



**HAL**  
open science

## The Chara genome

Tomoaki Nishiyama, Hidetoshi Sakayama, Jan de Vries, Henrik Buschmann,  
Denis Saint-Marcoux, Kristian K. Ullrich, Fabian B. Haas, Lisa  
Vanderstraeten, Dirk Becker, Daniel Lang, et al.

► **To cite this version:**

Tomoaki Nishiyama, Hidetoshi Sakayama, Jan de Vries, Henrik Buschmann, Denis Saint-Marcoux, et al.. The Chara genome. *Cell*, 2018, 174 (2), pp.448-464.e24. 10.1016/j.cell.2018.06.033 . hal-02624417

**HAL Id: hal-02624417**

**<https://hal.inrae.fr/hal-02624417v1>**

Submitted on 3 Sep 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## The *Chara* genome: secondary complexity and implications for plant terrestrialization

Tomoaki Nishiyama<sup>1,\*</sup>, Hidetoshi Sakayama<sup>2,\*</sup>, Jan de Vries<sup>4,5</sup>, Henrik Buschmann<sup>3</sup>, Denis Saint-Marcoux<sup>6,7</sup>, Kristian K. Ullrich<sup>8,40</sup>, Fabian B. Haas<sup>8</sup>, Lisa Vanderstraeten<sup>9</sup>, Dirk Becker<sup>10</sup>, Daniel Lang<sup>38</sup>, Stanislav Vosolsobě<sup>17</sup>, Stephane Rombauts<sup>11</sup>, Per K.I. Wilhelmsson<sup>8</sup>, Philipp Janitza<sup>12</sup>, Ramona Kern<sup>13</sup>, Alexander Heyl<sup>14</sup>, Florian Rümpler<sup>15</sup>, Luz Irina A. Calderón Villalobos<sup>30</sup>, John M. Clay<sup>16</sup>, Roman Skokan<sup>17</sup>, Atsushi Toyoda<sup>18</sup>, Yutaka Suzuki<sup>19</sup>, Hiroshi Kagoshima<sup>20</sup>, Elio Schijlen<sup>39</sup>, Navindra Tajeshwar<sup>14</sup>, Bruno Catarino<sup>6</sup>, Alexander J Hetherington<sup>6</sup>, Assia Saltykova<sup>11,21,22</sup>, Clemence Bonnot<sup>6,36</sup>, Holger Breuninger<sup>6,23</sup>, Aikaterini Symeonidi<sup>8</sup>, Guru V. Radhakrishnan<sup>24</sup>, Filip Van Nieuwerburgh<sup>37</sup>, Dieter Deforce<sup>37</sup>, Caren Chang<sup>16</sup>, Kenneth G. Karol<sup>25</sup>, Rainer Hedrich<sup>10</sup>, Peter Ulvskov<sup>26</sup>, Gernot Glöckner<sup>27</sup>, Charles F. Delwiche<sup>16</sup>, Jan Petrášek<sup>17</sup>, Yves Van de Peer<sup>11,28</sup>, Jiri Friml<sup>29</sup>, Mary Beilby<sup>31</sup>, Liam Dolan<sup>6</sup>, Yuji Kohara<sup>20</sup>, Sumio Sugano<sup>19</sup>, Asao Fujiyama<sup>18</sup>, Pierre-Marc Delaux<sup>32</sup>, Marcel Quint<sup>12,30</sup>, Günter Theißen<sup>15</sup>, Martin Hagemann<sup>13</sup>, Jesper Harholt<sup>33</sup>, Christophe Dunand<sup>32</sup>, Sabine Zachgo<sup>3</sup>, Jane Langdale<sup>6</sup>, Florian Maumus<sup>34</sup>, Dominique Van Der Straeten<sup>9</sup>, Sven B. Gould<sup>4</sup>, Stefan A. Rensing<sup>8,35,\*,+</sup>

<sup>1</sup> Advanced Science Research Center, Kanazawa University, Kanazawa 920-0934, Japan

<sup>2</sup> Graduate School of Science, Kobe University, Kobe 657-8501, Japan

<sup>3</sup> Botany Department, School of Biology and Chemistry, Osnabrück University, 49076 Osnabrück, Germany.

<sup>4</sup> Institute for Molecular Evolution, Heinrich Heine University, 40225 Düsseldorf, Germany

<sup>5</sup> Department of Biochemistry and Molecular Biology, Dalhousie University, Halifax, Nova Scotia B3H 4R2, Canada

<sup>6</sup> Department of Plant Sciences, University of Oxford, Oxford, OX1 3RB, United Kingdom

<sup>7</sup> Université de Lyon, UJM-Saint-Étienne, CNRS, BVPam FRE3727, 42023 Saint-Étienne, France

<sup>8</sup> Plant Cell Biology, Faculty of Biology, University of Marburg, 35043 Marburg, Germany

<sup>9</sup> Laboratory of Functional Plant Biology, Department of Biology, Gent University, 9000 Gent, Belgium

<sup>10</sup> Molecular Plant Physiology & Biophysics, University of Wuerzburg, 97082 Wuerzburg, Germany

<sup>11</sup> Department of Plant Biotechnology and Bioinformatics, Gent University and VIB Center for Plant Systems Biology, 9052 Gent, Belgium

<sup>12</sup> Institute of Agricultural and Nutritional Sciences, Martin-Luther-University Halle-Wittenberg, 06120 Halle (Saale), Germany

<sup>13</sup> Plant Physiology, University Rostock, 18051 Rostock, Germany

<sup>14</sup> Department of Biology, Adelphi University, Garden City, NY 11530, USA

- <sup>15</sup> Department of Genetics, Friedrich Schiller University Jena, 07743 Jena, Germany
- <sup>16</sup> CBMG, University of Maryland, College Park, MD 20742, USA
- <sup>17</sup> Department of Experimental Plant Biology, Faculty of Science, Charles University, 128 44 Prague 2, Czech Republic
- <sup>18</sup> Comparative Genomics Laboratory and Advanced Genomics Center, National Institute of Genetics, Shizuoka 411-8540, Japan
- <sup>19</sup> Department of Computational Biology and Medical Sciences, University of Tokyo, Kashiwa, Chiba 277-8562, Japan
- <sup>20</sup> Genome Biology Laboratory, National Institute of Genetics, Shizuoka 411-8540, Japan
- <sup>21</sup> Platform Biotechnology and Molecular Biology, Scientific Institute of Public Health (WIV-ISP), Brussels, Belgium
- <sup>22</sup> Department of Information Technology, Gent University, IMinds, 9052 Gent, Belgium
- <sup>23</sup> ZMBP, Entwicklungsgenetik, 72076 Tübingen, Germany
- <sup>24</sup> Department of Cell and Developmental Biology, John Innes Centre, Norwich NR4 7UH, United Kingdom
- <sup>25</sup> Lewis B. and Dorothy Cullman Program for Molecular Systematics, The New York Botanical Garden, Bronx, NY 10458, USA
- <sup>26</sup> Department of Plant and Environmental Sciences, University of Copenhagen, DK-1871 Frederiksberg C, Denmark
- <sup>27</sup> Biochemistry I, Medical Faculty, University of Cologne, 50931 Cologne, Germany
- <sup>28</sup> Department of Biochemistry, Genetics and Microbiology, University of Pretoria, Pretoria, 0028, South Africa
- <sup>29</sup> Institute of Science and Technology, 3400 Klosterneuburg, Austria
- <sup>30</sup> Department of Molecular Signal Processing, Leibniz Institute of Plant Biochemistry, 06120 Halle (Saale), Germany
- <sup>31</sup> School of Physics, University of NSW, Sydney, Kensington, 2052, NSW, Australia
- <sup>32</sup> Laboratoire de Recherche en Sciences Végétales, Université de Toulouse, CNRS, UPS, Auzeville, BP42617, 31326 Castanet Tolosan, France
- <sup>33</sup> Carlsberg Research Laboratory, 1799 Copenhagen V, Denmark
- <sup>34</sup> URGI, INRA, Université Paris-Saclay, 78026 Versailles, France
- <sup>35</sup> BIOSS Centre for Biological Signalling Studies, University Freiburg, Germany
- <sup>36</sup> Present address: Labex ARBRE, UMR 1136 INRA-Université de Lorraine (IAM), INRA-Grand Est-Nancy, Champenoux, France
- <sup>37</sup> Laboratory of Pharmaceutical Biotechnology, Gent University, 9000, Gent, Belgium
- <sup>38</sup> PGSB, Helmholtz Center Munich, 85764 Neuherberg, Germany

<sup>39</sup> Wageningen University, B.U. Bioscience, 6700 AA Wageningen, The Netherlands

<sup>40</sup> Present address: Max Planck Institute for Evolutionary Biology, 24306, Ploen, Germany.

