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## Mixotrophic growth of the extremophile *Galdieria sulphuraria* reveals the flexibility of its carbon assimilation metabolism

Gilles Curien, Dagmar Lyska, Erika Guglielmino, Phillip Westhoff, Janina Janetzko, Marianne Tardif, Clément Hallopeau, Sabine Brugière, Davide Dal Bo, Johan Decelle, et al.

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1                   **MIXOTROPHIC GROWTH OF THE EXTREMOPHILE *GALDIERIA***  
2                   ***SULPHURARIA* REVEALS THE FLEXIBILITY OF ITS CARBON**  
3                   **ASSIMILATION METABOLISM**

4  
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48 **Summary**

- 49       • *Galdieria sulphuraria* is a cosmopolitan microalga found in volcanic hot  
50       springs and calderas. It grows at low pH in photoautotrophic (use of light as  
51       a source of energy) or heterotrophic (respiration as a source of energy)  
52       conditions, using an unusually broad range of organic carbon sources.  
53       Previous data suggested that *G. sulphuraria* cannot grow mixotrophically  
54       (simultaneously exploiting light and organic carbon as energy sources), its  
55       photosynthetic machinery being repressed by organic carbon.
- 56       • Here, we show that *G. sulphuraria* SAG21.92 thrives in photoautotrophy,  
57       heterotrophy and mixotrophy. By comparing growth, biomass production,  
58       photosynthetic and respiratory performances in these three trophic modes,  
59       we show that addition of organic carbon to cultures (mixotrophy) relieves  
60       inorganic carbon limitation of photosynthesis thanks to increased CO<sub>2</sub>  
61       supply through respiration. This synergistic effect is lost when inorganic  
62       carbon limitation is artificially overcome by saturating photosynthesis with  
63       added external CO<sub>2</sub>.
- 64       • Proteomic and metabolic profiling corroborates this conclusion suggesting  
65       that mixotrophy is an opportunistic mechanism to increase intracellular CO<sub>2</sub>  
66       concentration under physiological conditions, boosting photosynthesis by  
67       enhancing the carboxylation activity of Rubisco and decreasing  
68       photorespiration.
- 69       • We discuss possible implications of these findings for the ecological  
70       success of *Galdieria* in extreme environments and for biotechnological  
71       applications.

72

73 **Keywords:** *Galdieria sulphuraria*, mixotrophy, photorespiration, photosynthesis,  
74 red algae

75

76

## 77 **Introduction**

78  
79 The unicellular red alga *Galdieria sulphuraria* belongs to the Cyanidiophyceae, a  
80 class that includes five species often flourishing in different extreme environments  
81 (Merola *et al.*, 1981; Gross *et al.*, 1998; Gross & Oesterhelt, 1999; Oesterhelt *et*  
82 *al.*, 2007). From a phylogenetic perspective, plastids of the red algae gave rise to  
83 the complex plastids of, e.g., diatoms via secondary endosymbiosis (Yoon *et al.*,  
84 2002; Bhattacharya *et al.*, 2003; Yoon *et al.*, 2004). Like other members of this  
85 class (Doemel & Brock, 1971; Reeb & Bhattacharya, 2010) *G. sulphuraria* has an  
86 extremophile lifestyle, withstanding low pH (pH optimum at 2) and elevated  
87 temperatures (up to 56°C). It thrives in soils and forms biomats on rocks  
88 surrounding hot springs, fumaroles, or acid mining sites and even on burning coal  
89 spoil heaps (Moreira *et al.*, 1994; Gross *et al.*, 1998; Castenholz & McDermott,  
90 2010; Barcyté *et al.*, 2018). Some mesophilic species have been isolated from  
91 environments with moderate temperatures and/ or a neutral pH (Gross, W. *et al.*,  
92 2002; Yoon *et al.*, 2006; Azúa-Bustos *et al.*, 2009; Iovinella *et al.*, 2018). Genome  
93 analysis (Barbier *et al.*, 2005; Schonknecht *et al.*, 2013; Rossoni *et al.*, 2019a) has  
94 pinpointed a very high metabolic flexibility of this alga, which is confirmed by its  
95 ability to grow in photoautotrophy (exclusive use of light as an energy source) and  
96 heterotrophy (organic carbon respiration of more than 50 different substrates,  
97 (Gross & Schnarrenberger, 1995)). This capacity, along with the peculiar pH  
98 optimum for growth, allow *G. sulphuraria* to be cultivated in open ponds containing  
99 organic matter, overcoming other microorganisms, considered as contaminants in  
100 this case. Given these advantages for large-scale cultivation, *G. sulphuraria* is  
101 considered an emerging system for biotechnology applications (Schmidt *et al.*,  
102 2005; Henkanatte-Gedera *et al.*, 2017; Cizkova *et al.*, 2019).

103 The relationship between photosynthesis and glycolysis/respiration in higher  
104 plants and microalgae is complex (Avelange *et al.*, 1988; Kromer *et al.*, 1988;  
105 Gemel & Randall, 1992; Pärnik & Keerberg, 1995; Hoefnagel *et al.*, 1998;  
106 Tcherkez *et al.*, 2008). Photosynthesis/glycolysis/respiration interactions are prone  
107 to perturbation by mixotrophy, in which external organic carbon often interferes  
108 with carbon flow between chloroplasts, the cytosol and mitochondria. Several

109 green microalgae are capable of mixotrophic growth (Combres *et al.*, 1994; Wan  
110 *et al.*, 2011; Johnson & Alric, 2012; Cecchin *et al.*, 2018). While mixotrophy has  
111 always beneficial consequences on respiration, its effects on photosynthesis differ  
112 depending on the microalga considered: enhancement of photosynthesis was  
113 reported in one case (*Ettlia oleoabundans*, (Ferroni *et al.*, 2018)), while in other  
114 algae, including the diatoms *Phaeodactylum tricornutum* (Liu *et al.*, 2009; Villanova  
115 *et al.*, 2017) and *Nannochloropsis* (Fang *et al.*, 2004; Xu *et al.*, 2004)  
116 photosynthesis was unaffected. Decreased photosynthetic activity in mixotrophy  
117 has been reported in *Chlorella vulgaris* (Martinez & Orus, 1991; Cecchin *et al.*,  
118 2018) and *Chlamydomonas reinhardtii* where the Carbon Concentrating  
119 Mechanism (CCM, (Bogaert *et al.*, 2019)) and the light harvesting capacity  
120 (Perrineau *et al.*, 2014) is decreased by acetate along with the enhancement of  
121 respiration. While it has been reported that *G. sulphuraria* 074G could grow in the  
122 simultaneous presence of light and a carbon source, heterotrophy seemed to  
123 prevail in these conditions, as no photosynthetic O<sub>2</sub> production could be measured  
124 in the presence of glucose (Oesterhelt *et al.*, 2007).

125 Here, we show instead that photosynthesis and carbon metabolism (glycolysis and  
126 respiration) operate simultaneously in *Galdieria sulphuraria* SAG21.92 (a close  
127 relative of the 074G strain) under mixotrophic conditions, provided that the  
128 temperature conditions are kept close to the ones experienced by this alga in its  
129 natural environment. We show that performances in mixotrophy, exemplified by  
130 photosynthetic activity and biomass production, actually exceed the sum of the  
131 heterotrophic and photoautotrophic yields under limiting inorganic carbon. This  
132 synergistic effect stems from a stimulation of photosynthesis by CO<sub>2</sub> of respiratory  
133 origin, which overcomes the limitation to the Calvin-Benson-Bassham cycle and  
134 suppresses photorespiration.

135 Limitation originates from the very low inorganic carbon concentration available in  
136 acidic conditions (pH 2) that constitute the alga's natural growth environment.  
137 Notably, under these conditions, inorganic carbon is almost exclusively available  
138 as dissolved CO<sub>2</sub> (around 10 μM) while soluble bicarbonate is virtually absent.  
139 Consistent with this hypothesis, the synergistic effect of 'light' and 'dark' energetic

140 metabolisms is sensitive to respiration inhibitors and is lost upon addition of  
141 exogenous CO<sub>2</sub>, which outcompetes endogenous CO<sub>2</sub> of respiratory origin in  
142 relieving inorganic carbon limitation of the Calvin-Benson-Bassham cycle. We  
143 conclude that mixotrophy constitutes an efficient mechanism to increase  
144 intracellular CO<sub>2</sub> concentration under physiological conditions, allowing *G.*  
145 *sulphuraria* to successfully exploit all the energy resources available for growth in  
146 its rather challenging environment.

147

## 148 **Materials and Methods**

149

### 150 ***Strains, growth and media composition***

151 *Galdieria sulphuraria* SAG21.92 and 074G were obtained from the Culture  
152 Collection of Algae at Göttingen University (SAG) and were grown in sterile 2xGS  
153 modified Allen medium, pH 2.0, containing 20 mM of NaNO<sub>3</sub>, and 5 mM of  
154 inorganic phosphate (K<sub>2</sub>HPO<sub>4</sub> and KH<sub>2</sub>PO<sub>4</sub> in a 2/1 ratio (Allen, 1959)) at 42°C  
155 without or with organic substrates as indicated in the text. The concentration of  
156 organic substrates was selected on the basis of data reported in literature  
157 (Oesterhelt *et al.*, 2007). More precisely, glucose was employed at the  
158 concentration of 25 mM, as in (Oesterhelt *et al.*, 2007). The concentration of all the  
159 other organic compounds was adjusted to reach the same carbon atom  
160 concentration (150 mM). *G. sulphuraria* was grown either in 250 mL flasks (50 mL  
161 culture volume), in an incubator (Infors, Switzerland, continuous light, 30 μmol  
162 photons m<sup>-2</sup> s<sup>-1</sup>, 42°C, 100 rpm) or in a photobioreactor (Multicultivator, Photon  
163 System Instruments, Czech Republic). Inside the multicultivator, cells were  
164 provided with air or CO<sub>2</sub>-enriched air by active bubbling (see Methods S1).  
165 Moreover, the incident light intensity was adjusted daily to maintain constant  
166 transmitted light through the culture (see Results). This ‘luminostat’ regime  
167 ensures maximal absorption of light without allowing a dark zone to develop inside  
168 the photobioreactor (Cuaresma *et al.*, 2011). Growth was monitored daily by cell  
169 counting with a LUNA cell counter (Logos Biosystems, Inc. USA). Sorbitol  
170 consumption was measured using the D-Sorbitol/Xylitol assay kit (Megazyme).

171

172 **Cell fresh weight and dry weight quantification**

173 Cell pellet was resuspended in a small volume of water and centrifuged in pre-  
174 weighed Eppendorf tubes and pellet was weighed. For dry weight determination  
175 fresh cells pellets were dried for three days at 60°C, weighed and expressed as  
176 g.L<sup>-1</sup>.

177

178 **Clark electrode oxygen measurements**

179 Oxygen exchanges in solution were measured with a Clark-type electrode  
180 (Hansatech Instruments, UK) at 42°C. Respiration and gross photosynthesis were  
181 quantified by measuring the slope of O<sub>2</sub> changes in the dark and under light  
182 exposure, respectively. Net photosynthesis was calculated assuming O<sub>2</sub>  
183 consumption by the mitochondrion in the light is identical to that in the dark (Net  
184 photosynthesis =  $v_{O_2\text{light}} + |v_{O_2\text{dark}}|$ ).

185

186 **Photophysiology measurements**

187 Photosynthetic parameters were derived from quantification of chlorophyll  
188 fluorescence emission by cultures within the multicultivator. To this aim, we  
189 employed a custom-made fluorescence imaging system based on a previously  
190 published setup (Johnson *et al.*, 2009) modified as described in Methods S1. The  
191 photosynthetic electron transfer rate, ETR (a proxy of the carbon assimilation  
192 capacity (Maxwell & Johnson, 2000)) was calculated as  $(F_m' - F_s) / F_m' * PFD$ , where  
193  $F_m'$  and  $F_s$  are the fluorescence intensities measured after exposure to a  
194 saturating pulse and in steady state, respectively, in light-acclimated cells and PFD  
195 (Photosynthetic Flux Density) is the incident light intensity, measured in  $\mu\text{mol}$   
196  $\text{photons m}^{-2} \text{s}^{-1}$ . The cells were allowed to reach steady state fluorescence  
197 emissions at each intensity (5-10 minutes of light exposure depending on the  
198 intensity) before increasing the photon flux.

199

200 **Biochemistry and Proteomic analysis**

201 Western blot analysis was performed on cells grown for 7 days in the indicated  
202 conditions. Cells ( $10^9$  cells) were broken with a Precellys homogenizer (Bertin,



203 France), through three cycles of 30 seconds at 10,000 rpm separated by a 30-  
204 seconds interval. Total protein extracts were analyzed by immunoblotting with an  
205 anti- RuBisCO antibody (Agrisera, Sweden). An antibody against the  $\beta$  subunit of  
206 the ATPsynthase complex (Agrisera, Sweden) was used as a loading control. 10  
207  $\mu$ g of protein was loaded per well.

208 For proteomic analysis, algae were cultivated under the three conditions  
209 photoautotrophy, mixotrophy and heterotrophy in parallel in the same cultivator.  
210 Three multicultivator experiments were carried out one week apart and constituted  
211 the three independent biological replicates. Cells were collected on day 7 (*i.e.* 4  
212 days after addition of 25 mM D-sorbitol to mixotrophic and heterotrophic cultures).  
213 Proteins from whole cell extracts (40  $\mu$ g each) were solubilized in Laemmli buffer  
214 before being stacked in the top of a 4–12% NuPAGE gel (Life Technologies, US),  
215 stained with R-250 Coomassie blue (Bio-Rad, US) and in-gel digested using  
216 modified trypsin (sequencing grade, Promega, US) as previously described  
217 (Bouchnak *et al.*, 2019). Resulting peptides were analyzed by online  
218 nanoLC-MS/MS (Ultimate 3,000 RSLCnano coupled to Q-Exactive HF, Thermo  
219 Fisher Scientific, US) using a 200-min gradient. Peptides and proteins were  
220 identified using Mascot (version 2.6.0, Matrix Science). Spectra were searched  
221 against Uniprot (*G. sulphuraria* taxonomy, July 2019 version, 7347 sequences)  
222 concomitantly with a home-made list of contaminants frequently observed in  
223 proteomics analyses (trypsins and keratins, 250 sequences).

224

225 The Proline software (Bouyssié *et al.*, 2020) was used to filter the results  
226 (conservation of rank 1 peptides, peptide identification FDR < 1% as calculated on  
227 peptide scores by employing the reverse database strategy, minimum peptide  
228 score of 25, and minimum of 1 specific peptide per identified protein group). Proline  
229 was then used to extract the MS1-based intensities values of protein groups from  
230 unique peptides. Proteins identified in the reverse and contaminant databases (*i.e.*  
231 trypsin or keratin), and proteins identified with only 1 peptide with a score <40 were  
232 further discarded from the list. Proteins identified in only one or two conditions were  
233 kept for analysis without statistical treatment. Proteins identified in all three

234 conditions were submitted to statistical differential analysis using ProStaR  
235 (Wieczorek *et al.*, 2017; Wieczorek *et al.*, 2019). Detailed procedures are  
236 described in Methods S1.

237

### 238 ***Metabolite extraction and analysis***

239 Cells grown in a multicultivator were harvested at day 5 by centrifugation (4°C, 5  
240 min and 3,000 rcf), washed with ice-cold 0.9 % (w/v) NaCl, snap frozen in liquid  
241 nitrogen, and lyophilized overnight. Cells ( $5 \times 10^8$ ) were disrupted in a Mixer Mill  
242 (MM 400, Retsch GmbH, Haan, Germany) for 60 seconds at 30 Hz using metal  
243 beads and 500  $\mu$ L of ice-cold chloroform and methanol (1:2.3 ratio; containing 5  
244  $\mu$ M Ribitol and 2,4-Dimethylphenylalanine (both Sigma-Aldrich, Munich, Germany)  
245 as internal standards) with another round of shaking in the Mixer Mill. After a 2 h  
246 incubation at -20°C, 400  $\mu$ L of ice-cold deionized water (Milli Q, Merck Chemicals  
247 GmbH, Darmstadt, Germany) were added to induce phase separation. The  
248 samples were vortexed and centrifuged for 5 min at 4°C and 16,000 rcf. The  
249 aqueous phase was transferred to a new reaction tube and the organic phase was  
250 re-extracted with 400  $\mu$ L of ice-cold deionized water. Aqueous phases of each  
251 sample were combined and lyophilized overnight. After resuspension in 500  $\mu$ L of  
252 50% methanol 50  $\mu$ L were dried in a glass inlet for analysis by GC-MS and IC-MS.

