supplied glyoxylate in the light^{37–39}. A similar pathway has been proposed as part of photorespiration in some algae⁴⁰. The formate produced could be decarboxylated further to CO₂ and H₂O by chloroplastic formate dehydrogenase⁴¹. As substantial GDH activity was detected in the chloroplasts of spinach¹⁹, a related pathway may exist in wild-type plants. Overexpression of the bacterial GDH would boost this pathway and divert more glycolate from photorespiration. Admittedly, no ribulose-1,5-bisphosphate would be regenerated in any such scenario and refixation of CO₂ released from the proposed pathway would therefore be limited rapidly. Further studies are needed to elucidate precisely how glycolate oxidation in the chloroplast improves biomass production and whether such effects will also be stable under the variable growth conditions of field-grown crops.

METHODS

Plasmid constructs. The coding sequences for glyoxylate carboligase (GCL), tartronic semialdehyde reductase (TSR), *glcD*, *glcE* and *glcF* were amplified by PCR from *E. coli* DNA using suitable oligonucleotides. All sequences are available from the *E. coli* K12 genome sequence (gi49175990). GCL and TSR were cloned into the binary plant expression vector pTRAK, a derivative of pPAM (gi13508478). The expression cassettes were flanked by the scaffold attachment region of the tobacco *RB7* gene (gi3522871). The *nptII* cassette of pPCV002 (ref. 42) was used for selection of transgenic plants on kanamycin. Transcription was controlled by the enhanced CaMV 35S promoter⁴³ and all transgenes were translationally fused to the chloroplast targeting peptide of the potato *rbcS1* gene (gi21562). For the expression of *glcD* and *glcE*, the same vector construct was used, carrying the sulfadiazine-resistance cassette from pGABII (gi44894182). For the expression of *glcF*, the same vector construct was used, carrying the phosphinothricin-resistance cassette from pAM-PAT (gi38231644).

Plant growth and transformation. Stable transformation of *A. thaliana* plants ecotype Columbia (Col-0) with the respective constructs was carried out by *Agrobacterium tumefaciens* (GV3101)-mediated floral dip transformation⁴⁴. The transgene integration sites were mapped by genome walking and are listed in **Supplementary Table 1** online. Plants used for physiological experiments were grown under short-day conditions (8 h illumination and 16 h darkness) in growth chambers at 22 °C with a photon flux density of 100 $\mu\text{mol m}^{-2} \text{s}^{-1}$. For low and high CO₂ treatments, the plants were shifted to a growth cabinet that was constantly supplied with air containing either 100 p.p.m. or 2,000 p.p.m. CO₂.

Chloroplast isolation and enzymatic assays. Intact chloroplasts were isolated from 4-week-old *A. thaliana* plants as described⁴⁵. Approximately 5 g leaf material was ground in 50 ml grinding buffer (50 mM HEPES-KOH pH 7.5, 1 mM MgCl₂, 1 mM EDTA, 1 g l⁻¹ BSA, 0.2 g l⁻¹ sodium ascorbate, 0.3 M mannitol, 5 g l⁻¹ polyvinylpyrrolidone). After filtration through three layers of Miracloth, the solution was centrifuged at 1,000g for 10 min. The pellets were resuspended in 1 ml SH-buffer (50 mM HEPES-KOH pH 7.5, 0.33 M sorbitol), and 0.5 ml of this solution was loaded on a 1-ml 35% Percoll gradient (35% Percoll, 65% SH-buffer). The gradient was centrifuged for 5 min at 500g. The chloroplast pellet was washed in 1 ml SH-buffer and chloroplast protein was extracted in 500 μl extraction buffer (50 mM HEPES-NaOH pH 7.5, 2 mM EDTA, 5 mM MgCl₂, 0.1% Triton X-100, 20% glycerol). Glycolate dehydrogenase and D-lactate dehydrogenase activities were measured as described^{14,46}. Glyoxylate carboligase and tartronic semialdehyde reductase were assayed in a coupled reaction⁴⁷. For labeling experiments (**Fig. 4c**), chloroplasts were loaded on an 8-ml gradient and centrifuged for 20 min at 40,000g. These preparations were free of contaminating catalase and fumarase activities (>95% purity).