+ Lead contact: Stefan A. Rensing

\* Authors for correspondence:

[tomoakin@staff.kanazawa-u.ac.jp](mailto:tomoakin@staff.kanazawa-u.ac.jp)

[hsak@port.kobe-u.ac.jp](mailto:hsak@port.kobe-u.ac.jp)

[stefan.rensing@biologie.uni-marburg.de](mailto:stefan.rensing@biologie.uni-marburg.de)

## 1 **Summary**

2 Land plants evolved from charophytic algae, among which Charophyceae possess the most  
3 complex body plans. We present the genome of *Chara braunii*; comparison of the genome to  
4 those of land plants identified evolutionary novelties for plant terrestrialization and land plant  
5 heritage genes. *C. braunii* employs unique xylan synthases for cell wall biosynthesis, a  
6 phragmoplast (cell separation) mechanism similar to that of land plants, and many  
7 phytohormones. *C. braunii* plastids are controlled *via* land plant-like retrograde signaling, and  
8 transcriptional regulation is more elaborate than in other algae. The morphological complexity  
9 of this organism may result from expanded gene families, with three cases of particular note:  
10 genes effecting tolerance to reactive oxygen species (ROS), LysM receptor-like kinases, and  
11 transcription factors (TFs). Transcriptomic analysis of sexual reproductive structures reveals  
12 intricate control by TFs, activity of the ROS gene network, and the ancestral use of plant-like  
13 storage and stress protection proteins in the zygote.

14

15 **Keywords:** plant evolution, charophyte, phytohormones, transcriptional regulation,  
16 Phragmoplastophyta, Chara, streptophyte, reactive oxygen species, phragmoplast

17 **Introduction**

18 A pivotal event in the emergence of plant life was the mid-Paleozoic adaptation to land. While  
19 several algal lineages evolved to occupy terrestrial environments, only one represents the land  
20 plant ancestor; its terrestrialization event was fostered by a range of evolutionary novelties. The  
21 specific complement of traits that allowed a particular algal lineage to give rise to land plants  
22 and dominate the terrestrial environment remains under active study. Similarity of critical plant  
23 developmental, sensory, and regulatory pathways to homologous pathways in charophyte green  
24 algae has been demonstrated in several recent studies, emphasizing the close relationship  
25 among these lineages (reviewed in (Rensing, 2018)).

26 Charophytic algae are the closest living relatives of land plants (embryophytes), with both  
27 groups collectively referred to as streptophytes (Fig. 1). The Charophyceae,  
28 Coleochaetophyceae, and Zygnematophyceae together with the land plants represent the clade  
29 Phragmoplastophyta (Lecointre and Le Guyader, 2006), united by the presence of the  
30 phragmoplast (Pickett-Heaps, 1975), an array of microtubules perpendicular to the cell division  
31 plane that functions in the formation of the nascent cell wall. The Klebsormidiophyceae,  
32 Chlorokybophyceae, and Mesostigmatophyceae share fewer traits with land plants (Fig. 1).  
33 While Charophyceae were hypothesized to be most closely related to land plants on the basis  
34 of similar body plans (Pringsheim, 1862), recent studies indicated that the Zygnematophyceae  
35 are the land plant sister group (Wickett et al., 2014).

36 Extant Zygnematophyceae have simple body plans that seem to reflect secondary loss of  
37 morphological complexity. In contrast, the earlier diverging Charophyceae are morphologically  
38 more complex than all other charophytic algae: the haploid thallus body plan encompasses a  
39 shoot-like axis consisting of nodes with whorls, internodes, a simplex apical meristem, plus  
40 multicellular rhizoids (Fig. 2). Cells of the internode are large and complex, featuring endo-  
41 and ectoplasma, multiple plastids and nuclei, and communicate *via* electrical signals. The  
42 morphology of extant charophytic groups thus infers mosaic evolution and suggests that the  
43 genomes of Charophyceae, not Zygnematophyceae, will likely reveal the suite of traits that  
44 facilitated terrestrialization (Delwiche, 2016).

45 Here we present the genome sequence of the charophycean alga *Chara braunii*, one of the most  
46 morphologically complex extant Charophyta, shedding light on early embryophyte  
47 diversification and the colonization of land by plants.

## 48 Results and Discussion

49

### 50 The *Chara braunii* genome: assembly, annotation and comparison

51 *C. braunii* features a haplontic life cycle (Fig. 2), the draft sequence reported here represents a  
52 haploid genome. 1.75 Gbp of nuclear scaffold data were obtained, of which 1.43 Gbp were  
53 assembled into contigs, corresponding to ~74% of the *C. braunii* genome. RNA-seq of  
54 vegetative and reproductive stages was used together with full-length cDNA sequences to  
55 annotate the genome. 23,546 putative protein coding gene models were identified, of which  
56 53% are supported by RNA-seq data (Table S4). At least 94% of several conserved core gene  
57 sets are encoded by the genome, indicating its suitability for genomic and comparative analyses  
58 (STAR Methods).

59 The observed chromosome number  $n=14$  (Fig. S1) corresponds to the base chromosome  
60 number of *Chara* species. Indeed, synonymous substitution distance (Ks)-based analysis of *C.*  
61 *braunii* paralogs revealed no evidence of whole genome duplication (WGD) events (Fig. S3)  
62 and thus paralog acquisition and retention is probably due to small-scale duplications.  
63 Repetitive elements (Table S1F, S1G) collectively contribute approximately 1.1 Gbp (61%, or  
64 75% if gaps are excluded). Unlike in most plants and green algae, there are no Copia-type long  
65 terminal repeat (LTR) retrotransposons (RT) detectable. We discovered a family of repeats with  
66 putative GIY-YIG homing endonuclease and reverse transcriptase domains, which are  
67 hallmarks of Penelope RTs and group II introns that are uncommon in plant genomes.

68 The density of LTR elements in the genome is intermediate between compact genomes like  
69 those of *Arabidopsis thaliana* or *Klebsormidium nitens*, and other large genomes such as maize  
70 and barley (Fig. 3). *C. braunii* introns are an order of magnitude longer than in any of the other  
71 genomes investigated here (Table S1L), although intron boundaries appear to be conserved. The  
72 high intron length coincides with a low number of introns per gene (3.82), similar to the value  
73 for the barley genome (3.89, Table S1L); intron length and number show negative correlation  
74 ( $r = -0.42$ ). Repetitive elements represent 39% of the intron space (Fig. 3, Mendeley archive)  
75 which is strikingly enriched with Penelope-like elements and depleted of other types of repeats  
76 including Class 2 transposable elements (Helitrons and DNA transposons), suggesting  
77 differential integration bias and/or retention in introns as compared to intergenic space (Table  
78 S1L).

79

### 80 Evolutionary novelties enabling terrestrialization and land plant heritage genes (LPHG)

81 The lineage harboring *C. braunii* diverged from land plants 550–750 Ma (Morris et al., 2018).  
82 By identifying features that are shared between the *C. braunii* genome and extant land plants,  
83 putative ancestral traits can be identified that have been retained over several hundred Ma. Here  
84 we refer to the genes underlying these traits as land plant heritage genes (LPHG) and similarly  
85 deduce evolutionary novelties.

86

87 *Cell division and cell wall*

88 *C. braunii*, like land plants, performs cytokinesis by assembling a cell plate using a  
89 phragmoplast microtubule array while *K. nitens* divides by an evolutionarily older cleavage  
90 (Fig. 1). Phragmoplast-mediated cell division is assumed to have enabled filament branching  
91 through a shift in the plane of cell division (Buschmann and Zachgo, 2016). Land plants also  
92 evolved another microtubule array, the preprophase band (PPB), which functions in  
93 phragmoplast and cell plate guidance. Focusing on genes for phragmoplast and PPB function,  
94 a list of 221 *A. thaliana* cytokinesis genes was compiled (Table S1C). Sequence comparisons  
95 showed that the genomes of *A. thaliana*, *P. patens*, *C. braunii* and *K. nitens* have a highly similar  
96 complement of cytokinesis-related genes while the unicellular chlorophyte *Chlamydomonas*  
97 *reinhardtii* is divergent. Interestingly, the *C. braunii* genome lacks the *TANGLED1* gene. In  
98 land plants, microtubule-associated TANGLED1 localizes to PPBs and is required for  
99 phragmoplast guidance (Walker et al., 2007). Since TANGLED1 homologs are found in several  
100 bryophytes, but none in any algae, this gene likely played an important role in PPB evolution  
101 (Fig. 1). To gain further insight into the evolution of the phragmoplast, we determined how  
102 many paralogs each of the cytokinesis genes has in *C. braunii* as compared to *K. nitens*. In this  
103 way we identified possible phragmoplast signature genes (Table S1C). Among others, we  
104 detected expansion of cyclins as well as EXOCYST and SNARE complex members (Table  
105 S1C, Data S1Q-S). The expansion of phragmoplast-related gene families in *C. braunii* / the  
106 Phragmoplastophyta, but not in Chlorophyta, *K. nitens* or *M. viride*, suggests their sub- and  
107 neofunctionalization to enable phragmoplast function.

108 Like land plant cell walls, those of *C. braunii* consist of cellulose embedded within a pectin and  
109 hemicellulose matrix (Sorensen et al., 2011), its synthesis is orchestrated by a repertoire of  
110 glycosyltransferases much like in land plants (Table S1H), with the exception of an apparently  
111 unique mechanism for xylan synthesis. The GT47 xylan synthase XYS1 has been identified in  
112 *K. nitens*, as well as IRX9 and IRX14 from GT43 (Data S1A), implicated in xylan biosynthesis  
113 despite no apparent requirement for being an active enzyme (Ren et al., 2014). Orthologs to  
114 neither XYS1 nor IRX9/14 could be identified in *C. braunii*, however, a deep branching, highly  
115 diverged form of GT43 was identified as the most likely *C. braunii* xylan synthase, providing  
116 the first hint that GT43 sequences are enzymatically involved in synthesizing xylan.