253

254 For GC-MS analysis the samples were prepared and analyzed as described (Gu  
255 *et al.*, 2012) and (Shim *et al.*, 2020). Identification of metabolites was performed  
256 with MassHunter Qualitative (v b08.00, Agilent Technologies) by comparing  
257 spectra to the NIST14 Mass Spectral Library ([https://www.nist.gov/srd/nist-](https://www.nist.gov/srd/nist-standard-reference-database-1a-v14)  
258 [standard-reference-database-1a-v14](https://www.nist.gov/srd/nist-standard-reference-database-1a-v14)) and to a quality control sample containing  
259 all target compounds. Peaks were integrated using MassHunter Quantitative (v  
260 b08.00, Agilent Technologies). For relative quantification, all metabolite peak  
261 areas were normalized to the peak area of the internal standard ribitol.

262 For IC-MS a combination of a Dionex ICS-6000 HPIC and a high field Thermo  
263 Scientific Q Exactive Plus quadrupole-Orbitrap mass spectrometer following the  
264 method described in (Schwaiger *et al.*, 2017) and in Methods S1. Data Analysis

265 was conducted using Compound Discoverer (version 3.1, Thermo Scientific).  
266 Setting parameters for the untargeted metabolomics workflow and peak annotation  
267 criteria are described in Methods S1.

268

### 269 **Labelling experiments with $^{13}\text{C}$ -glucose**

270 Cells were cultivated in 250 mL Erlenmeyer flasks (50 mL culture volume) for four  
271 days under continuous light at  $60 \mu\text{mol m}^{-2} \text{s}^{-1}$ ,  $40^\circ\text{C}$  and ambient air (0.04%  $\text{CO}_2$ ).  
272  $\text{U-}^{13}\text{C}_6$ -glucose (Cambridge Isotope Laboratories Inc, Tewksbury, Massachusetts)  
273 was added at day 4 in a final concentration of 25 mM and the irradiance was  
274 increased to  $100 \mu\text{mol m}^{-2} \text{s}^{-1}$  either under ambient or elevated (2%)  $\text{CO}_2$   
275 conditions.

276  $1\text{-}2.5 \times 10^8$  cells were harvested 1, 4, 12, 24, 36, 48 and 60 hours after glucose  
277 addition as described above. Metabolites were extracted and measured by IC-MS  
278 as described above.

279 Data analysis was conducted with Compound Discoverer (version 3.1, Thermo  
280 Scientific) and the standard workflow for stable isotope labelling from Compound  
281 Discoverer was chosen. The default settings, which are 5 ppm mass tolerance, 30  
282 % intensity tolerance and 0.1 % intensity threshold for isotope pattern matching  
283 were used and the maximum exchange rate was set to 95%.

284

285

## 286 **Results**

287

### 288 ***G. sulphuraria* metabolises several organic substrates.**

289 Previous work (Oesterhelt *et al.*, 2007) has suggested that *G. sulphuraria* is unable  
290 to grow mixotrophically in the presence of light plus organic carbon but rather  
291 alternates between heterotrophy (in the presence of an external source of organic  
292 carbon) and phototrophy (upon inorganic carbon consumption). This conclusion  
293 was based on experiments carried out at  $25^\circ\text{C}$ , *i.e.* a temperature that is far from  
294 the physiological optimum of this alga (above  $40^\circ\text{C}$ ), and therefore decreases  
295 photosynthetic performances (Doemel & Brock, 1971; Ford, 1979; Rossoni *et al.*,  
296 2019b; Rossoni & Weber, 2019). Thus, we decided to reinvestigate the possible

297 occurrence of mixotrophy under conditions that resemble natural growth conditions  
298 (42°C, pH 2.0) in which *G. sulphuraria* displays maximum photosynthetic capacity.  
299 First, we sought compounds that could improve algal growth in presence of light.  
300 We found that several hexoses, disaccharides and pentoses, but also some  
301 polyols and amino acids (L-alanine, L-glutamate) were able to boost *G.*  
302 *sulphuraria*'s growth when compared to strict photoautotrophic conditions (Fig.  
303 S1). Conversely, some organic acids (malic and citric acid) and amino acids (L-  
304 aspartate, L-leucine, L-valine, L-isoleucine, L-asparagine) had either no effect or  
305 led to a growth inhibition when compared to photoautotrophic conditions. Acetic  
306 acid was lethal to the cells. Compound concentrations were 25 mM, i.e., the same  
307 value employed in the study by Oesterhelt and colleagues. In the case of  
308 disaccharides, we reduced the concentration by a factor of two, to keep the overall  
309 carbon atoms concentration constant.

310 Based on these results, we focused on sorbitol, a compound that boosts growth in  
311 the dark without inducing a significant loss of photosynthetic pigments (Gross &  
312 Schnarrenberger, 1995). We confirmed that sorbitol was able to sustain cell  
313 division in the dark (Fig. 1), but its effect on growth was largely enhanced by a  
314 concomitant exposure to light. The final dry weight and number of cells collected  
315 at the end of the exponential phase in the light plus carbon condition (orange  
316 symbols) exceeded the sum of cells obtained in the heterotrophic (black) plus the  
317 photoautotrophic (green) conditions (Fig. 1a-b). This finding indicates that *G.*  
318 *sulphuraria* is not only able to perform true mixotrophy under high temperature,  
319 dim light and presence of external organic carbon sources, but that this trophic  
320 mode is highly beneficial for its growth capacity. We obtained similar effects  
321 replacing sorbitol with a monosaccharide (glucose) and a disaccharide  
322 (saccharose) (Fig. S2).

323

### 324 ***Respiration boosts photosynthesis in mixotrophic Galdieria cells.***

325 To further characterize the consequences of mixotrophy in *G. sulphuraria*, we  
326 transferred half of the cells grown in mixotrophy for five days (Fig. 1) to  
327 heterotrophic condition and monitored growth of the four samples

328 (photoautotrophic: green, heterotrophic: black, mixotrophic: orange and  
329 mixotrophic transferred to heterotrophy: grey) for another five days. While the  
330 mixotrophic cells continued to display a higher growth capacity than the  
331 heterotrophic plus photoautotrophic ones, the mixotrophic cells transferred to the  
332 dark (grey) slowly reached the same cell density (Fig. 1a) and dry weight (Fig. 1b)  
333 as the heterotrophic culture, *i.e.*, they lost the benefits provided by the  
334 simultaneous exposure to light and organic carbon within a few days. We conclude  
335 therefore that mixotrophy promotes a synergistic interaction between light and dark  
336 energy metabolisms, which slowly disappears when the light supply is halted.

337 In the experiments described above, photoautotrophic growth was most likely  
338 limited by the low light intensity ( $30 \mu\text{mol photons m}^{-2} \text{s}^{-1}$ ), which was kept constant  
339 during growth, and therefore rapidly became limiting for photosynthesis when the  
340 cell concentration was increased in the flasks. Gas diffusion could also be limiting  
341 in flasks. Therefore, we repeated experiments in a photobioreactor (Multicultivator,  
342 PSI, Czeck Republic, Fig. S3), where air bubbling ensured a more efficient gas  
343 delivery to the algae. Moreover, the intensity of the incident light was progressively  
344 increased in this setup to maintain a linear relationship between the cell number  
345 and the absorption. We reproduced the improvement of biomass productivity in  
346 mixotrophy with the photobioreactor (Fig. 2), where we could monitor biomass  
347 production and photosynthetic performances on actively growing cells using a  
348 custom-built fluorescence imaging setup to monitor photosynthesis via the electron  
349 transfer rate (ETR) parameter (Maxwell & Johnson, 2000) (Fig. S3).

350 The ETR in the photoautotrophic cultures was lower than in mixotrophic ones (Fig.  
351 2a). The difference was larger during the first days of culturing (Fig. S4, days 4  
352 and 5, *i.e.* the first and second day after sorbitol addition), and then photosynthesis  
353 progressively diminished in the mixotrophic cells (Fig. S4, days 6 and 7, *i.e.* the  
354 third and fourth day of mixotrophy), where we also observed a large variability in  
355 the photosynthetic capacity (Fig. S4, day 7). We ascribe this variability to a  
356 differential consumption of sorbitol, and therefore of the mixotrophic synergistic  
357 effect, in the various samples. Consistent with this hypothesis, enhancement of  
358 photosynthesis was re-established in mixotrophic cultures, provided that sorbitol,

359 nearly exhausted after four days (Fig. S5, day 7) was added again to the growth  
360 medium (Fig. S6).

361 To explain the synergistic effect of mixotrophy, we reasoned that photosynthesis  
362 could be limited by the availability of inorganic carbon in photoautotrophic cells.  
363 The latter is present only as CO<sub>2</sub> and at very low concentration (10 μM, (Gross *et*  
364 *al.*, 1998)) at ambient air in *G. sulphuraria*'s cultures, due to the acidic pH (pH 2).  
365 Mixotrophy could alleviate this limitation by providing extra CO<sub>2</sub> of mitochondrial  
366 origin via enhanced respiration (Fig. 2c, Fig. S7). We tested this hypothesis by two  
367 approaches. First, we poisoned mixotrophic and photoautotrophic cultures with  
368 myxothiazol and SHAM, known inhibitors of the cyanide sensitive and insensitive  
369 respiratory pathways, respectively, and measured consequences on  
370 photosynthetic activity. Addition of these inhibitors completely abolished the  
371 enhancement of photosynthetic activity and of biomass productivity by mixotrophy  
372 (Fig. 2d-f). Next, we increased the CO<sub>2</sub> availability to the cells in mixotrophic  
373 cultures, to outcompete endogenous CO<sub>2</sub> of respiratory origin with an excess of  
374 exogenous inorganic carbon. As a prerequisite for this experiment, we calibrated  
375 the CO<sub>2</sub> requirement for optimum photosynthesis in our growth conditions  
376 (transmitted light of 10 μmol photons m<sup>-2</sup> s<sup>-1</sup>). We found that photoautotrophic  
377 growth was increased by CO<sub>2</sub> up to a concentration of 2% CO<sub>2</sub> (Fig. S8a), the  
378 apparent affinity for CO<sub>2</sub> being 0.5 % ca. Upon addition of external CO<sub>2</sub>, the  
379 photosynthetic capacity in photoautotrophic conditions increased and the biomass  
380 produced in heterotrophic plus photoautotrophic conditions became equal to that  
381 observed in mixotrophy (Fig. 2g-i). Overall, these data indicate that the synergy  
382 between respiration and photosynthesis is lost when the respiration is inhibited or  
383 when the photosynthesis becomes saturated with externally supplied CO<sub>2</sub>.  
384 Moreover, we hypothesize that photorespiration should be decreased to very low  
385 rates at saturating CO<sub>2</sub>, possibly contributing to the gain in biomass productivity at  
386 high CO<sub>2</sub> concentrations. In these experiments, we also observed that the amount  
387 of biomass produced by phototrophic cells supplemented with air was the same  
388 irrespective of the light intensity employed (Fig S8b). Conversely, biomass  
389 production could be increased by increasing the light intensity in both phototrophic

390 cells supplemented with 0.5% CO<sub>2</sub> (Fig S8c) or in mixotrophic cells (Fig S8d).  
391 These findings are fully consistent with the hypothesis that photosynthesis is CO<sub>2</sub>  
392 limited in air, and that this limitation can be alleviated by endogenous (mixotrophy)  
393 or exogenous CO<sub>2</sub>.

394

395 ***Metabolic acclimation to mixotrophy in G. sulphuraria.***

396 The observation that mixotrophy enhances photosynthesis to a similar level as  
397 upon addition of external CO<sub>2</sub> to *G. sulphuraria*, suggests that mixotrophy behaves  
398 as a strategy to traffic CO<sub>2</sub> from the mitochondria to the plastid, allowing this alga  
399 to successfully exploit all the energy resources available for growth and to  
400 minimize energy loss through photorespiration.

401 To substantiate this hypothesis, we performed a complete survey of the metabolic  
402 changes between the three trophic lifestyles, and relate these changes to  
403 modifications in the cell proteome. We found that photosynthetic proteins  
404 (complexes of the electron transfer chain, enzymes of the Calvin-Benson-  
405 Bassham cycle and transporters involved in triose phosphate export) were  
406 downregulated in mixotrophic conditions compared to photoautotrophic conditions  
407 (Fig. 3), in agreement with previous suggestions (Gross & Schnarrenberger, 1995;  
408 Oesterhelt *et al.*, 2007). Conversely, respiratory protein levels remained relatively  
409 constant in the three conditions. This observation (photosynthetic activity is  
410 enhanced in mixotrophy despite the downregulation of the photosynthetic  
411 machinery) fully supports the conclusion that intracellular increase in CO<sub>2</sub> due to  
412 enhanced respiratory activity more than compensates for the decrease in Rubisco  
413 (see also Fig. S9).

414 In line with the hypothesis that mixotrophy channels CO<sub>2</sub> from respiration to  
415 photosynthesis, proteomic analysis indicates that all the enzymes involved in  
416 photorespiration (phosphoglycolate phosphatase, glycolate oxidase, serine-  
417 glyoxylate aminotransferase, glycine decarboxylase, glycine/serine  
418 hydroxymethyltransferase, hydroxypyruvate reductase, glycerate kinase) were  
419 less abundant in mixotrophy. This is also true for Rubisco activase (Gasu\_19410,  
420 dataset S1-2), an enzyme that was shown to be important under low CO<sub>2</sub> in

421 *Chlamydomonas* (Pollock *et al.*, 2003). These findings are also corroborated by  
422 metabolite analysis (Fig. 4a). The amounts of the oxygenation product of Rubisco,  
423 2-phosphoglycolate are highest under photoautotrophic conditions, lower in  
424 mixotrophic conditions, and very low in heterotrophic conditions. Glycine  
425 accumulates, likely due to a higher reduction potential inside the mitochondrial  
426 matrix under mixotrophic conditions, which will reduce the rate of oxidative  
427 decarboxylation of glycine by glycine decarboxylase. Consequently, the glycine to  
428 serine ratio was inverted compared to photoautotrophic conditions. The amounts  
429 of glycerate and 3-phosphoglycerate under mixotrophic conditions are mimicking  
430 those in heterotrophically grown cells (Fig. 4a).

431 Proteins involved in a putative C4-like carbon concentrating cycle (Rademacher *et al.*, 2017) (Fig. 3, 4b) followed the same pattern as the photorespiratory enzymes.  
432 Carbonic anhydrase and phosphoenolpyruvate carboxylase were more abundant  
433 under photoautotrophic conditions than under mixotrophic or heterotrophic  
434 conditions, and, in agreement with this finding, photoautotrophic cells also  
435 contained higher amounts of phosphoenolpyruvate (PEP) than mixotrophic or  
436 heterotrophic cells (Fig. 4b). The presence of this carbon concentrating cycle in  
437 photoautotrophic conditions could be supported by increased steady-state levels  
438 of phosphorylated C3 compounds, as suggested by the downregulation of  
439 pyruvate kinases in phototrophy (PEP consumption might be decreased) and  
440 strong induction of pyruvate ortho-phosphate dikinase (producing PEP). We  
441 assume that oxaloacetate (OAA) under photoautotrophic conditions is  
442 decarboxylated by PEP carboxykinase (PEPCK), and not after reduction into  
443 malate by malate dehydrogenase and decarboxylation by mitochondrial malic  
444 enzyme. This hypothesis is supported by the finding that mitochondrial malic  
445 enzyme (ME) is strongly decreased in photoautotrophy (Fig. 3) and the malate pool  
446 size is smaller under this condition than in mixo- or heterotrophy. We note that  
447 decarboxylation by PEPCK (as compared to ME) is energy conserving and directly  
448 yields PEP for a new round of carboxylation by PEP carboxylase.