CO₂ release from labeled glycolate in chloroplast extracts. We added 1 μCi of [1,2-¹⁴C]-glycolate (Hartmann Analytics) to 50 μg of chloroplast protein extract in a tightly closed 15-ml reaction tube. Released CO₂ was absorbed in a 500- μl reaction tube containing 0.5 M NaOH attached to the inner wall of the

15-ml tube. Samples were incubated for 5 h and the gas phase in the reaction tube was frequently mixed with a syringe.

Determination of metabolites and chlorophyll contents. Two plant leaf discs (1.5 cm² each) were harvested after 4 h of illumination and immediately frozen. Soluble sugars were then extracted using 80% (vol/vol) boiling ethanol. Starch was extracted from bleached leaf discs and was hydrolyzed enzymatically. The glucose released from starch and the contents of soluble sugars in the ethanolic extracts were determined enzymatically⁴⁸. For the determination of glycine and serine, whole leaf rosettes were harvested and immediately frozen in liquid nitrogen. The abundance of the amino acids was analyzed and quantified by gas chromatography/mass spectrometry using a Chemstation 5890 Series II gas chromatograph (Hewlett Packard). Extraction and derivatization of samples were performed as described⁴⁹. A dilution series of standard substances for peak identification was prepared and a SIM-mode was implemented for quantification of each substance. The *m/z* values were: glycine (147, 174, 248), serine (116, 204, 218), ribitol (205, 217, 319). Peak areas were integrated by the auto-integration software supplied by the manufacturer.

Gas exchange and chlorophyll fluorescence measurements. Gas exchange and chlorophyll fluorescence measurements were performed using the LI-6400 system (Li-Cor) and parameters were calculated with the software supplied by the manufacturer. Conditions were: photon flux density = 1,000 $\mu\text{mol m}^{-2} \text{s}^{-1}$, chamber temperature = 26 °C, flow rate = 100 $\mu\text{mol s}^{-1}$, relative humidity = 60–70%. The oxygen inhibition of carbon assimilation (*A*) was calculated from *A* at *C_a* = 400 p.p.m. and atmospheric oxygen concentrations of 21% and 40%, respectively, using the equation: $\text{ox-inh.(\%)} = (A_{21} - A_{40})/A_{21} \times 100$. The apparent CO₂ compensation point (Γ) was deduced from *A/C_i* curves by regression analysis in the linear range of the curve. The CO₂ compensation point in the absence of dark respiration in the light (Γ^*) was measured as described²¹. The postillumination CO₂ burst (PIB) was measured under photorespiratory conditions (PFD = 1,000 $\mu\text{mol m}^{-2} \text{s}^{-1}$; *C_a* = 100 p.p.m.) as described²⁰. The determination of Γ^* and PIB is also described in **Supplementary Figures 4 and 5**.

Statistical analysis. Significance was determined according to Student's *t*-test using Excel software (Microsoft). Two-sided tests were performed for homoscedastic matrices.

Note: Supplementary information is available on the Nature Biotechnology website.

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AUTHOR CONTRIBUTIONS

R.K. established the transgenic lines. R.K. and M.N. conducted most of the physiological experiments. K.T. contributed to physiological and growth measurements. R.B. cloned the genes and established initial transgenic lines. H.-J.H. helped to establish enzymatic assays and metabolite measurements. R.R. established techniques for the estimation of photorespiration. N.S. and B.S. determined the chromosomal T-DNA integration sites. C.P. and F.K. designed the approach. C.P. supervised the work and wrote the manuscript.

COMPETING INTERESTS STATEMENT

The authors declare no competing financial interests.

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