117

#### 118 *Phytohormones*

119 Phytohormones enable the integration of environmental stimuli with developmental programs.  
120 As such, they are a key feature of land plants, with some apparently having origins in algae  
121 (Hori et al., 2014; Ju et al., 2015; Wang et al., 2015). Potential orthologs of phytohormone  
122 pathway genes were defined across *K. nitens*, *C. braunii*, *P. patens* and *A. thaliana* (Table 1,  
123 Fig. 4, Table S1J).

#### 124 *Auxin (AUX)*

125 AUX is one of the major regulators of plant growth and development. Biosynthesis of AUX  
126 (Hori et al., 2014) as well as transcriptional and physiological response to high concentrations  
127 have been shown in *K. nitens* (Ohtaka et al., 2017). In contrast to *K. nitens*, genes encoding  
128 biosynthetic enzymes of the TAA and YUCCA families are absent from *C. braunii* (Table 1).  
129 In *C. australis* IAA, serotonin and melatonin accumulate in a synchronized manner during the

130 day/night cycle (Beilby et al., 2015). As the tryptamine IAA biosynthetic pathway intersects  
131 with the serotonin/melatonin pathway (Tivendale et al., 2014), *Chara* may synthesize and  
132 metabolize AUX *via* a different route than land plants.

133 Homologous genes for both *PINs* and *ABCs* are present in the *C. braunii* genome (Table 1,  
134 Table S1K), supporting previous data on polar AUX transport (PAT) in *K. nitens* (Hori et al.,  
135 2014) and Charales (Boot et al., 2012). Homologous sequences for AUX1/LAX-like influx  
136 carriers as well as the intracellular PIN-like (PILS) transporters, however, are absent from the  
137 *C. braunii* genome (Table 1), suggesting that AUX transport and homeostasis display an  
138 evolutionary history different from other streptophytes.

139 The land plant-type AUX signaling cascade, consisting of SCF<sup>TIR1/AFB</sup> and Aux/IAA co-  
140 receptors and ARF TFs, was suggested to be absent in *K. nitens* (Hori et al., 2014; Ohtaka et  
141 al., 2017). *K. nitens* encodes an Aux/IAA domain containing protein (Wang et al., 2015) that  
142 features an additional B3 domain, is not induced by IAA (Ohtaka et al., 2017) and thus not  
143 classified as canonical Aux/IAA (Table 1). In addition to all components of the ubiquitin-  
144 proteasome system (Table S1I), *C. braunii* features a single ARF (Data S1E) with land plant-  
145 like domain composition (Flores-Sandoval et al., 2018), and two Aux/IAA-like sequences  
146 (Table 1, Data S1F) clustering with the *A. thaliana* non-canonical IAA33 (lacking a TOPLESS  
147 interacting motif and degron for AUX-dependent SCF<sup>TIR1/AFB</sup>-Aux/IAA interactions.

148 *C. braunii* also encodes several F-box proteins (FBPs) with sequence similarity to land plant  
149 phytohormone co-receptors (Data S1P). None of the TIR1/AFB-like FBPs cluster with the land  
150 plant AUX co-receptor gene family (Data S1G). Structural modeling, however, reveals that the  
151 *C. braunii* sequences adopt a solenoid-fold architecture resembling TIR1 (Tan et al., 2007).  
152 Ligand binding modeling supported the potential ability to form an AUX binding pocket (Data  
153 S1P). The existence of only degron-less *C. braunii* Aux/IAAs, however, prompts to postulate  
154 that a land plant-like TIR1/AFB-Aux/IAA co-receptor pair is most likely not functional in *C.*  
155 *braunii*.

156 Consequently, while obvious candidates for canonical land plant AUX biosynthesis genes are  
157 lacking, there is a partial candidate gene set of the major land plant AUX signaling and PAT  
158 pathways in *C. braunii*. In conclusion, AUX biosynthesis, transport, and some form of signaling  
159 were already present in the last common ancestor of *C. braunii* and *K. nitens*, but AUX  
160 signaling *via* ARFs was apparently gained in the common ancestor of Phragmoplastophyta, as  
161 was ARF repression by Aux/IAAs (Table S1Q, Fig. 4).

162

### 163 Cytokinin (CK)

164 The CK signaling pathway consists of four protein families: the receptor, the histidine-  
165 containing phosphotransfer protein, and the type A and B response regulators (RRA and RRB)  
166 (Heyl et al., 2013). The *C. braunii* genome encodes members of the first three, but no RRBs  
167 (Table 1, Fig. 4). This is contrast to their presence in all chlorophytes and charophytes analysed  
168 (Hori et al., 2014; Wang et al., 2015). Several RR domains closely related to RRBs were found,  
169 but none contained the Myb domain essential for RRB function (Table S1J). Given the  
170 complexity of the *C. braunii* genome, it is possible that not all genes were correctly or  
171 completely predicted, but neither genome nor transcriptome data (Data S1H) provide evidence

Commented [R1]: Marcel Quint: suggest to remove

Commented [R2R1]: Not so sure, because readers might want to compare with Wang et al.



172 for RRB genes. Their loss suggests either the rewiring of CK signaling or substitution of RRB  
173 function by other genes.

174

#### 175 *Ethylene (ETH)*

176 The *C. braunii* genome possesses one or more potential homologs of all of the core components  
177 associated with ETH signaling (Table 1, Fig. 4 and Table S1J). *Chara* exhibits ETH-binding  
178 activity (Wang et al., 2006), and *C. braunii* encodes several ETH receptor homologs. Notably,  
179 *C. braunii* possesses a full-length homolog of *EIN2*, a central regulator in ETH signaling. This  
180 is in contrast to both the *K. nitens* genome, which lacks *EIN2* (Hori et al., 2014), and the  
181 *Spirogyra pratensis* transcriptome, which shows only a partial *EIN2* sequence (Ju et al., 2015).  
182 Except for *EIN2*, *S. pratensis* possesses an ETH signaling pathway that is functionally  
183 conserved with the pathway known in land plants (Ju et al., 2015). These findings indicate that  
184 the land plant-like ETH signaling pathway was established in the common ancestor of the  
185 Phragmoplastophyta, after its divergence from the lineage leading to *Klebsormidium*.

186

#### 187 *Abscisic acid (ABA)*

188 Orthologs of the core ABA signaling components are present in bryophytes and it has been  
189 suggested that all ABA biosynthesis/signaling components were gained in the common ancestor  
190 of Charophyta (Ju et al., 2015; Wang et al., 2015), with the exception of PYR/PYL receptors  
191 that were probably gained in the common ancestor of Zygnematophyceae and land plants (de  
192 Vries et al., 2018). The *C. braunii* genome does not contain homologs of the co-receptors  
193 ABI/HAB, nor the PYR/RCAR family of receptors (Park et al., 2009), but possesses homologs  
194 of genes encoding enzymes that act early in the ABA synthesis pathway (from carotenoid  
195 synthesis to violaxanthin; Table 1, Fig. 4 and Table S1J). Given that the presence of ABA has  
196 been confirmed in *C. braunii* (Hackenberg and Pandey, 2014), it is likely that the biosynthetic  
197 pathway differs from that found in land plants, with ABA possibly being synthesized directly  
198 from farnesyl pyrophosphate.

199

#### 200 *Strigolactones (SL)*

201 Orthologs of all the core SL signaling components have been identified exclusively in the  
202 genomes of seed plants; however, D14-like receptor homologs are found encoded by  
203 bryophytes and charophytes (Bythell-Douglas et al., 2017; Wang et al., 2015). Two SL-related  
204 homologs were identified in *C. braunii*, one encoding beta-carotene isomerase D27, and one  
205 encoding the candidate SL/karrikin receptor D14-like (Table 1, Fig. 4 and Table S1J). Given  
206 the presence of SL in several Charales species, and the activity of the synthetic SL GR24 on  
207 *Chara corallina* rhizoid growth (Delaux et al., 2012), it is likely that SL synthesis and signaling  
208 differ in charophyceans and in seed plants (Bythell-Douglas et al., 2017). It has been suggested  
209 that D14-like proteins might act as (the) SL receptor(s) in this group.

210 In summary, although the phytohormones AUX and CK seem to be ancestral features of  
211 streptophytes, and SL and ABA of Phragmoplastophyta (Fig. 1), the respective biosynthesis  
212 and/or signaling pathways differ between seed plants and *C. braunii*. Some features of these

213 four phytohormone networks, and of ETH signaling, first appeared in the Phragmoplastophyta  
214 as evident by their presence in *C. braunii*. Others were either not present in the ancestor or have  
215 since diverged.