450 While part of the increase in biomass production in mixotrophic conditions can be  
451 attributed to the repression of photorespiration, other benefits of the mixotrophic



452 lifestyle may come from more carbon units being shuttled into anabolic pathways.  
453 Indeed, we observed a general increase of metabolites of the oxidative pentose  
454 phosphate pathway (Ribulose-5P, Sedoheptulose-7P) and nucleoside  
455 triphosphates (ATP, GTP, UTP, CTP) as successor metabolites (Fig. 4c). The  
456 amounts do not differ between autotrophic and heterotrophic cultures but are  
457 clearly increased under mixotrophic conditions providing evidence for a higher flux  
458 of carbon at least into purine and pyrimidine synthesis.

459 Labelling experiments using  $^{13}\text{C}$ -labelled glucose, a sugar with similar effects on  
460 cell growth and biomass production as sorbitol (Fig. S2), further support this notion.  
461 We found a rapid incorporation of  $\text{CO}_2$  from  $^{13}\text{C}$  glucose into photosynthetic  
462 metabolites, such as Ribulose1,5-bisphosphate (RuBP), Sedoheptulose 1,7-  
463 bisphosphate (SBP), and 2-phosphoglycolate (2-PG) (Fig. 5). While RuBP also  
464 occurs in the oxidative pentose phosphate pathway, SBP and 2-PG are  
465 metabolites solely formed in the Calvin-Benson-Bassham cycle and can only carry  
466 a label when  $^{13}\text{CO}_2$  released by respiration is fixed. Incorporation of the label by  
467 shuttling of carbon backbones from the cytosol into the chloroplast is unlikely since  
468 the solute transporters in the *G. sulphuraria*'s chloroplast envelope do not favor  
469 the import of glycolytic intermediates under photosynthetic conditions (Linka *et al.*,  
470 2008). The rate of incorporation of  $^{13}\text{C}$  is much reduced when external  $\text{CO}_2$  levels  
471 are increased to 2%. Interestingly, the tricarboxylic acid cycle intermediate  
472 succinate exhibits a similar pattern of delayed labelling under high  $\text{CO}_2$  conditions  
473 when compared to ambient air, indicating a slowed down glucose usage. Thus, the  
474 delay of label incorporation into the Calvin-Benson-Bassham cycle intermediates  
475 can be traced back to lower levels of labelled respiratory  $\text{CO}_2$  under  $\text{CO}_2$  saturated  
476 conditions.

477

## 478 **Discussion**

479

480 At variance with a previous report (Oesterhelt *et al.*, 2007), *G. sulphuraria* cells are  
481 capable of a true mixotrophy, when transferred from strictly photoautotrophic  
482 conditions to a light and organic carbon regime, provided that the temperature  
483 conditions are kept close to the ones experienced by this alga in its natural

484 environment. This is not only true for the *G. sulphuraria* SAG21.92 strain used  
485 here, but also for *G. sulphuraria* 074G, *i.e.*, the strain used in the previous study  
486 by Oesterhelt *et al.*, (2007) when tested in the presence of the same external  
487 organic carbon sources employed here (See Fig. S10). Acclimation of the strictly  
488 photoautotrophic Cyanidiophyceae *Cyanidioschyzon merolae* to suboptimal  
489 growth temperatures of 25°C, led to massive rearrangements of the photosynthetic  
490 apparatus and a lower photon-to-oxygen conversion rate when compared to cells  
491 grown at 42°C (Nikolova *et al.*, 2017). Also, cultivation of *G. sulphuraria* at 25°C  
492 led to a downregulation of transcripts encoding components of the photosynthetic  
493 machinery (Rossoni *et al.*, 2019b). Therefore, cultivation at suboptimal  
494 temperatures may not be in favor of high photosynthetic rates and drive  
495 Cyanidiophyceae species capable of heterotrophic growth towards this trophic  
496 state.

497 Mixotrophy deeply alters the carbon metabolism of *G. sulphuraria* cells. Under  
498 photoautotrophic conditions, CO<sub>2</sub> is mainly concentrated by the PEPC/PEPCK  
499 driven CCM (Rademacher *et al.*, 2017). This process is repressed in mixotrophy.  
500 Moreover, enhanced respiration relieves the limitation of photosynthesis by  
501 inorganic carbon, which is at a low concentration (µmolar range) in the acid growth  
502 medium of this alga. We can quantify the extent of this process using the Clark  
503 electrode (as in Fig S7) in a closed configuration, to avoid gas exchanges with the  
504 atmosphere (representative traces in Fig S11a,c). In this case, the amount of O<sub>2</sub>  
505 produced by photosynthesis (32.3 ± 7.5 µM and 76.6 ± 2 µM in photoautotrophy  
506 and mixotrophy, respectively) is commensurate with the amount of CO<sub>2</sub> available  
507 to Rubisco, *i.e.* the sum of respiratory CO<sub>2</sub> (22 ± 10.5 µM and 61 ± 1.5 µM  
508 respectively, assuming a 1/1 stoichiometry with consumed O<sub>2</sub>) plus the small CO<sub>2</sub>  
509 amount present in the medium (10 µM *ca* at pH 2) (Fig. S11c,d). These estimates  
510 clearly indicate that respiration in mixotrophy sets the rate of photosynthesis under  
511 limited CO<sub>2</sub> conditions. The proximity between mitochondria and chloroplasts  
512 (highlighted in red and green, respectively, in Fig. S12) may favor this process,  
513 facilitating intracellular gas exchange between the two cell organelles, as already  
514 shown in the case of other microalgae (Lavergne, 1989).

515 At the same time, increased intracellular CO<sub>2</sub> concentration is expected to lower  
516 the rate of photorespiration in mixotrophy. Although the Rubisco enzymes from  
517 Cyanidiophyceae show some of the highest carboxylation specificities reported to  
518 date (Sugawara *et al.*, 1999), photorespiration is expected to proceed at high rates  
519 at the high temperatures and low CO<sub>2</sub> concentrations under which *Galdieria* grows.  
520 Indeed, knockout of peroxisomal glycolate oxidase in the transformable  
521 Cyanidiales alga *C. merolae* demonstrated that a functional photorespiratory  
522 pathway is essential for survival of these algae under ambient CO<sub>2</sub> concentrations  
523 (Rademacher *et al.*, 2016). The observed increase in the rate of photosynthesis  
524 and gain of biomass under high CO<sub>2</sub> and mixotrophic conditions (25 ± 6 %, when  
525 combining data from Fig. 1-2) is consistent with overcoming the expected loss of  
526 biomass gain due to photorespiration under photoautotrophic conditions.

527 In conclusion, by bypassing the possible metabolic antagonism between  
528 respiration and photosynthesis, *G. sulphuraria* can exploit the plethora of  
529 transporters encoded by its genome (Schonknecht *et al.*, 2013; Rossoni *et al.*,  
530 2019a) and import organic carbon available in its environment and to boost CO<sub>2</sub>  
531 availability for photosynthesis. While this phenomenon certainly exists in other  
532 phototrophs (e.g. Rolland *et al.*, 1997), the capacity to enhance photosynthesis  
533 with respiratory CO<sub>2</sub> when the latter process is increased by exogenous carbon  
534 sources could be particularly relevant in *G. sulphuraria*. This alga thrives in an  
535 extreme environment, where growth is limited by low pH, high temperature and  
536 possibly light availability. Dissolved inorganic carbon is very low in this hot and  
537 acidic milieu (in fact its concentration inversely correlates with the pH of different  
538 collection sites in Yellowstone National Park) (Boyd *et al.*, 2012; Hamilton *et al.*,  
539 2012) and its light-driven uptake is fairly low when compared to alkaline thermal  
540 habitats. Conversely, the concentration of dissolved organic carbon can be  
541 relatively high in the acidic hot springs (from 17 µM to 3 mM (Nye *et al.*, 2020)).  
542 Values could become much higher when this alga proliferates in mats (Gross *et al.*,  
543 1998), where by-products of every group of microorganisms may serve as  
544 "food" for other groups.

545 Based on these considerations, it is tempting to speculate that while  
546 photosynthesis should allow cells to colonize new environments devoid of any  
547 organic carbon source, the peculiar division mode of *G. sulphuraria* (formation of  
548 endospores associated with the release in the media of the mother cell wall  
549 remnants), may favor mixotrophy on a longer time scale. In the acidic conditions  
550 where *G. sulphuraria* lives, this material is probably rapidly hydrolyzed, providing  
551 an organic carbon source to the algae, along with other external sources for  
552 dissolved organic carbon, like e.g. high-temperature acid-digested wood (Nye *et*  
553 *al.*, 2020). Thanks to the abundance of transporters, this alga could outcompete  
554 other microorganisms such as fungi, which are also found in these extreme  
555 conditions, for growth. Thus, the coexistence of phototrophic, mixotrophic, and  
556 heterotrophic lifestyles thanks to the subtle compromise between the activity of the  
557 two energy-producing pathways (photosynthesis and respiration) would represent  
558 a key element for fitness and explain the success of *G. sulphuraria* to thrive in its  
559 extreme ecological niche. High fluctuations in the availability of dissolved organic  
560 and inorganic carbon, light, temperature, etc. in these environments possibly  
561 selected for the maintenance of a metabolic flexibility (Gross, 1999; Gross,  
562 Wolfgang *et al.*, 2002; Ciniglia *et al.*, 2004; Cho *et al.*, 2020), which may have also  
563 allowed Cyanidiales to invade more moderate habitats (Yoon *et al.*, 2006; Azúa-  
564 Bustos *et al.*, 2009; Castenholz & McDermott, 2010) and to disperse over long  
565 distances to geographically isolated extreme habitats (Rossoni *et al.*, 2019a).  
566 The same metabolic flexibility opens interesting perspectives to exploit this alga  
567 for biotechnology applications. *G. sulphuraria* has already been employed in the  
568 fields of pigment/antioxidant production, bioremediation and bioenergy (Cizkova *et*  
569 *al.*, 2019) and the possibility to exploit its lifestyle flexibility should be explored to  
570 cultivate this alga in organic matter-rich open ponds without contamination by other  
571 microorganisms.

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596

597 **Author Contributions**

598 G.C., D.L., A.P.M.W. and G.F. designed research; G.C., D.L., E.G., P.W., J.J.,  
599 C.H., S.B., D.D.B., J.D., B.G., D.F., M.C. and G.F. performed research; G.C.,  
600 D.L., P.W., M.T., C.R., M.F., A.P.M.W. and G.F. analyzed data; G.C., D.L.,  
601 A.P.M.W and G.F. wrote the paper.

602

603 **Data availability**

604 The original contributions presented in the study are included in the article and in  
605 the Supplementary information and supplementary dataset files. Further inquiries  
606 can be directed to the corresponding author

607

608

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- 850  
851  
852
- 853 **Dataset S1:** Proteins involved in photosynthesis, central metabolism and  
854 respiration were selected from the complete proteomic dataset (see  
855 Supplementary Dataset S2) and used to build Fig. 3.
- 856
- 857 **Dataset S2:** Compared proteomic analysis between photoautotrophic, mixotrophic  
858 and heterotrophic growth conditions.
- 859
- 860 **Dataset S3:** Compared metabolomic analysis between photoautotrophic,  
861 mixotrophic and heterotrophic growth conditions.
- 862
- 863 **Figure S1:** Consequences of different substrates on *G. sulphuraria* growth in the  
864 light.
- 865 **Figure S2:** *G. sulphuraria* growth in photoautotrophic, mixotrophic and  
866 heterotrophic conditions driven by a polyol, an hexose and a disaccharide.
- 867 **Figure S3:** Experimental setup to expose cells to a constant photons/cell ratio.
- 868 **Figure S4:** *In situ* measurements of photosynthetic electron transfer rate (ETR) in  
869 photoautotrophic (light) and mixotrophic (light + 25 mM D-sorbitol) cells.
- 870 **Figure S5:** Enhancement of cell growth by mixotrophy and sorbitol consumption  
871 in *G. sulphuraria*.
- 872 **Figure S6:** Mixotrophy is restored in *G. sulphuraria* upon addition of a carbon  
873 source.
- 874 **Figure S7:** Respiration and net photosynthesis were measured every day in the  
875 three different growth conditions (photoautotrophy, mixotrophy and heterotrophy).
- 876 **Figure S8:** Biomass production as a function of transmitted light intensity and CO<sub>2</sub>  
877 concentration.
- 878 **Figure S9:** Immunodetection of RuBisCO in phototrophic and mixotrophic cultures  
879 under ambient and enhanced CO<sub>2</sub> atmosphere.

880 **Figure S10:** Comparative analysis of phototrophic, mixotrophic and heterotrophic  
881 performances in *G. sulphuraria* 074 G and SAG21.92 species with D-sorbitol and  
882 D-glucose.

883 **Figure S11:** Respiration fuels photosynthesis in photoautotrophic and mixotrophic  
884 *G. sulphuraria* cultures.

885 **Figure S12:** Transmission electron microscopy of *G. sulphuraria* SAG21.92 grown  
886 5 days under photoautotrophic, mixotrophic and heterotrophic conditions.

887

888 **Methods S1:** Microalgae and media composition, growth, cell fresh weight and dry  
889 weight estimates, Clark electrode oxygen and photophysiology measurements,  
890 mass spectrometry-based proteomic analyses, metabolic analyses by IC-MS,  
891 electron microscopy sample preparation and observation.

892

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895

896 **Figure legends**

897

898 **Figure 1: Growth enhancement of *Galdieria sulphuraria* SAG21.92 by**  
899 **reduced carbon sources is light dependent. a**, Growth curves. Data from 3  
900 biological replicates  $\pm$  S.D. Error bars are shown when larger than the symbol size.  
901 *G. sulphuraria* was grown in flasks at ambient CO<sub>2</sub> in photoautotrophic (light only,  
902 30  $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$ , green), mixotrophic (30  $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$  plus D-  
903 sorbitol 25 mM, orange) and heterotrophic (absence of light, presence of D-sorbitol  
904 25 mM, black). The initial cell concentration was  $1.5 \times 10^6$  cells per mL. At day 5, the  
905 mixotrophic culture was split in two parts, and light was switched off in one culture,  
906 (grey). Growth was carried out at 42°C with shaking at 100 rpm, pH 2. **b**, Dry weight  
907 estimated at day 9. Mixotrophic biomass (orange bars) exceeds the sum of  
908 photoautotrophic (green bars) and heterotrophic (black bars) biomass, highlighting  
909 the existence of a synergy under mixotrophic conditions. Data from 3 biological  
910 replicates  $\pm$  S.D. \*\* indicate that at the 0.01 level the means of the two populations  
911 (mixotrophy on one side; heterotrophy + photoautotrophy on the other one) means  
912 are statistically different (Anova test). The concentration of inorganic nitrogen was  
913 20 mM, while that of inorganic phosphate was 5 mM.