216

#### 217 *Plastid evolution: photorespiration and retrograde signaling*

218 Photorespiration, which recycles the 2-carbon compound formed when ribulose biphosphate  
219 carboxylase/oxygenase reacts with oxygen instead of CO<sub>2</sub>, is crucial to photosynthesis in an  
220 oxygen-rich atmosphere. The *C. braunii* genome encodes proteins necessary to carry out a  
221 plant-like photorespiratory cycle, including a plant-type glycolate oxidase (GOX) (Table S1M)  
222 with structural features preferring glycolate over lactate (Hackenberg et al., 2011). Plant-type  
223 GOX is also present in *K. nitens*, while *C. reinhardtii* uses a mitochondrial glycolate  
224 dehydrogenase for photorespiratory glycolate metabolism (Nakamura et al., 2005). Apparently,  
225 plant-like photorespiration was present in the common ancestor of Streptophyta, the pathway  
226 being a feature that might have aided terrestrialization.

227 The plastid to nucleus signaling network optimizes plastid function in land plants. All  
228 Chloroplastida (Fig. 1) share EXECUTOR-transduced singlet oxygen and a rudimentary  
229 tetrapyrrole-derived retrograde signaling, to which streptophytes recruited GUN2/3 (Fig. 5A).  
230 Our data show that *C. braunii*, but not *K. nitens*, encodes GUN1, at which multiple retrograde  
231 signals converge in land plants (reviewed by (Chan et al., 2016)). The only GUN1 candidate  
232 protein in *K. nitens* (kfl00096\_0090) clustered with streptophyte algae- and bryophyte-specific  
233 PPRs, but not GUN1 (Data S1I). Hence, retrograde signaling featuring GUN1 might represent  
234 an evolutionary novelty of the Phragmoplastophyta (Fig. 1).

235 Plastid-encoded RNA-polymerase (PEP) is the ancestral and for most Archaeplastida the only  
236 PEP. In land plants, PEP activity is controlled through PEP-associated proteins (PAPs) (Pfalz  
237 and Pfannschmidt, 2013). We detected 5, 8, 10 and 11 PAP orthologs in *C. reinhardtii*, *K. nitens*,  
238 *C. braunii*, and *P. patens*, respectively. PAPs were thus already present in streptophyte algae  
239 (Fig. 5A) and underwent expansion in land plants. Most of the detected PAPs are predicted to  
240 be targeted to the chloroplast, the mitochondrion or both (Table S1N); dual-localization of PAPs  
241 to both organelles might be an ancient and conserved character state.

242

#### 243 *Transcriptional regulation*

244 Within the Chloroplastida, morphological complexity correlates with the number of TF (acting  
245 in a sequence-specific manner, typically by binding to *cis*-regulatory elements) and  
246 transcriptional regulator (TR, acting on chromatin or *via* protein-protein interaction) genes  
247 (Lang et al., 2010). We identified 730 TF/TR genes in the *C. braunii* genome (Table S1Q), the  
248 complement of such proteins thus being larger than in *K. nitens* (627) or *C. reinhardtii* (542),  
249 coinciding with morphological complexity. *C. braunii* encodes several TFs that are not present  
250 in other algae, including *K. nitens*. Based on the available data, these families first appear in the  
251 Phragmoplastophyta, although they were previously thought to have been gained in the  
252 common ancestor of Coleochaetophyceae, Zygnematophyceae and land plants (Wilhelmsson et  
253 al., 2017). They include the single canonical ARF mentioned before, as well as TCP, HRT and

254 Zn cluster TFs (Fig. 1). The *C. braunii* genome encodes two TCP genes, which belong to TCP-  
255 P (class I) and TCP-C (class II). The two TCP subgroups are known to exert antagonistic  
256 functions in *A. thaliana* with regard to growth proliferation of organs and tissues (Nicolas and  
257 Cubas, 2016), implying that the appearance of two different TCP genes might have contributed  
258 to regulation of proliferation in the Phragmoplastophyta.

259 Two separate clades of MADS-box genes exist (Type I and II), with land plant Type II genes  
260 further subdivided into so called MIKC<sup>C</sup> and MIKC\*-type genes (Gramzow and Theißen,  
261 2010). No Type I genes were identified in the *C. braunii* genome, but three Type II genes, of  
262 which only *CbMADS1* shows a canonical MIKC-type domain structure. Phylogeny  
263 reconstructions together with exon-intron structure analysis (Fig. 5B; Fig. S5, Data S1K)  
264 suggest that MIKC<sup>C</sup> and MIKC\*-type genes evolved from the duplication of an ancestral Type  
265 II gene followed by different exon duplications in both gene lineages. As such, *CbMADS1* may  
266 serve as a model for the ancestral MIKC-type gene that gave rise to MIKC<sup>C</sup>- and MIKC\*-type  
267 genes of land plants.

268 *C. braunii* encodes 11 bHLH TFs in 5 subfamilies. The Va(2) subfamily is present in  
269 chlorophytic and charophytic genomes and not present in land plants, suggesting that this  
270 subfamily was lost in the lineage leading to land plants (Table S1O, S1P). The *C. braunii*  
271 genome encodes 11 homeodomain (HD) TFs grouped into 9 subfamilies (Table S1O, S1P).  
272 Consistent with previous analyses (Catarino et al., 2016), *C. braunii* contains members of the  
273 KNOX, BEL, DDT and PINTOX subfamilies that are conserved in chlorophytes.

274

#### 275 *Zygotes and spores as analogs to seeds*

276 Dormant haploid spores of mosses share features of regulation and coat biosynthesis with  
277 diploid seeds of flowering plants (Daku et al., 2016; Vesty et al., 2016). The diploid zygotes of  
278 *Chara* are dormant diaspores that presumably undergo meiosis and germinate upon suitable  
279 environmental cues (Delwiche and Cooper, 2015). Differential expression analysis shows that  
280 a number of transcripts related to seed storage proteins (cupin superfamily, oleosins) and to  
281 stress tolerance proteins found in seeds (e.g. late embryogenesis abundant), accumulate to high  
282 levels in zygotes (Fig. S4). These proteins probably enable the *C. braunii* zygotes to withstand  
283 harsh environmental conditions and represent a reservoir of nutrients to facilitate germination  
284 and growth. Homologs of these genes have apparently been adopted during land plant evolution  
285 to enable dormancy in other diaspores, namely spores and seeds.

286

#### 287 **Evolutionary novelties of the *Chara* lineage**

##### 288 *Trihelix TFs*

289 The number of TFs per family is lower in *C. braunii* than in land plants for most families, with  
290 the trihelix family being an exception: 302 members are encoded, while land plant genomes  
291 typically encode ca. 30 copies (Table S1Q). Trihelix TFs are involved in the regulation of  
292 development (e.g. embryogenesis, flower development), as well as responses to abiotic and  
293 biotic factors. Based on RNA-seq data, at least 28 of the *C. braunii* genes are expressed (Table  
294 S4, Fig. S4); 19 in vegetative tissue (of which 6 are expressed exclusively in vegetative tissue)

295 and 22 in reproductive tissues (antheridia, oogonia, zygotes; Fig. S4). Phylogenetic analysis  
296 shows that the vast majority of *C. braunii* trihelix paralogs groups outside of the four clades  
297 previously defined (Kaplan-Levy et al., 2012) (Data S1J). Similar to secondary expansion of  
298 TF families in other lineages the expansion of trihelix TFs in *C. braunii* might be connected to  
299 the independent evolution of morphological complexity.

300

#### 301 *Phytohormones: PINs*

302 There are six PIN AUX transporter proteins potentially encoded by the *C. braunii* genome  
303 (Table S1J). In land plants, the evolution of morphological complexity in the gametophytic  
304 generation, and later in the sporophytic generation, coincides with independent radiations  
305 within the *PIN* gene family (Bennett, 2015). Given its high morphological complexity, the same  
306 might have occurred in *C. braunii*.

307

#### 308 *Motor network*

309 The evolution of land plants is accompanied by increased abundance of myosin and kinesin  
310 domain proteins. Because *K. nitens* has slightly more predicted kinesins than *C. braunii* (Table  
311 S1S), it appears that phragmoplast evolution did not depend on the neofunctionalization of  
312 kinesin paralogs. However, myosin motors use filamentous actin as tracks. The expansion of  
313 the actin family in *C. braunii* (*K. nitens* and *C. reinhardtii* encode 7 actin genes, whereas *C.*  
314 *braunii* has 16; Data S1T, U), with each gene encoding a slightly different protein, hints at  
315 varying functions among the cytoskeleton. Land plants have 9 actin genes (*Marchantia*  
316 *polymorpha*) to often 12 (*A. thaliana*, papaya, *Amborella trichocarpa*), and up to 34 in the  
317 polyploid maize, while transcriptomic data of other Charales suggests high numbers of  
318 underlying genes, e.g. 27 transcripts in *Nitella mirabilis*, 101 in *N. hyalina* (and 46 in the desmid  
319 *Penium margaritaceum*). The high numbers of actin genes detected in the amoebal protist  
320 *Naegleria gruberi* (86), and the slime mold *Dictyostelium discoideum* (39) (Joseph et al., 2008),  
321 can to a large part be explained by their involvement in cell movement. Thus, the additional  
322 actin genes of *Chara*, *Nitella* and *Penium* may serve the enhanced cytoplasmic streaming  
323 observed in these organisms.

324

#### 325 *Electrical excitability*

326 Inspired by the work of (Hodgkin and Huxley, 1952) on the squid axon, the large internodal  
327 cells of *Chara* emerged as an excellent experimental system for electrophysiological studies on  
328 plant excitability - the “Green Axon” (Beilby, 2007). On a slower time scale (1000x), the  
329 internodal cells fire action potentials (APs) in response to such as depolarization, light, heat  
330 shock, injury or touch. The *C. braunii* genome encodes several putative Touch/Mechano-  
331 Sensitive (MS) channels: two members of the MscS-like (MSL) family, as well as an ortholog  
332 of the eukaryote specific Piezo-type channel. The negative resting potential (up to -250 mV)  
333 across the plasma membrane is generated by the P-type H<sup>+</sup>-ATPases, encoded in the *C. braunii*  
334 genome (Table S1R). Ca<sup>2+</sup> and Cl<sup>-</sup> contribute to the depolarizing phase of the *Chara* AP, while  
335 K<sup>+</sup> efflux shapes the AP repolarization phase as in animals. No animal-like voltage-gated Na<sup>+</sup>

**Commented [R3]:** Marcel Quint: suggest to remove or integrate with auxin part

**Commented [R4R3]:** But it is mentioned here are one of the expansions, I would keep it as is. Is also mentioned in the cladogram Figure

336 or Ca<sup>2+</sup> channels were identified, but a single ALMT-type anion channel gene is present in *C.*  
337 *braunii*. The anion channel in *Chara* is Ca<sup>2+</sup>-activated and voltage sensitive, so an Anoctamin-  
338 like channel poses another possibility. A Shaker-type, voltage-gated K<sup>+</sup> channel in *C. braunii*  
339 genome probably mediates the depolarization-activated potassium efflux of the AP  
340 repolarization phase. The *C. braunii* habit of long internodal cells might require long distance  
341 electrical signaling (Beilby, 2015) enabled by its peculiar set of ion channels. The similarities  
342 or differences of *C. braunii* AP, as compared to flowering plants, are yet to be established.

343

#### 344 *Sensing of biotic interaction and microbiome*

345 Land plants harbor a large number of LysM receptor-like kinases (RLK) involved in the  
346 perception of chitin-based signals produced by pathogenic and beneficial microorganisms. One  
347 member of this family has been described in charophytic algae suggesting either an inability to  
348 discriminate microorganisms or an alternative system to do so (Delaux et al., 2015). The *C.*  
349 *braunii* genome revealed the presence of seven LysM-RLKs (Fig. 5C; Data S1N) that expanded  
350 independently of land plant LysM-RLKs. This expansion may reflect an adaptation of *C.*  
351 *braunii* to an extended range of interacting microorganisms (co-cultured bacteria: Table S1T,  
352 S1U). This is noteworthy given that many have failed to axenically cultivate Charophyceae,  
353 raising the possibility that growth may be dependent on microbiotic commensalism or  
354 mutualism.

355

#### 356 *Sexual reproduction and the ROS network*

357 To analyze reproductive mechanisms, transcriptomes of antheridia, oogonia and zygotes were  
358 generated (Fig. 5/6, Fig. S6, Table S2 & S3). For antheridia, the data demonstrate that cell  
359 motility is up-regulated as expected (Fig. 5D; Fig. S6A). Of 949 differentially expressed genes  
360 (DEGs) upregulated in antheridia, 49 encode proteins harboring dynein heavy chains. Dynein-  
361 mediated transport is employed in flagellate cells such as spermatozooids and was lost during  
362 land plant evolution, concomitant with the loss of motile cells (Rensing et al., 2008). 22 of 302  
363 trihelix TFs are expressed in reproductive tissues. Of those, 9 are expressed in all three tissues,  
364 5 specifically in antheridia, 7 in oogonia and antheridia, and 1 specifically in the zygote (Fig.  
365 S4B). This expression profile may suggest a possible role for these genes in sexual  
366 reproduction, in particular in antheridia. Transcripts of a HMG TR and a RWP-RK TF also  
367 specifically accumulated in antheridia. Members of these families were shown to be involved  
368 in mating in fungi (Barve et al., 2003) and gamete differentiation in *C. reinhardtii* (Lin and  
369 Goodenough, 2007), and the single RWP-RK TF in *M. polymorpha* keeps egg cells quiescent  
370 in the absence of fertilization (Rovekamp et al., 2016).

371 Zygote transcriptome profiles are characterized by transcription, microtubule-based movement  
372 and protein kinase activities (Fig. S6D), processes that might be hallmarks of the diploid zygote  
373 maturing and entering dormancy. 87 TFs/TRs are differentially expressed between zygotes and  
374 oogonia, among them families typically linked to the regulation of development (e.g. bHLH,  
375 HD, AP2/EREBP; Fig. S4C), supporting the hypothesis that transcription undergoes a switch  
376 after fertilization. One of the seven LysM RLKs (g44510) is strongly induced in zygotes. In  
377 line with potential commensalism mentioned above, this protein might detect the presence of

378 beneficial microbes as a putative factor triggering meiosis and germination of the dormant  
379 zygote.

380 Of particular interest is the up-regulation of oxidation reduction processes in oogonia as  
381 compared to antheridia or zygotes (Fig. 5E; Fig. S6B/C). Like all living organisms, *C. braunii*  
382 needs to deal with constitutive production of reactive oxygen species (ROS) using the ROS  
383 gene network (Fig. S7, Table S1X). In contrast to land plants, aquatic plants have the option to  
384 let ROS diffuse into the water. *C. braunii* encodes all families responsible for ROS scavenging,  
385 but with lower gene copy number in comparison to land plants. In contrast, CC-type  
386 glutaredoxins (GRX) (ROXYs in *A. thaliana*), which exert crucial functions during angiosperm  
387 reproductive development (Gutsche et al., 2015), could not be detected (Table S1X). Among  
388 redox-associated genes (Table S1X) the class III peroxidases (Prx), thioredoxins and respiratory  
389 burst oxidase homologs expanded greatly during land plant evolution. However, only Prx  
390 expanded in *C. braunii* compared to *K. nitens* (Data S1O). With both peroxidative and  
391 hydroxylic catalytic cycles, these enzymes can regulate ROS and polymerize cell wall  
392 compounds (Francoz et al., 2015). Most of the *C. braunii* Prx are predicted to be secreted, as  
393 such, they may contribute to the formation of the strikingly elaborate reproductive structures,  
394 e.g. the thick zygote wall (Fig. 2).

395 7 out of 12 Prx are 2-8 fold higher expressed in oogonia than in antheridia or zygotes (Fig. 6).  
396 The higher expression of the ROS gene network could be related to the ROS homeostasis  
397 regulation necessary for an optimum fecundation. Flowering plant stigmas exhibit high levels  
398 of peroxidase activity when receptive to pollen (McInnis et al., 2006) and have been discussed  
399 to be involved in pollen-pistil interaction or pollen tube growth/penetration (Beltramo et al.,  
400 2012). For *A. thaliana* root and shoot apical meristems it was shown that stem cell-specific Prx  
401 fine tune the balance between superoxide anions ( $O_2^-$ ) and hydrogen peroxide ( $H_2O_2$ ) and  
402 thereby affect the switch between cell maintenance and differentiation (Zeng et al., 2017).  
403 Differential regulation of ROS levels by Prx might control sexual reproduction in *C. braunii*.  
404 Potentially, this mechanism arose in the common ancestor of Phragmoplastophyta and has been  
405 recruited from the gametophyte to the sporophyte during land plant evolution.

406

## 407 **Conclusions**

408 The *C. braunii* genome encodes more proteins than other algae, but less than most land plants.  
409 Both, specific gains / expansions and losses, can be attributed to the *Chara* lineage (Fig. 1). In  
410 absence of a WGD gene family expansions resulted from gene duplication and differential loss.  
411 Many of these events likely represent secondary gains in *Chara* complexity *via* sub- and  
412 neofunctionalization. We hypothesize that many gene family expansions detected in the *C.*  
413 *braunii* genome underpin its strikingly complex morphology.

414 Comparative genome analysis clearly reflects the phylogenetic placement of *C. braunii* as a  
415 close relative of land plants, with both striking similarities and important differences. It  
416 demonstrates the substantial insights into fundamental aspects of plant biology that can be  
417 gained by comparing diverse relatives. Molecular signatures across genomes reveal that AUX  
418 transport *via* PINs, trihelix TFs, MIKC-type MADS genes as well as photorespiration and

419 diaspore storage proteins were present prior to the divergence of *K. nitens* (Fig. 1). Other  
420 features, such as the non-motile vegetative phase and filamentous growth, evolved later.

421 Hence, much of what was previously considered land plant-like features clearly evolved in the  
422 common ancestor of the Phragmoplastophyta (Fig. 1). These features include polyplastidy,  
423 branching, cellulose synthase rosettes, apical cell growth, several features of phytohormone  
424 networks, potential involvement of ROS in sexual reproduction and the phragmoplast. Some  
425 features evolved after the split of Charophyceae or Coleochaetophyceae such as GRAS TFs and  
426 the PPB-like isthmus band of microtubules. Life on land meant increased exposure to UV light.  
427 RNA editing repairs UV-B induced mutations in land plants (Maier et al., 2008). Editing  
428 evolved after the divergence of Charophyceae from the lineage leading to Zygnematophyceae  
429 and land plants (Cahoon et al., 2017). Key editing factors (PPR proteins) are much less abundant  
430 in *C. braunii* (57) than in the *Spirogyra* (379) or *P. patens* (100) genomes (Table S1Y). Other  
431 features, such as the multicellular sporophyte and embryogenesis, the synthesis of a complex  
432 cuticle and the ability to associate with arbuscular mycorrhizal fungi evolved at the base of the  
433 land plants, and further during land plant evolution (Fig. 1). Among the latter features are  
434 hallmarks of plants' adaptations to land. Yet, before any of these adaptations evolved, LPHGs  
435 enabled the first steps of terrestrialization. The key to their identification lies in comparative  
436 genomics studies using streptophyte algae, as exemplified here for *C. braunii*.