914

915

916 **Figure 2: *In situ* measurements of photosynthetic electron transfer rate (ETR)**  
917 **in photoautotrophic (light) and mixotrophic (light + 25 mM D-sorbitol)**  
918 ***Galdieria sulphuraria* SAG21.92 cells and biomass production.** Cells were  
919 inoculated at  $3.5 \times 10^6$  cell per mL and grown in a photobioreactor in the light  
920 (transmitted light 10  $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$ ) and air before D-sorbitol was added in  
921 the absence (heterotrophy, black) and in the presence of light (mixotrophy,  
922 orange). Light was increased every day to keep the transmitted light to a constant  
923 value of 10  $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$ . Growth was followed at 42°C and pH 2. **a, d, g**,  
924 after five days of growth (*i.e.* 2 days after the addition of D-sorbitol), ETR was  
925 measured directly on cultures within the photobioreactor, to avoid possible

926 temperature stress. Measurements were done in air, in the absence (**a, b**) and  
 927 presence (**d, e**) of respiratory inhibitors (SHAM 1 mM and myxothiazol (10  $\mu$ M),  
 928 added 24 h before measurements), or in a CO<sub>2</sub>-enriched (0.5%) atmosphere (**g**,  
 929 **h**). **a, b, g** photosynthetic electron transfer: data from 3 biological replicates  $\pm$  S.D.  
 930 **b, e, h**, Biomass production in photoautotrophic (green, data from 12 biological  
 931 replicates  $\pm$  S.D.), heterotrophic (black, data from 8 biological replicates  $\pm$  S.D.)  
 932 and mixotrophic (orange, data from 8 biological replicates  $\pm$  S.D.) conditions,  
 933 respectively. Cells were collected after 7 days of growth (i.e. 4 days after addition  
 934 of D-sorbitol). **c, f, i**, Sketches representing possible CO<sub>2</sub> sources for  
 935 photosynthesis in the three examined conditions. \*\* indicate that at the 0.01 level  
 936 the means of the two populations (mixotrophy on one side;  
 937 heterotrophy+photoautotrophy on the other one) means are statistically different  
 938 (Anova test).

939

940 **Figure 3: Synthesis of proteomic changes between phototrophic,**  
 941 **mixotrophic and heterotrophic growth conditions of *Galdieria sulphuraria***  
 942 **SAG21.92.** Plastid is indicated in green, cytosol in white, mitochondrion in orange  
 943 and peroxisome in grey. Proteins are identified by their SwissProt accessions;  
 944 boxes on top of protein names represent fold-changes (protein average  
 945 abundance in one condition was compared with the average abundance of the  
 946 other two conditions - left photoautotrophy, middle mixotrophy, right heterotrophy).  
 947 Proteins displaying statistically significant changes (see methods) are highlighted  
 948 in yellow. They include proteins involved in carbon concentrating mechanism  
 949 (Pyruvate phosphate dikinase -M2XY57, carbonic anhydrase-M2XTP2, PEP  
 950 carboxylase-M2XIX2), which are much more abundant in photoautotrophic  
 951 conditions than in mixotrophic or heterotrophic conditions. Enzymes involved in  
 952 photorespiration-dashed arrows-(Phosphoglycolate phosphatase-M2XAQ1,  
 953 Glycolate oxidase-M2WRR8, Serine-glyoxylate aminotransferase-M2Y9J6,  
 954 Glycine decarboxylase P proteins-M2X9U4, Glycine/serine  
 955 hydroxymethyltransferase-M2XX08, Hydroxypyruvate reductase-M2XII5,  
 956 Glycerate kinase-M2XRC5) follow the same pattern as CCM enzymes.

957 Conversely, pyruvate kinases (especially M2WVY6) are strongly repressed under  
958 phototrophic condition, possibly to maintain a high PEP-oxaloacetate (OAA) pool  
959 for efficient fluxes in the carbon concentration cycle. Enzymes involved in  
960 photosynthesis are reduced under mixotrophic condition compared to  
961 photoautotrophic condition and strongly reduced under heterotrophic conditions.  
962 Mitochondrial respiratory proteins involved in the Krebs cycle or in ATP production  
963 are virtually not affected with the exception of fumarase and malic enzyme strongly  
964 reduced under phototrophic condition. Only representative proteins of the different  
965 complexes (e.g. photosynthesis, respiration) are represented. A more complete list  
966 of proteins can be found in Dataset S1. The complete set of proteomic data is  
967 available in Dataset S2.

968

969 **Figure 4: Metabolic changes between phototrophic, mixotrophic and**  
970 **heterotrophic growth conditions of *Galdieria sulphuraria* SAG21.92.** Non-  
971 phosphorylated metabolites were analyzed by GC-MS, phosphorylated  
972 metabolites were analyzed using IC-MS. Quantification of metabolites is provided  
973 in Dataset S3. Green bars: photoautotrophy; orange bars: mixotrophy; black bars:  
974 heterotrophy. **a**, Changes of metabolites involved in photorespiration. 2P-glycolate  
975 as a photorespiration-specific metabolite is boxed in red. Glycolate, glycine, serine  
976 and glycerate are transported between cellular compartments as indicated by  
977 dashed arrows. PGLP: phosphoglycolate phosphatase; GOX: glycolate oxidase;  
978 GGAT: glutamate:glyoxylate aminotransferase; GDC: glycine decarboxylase  
979 complex; SHMT: serine hydroxymethyltransferase; SGAT: serine:glyoxylate  
980 aminotransferase; HPR: hydroxypyruvate reductase; GLYK: glycerate kinase. **b**,  
981 Metabolites involved in a putative C4-type CCM. CA: Carbonic anhydrase; PPC:  
982 phosphoenolpyruvate carboxylase; PEPCK: phosphoenolpyruvate carboxykinase;  
983 PPK: pyruvate phosphate dikinase; PEP: phosphoenolpyruvate. **c**, Metabolic  
984 changes of intermediates of upper glycolytic pathways (EMP, ED, PPP) and  
985 purine/ pyrimidine metabolism. The pentose-5P (ribulose-5P, xylulose-5P, ribose-  
986 5P, marked with an asterisk) could not be distinguished and are plotted in a single  
987 boxed graph. SDH: sorbitol dehydrogenase; FRK: fructokinase; GPI: glucose-6P

988 isomerase; G6PD: glucose-6P dehydrogenase; GND: 6-phosphogluconate  
989 dehydrogenase; EBB: phosphogluconate dehydratase; EDA: KDPG aldolase;  
990 PFK: 6-phosphofructokinase; FBPase: fructose-1,6P bisphosphatase; FBA:  
991 fructose bisphosphate aldolase; TIM: triosephosphate isomerase; RPE: ribulose-  
992 5P epimerase; RPI: ribulose-5P isomerase; TKT: transketolase; TAL:  
993 transaldolase. The full list of metabolite changes can be found in Dataset S3. Y  
994 axes in the graphs correspond to normalized peak areas and error bars represent  
995 the standard deviation of biological quadruplicates.

996

997

998 **Figure 5: Incorporation of carbon derived from  $^{13}\text{C}$ -labelled glucose into**  
999 **intermediates of the Calvin-Benson-Bassham (a) and tricarboxylic acid (b)**  
1000 **cycles during mixotrophic cultivation of *Galdieria sulphuraria* SAG21.92 in**  
1001 **two different  $\text{CO}_2$  concentrations.** Incorporation rates are displayed as average  
1002 number of labelled carbon atoms in each molecule (average exchange). Error bars  
1003 represent the standard deviation of biological quadruplicates. Light orange: cells  
1004 grown in ambient air (0.02%  $\text{CO}_2$ ). Dark orange cells grown in air supplied with 2%  
1005  $\text{CO}_2$ .

1006 RuBP: Ribulose 1,5-bisphosphate; 3-PGA: 3-phosphoglycerate; 2-PG: 2-  
1007 phosphoglycolate; BPG: 1,3-bisphosphoglycerate; DHAP: Dihydroxyacetone  
1008 phosphate; GAP: glyceraldehyde 3-phosphate; FBP: Fructose 1,6-bisphosphate;  
1009 F6P: Fructose 6-phosphate; E4P: Erythrose 4-phosphate; Xu5P: Xylulose 5-  
1010 phosphate; SBP: Seduheptulose 1,7-bisphosphate; S7P: Seduheptulose 7-  
1011 phosphate; R5P: Ribose 5-phosphate; Ru5P: Ribulose 5-phosphate.

1012

1013



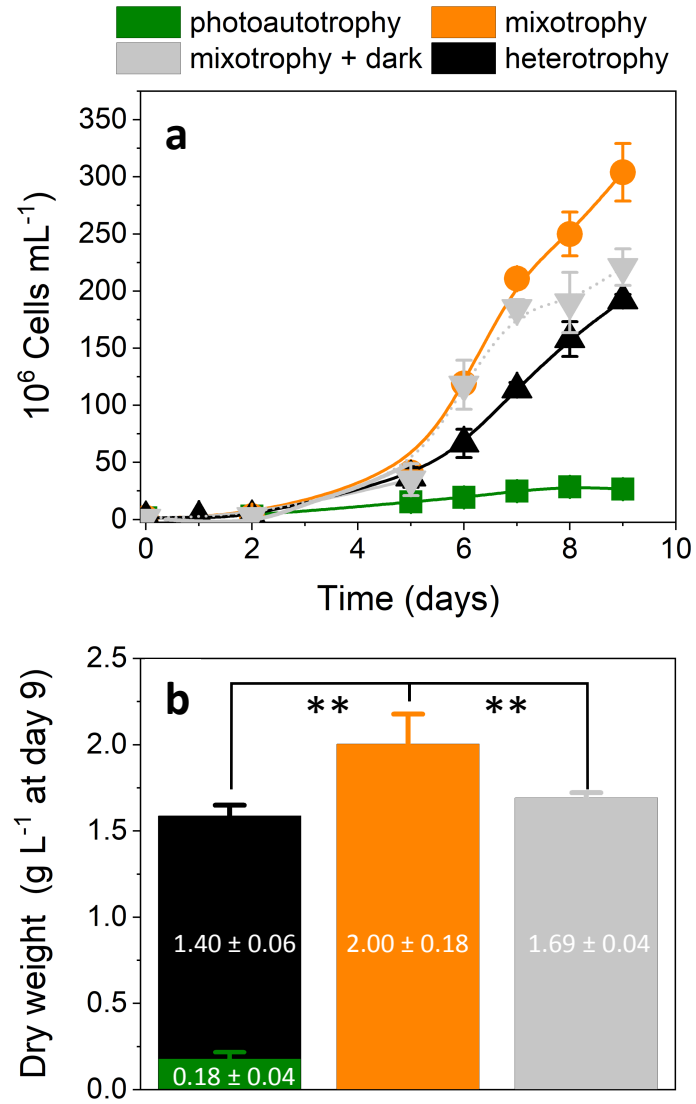


Figure 1

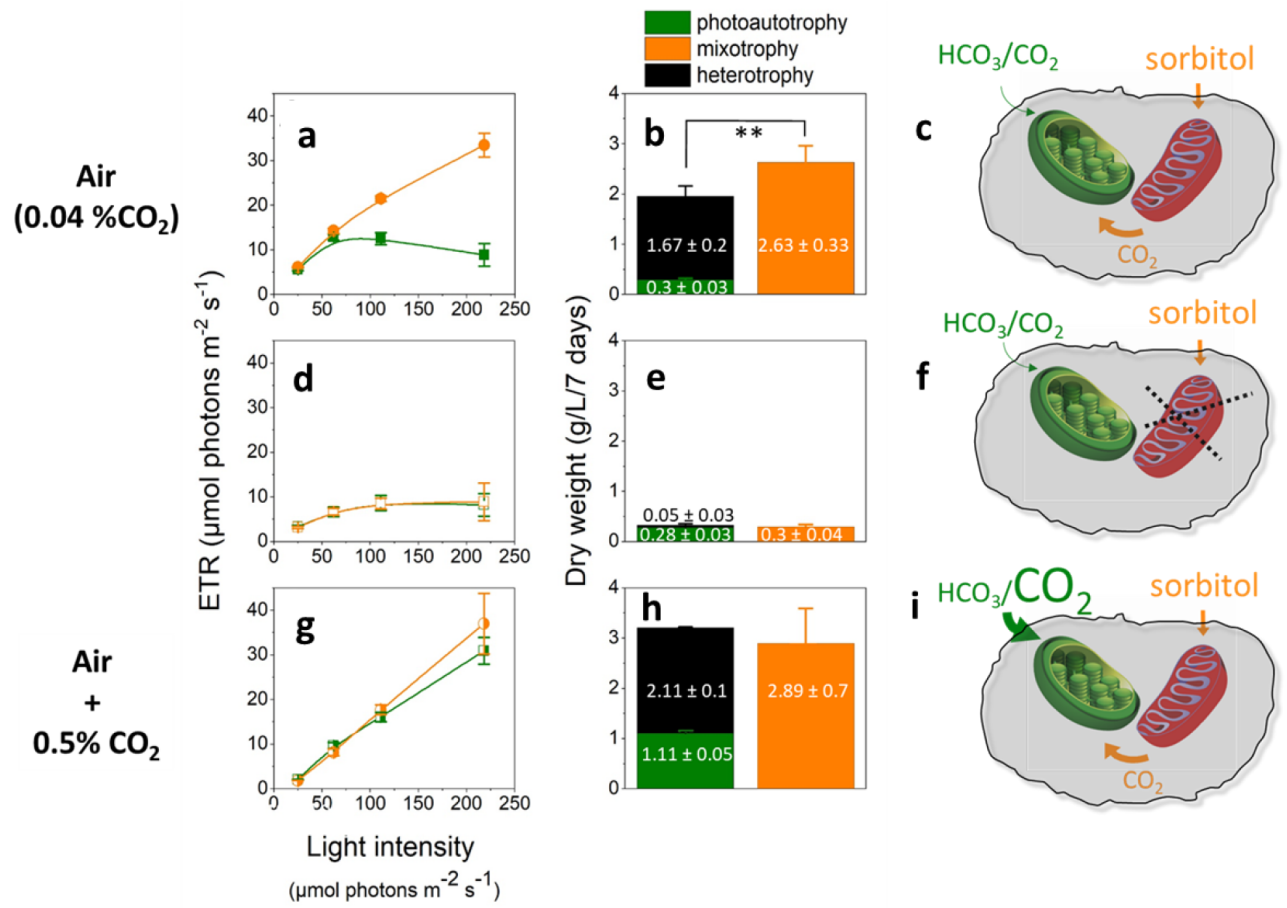
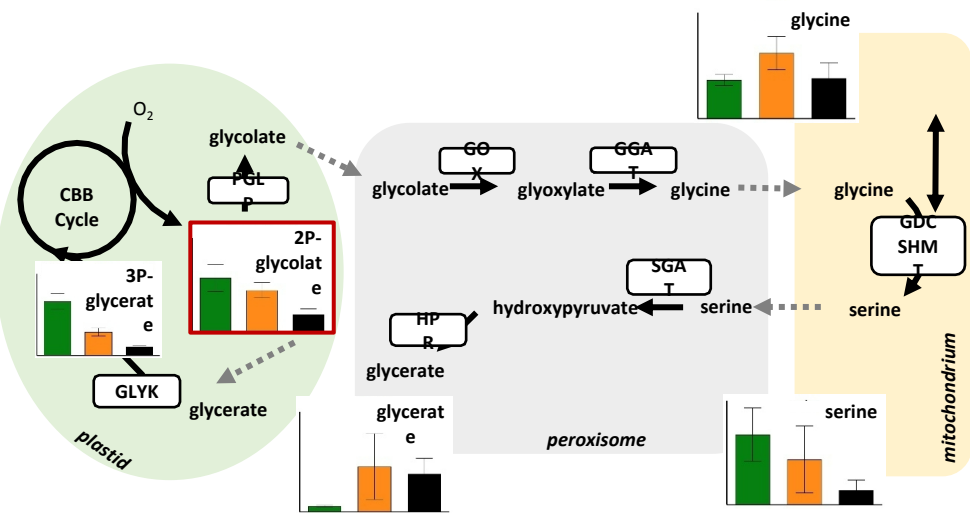