437

438 **Acknowledgements**

439 We thank K. Yamada, M. Göttig, M. Schallenberg-Rüdinger and F. Donges for technical  
440 assistance and S. Kato for kind assistance with strain isolation. Financial support was provided  
441 MEXT & JSPS KAKENHI (17020008 to YK, YS, SS, 20017013, 22128008, 24370095 to TN,  
442 22770083, 24570100, 15K07185 to HS, 221S0002 to AT, AF, YS, SS); Hyogo Science and  
443 Technology Association grant to HS; DFG (GO1825/4-1 & CRC1208 to SBG, VR 132/1-1 to  
444 JdV, SFB 944 to HB and SZ, FOR964 to DB and RH, SFB 924 for DL); MEYS CR project  
445 LO1417 to SV, RS and JP; Carlsberg Foundation and the Villum Foundation's Young  
446 Investigator Programme to JH; LRSV laboratory (ANR-10-LABX-41) to PMD; Gent  
447 University to DVDS; Research Foundation Flanders (G.0317.17N to DVDS and PhD  
448 fellowship 1S17917N to LV); ERC Advanced Grants (EVO500 to LD, ETAP to JF and EDIP  
449 to JAL); Leibniz Association to MQ; NSF (DEB-1020660 and DEB-1036466 to KGK,  
450 MCB1714993 to CC, DEB 1036506 to CFD). Computation was partially performed at NIG and  
451 NIBB, Japan & High Performance and Cloud Computing University Tübingen, Baden-  
452 Württemberg bwHPC, Germany.

453

454 **Authors' contributions**

455 AF, AT, ES, HK, HS, JF, JAL, LD, MB, MQ, SAR, SR, SS, TN, YK, YS, YVP provided  
456 resources and materials.

457 AF, AiS, AT, SAR, SR, TN generated the draft genome.

458 AH, AiS, AsS, BC, CC, CD, CFD, DB, DL, DS-M, DVDS, FBH, FM, FR, GG, GT, GVR, HB,  
459 HS, JdV, JH, JMC, JP, KGK, KKKU, LIACV, LV, MH, NT, PJ, PKIW, PMD, PU, RH, RK, RS,  
460 SAR, SG, SH, SR, SV, SZ, TN analyzed data.

461 JdV, JAL, LD, SAR, SG, TN wrote the paper.

462 All authors helped discuss the results and write the paper.

463

464 **Declaration of Interests**

465 The authors declare no competing interests.

466

467 **References**

- 468 Abouelhoda, M.I., Kurtz, S., and Ohlebusch, E. (2004). Replacing suffix trees with enhanced suffix  
469 arrays. *Journal of Discrete Algorithms* 2, 53-86.
- 470 Alneberg, J., Bjarnason, B.S., de Bruijn, I., Schirmer, M., Quick, J., Ijaz, U.Z., Lahti, L., Loman, N.J.,  
471 Andersson, A.F., and Quince, C. (2014). Binning metagenomic contigs by coverage and composition.  
472 *Nat Methods* 11, 1144-1146.
- 473 Altschul, S.F., Madden, T.L., Schaffer, A.A., Zhang, J., Zhang, Z., Miller, W., and Lipman, D.J. (1997).  
474 Gapped BLAST and PSI-BLAST: a new generation of protein database search programs. *Nucleic Acids*  
475 *Res* 25, 3389-3402.
- 476 Barve, M.P., Arie, T., Salimath, S.S., Muehlbauer, F.J., and Peever, T.L. (2003). Cloning and  
477 characterization of the mating type (MAT) locus from *Ascochyta rabiei* (teleomorph: *Didymella rabiei*)  
478 and a MAT phylogeny of legume-associated *Ascochyta* spp. *Fungal Genet Biol* 39, 151-167.



479 Bauwe, H., Hagemann, M., and Fernie, A.R. (2010). Photorespiration: players, partners and origin.  
480 Trends Plant Sci 15, 330-336.

481 Beilby, M.J. (2007). Action potential in charophytes. Int Rev Cytol 257, 43-82.

482 Beilby, M.J. (2015). Salt tolerance at single cell level in giant-celled Characeae. Front Plant Sci 6, 226.

483 Beilby, M.J., Turi, C.E., Baker, T.C., Tymm, F.J., and Murch, S.J. (2015). Circadian changes in endogenous  
484 concentrations of indole-3-acetic acid, melatonin, serotonin, abscisic acid and jasmonic acid in  
485 Characeae (*Chara australis* Brown). Plant Signal Behav 10, e1082697.

486 Beltramo, C., Torello Marinoni, D., Perrone, I., and Botta, R. (2012). Isolation of a gene encoding for a  
487 class III peroxidase in female flower of *Corylus avellana* L. Mol Biol Rep 39, 4997-5008.

488 Bennett, T. (2015). PIN proteins and the evolution of plant development. Trends Plant Sci 20, 498-507.

489 Bolger, A.M., Lohse, M., and Usadel, B. (2014). Trimmomatic: a flexible trimmer for Illumina sequence  
490 data. Bioinformatics 30, 2114-2120.

491 Boot, K.J., Libbenga, K.R., Hille, S.C., Offringa, R., and van Duijn, B. (2012). Polar auxin transport: a  
492 early invention. J Exp Bot 63, 4213-4218.

493 Buschmann, H., and Zachgo, S. (2016). The Evolution of Cell Division: From Streptophyte Algae to Land  
494 Plants. Trends Plant Sci 21, 872-883.

495 Bythell-Douglas, R., Rothfels, C.J., Stevenson, D.W.D., Graham, S.W., Wong, G.K., Nelson, D.C., and  
496 Bennett, T. (2017). Evolution of strigolactone receptors by gradual neo-functionalization of KAI2  
497 paralogues. BMC Biol 15, 52.

498 Cahoon, A.B., Naus, J.A., Stanley, C.D., and Qureshi, A. (2017). Deep Transcriptome Sequencing of Two  
499 Green Algae, *Chara vulgaris* and *Chlamydomonas reinhardtii*, Provides No Evidence of Organellar RNA  
500 Editing. Genes (Basel) 8.

501 Catarino, B., Hetherington, A.J., Emms, D.M., Kelly, S., and Dolan, L. (2016). The Stepwise Increase in  
502 the Number of Transcription Factor Families in the Precambrian Predated the Diversification of Plants  
503 On Land. Mol Biol Evol 33, 2815-2819.

504 Chan, K.X., Phua, S.Y., Crisp, P., McQuinn, R., and Pogson, B.J. (2016). Learning the Languages of the  
505 Chloroplast: Retrograde Signaling and Beyond. Annu Rev Plant Biol 67, 25-53.

506 Chin, C.S., Alexander, D.H., Marks, P., Klammer, A.A., Drake, J., Heiner, C., Clum, A., Copeland, A.,  
507 Huddleston, J., Eichler, E.E., et al. (2013). Nonhybrid, finished microbial genome assemblies from long-  
508 read SMRT sequencing data. Nat Methods 10, 563-569.

509 Daku, R.M., Rabbi, F., Buttigieg, J., Coulson, I.M., Horne, D., Martens, G., Ashton, N.W., and Suh, D.Y.  
510 (2016). PpASCL, the *Physcomitrella patens* Anther-Specific Chalcone Synthase-Like Enzyme Implicated  
511 in Sporopollenin Biosynthesis, Is Needed for Integrity of the Moss Spore Wall and Spore Viability. PLoS  
512 One 11, e0146817.

513 Darriba, D., Taboada, G.L., Doallo, R., and Posada, D. (2011). ProtTest 3: fast selection of best-fit models  
514 of protein evolution. Bioinformatics 27, 1164-1165.

515 de Vries, J., Curtis, B.A., Gould, S.B., and Archibald, J.M. (2018). Embryophyte stress signaling evolved  
516 in the algal progenitors of land plants. Proc Natl Acad Sci U S A.

517 Delaux, P.-M., Xie, X., Timme, R.E., Puech-Pages, V., Dunand, C., Lecompte, E., Delwiche, C.F., Yoneyama,  
518 K., Bécard, G., and Séjalon-Delmas, N. (2012). Origin of strigolactones in the green lineage. New  
519 Phytologist 195, 857-871.

520 Delaux, P.M., Radhakrishnan, G.V., Jayaraman, D., Cheema, J., Malbreil, M., Volkening, J.D., Sekimoto,  
521 H., Nishiyama, T., Melkonian, M., Pokorný, L., et al. (2015). Algal ancestor of land plants was preadapted  
522 for symbiosis. Proc Natl Acad Sci U S A 112, 13390-13395.

523 Delcher, A.L., Kasif, S., Fleischmann, R.D., Peterson, J., White, O., and Salzberg, S.L. (1999). Alignment  
524 of whole genomes. Nucleic Acids Res 27, 2369-2376.

525 Delwiche, C.F. (2016). The genomes of charophyte green algae. Adv Bot Res 78, 255-270.

526 Delwiche, C.F., and Cooper, E.D. (2015). The Evolutionary Origin of a Terrestrial Flora. Current biology :  
527 CB 25, R899-910.

528 Dierckxsens, N., Mardulyn, P., and Smits, G. (2017). NOVOPlasty: de novo assembly of organelle  
529 genomes from whole genome data. Nucleic Acids Res 45, e18.

530 Duong, T., Cowling, A., Koch, I., and Wand, M.P. (2008). Feature significance for multivariate kernel  
531 density estimation. *Computational Statistics & Data Analysis* 52, 4225-4242.

532 Edgar, R.C. (2004). MUSCLE: a multiple sequence alignment method with reduced time and space  
533 complexity. *BMC Bioinformatics* 5, 113.

534 Flores-Sandoval, E., Eklund, D.M., Hong, S.F., Alvarez, J.P., Fisher, T.J., Lampugnani, E.R., Golz, J.F.,  
535 Vazquez-Lobo, A., Dierschke, T., Lin, S.S., *et al.* (2018). Class C ARFs evolved before the origin of land  
536 plants and antagonize differentiation and developmental transitions in *Marchantia polymorpha*. *New*  
537 *Phytol* 218, 1612-1630.

538 Francoz, E., Ranocha, P., Nguyen-Kim, H., Jamet, E., Burlat, V., and Dunand, C. (2015). Roles of cell wall  
539 peroxidases in plant development. *Phytochemistry* 112, 15-21.

540 Gao, X.H., Huang, X.Z., Xiao, S.L., and Fu, X.D. (2008). Evolutionarily conserved DELLA-mediated  
541 gibberellin signaling in plants. *J Integr Plant Biol* 50, 825-834.

542 Garcia, M., Myouga, F., Takechi, K., Sato, H., Nabeshima, K., Nagata, N., Takio, S., Shinozaki, K., and  
543 Takano, H. (2008). An *Arabidopsis* homolog of the bacterial peptidoglycan synthesis enzyme MurE has  
544 an essential role in chloroplast development. *Plant J* 53, 924-934.

545 Gnerre, S., Maccallum, I., Przybylski, D., Ribeiro, F.J., Burton, J.N., Walker, B.J., Sharpe, T., Hall, G., Shea,  
546 T.P., Sykes, S., *et al.* (2011). High-quality draft assemblies of mammalian genomes from massively  
547 parallel sequence data. *Proc Natl Acad Sci U S A* 108, 1513-1518.

548 Gramzow, L., and Theißen, G. (2010). A hitchhiker's guide to the MADS world of plants. *Genome Biology*  
549 11, 214.

550 Guindon, S., Dufayard, J.F., Lefort, V., Anisimova, M., Hordijk, W., and Gascuel, O. (2010). New  
551 algorithms and methods to estimate maximum-likelihood phylogenies: assessing the performance of  
552 PhyML 3.0. *Syst Biol* 59, 307-321.

553 Gutsche, N., Thurow, C., Zachgo, S., and Gatz, C. (2015). Plant-specific CC-type glutaredoxins: functions  
554 in developmental processes and stress responses. *Biol Chem* 396, 495-509.

555 Haas, B.J., Papanicolaou, A., Yassour, M., Grabherr, M., Blood, P.D., Bowden, J., Couger, M.B., Eccles, D.,  
556 Li, B., Lieber, M., *et al.* (2013). De novo transcript sequence reconstruction from RNA-seq using the  
557 Trinity platform for reference generation and analysis. *Nature protocols* 8, 1494-1512.

558 Hackenberg, C., Kern, R., Hüge, J., Stal, L.J., Tsuji, Y., Kopka, J., Shiraiwa, Y., Bauwe, H., and Hagemann,  
559 M. (2011). Cyanobacterial lactate oxidases serve as essential partners in N<sub>2</sub> fixation and evolved into  
560 photorespiratory glycolate oxidases in plants. *Plant Cell* 23, 2978-2990.

561 Hackenberg, D., and Pandey, S. (2014). Heterotrimeric G-proteins in green algae. An early innovation in  
562 the evolution of the plant lineage. *Plant Signal Behav* 9, e28457.

563 Han, G.Z. (2017). Evolution of jasmonate biosynthesis and signaling mechanisms. *J Exp Bot* 68, 1323-  
564 1331.

565 Heyl, A., Brault, M., Frugier, F., Kuderova, A., Lindner, A.C., Motyka, V., Rashotte, A.M., Schwartzberg,  
566 K.V., Vankova, R., and Schaller, G.E. (2013). Nomenclature for members of the two-component signaling  
567 pathway of plants. *Plant Physiol* 161, 1063-1065.

568 Hodgkin, A.L., and Huxley, A.F. (1952). A quantitative description of membrane current and its  
569 application to conduction and excitation in nerve. *J Physiol* 117, 500-544.

570 Hori, K., Maruyama, F., Fujisawa, T., Togashi, T., Yamamoto, N., Seo, M., Sato, S., Yamada, T., Mori, H.,  
571 Tajima, N., *et al.* (2014). *Klebsormidium flaccidum* genome reveals primary factors for plant terrestrial  
572 adaptation. *Nature Communications* 5, 3978.

573 Huang, X., and Madan, A. (1999). CAP3: A DNA sequence assembly program. *Genome Res* 9, 868-877.

574 Huelsenbeck, J.P., and Ronquist, F. (2001). MRBAYES: Bayesian inference of phylogenetic trees.  
575 *Bioinformatics* 17, 754-755.

576 Huson, D.H., Beier, S., Flade, I., Gorska, A., El-Hadidi, M., Mitra, S., Ruscheweyh, H.J., and Tappu, R.  
577 (2016). MEGAN Community Edition - Interactive Exploration and Analysis of Large-Scale Microbiome  
578 Sequencing Data. *PLoS Comput Biol* 12, e1004957.

579 Inupakutika, M.A., Sengupta, S., Devireddy, A.R., Azad, R.K., and Mittler, R. (2016). The evolution of  
580 reactive oxygen species metabolism. *J Exp Bot* 67, 5933-5943.

581 Iseli, C., Jongeneel, C.V., and Bucher, P. (1999). ESTScan: a program for detecting, evaluating, and  
582 reconstructing potential coding regions in EST sequences. In Proc Int Conf Intell Syst Mol Biol (Menlo  
583 Park, CA, USA: American Association for Artificial Intelligence ), pp. 138-148.

584 Joseph, J.M., Fey, P., Ramalingam, N., Liu, X.L., Rohlf, M., Noegel, A.A., Muller-Taubenberger, A.,  
585 Glockner, G., and Schleicher, M. (2008). The actinome of *Dictyostelium discoideum* in comparison to  
586 actins and actin-related proteins from other organisms. *PLoS One* 3, e2654.

587 Jouffroy, O., Saha, S., Mueller, L., Quesneville, H., and Maumus, F. (2016). Comprehensive repeatome  
588 annotation reveals strong potential impact of repetitive elements on tomato ripening. *BMC Genomics*  
589 17, 624.

590 Ju, C., Van de Poel, B., Cooper, E.D., Thierer, J.H., Gibbons, T.R., Delwiche, C.F., and Chang, C. (2015).  
591 Conservation of ethylene as a plant hormone over 450 million years of evolution. *Nat Plants* 1, 14004.

592 Kaplan-Levy, R.N., Brewer, P.B., Quon, T., and Smyth, D.R. (2012). The trihelix family of transcription  
593 factors--light, stress and development. *Trends Plant Sci* 17, 163-171.

594 Katoh, K., and Standley, D.M. (2013). MAFFT Multiple Sequence Alignment Software Version 7:  
595 Improvements in Performance and Usability. *Molecular Biology and Evolution* 30, 772-780.

596 Keller, O., Kollmar, M., Stanke, M., and Waack, S. (2011). A novel hybrid gene prediction method  
597 employing protein multiple sequence alignments. *Bioinformatics* 27, 757-763.

598 Kelley, L.A., Mezulis, S., Yates, C.M., Wass, M.N., and Sternberg, M.J. (2015). The Phyre2 web portal for  
599 protein modeling, prediction and analysis. *Nat Protoc* 10, 845-858.

600 Kent, W.J. (2002). BLAT--the BLAST-like alignment tool. *Genome Res* 12, 656-664.

601 Kim, D., Pertea, G., Trapnell, C., Pimentel, H., Kelley, R., and Salzberg, S.L. (2013). TopHat2: accurate  
602 alignment of transcriptomes in the presence of insertions, deletions and gene fusions. *Genome Biol*  
603 14, R36.

604 Köster, J., and Rahmann, S. (2012). Snakemake--a scalable bioinformatics workflow engine.  
605 *Bioinformatics* 28, 2520-2522.

606 Kwantes, M., Liebsch, D., and Verelst, W. (2012). How MIKC\* MADS-box genes originated and evidence  
607 for their conserved function throughout the evolution of vascular plant gametophytes. *Mol Biol Evol*  
608 29, 293-302.