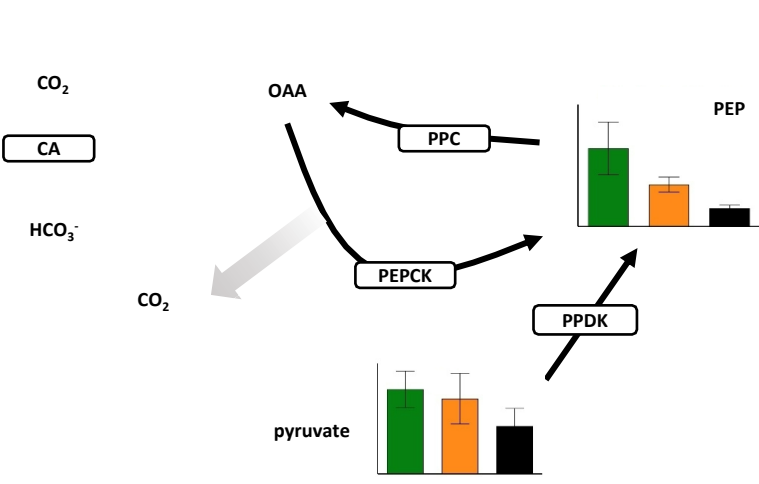
Figure 2



**a Photorespiration**



**b C4-like CCM**



**c Upper glycolysis**

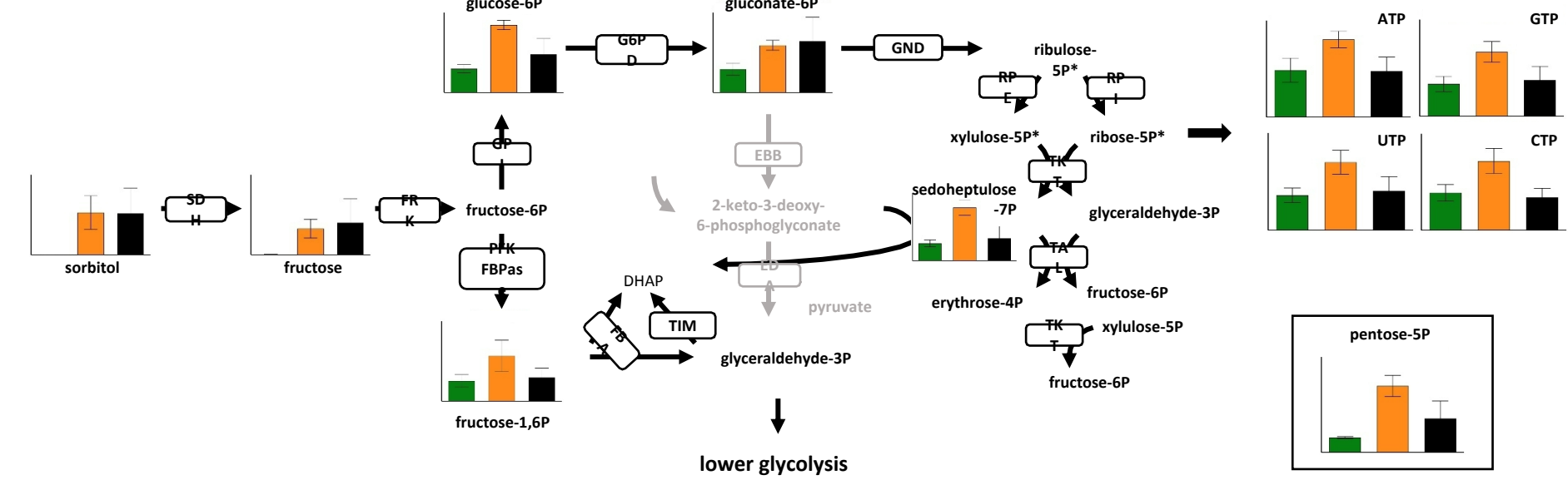


Figure 4



— ambient  $CO_2$   
— high  $CO_2$

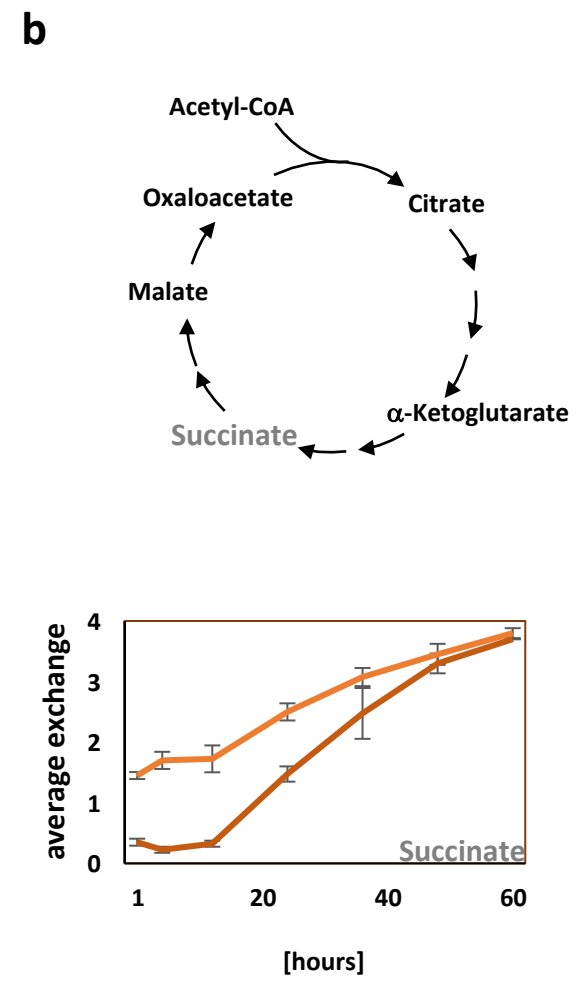
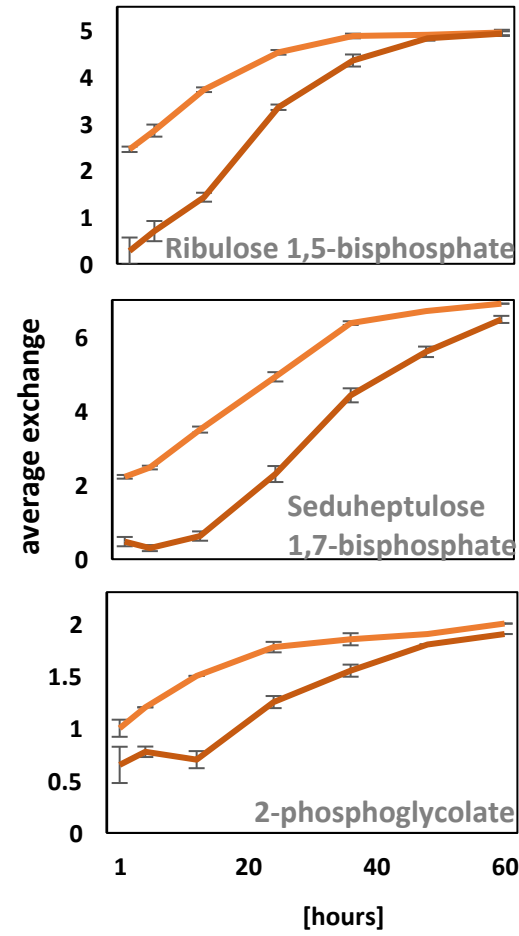
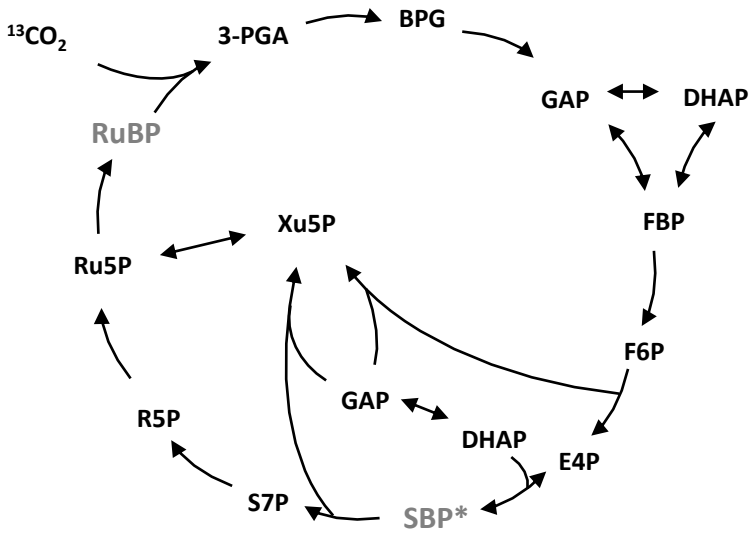


Figure 5

Supporting Information for

**MIXOTROPHIC GROWTH OF THE EXTREMOPHILE *GALDIERIA*  
*SULPHURARIA* REVEALS THE FLEXIBILITY OF ITS CARBON  
ASSIMILATION METABOLISM**

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**This file includes:**

Methods S1  
Figures S1 to S12  
Legends for Datasets S1 to S3

**Other supplementary materials for this manuscript include the following:**

Datasets S1 to S3

## Methods S1

### ***Microalgae and media composition***

*Galdieria sulphuraria* SAG21.92 and 074G were obtained from the Culture Collection of Algae at Göttingen University (SAG) and was grown in sterile 2xGS modified Allen medium, pH 2.0, containing 20 mM of NaNO<sub>3</sub>, and 5 mM of inorganic phosphate (K<sub>2</sub>HPO<sub>4</sub> and KH<sub>2</sub>PO<sub>4</sub> in a 2/1 ratio, (Allen, 1959)) at 42°C. The medium and flasks were sterilized in an autoclave for 20 min at 121 °C in order to prevent any contamination. For the experiments with different organic carbon sources, the 2xGS modified Allen media was supplemented by adding filter-sterilized concentrated organic substrate solutions as indicated in the text. The concentration of organic substrates was selected on the basis of data reported in literature (Oesterhelt *et al.*, 2007). *G. sulphuraria* was grown either in 250 mL flasks (50 mL culture volume) in an incubator (Infors, Switzerland, continuous light, 30 μmol photons m<sup>-2</sup> s<sup>-1</sup>, 42°C, 100 rpm) or in a multicultivator (Photon System Instruments, Czech Republic). For growth in the multicultivator, cells were provided with air or CO<sub>2</sub>-enriched air (see below) bubbled into the solution ensuring both aeration and mixing. Culture volume was 80 mL. Incident light intensity was adjusted daily to maintain constant transmitted light thus offering a constant light intensity to the cells (see Results and below). The fraction of CO<sub>2</sub> in the feed air was regulated by a flow metering system (Photon System Instruments, Czech Republic). The total gas flow was 0.4 L/min for each culture.

### ***Growth***

Cultures used to inoculate flasks or multicultivator tubes were grown photoautotrophically in the air in flasks placed in the incubator. Adequate volumes of cultures at a density of 7 x 10<sup>7</sup> cells per mL were centrifuged and resuspended in a fresh medium to obtain an initial cell concentration of 1.5 x 10<sup>6</sup> cells per mL (in flasks) or 3.5 x 10<sup>6</sup> cells per mL (multicultivator). For organic substrates screening in flasks under mixotrophic conditions (see Fig. S1 & S2), substrate was added at a concentration of 150 mM carbon atom (e.g. 12.5 mM saccharose). For growth in the multicultivator cells were adapted for 3 days with an incident light of 60 μmol

photons  $\text{m}^{-2} \text{s}^{-1}$  (transmitted light  $\sim 10 \mu\text{mol photons. m}^2.\text{s}^{-1}$ ), before addition of organic carbon (150 mM C) for the mixotrophic and heterotrophic conditions. For the heterotrophic condition, light was switched-off and tubes were covered with aluminum foil to keep them in the dark. For experiments with the multicultivator, the incident light intensity was adjusted daily to maintain constant transmitted light through the culture (see Results). This 'luminostat' regime should ensure maximal absorption of light without allowing a dark zone to develop inside the multicultivator (Cuaresma *et al.*, 2011) (see Supplementary Fig. S3). For most conditions, a transmitted light of  $10 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  was used. Tests were carried out in the range from 5 to  $30 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  (see Supplementary Fig. S8). Experiments were either carried out in air or in air enriched with  $\text{CO}_2$  (0.5 to 4%, see Supplementary Fig. S8). Sorbitol consumption was measured using the D Sorbitol/Xylitol assay kit (Megazyme).

To monitor algal growth, samples were taken daily and growth was estimated using a LUNA™ cell counter (Logos Biosystems, Inc. USA).

### ***Cell fresh weight and dry weight estimates***

Cells were collected by centrifugation in 50 mL tubes, cell pellet was resuspended in a small volume of water and centrifuged in pre-weighted eppendorf tubes and pellet was weighted. For dry weight determination fresh cells pellets were exposed for three days at  $60^\circ\text{C}$ , weighted and expressed as  $\text{g L}^{-1}$ .

### ***Clark electrode oxygen measurements***

Net oxygen exchanges in solution were measured with a Clark-type electrode (Hansatech Instruments, UK) at  $42^\circ\text{C}$ . The electrode equilibrated for 12 h in distilled water was calibrated at  $42^\circ\text{C}$  in the air (100% of  $\text{O}_2$ ) and by bubbling argon (0% of  $\text{O}_2$ ). For oxygen exchanges measurements, an aliquot of the cell culture was collected immediately before the measurement ( $30 \times 10^6$  cells) and centrifuged at  $42^\circ\text{C}$ . The pellet was resuspended in 1 mL 2 x GS medium, pH 2.0,  $42^\circ\text{C}$  and introduced in the measure chamber thermostated at  $42^\circ\text{C}$ . The electrode was closed and measurement was first carried out in the dark for 10 minutes before light was switched on ( $320 \mu\text{mol photons m}^{-2} \text{s}^{-1}$ ). Respiration and gross



photosynthesis were quantified by measuring the slope of oxygen changes in the dark and under light exposure. Net photosynthesis was calculated assuming O<sub>2</sub> consumption by the mitochondrion in the light is identical to that in the dark (Net photosynthesis =  $V_{O_2\text{light}} + |V_{O_2\text{dark}}|$ ).

### ***Photophysiology measurements***

Photosynthetic parameters were derived from quantification of chlorophyll fluorescence emission by cultures within the multicultivator. To this aim, we employed a custom-made fluorescence imaging system based on a previously published setup (Johnson *et al.*, 2009). The system was modified by replacing the green LEDs providing actinic light with orange LEDs (emission peak 630 nm, Full Width at Half Maximum: 40 nm), and the acquisition setup with a GigE µeye camera (IDS, Germany). Measuring light was provided by a LED peaking at 590 nm, to maximize excitation of the phycobiliprotein complexes of *Galdieria*. The photosynthetic electron transfer rate, ETR<sub>PSII</sub>, was calculated as the product of the light intensity times the photochemical yield in the light  $(F_m' - F_s) / F_m' \times \text{PFD}$ , where  $F_m'$  and  $F_s$  are the fluorescence intensities measured after exposure to a saturating pulse and in steady state, respectively, in light-acclimated cells and PFD (Photosynthetic Flux Density) is the incident light intensity, measured in  $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$ . (see (Maxwell & Johnson, 2000) for more details). Cells were allowed to reach steady state fluorescence emissions at every light (5-10 minutes of light exposure depending on the intensity) before increasing the photon flux.

### ***Mass spectrometry-based proteomic analyses***

#### Experimental design

*Galdieria sulphuraria* SAG21.92 was cultivated under the three conditions (photoautotrophy, mixotrophy and heterotrophy) in parallel in the same cultivator (2-3 tubes per condition). Three multicultivator experiments were carried out one week apart and constituted the biological replicates. Only one tube per condition and per cultivator was chosen having the closest ODs within the same condition.

Cell breakage was performed on  $10^9$  cells with a Precellys homogenizer (Bertin, France).

### Protein digestion

Each protein sample (40  $\mu$ g) was stacked by a 1 cm-migration on the top of a NuPAGE 4–12% gel, (Invitrogen) before Coomassie blue staining (R250, Bio-Rad). Gel bands of concentrated proteins were manually excised and cut into pieces before being washed by 6 successive incubations of 15 min in 25 mM  $\text{NH}_4\text{HCO}_3$  containing 50% (v/v) acetonitrile. Gel pieces were then dehydrated in 100% acetonitrile and incubated at 53 °C with 10 mM DTT in 25 mM  $\text{NH}_4\text{HCO}_3$  for 45 min and in the dark with 55 mM iodoacetamide in 25 mM  $\text{NH}_4\text{HCO}_3$  for 35 min. Alkylation was stopped by adding 10 mM DTT in 25 mM  $\text{NH}_4\text{HCO}_3$  and mixing for 10 min. Gel pieces were then washed again by incubation in 25 mM  $\text{NH}_4\text{HCO}_3$  before dehydration with 100% acetonitrile. Modified trypsin (Promega, sequencing grade) in 25 mM  $\text{NH}_4\text{HCO}_3$  was added to the dehydrated gel pieces for an overnight incubation at 37 °C. Peptides were then extracted from gel pieces in three 15-min sequential extraction steps in 30  $\mu$ l of 50% acetonitrile, 30  $\mu$ l of 5% formic acid and finally 30  $\mu$ l of 100% acetonitrile. The pooled supernatants were then vacuum-dried.

### MS/MS analysis

The dried extracted peptides were resuspended in acetonitrile 5%, trifluoroacetic acid 0.1% and analyzed via online nano-LC-MS/MS (nano-liquid chromatography-tandem mass spectrometry; Ultimate 3000 RSLCnano and Q-Ex HF, Thermo Fischer Scientific, Thermo Scientific, Waltham, MA, USA). Peptide mixtures were desalted on line using a reverse phase precolumn (PepMap C18 Thermo Fisher Scientific) and resolved on a C18 column (ReproSil-Pur 120 C18-AQ 1.9  $\mu$ m column, Dr. Maisch GmbH). The nanoLC method consisted in a 200-min gradient at a flow rate of 300 nL·min<sup>-1</sup> ranging from 5.1% to 72.2% acetonitrile in 0.08% formic acid in 182 min. This gradient was operated as multi-steps optimized by GOAT software (V1.0.1) for *Galdieria* whole cell extracts. MS (mass spectrometry) and MS/MS data were acquired using the Xcalibur software (Thermo Fisher

Scientific). The spray voltage was set at 2 kV and the heated capillary was adjusted to 270 °C. Survey full-scan MS spectra ( $m/z = 400\text{--}1600$ ) were obtained in the Orbitrap with a resolution of 60,000 after accumulation of  $10^6$  ions (maximum filling time: 200 ms). The 20 most intense ions from the preview survey scan delivered by the Orbitrap were fragmented via collision-induced dissociation in the LTQ after accumulation of  $1e5$  ions (maximum filling time: 50 ms).

#### Database searches and quantification

Data were processed automatically using the Mascot Distiller software (version 2.7.1.0, Matrix Science). Peptides and proteins were identified using Mascot (version 2.6.0) through concomitant searches against Uniprot (*Galdieria sulphuraria* taxonomy, July 2019 version), classical contaminants database (homemade) and their corresponding reversed databases. Trypsin/P was chosen as the enzyme and three missed cleavages were allowed. Precursor and fragment mass error tolerance were set, respectively, to 10 ppm and 25 mmu. Peptide modifications allowed during the search were: carbamidomethylation (fixed), acetyl (protein N-terminal, variable) and methionine oxidation (variable). The Proline software ((Bouyssie *et al.*, 2020), <http://proline.profiptoteomics.fr>) was used to filter the merged results: conservation of rank 1 peptide-spectrum match (PSM) with a minimal length of 7 and a minimal score of 25. PSM score filtering is then optimized to reach a False Discovery Rate (FDR) of PSM identification below 1% by employing the target decoy approach. A minimum of one specific peptide per identified protein group was set. Proline was then used to perform MS1-based label free quantification of the peptides and protein groups. The “Cross-assignment” option was activated and allowed within replicates of the same condition only. Intensity values were extracted from specific peptides and used to infer protein abundances from the different samples. An ultimate filter was applied to discard non-relevant or doubtful identifications. This concerns proteins identified in the reverse and contaminant databases, proteins identified with only one peptide with a Mascot score inferior to 40 and few unquantified proteins. Proteins identified in the reverse and contaminant databases (i.e. trypsin or keratin), and proteins identified with only 1 peptide with a score <40 were further discarded from the list.

### Statistical treatment

The remaining list was considered for bioanalysis. Since there were many missing proteins in the photoautotrophy condition compared to the other two conditions, the list was divided into two sets. One set on which no statistical treatment was applied was constituted of proteins entirely missing in one condition (having no abundance values in all 3 replicates). The other set (proteins having at least 1 abundance value in all three conditions) was used for differential analysis using ProStaR (Wieczorek *et al.*, 2017; Wieczorek *et al.*, 2019). For this, the intensity values were log<sub>2</sub> transformed and normalized by Variance Stabilizing Normalization (VSN) algorithm (Huber *et al.*, 2002) with the « overall » option. The missing abundances were imputed according to the Structured Least Square Adaptive (SLSA) method. The Limma test was applied for comparison of one condition versus the other two combined. Due to huge differences in the matrix – proteins identified and intensities – in photoautotrophy compared to mixotrophy or heterotrophy, the strategy consisting of comparing one condition to the average of the other two (option “One\_vs\_All” in ProStaR) gave better discriminating results than comparisons of one condition to another one condition (“One\_vs\_One” option in ProStaR). Differentially recovered proteins were sorted out using a log<sub>2</sub> fold-change (FC) cut-off of 1 and a p-value threshold (on the remaining proteins) that guarantees a Benjamini–Hochberg FDR of approximately 0.01%. The variations in abundance between the three cultivation conditions are important which made it difficult to objectively determine the latter threshold. We deliberately chose a very low FDR threshold to select a protein set of reasonable size in each comparison.

### ***Metabolic analyses by IC-MS***

The dried sample was reconstituted in 100 µL deionized water and 5 µL were injected via a Dionex AS-AP autosampler in push partial mode with a 10 µL loop. The temperature of the autosampler was set to 4 °C to maintain sample stability. Anion exchange chromatography was conducted on a Dionex IonPac AS11-HC column (2 mm × 250 mm, 4 µm particle size, Thermo Scientific) equipped with a Dionex IonPac AG11-HC guard column (2 mm × 50 mm, 4 µm, Thermo Scientific)

at 30 °C. The mobile phase was established using an eluent generator with a potassium hydroxide cartridge to produce a potassium hydroxide gradient. The column flow rate was set to 380  $\mu\text{L min}^{-1}$  with a starting KOH concentration of 10 mM. The concentration was held for 3 min, then increased to 50% within 9 min followed by a steeper increase to 100% within 7 min. After 2 min of plateau the concentration dropped immediately back to 10 % for 8 min of equilibration. To prevent the high amounts of salt from entering the ESI source a Dionex ADRS 600, 2 mm suppressor was used in dynamic mode at a temperature of 15 °C. Spray stability was achieved with a make up consisting of methanol with 10 mM acetic acid delivered with 150  $\mu\text{L min}^{-1}$  by an AXP Pump. The electro spray was achieved in the ESI source using the following parameters: sheath gas 30, auxiliary gas 15, sweep gas 0, spray voltage - 2.8 kV, capillary temperature 300 °C, S-Lens RF level 45, and auxiliary gas heater 380 °C. For the untargeted approach the mass spectrometer operated in a combination of full mass scan and a data-dependent Top5 MS2 (ddMS2) experiment. The full scan (60-800 m/z) was conducted with a resolution of 140.000 and an automatic gain control (AGC) target of  $10^6$  ions with a maximum injection time (IT) of 500 ms. The Top5 ddMS2 experiment was carried out with a resolution of 17.500 and an AGC target of  $10^5$  and a maximum IT of 50 ms. The stepped collision energy was used with the steps (15,25,35) to create an average of NCE 25.

Untargeted data analysis was conducted using Compound Discoverer (version 3.1, Thermo Scientific) using the “untargeted Metabolomics workflow”. In this workflow automatic retention time alignment is performed in a window of 2 min within 5 ppm mass accuracy as well as unknown compound detection, and compound grouping across all samples. Elemental compositions are predicted based on accurate mass and chemical background is subtracted by using blank extraction samples. Levels of peak annotation are indicated in the supplementary Dataset S3. Lowest level of annotation is based on accurate mass (3 ppm mass accuracy) on MS<sup>1</sup> level and allows to evaluate potential sum compositions and comparisons with databases such as Chemspider (<http://www.chemspider.com>) with ranking by the mzLogic algorithm. The next level of identification is via MS<sup>2</sup>

level by comparing MS<sup>2</sup> fragment spectra using mzCloud (ddMS2) (match factor 50) and MS<sup>1</sup> level ChemSpider (by formula or exact mass). Highest identification level via an in-house MS<sup>2</sup> spectral library and retention time was established using mzVault. QC-based batch normalization was performed with QC sample injection every 5 samples during the sequence. Differential analysis, determination of p-values, adjusted p-values, ratios, fold change, were also calculated using Compound Discoverer.

### **Labelling experiments with <sup>13</sup>C-glucose**

Cells were cultivated in 250 mL Erlenmeyer flasks (50 mL culture volume) for four days under continuous light at 60  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , 40 °C and ambient air (0.04% CO<sub>2</sub>). U-<sup>13</sup>C<sub>6</sub>-glucose (Cambridge Isotope Laboratories Inc, Tewksbury, Massachusetts) was added at day 4 in a final concentration of 25 mM and the irradiance was increased to 100  $\mu\text{mol m}^{-2} \text{s}^{-1}$  either under ambient or elevated (2%) CO<sub>2</sub> conditions.

1-2.5 x10<sup>8</sup> cells were harvested 1, 4, 12, 24, 36, 48 and 60 hours after glucose addition as described above. Metabolites were extracted and measured by IC-MS as described above.

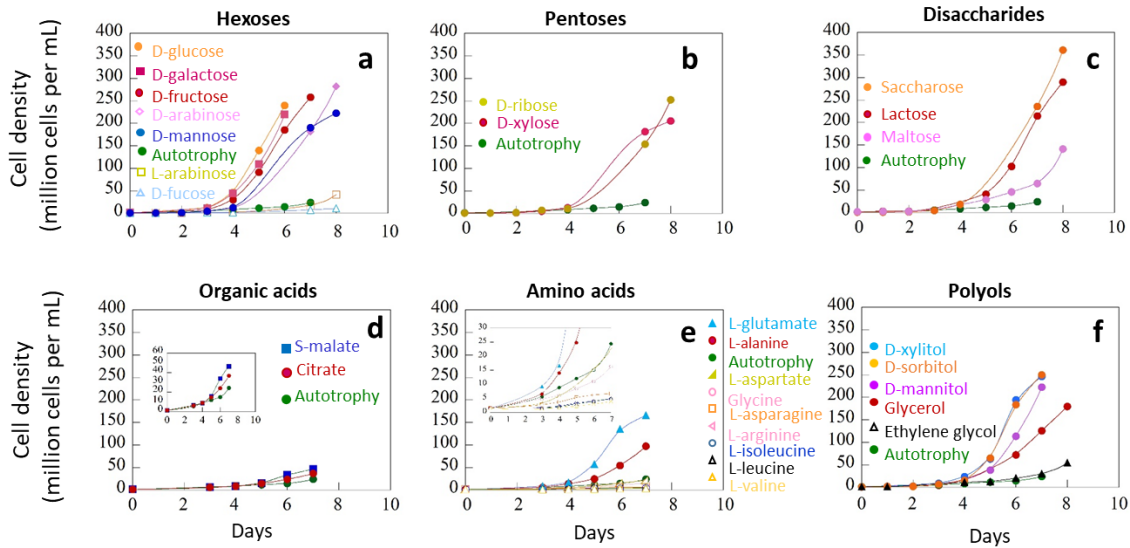
Data analysis was conducted with Compound Discoverer (version 3.1, Thermo Scientific) and the standard workflow for stable isotope labelling from Compound Discoverer was chosen. The default settings, which are 5 ppm mass tolerance, 30 % intensity tolerance and 0.1 % intensity threshold for isotope pattern matching were used and the maximum exchange rate was set to 95%.

### ***Electron microscopy sample preparation and observation***

Cells were pelleted (1000g, 5 min, 4°C) and fixed in reduced osmium tetroxide. To this end, cell pellets were resuspended in 0.1 M phosphate buffer (pH 7.4) and 2.5% glutaraldehyde and incubated overnight at 4°C. Cells were then pelleted and washed five times in 0.1 M phosphate buffer. Cells were fixed by a 1h incubation on ice in 500  $\mu\text{L}$  0.1 M phosphate buffer containing 1% osmium and 1.5% ferricyanide potassium red before they were pelleted and washed five times with

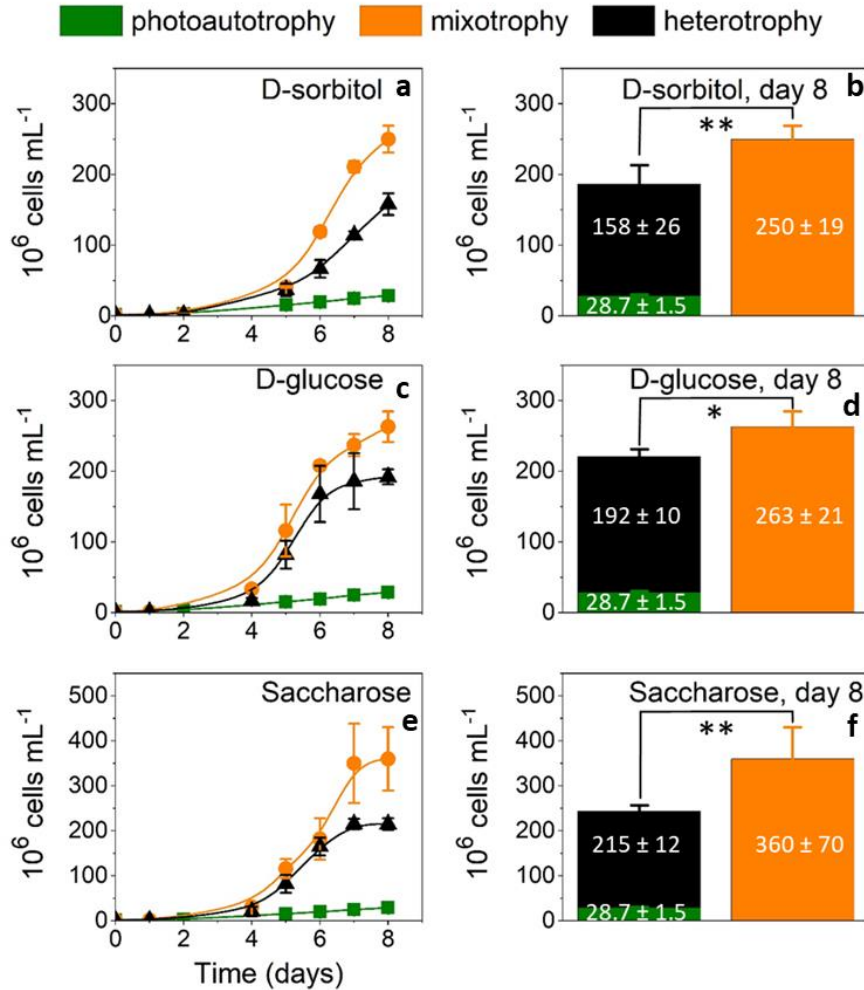
0.1 M phosphate buffer. Pellets were resuspended in 0.1 M phosphate buffer containing 0.1% tannic acid and incubated for 30 min in the dark at room temperature. Again, cells were pelleted and washed five times with 0.1 M phosphate buffer. The samples were dehydrated in ascending sequences of ethanol and infiltrated with ethanol/Epon resin mixture. Finally, the cells were embedded in Epon. Ultrathin sections (70 nm) were prepared with a diamond knife on a PowerTome ultramicrotome (RMC products) and collected on nickel grids. Ultrathin sections were examined on a Philips CM120 transmission electron microscope operating at 80 kV.

Figures S1 to S12

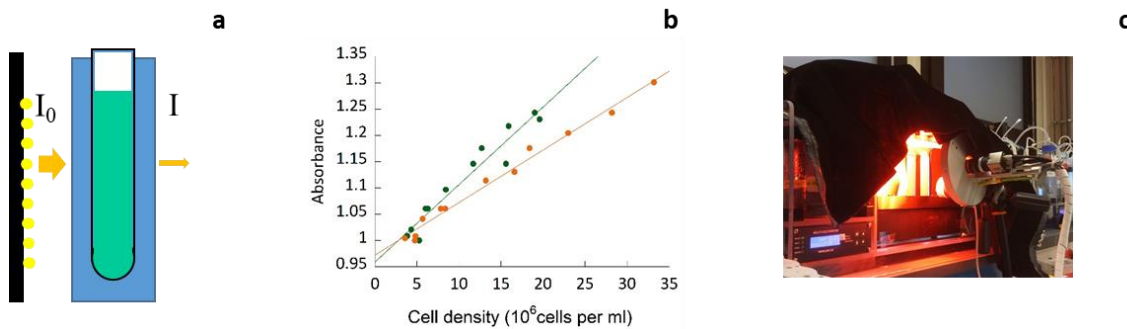


**Figure S1: Consequences of different substrates on *G. sulphuraria* SAG21.92 growth in the light.** Growth was measured in flasks at ambient CO<sub>2</sub> in the presence of 25 mM reduced carbon source added from the beginning of the culture (day 0). Cultures were inoculated at a cell density of  $1.5 \cdot 10^6$  photoautotrophic cells mL<sup>-1</sup>. Growth of photoautotrophic cells is indicated in green, for comparison. Light intensity was 30  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ . Experiments were carried out at 42°C with shaking at 100 rpm, pH 2. **a**, hexoses, **b**, pentoses, **c**, disaccharides, **d**, organic acids, **e**, amino acids, **f**, polyols. Inserts in panel **d** and **e** are zooms on the data.

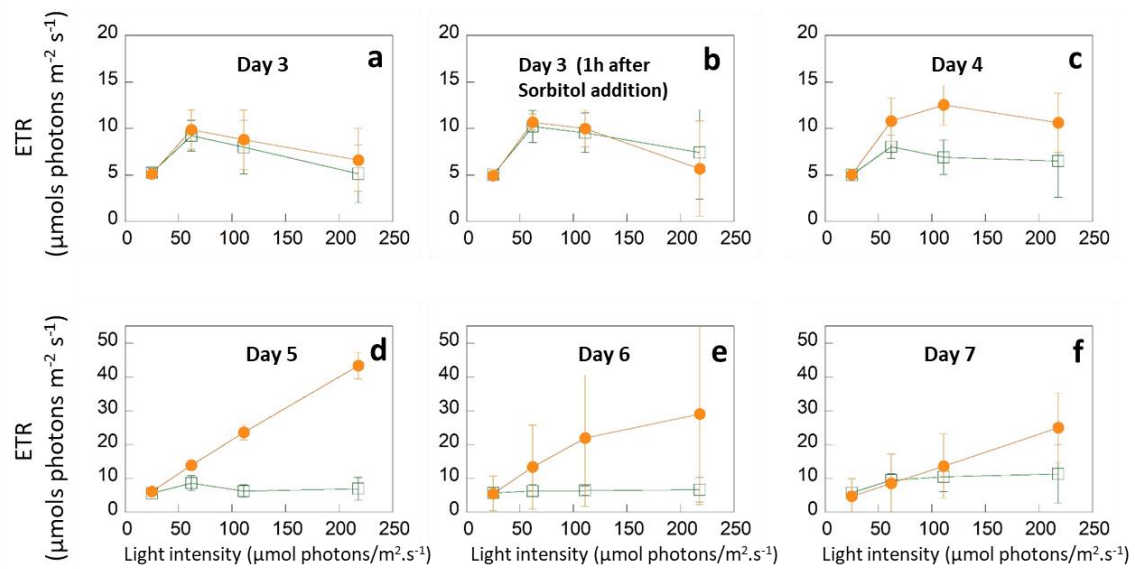




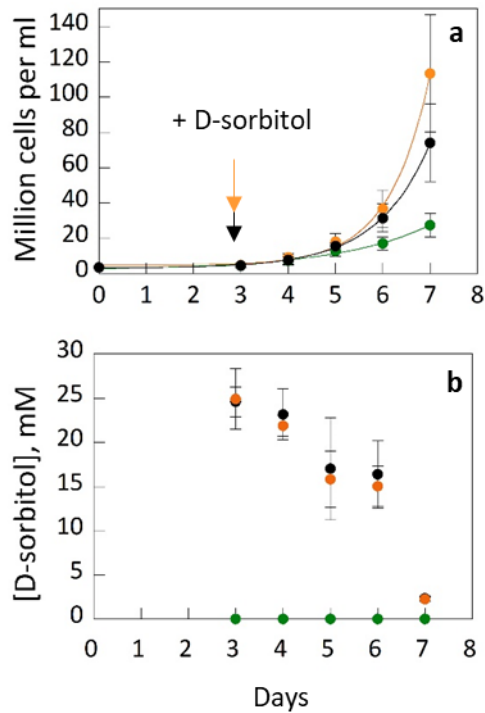
**Figure S2: *G. sulphuraria* SAG21.92 growth in photoautotrophic, mixotrophic and heterotrophic conditions driven by a polyol, an hexose and a disaccharide.** Cells were grown in flasks, in photoautotrophic (light only, 30  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ , green), mixotrophic (30  $\mu\text{mol photons. m}^{-2}.\text{s}^{-1}$  plus a source of reduced carbon, orange) and heterotrophic (absence of light, presence of a source of reduced carbon, black) conditions at ambient  $\text{CO}_2$ , 42°C and pH 2. **a,b:** D-sorbitol 25 mM; **c,d:** D-glucose 25 mM; **e,f:** saccharose 12.5 mM. **b-d-f:** Mixotrophic growth (orange bars) exceeds the sum of photoautotrophic (green bars) and heterotrophic (black bars) growth, highlighting the existence of a synergy under mixotrophic conditions. Cultures were started from photoautotrophic cells, which were diluted at 1.5  $10^6$  cells  $\text{mL}^{-1}$  for each condition. Experiments were carried out at 42°C with shaking at 100 rpm. **b, d, f,** Final cell concentration (day 8) in photoautotrophic, heterotrophic and mixotrophic conditions. Data from 3 biological replicates  $\pm$  S.D. \* indicate that at the 0.05 level the means of the two populations (mixotrophy on one side, heterotrophy+photoautotrophy on the other one) means are statistically different (Anova test). \*\* indicate that at the 0.01 level the means of the two populations (mixotrophy on one side, heterotrophy+photoautotrophy on the other one) means are statistically different (Anova test).



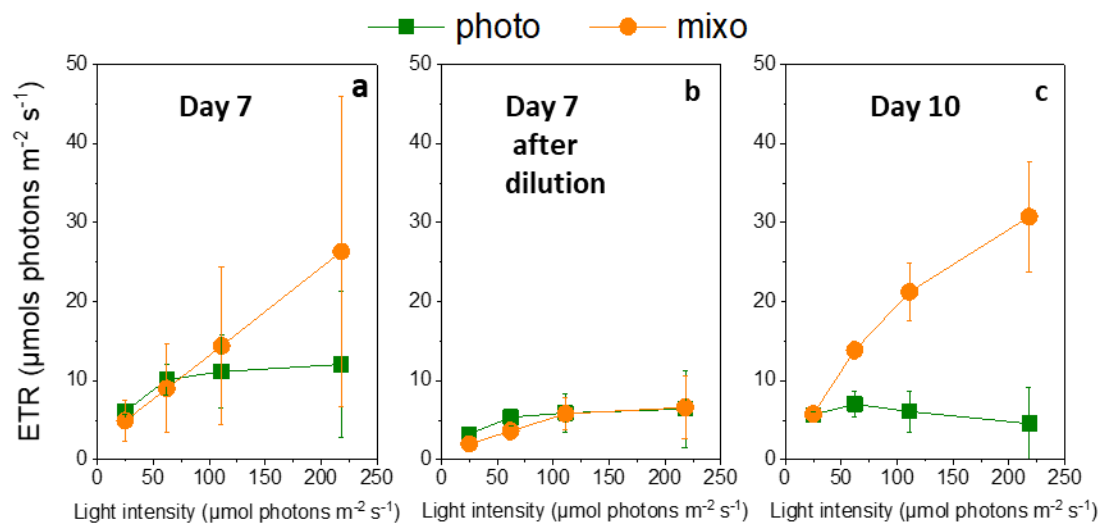
**Figure S3: Experimental setup to expose cells to a constant photons/cell ratio.** **a**, Schematic side view of the photobioreactor with the LED panel (yellow spots), water bath (blue) and culture tube (green).  $I_0$  and  $I$  represent the incident light (settings on the device) and the light transmitted through the device, respectively.  $I_0$  was progressively increased during cell growth, to keep a linear relation between cell density and absorption. **b**, Relation between absorbance and cell number under mixotrophic and photoautotrophic conditions for  $I = 10 \mu\text{mol photons m}^{-2} \text{s}^{-1}$ . The slopes differ for mixotrophic (orange) and photoautotrophic (dark green) cells possibly because the photosynthetic apparatus is down-regulated in the presence of organic carbon. The lower amount of photosynthetic complexes reduces light absorption for the same amount of cell. **c**, Custom-made setup to evaluate photosynthetic performances of *G. sulphuraria* cells within the photobioreactor. The system is equipped with orange LEDs ( $\lambda = 590 \text{ nm}$ ), to enhance absorption by the phycobiliprotein complexes of *G. sulphuraria*, and a near infrared camera to measure fluorescence emitted by the algae inside the photobioreactor (PBR tubes).



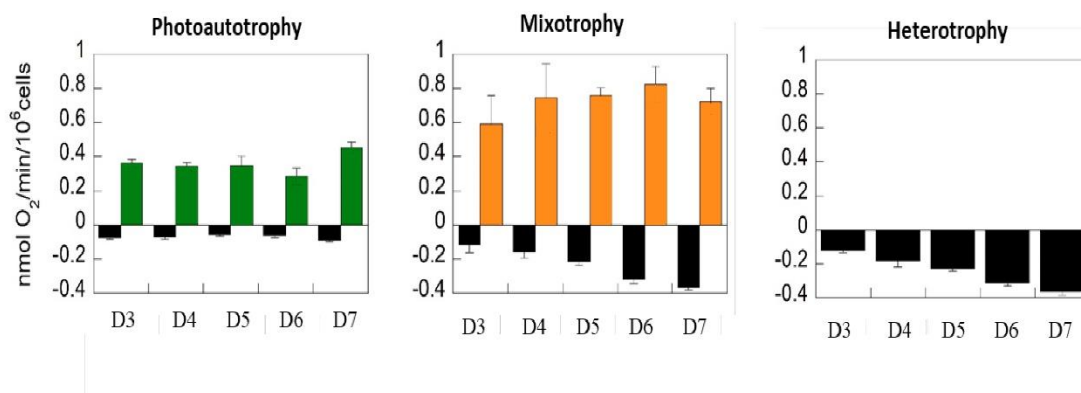
**Figure S4: *In situ* measurements of photosynthetic electron transfer rate (ETR) in photoautotrophic (light) and mixotrophic (light + 25 mM D-sorbitol) *G. sulphuraria* SAG21.92 cells.** Cells were inoculated at  $3.5 \times 10^6$  cell  $\text{mL}^{-1}$  and grown in the light (transmitted light  $10 \mu\text{mol photons m}^{-2} \text{s}^{-1}$ ) and air for three days before D-sorbitol was added (mixotrophy, orange) or not (autotrophy, green). Light was increased every day to keep the transmitted light to a constant value of  $10 \mu\text{mol photons m}^{-2} \text{s}^{-1}$ . **a-f**, After three days of growth, ETR was followed every day directly on cultures within the photobioreactor, to avoid possible temperature stress. Data from 3 biological replicates  $\pm$  S.D.



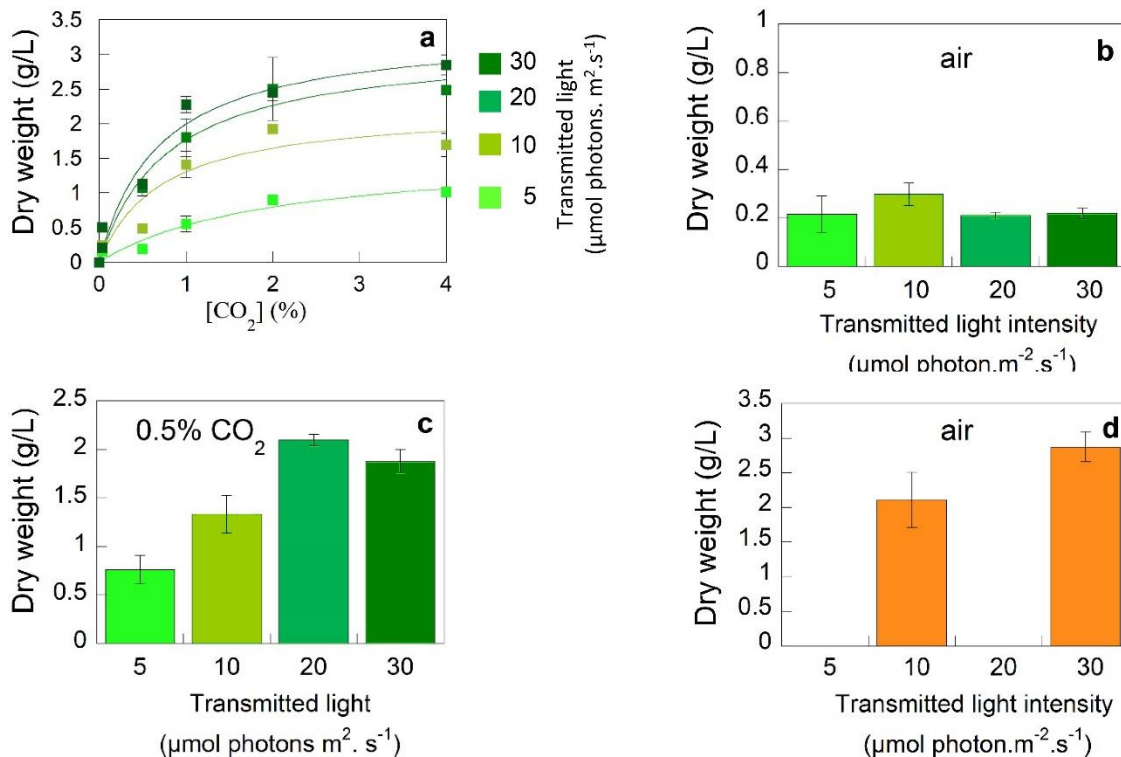
**Figure S5: Enhancement of cell growth by mixotrophy and sorbitol consumption in *G. sulphuraria* SAG21.92.** *G. sulphuraria* was inoculated at  $3.5 \times 10^6$  cells  $\text{mL}^{-1}$ . At day 3, cultures were either continued without any addition (photoautotrophy, green), or supplemented with 25 mM D-sorbitol in the presence of light (mixotrophy, orange) or in the dark (heterotrophy, black). **a**, Growth curves (data from 12 biological replicates  $\pm$  S.D.). Growth rates were  $0.5 \pm 0.1 \text{ day}^{-1}$ ;  $1.2 \pm 0.1 \text{ day}^{-1}$  and  $0.9 \pm 0.05 \text{ day}^{-1}$  in photoautotrophic, mixotrophic and heterotrophic cultures, respectively. **b**, Sorbitol consumption in mixotrophic and heterotrophic cultures. Data from 3 biological replicates  $\pm$  S.D.



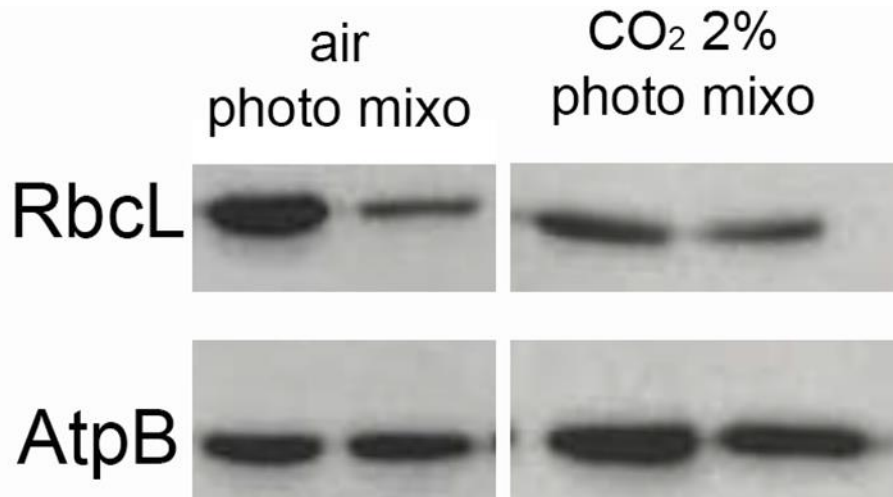
**Figure S6: Mixotrophy is restored in *G. sulphuraria* SAG21.92 upon addition of a carbon source.** **a**, Mixotrophic cells (orange) were let consuming sorbitol (day 7, *i.e.* 4 days after addition of D-sorbitol). **b**, Cells at day 7 were diluted to  $3.5 \times 10^6$  cells  $\text{mL}^{-1}$ , and growth was resumed in the light (transmitted light  $10 \mu\text{mol photons m}^{-2} \text{s}^{-1}$ ) without D-sorbitol (photoautotrophy, green) or in the presence of 25 mM D-sorbitol (orange). ETR measurements carried three days later (**c**) indicate that mixotrophic photosynthetic capacity was fully restored. Data from 3 biological replicates  $\pm$  S.D.



**Figure S7: Respiration and net photosynthesis of *G. sulphuraria* SAG21.92 were measured every day in the three different growth conditions (photoautotrophy, mixotrophy and heterotrophy). O<sub>2</sub> consumption or production were measured with a Clark electrode at 42°C. Cells were centrifuged and resuspended at  $3 \times 10^7$  cells in 1 mL of fresh 2xGS medium. Net photosynthesis corresponds to gross photosynthesis +|respiration|. Data from 3 biological replicates  $\pm$  S.D.**

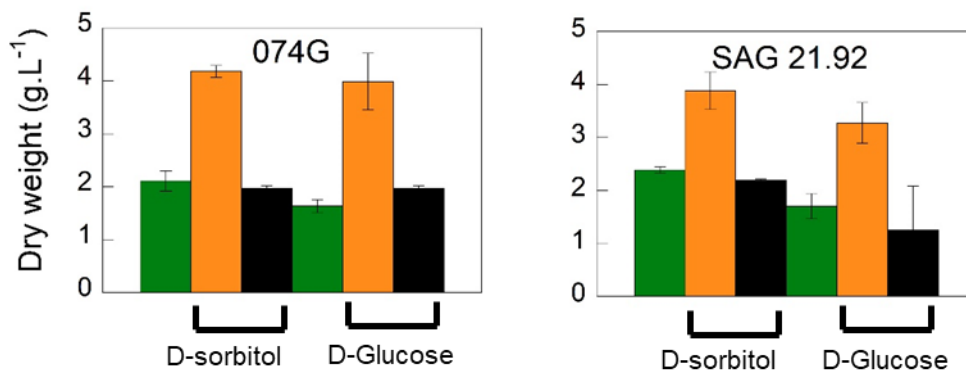


**Figure S8: Biomass production of *G. sulphuraria* SAG21.92 as a function of transmitted light intensity and CO<sub>2</sub> concentration.** **a**, Cells were grown in a photobioreactor at four different constant transmitted light intensities and different CO<sub>2</sub> concentrations. During growth, the light intensity was increased to maintain a constant transmitted light (from 5 to 30 μmol photons m<sup>-2</sup> s<sup>-1</sup>). Cells exposed to a given light ramp were used to inoculate the next experiment at higher CO<sub>2</sub> concentration, while repeating the same light ramp. Progressive adaptation to higher CO<sub>2</sub> concentration was chosen to avoid acidification of the cytosol in the presence of high CO<sub>2</sub> concentration and to induce a progressive reduction in the accumulation of carbonic anhydrase concentration, which is expected to be high in low CO<sub>2</sub> grown cells. After three days of adaptation, cells were grown for 4 additional days and collected at day 7, dried for three days at 60°C and weighted. Data from 3 biological replicates ± S.D. **b**: Focus on the light dependency of biomass production in phototrophic conditions in air. Same colour code as in panel a. Data from 3 biological replicates ± S.D. **c**, Focus on the light dependency of biomass production in phototrophic conditions supplemented with 0.5% CO<sub>2</sub>. Same colour code as in panel a. Data from 3 biological replicates ± S.D. **d**, Focus on the light dependency of biomass production in mixotrophic conditions (sorbitol 25 mM). Two light intensities were tested corresponding to a transmitted light of 10 and 30 μmol photons m<sup>-2</sup> s<sup>-1</sup>. Data from 3 biological replicates ± S.D.

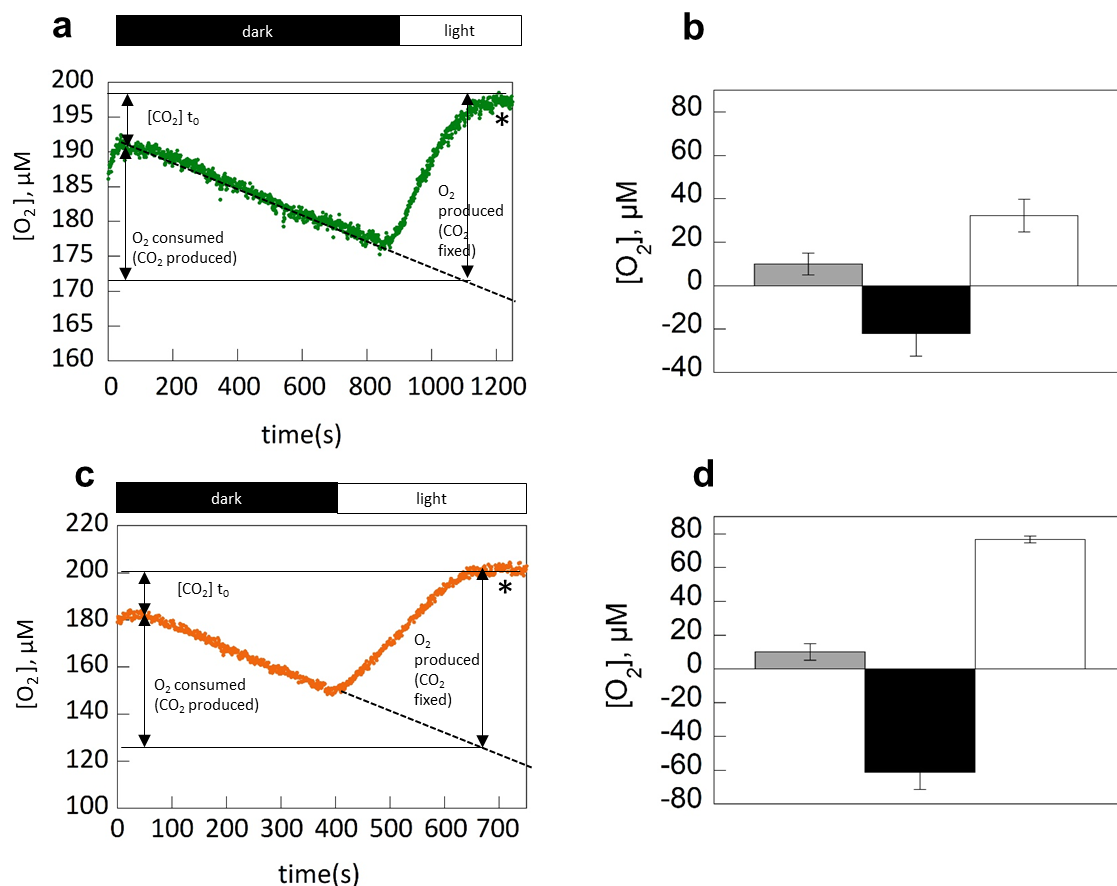


**Figure S9: Immunodetection of RuBisCO in phototrophic and mixotrophic cultures of *G. sulphuraria* SAG21.92 under ambient and enhanced CO<sub>2</sub> atmosphere.** Cells were grown in a photobioreactor in air ([CO<sub>2</sub>]= 0.04 %) or air supplemented with CO<sub>2</sub>. After 7 days of adaptation, cells were collected and broken with a Precellys homogeniser, through three cycles of 30 seconds at 10.000 rpm separated by a 30 seconds interval. Total protein extracts were analyzed by immunoblotting with anti- RuBisCO (AS03 037, Agrisera, Sweden). An antibody against the  $\beta$  subunit of the ATP synthase complex (AS05 085, Agrisera, Sweden) was used as a loading control. 10  $\mu$ g of protein was loaded per well.

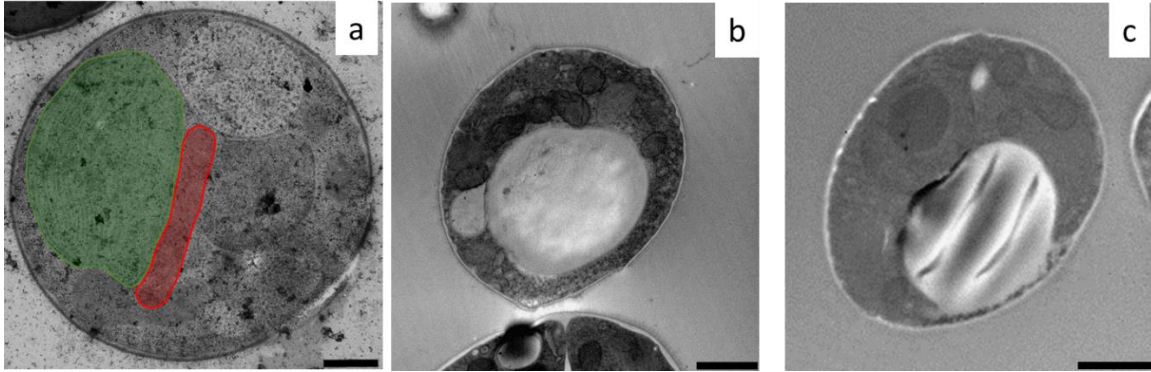




**Figure S10: Comparative analysis of phototrophic (green), mixotrophic (orange) and heterotrophic (black) performances in *G. sulphuraria* 074 G and SAG21.92 species with D-sorbitol and D-glucose.** *G. sulphuraria* 074 G and SAG21.92 species were grown in a photobioreactor as described in Fig. S3 & S4 under conditions similar to those described in Oesterhelt et al. (2007) in the presence of 2% CO<sub>2</sub> but at 42°C. At day 3 cells were either placed in the dark (black) in the presence of 25 mM D-sorbitol or D-glucose or exposed to light (transmitted light 10 μmol photons m<sup>-2</sup> s<sup>-1</sup>) in the absence of organic carbon (green) or in the presence of either 25 mM D-sorbitol or D-glucose as indicated in the graph. Cells were collected at day 7, dried and weighted. Growth performances of the 074G and SAG21.92 strains are very similar in the presence of D-glucose or D-sorbitol. Data from 3 biological replicates ± S.D.



**Figure S11: Respiration fuels photosynthesis in photoautotrophic (green) and mixotrophic (orange) *G. sulphuraria* SAG21.92 cultures.** **a,c:** representative experiment of  $O_2$  consumption or production measured in a closed system (Clark electrode) at  $42^\circ C$ . Photoautotrophic cells (a,b) or mixotrophic cells (c,d) were centrifuged and resuspended at  $30 \times 10^6$  cells in 1 mL of fresh 2xGS medium. Stars indicate a dynamic equilibrium reached when all excess  $CO_2$  from the media ( $CO_2$  initially present plus  $CO_2$  produced by respiration) is fixed. Thus, photosynthesis becomes limited by  $CO_2$  production by respiration, leading to the compensation point. **b (photoautotrophic cells)**, **d (mixotrophic cells):** the amount of  $O_2$  produced by photosynthesis (white) is commensurate with the amount of  $CO_2$  available to Rubisco, i.e. the sum of respiratory  $CO_2$  (evaluated from  $O_2$  consumption, assuming a 1/1 stoichiometry between  $CO_2$  released and consumed oxygen, black) plus the small  $CO_2$  amount initially present in the medium ( $10 \mu M$  ca at pH 2, grey), Data from 3 biological replicates  $\pm$  S.D.



**Figure S12: Transmission electron microscopy of *G. sulphuraria* SAG21.92 grown 5 days under photoautotrophic (a), mixotrophic (b) and heterotrophic (c) conditions. b, c show the presence of a huge floridean starch grain in the cytosol of the cells four days after addition of 25 mM D-sorbitol. Scale bars: a: 0.5  $\mu\text{m}$ ; b, c: 1  $\mu\text{m}$ . In a, mitochondria and plastids are highlighted in red and green, respectively.**

**Dataset S1 (separate file).** Proteins involved in photosynthesis, central metabolism and respiration were selected from the complete proteomic dataset (see Supplementary Dataset S2) and used to build Fig. 3. Proteins function and predicted localizations were checked manually (column “Manual annotation”). Cells highlighted in yellow in this column indicate proteins with statistically significant changes in abundance (see Threshold described in Supplementary Dataset S1). Blue-color and orange-color scales indicate decrease and increase in abundance, respectively (See Legend sheet).

**Dataset S2 (separate file).** Compared proteomic analysis between photoautotrophic, mixotrophic and heterotrophic growth conditions. Proteomics analyses were performed on biological triplicates for each growth condition. Quantification was obtained from extracting the MS1 intensity. Merging of results and filtering on both identification and quantification criteria as described in the Supporting Information resulted into 2100 proteins (“protein sets”, sheet **Dataset S2-ALL**). These 2100 proteins were further divided into 694 proteins entirely missing in at least 1 condition (sheet **Dataset S2-MissingInOneCond.**) and 1406 proteins that have been quantified in all three conditions (in at least 1 replicate, sheet **Dataset S2-SeenInAllConditions**). This latter subset was submitted to differential analysis. Highlighted in blue : imputed values (in Dataset S2-SeenInAllConditions) that were assigned to partially missing abundance values (i.e. within one condition, in Dataset S2-ALL).

**Dataset S3 (separate file).** Compared metabolomic analysis between photoautotrophic, mixotrophic and heterotrophic growth conditions.

**GC-MS sheet:** In the table 32 compounds are listed with their retention time and chosen quantifier ion fragment. Compound identification was based on retention time and fragment pattern match with an in-house library or the NIST library. Peak areas of each compound were normalized to the internal standard and transformed to readable values by a multiplier. The p-value for the sample group was calculated using the multiple comparison function from PRISM software based on

the Students t-test. **IC-MS sheet:** In the table 31 compounds are listed with their retention times and calculated molecular weights. Compound identification was based on 5 different sources of which the in-house database created with mzVault was the preferred source of identification. Batch normalization was carried out with pooled QC samples frequently measured during the batch. The p-value for the sample group was calculated in Compound Discoverer by running the Tukey HSD test (posthoc) after an analysis of variance (ANOVA) test and correction was performed by using the Benjamini-Hochberg algorithm for the false discovery rate.

### Supporting information references

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