609 Lagesen, K., Hallin, P., Rodland, E.A., Staerfeldt, H.H., Rognes, T., and Ussery, D.W. (2007). RNAmmr:  
610 consistent and rapid annotation of ribosomal RNA genes. *Nucleic Acids Res* 35, 3100-3108.

611 Lang, D., Ullrich, K.K., Murat, F., Fuchs, J., Jenkins, J., Haas, F.B., Piednoel, M., Gundlach, H., Van Bel, M.,  
612 Meyberg, R., *et al.* (2018). The *Physcomitrella patens* chromosome-scale assembly reveals moss  
613 genome structure and evolution. *Plant J* 93, 515-533.

614 Lang, D., Weiche, B., Timmerhaus, G., Richardt, S., Riano-Pachon, D.M., Correa, L.G., Reski, R., Mueller-  
615 Roeber, B., and Rensing, S.A. (2010). Genome-wide phylogenetic comparative analysis of plant  
616 transcriptional regulation: a timeline of loss, gain, expansion, and correlation with complexity. *Genome*  
617 *Biol Evol* 2, 488-503.

618 Lawrence, M., Huber, W., Pages, H., Aboyoun, P., Carlson, M., Gentleman, R., Morgan, M.T., and Carey,  
619 V.J. (2013). Software for computing and annotating genomic ranges. *PLoS Comput Biol* 9, e1003118.

620 Lecointre, G., and Le Guyader, H. (2006). *The Tree of Life: A Phylogenetic Classification* (Harvard  
621 University Press).

622 Lee, E., Helt, G.A., Reese, J.T., Munoz-Torres, M.C., Childers, C.P., Buels, R.M., Stein, L., Holmes, I.H.,  
623 Elsik, C.G., and Lewis, S.E. (2013). Web Apollo: a web-based genomic annotation editing platform.  
624 *Genome Biol* 14, R93.

625 Leinonen, R., Sugawara, H., Shumway, M., and International Nucleotide Sequence Database, C. (2011).  
626 The sequence read archive. *Nucleic Acids Res* 39, D19-21.

627 Li, B., and Dewey, C.N. (2011). RSEM: accurate transcript quantification from RNA-Seq data with or  
628 without a reference genome. *BMC Bioinformatics* 12, 323.

629 Li, H., and Durbin, R. (2010). Fast and accurate long-read alignment with Burrows-Wheeler transform.  
630 *Bioinformatics* 26, 589-595.

631 Lin, H., and Goodenough, U.W. (2007). Gametogenesis in the *Chlamydomonas reinhardtii* minus mating  
632 type is controlled by two genes, MID and MTD1. *Genetics* 176, 913-925.

633 Love, M.I., Huber, W., and Anders, S. (2014). Moderated estimation of fold change and dispersion for  
634 RNA-seq data with DESeq2. *Genome Biol* 15, 550.

635 Maier, U.G., Bozarth, A., Funk, H.T., Zauner, S., Rensing, S.A., Schmitz-Linneweber, C., Borner, T., and  
636 Tillich, M. (2008). Complex chloroplast RNA metabolism: just debugging the genetic programme? *BMC*  
637 *Biol* 6, 36.

638 Marcais, G., and Kingsford, C. (2011). A fast, lock-free approach for efficient parallel counting of  
639 occurrences of k-mers. *Bioinformatics* 27, 764-770.

640 McInnis, S.M., Desikan, R., Hancock, J.T., and Hiscock, S.J. (2006). Production of reactive oxygen species  
641 and reactive nitrogen species by angiosperm stigmas and pollen: potential signalling crosstalk? *New*  
642 *Phytol* 172, 221-228.

643 Morris, J.L., Puttick, M.N., Clark, J.W., Edwards, D., Kenrick, P., Pressel, S., Wellman, C.H., Yang, Z.,  
644 Schneider, H., and Donoghue, P.C.J. (2018). The timescale of early land plant evolution. *Proc Natl Acad*  
645 *Sci U S A*.

646 Nakamura, Y., Kanakagiri, S., Van, K., He, W., and Spalding, M.H. (2005). Disruption of the glycolate  
647 dehydrogenase gene in the high-CO<sub>2</sub>-requiring mutant HCR89 of *Chlamydomonas reinhardtii*.  
648 *Canadian Journal of Botany* 83, 820-833.

649 Nguyen, L.T., Schmidt, H.A., von Haeseler, A., and Minh, B.Q. (2015). IQ-TREE: a fast and effective  
650 stochastic algorithm for estimating maximum-likelihood phylogenies. *Mol Biol Evol* 32, 268-274.

651 Nicolas, M., and Cubas, P. (2016). TCP factors: new kids on the signaling block. *Curr Opin Plant Biol* 33,  
652 33-41.

653 Ohtaka, K., Hori, K., Kanno, Y., Seo, M., and Ohta, H. (2017). Primitive Auxin Response without TIR1 and  
654 Aux/IAA in the Charophyte Alga *Klebsormidium nitens*. *Plant Physiol* 174, 1621-1632.

655 Park, S.Y., Fung, P., Nishimura, N., Jensen, D.R., Fujii, H., Zhao, Y., Lumba, S., Santiago, J., Rodrigues, A.,  
656 Chow, T.F., *et al.* (2009). Abscisic acid inhibits type 2C protein phosphatases via the PYR/PYL family of  
657 START proteins. *Science* 324, 1068-1071.

658 Parra, G., Bradnam, K., and Korf, I. (2007). CEGMA: a pipeline to accurately annotate core genes in  
659 eukaryotic genomes. *Bioinformatics* 23, 1061-1067.

660 Pfalz, J., and Pfannschmidt, T. (2013). Essential nucleoid proteins in early chloroplast development.  
661 *Trends Plant Sci* 18, 186-194.

662 Pickett-Heaps, J.D. (1975). *Green Algae: Structure, Reproduction and Evolution in Selected Genera*  
663 (Sinauer).

664 Pringsheim, M. (1862). On the Pro-Embryos of the Charae. *The Annals and Magazine of Natural History*  
665 59, 321-326.

666 Pruesse, E., Peplies, J., and Glockner, F.O. (2012). SINA: accurate high-throughput multiple sequence  
667 alignment of ribosomal RNA genes. *Bioinformatics* 28, 1823-1829.

668 Puranik, S., Acajjaoui, S., Conn, S., Costa, L., Conn, V., Vial, A., Marcellin, R., Melzer, R., Brown, E., Hart,  
669 D., *et al.* (2014). Structural basis for the oligomerization of the MADS domain transcription factor  
670 SEPALLATA3 in *Arabidopsis*. *Plant Cell* 26, 3603-3615.

671 Quinlan, A.R. (2014). BEDTools: The Swiss-Army Tool for Genome Feature Analysis. *Curr Protoc*  
672 *Bioinformatics* 47, 11 12 11-34.

673 Ren, Y., Hansen, S.F., Ebert, B., Lau, J., and Scheller, H.V. (2014). Site-directed mutagenesis of IRX9,  
674 IRX9L and IRX14 proteins involved in xylan biosynthesis: glycosyltransferase activity is not required for  
675 IRX9 function in *Arabidopsis*. *PLoS One* 9, e105014.

676 Rensing, S.A. (2018). Great moments in evolution: the conquest of land by plants. *Curr Opin Plant Biol*  
677 42, 49-54.

678 Rensing, S.A., Ick, J., Fawcett, J.A., Lang, D., Zimmer, A., Van de Peer, Y., and Reski, R. (2007). An ancient  
679 genome duplication contributed to the abundance of metabolic genes in the moss *Physcomitrella*  
680 *patens*. *BMC Evol Biol* 7, 130.

681 Rensing, S.A., Lang, D., Zimmer, A.D., Terry, A., Salamov, A., Shapiro, H., Nishiyama, T., Perroud, P.-F.,  
682 Lindquist, E.A., Kamisugi, Y., *et al.* (2008). The *Physcomitrella* genome reveals evolutionary insights into  
683 the conquest of land by plants. *Science* 319, 64-69.

684 Ronquist, F., Teslenko, M., van der Mark, P., Ayres, D.L., Darling, A., Hohna, S., Larget, B., Liu, L., Suchard,  
685 M.A., and Huelsenbeck, J.P. (2012). MrBayes 3.2: Efficient Bayesian Phylogenetic Inference and Model  
686 Choice Across a Large Model Space. *Syst Biol* *61*, 539-542.

687 Rost, B. (1999). Twilight zone of protein sequence alignments. *Protein Eng* *12*, 85-94.

688 Rovekamp, M., Bowman, J.L., and Grossniklaus, U. (2016). *Marchantia* MpRKD Regulates the  
689 Gametophyte-Sporophyte Transition by Keeping Egg Cells Quiescent in the Absence of Fertilization.  
690 *Curr Biol* *26*, 1782-1789.

691 Saier, M.H., Jr., Reddy, V.S., Tsu, B.V., Ahmed, M.S., Li, C., and Moreno-Hagelsieb, G. (2016). The  
692 Transporter Classification Database (TCDB): recent advances. *Nucleic Acids Res* *44*, D372-379.

693 Sakayama, H., Kasai, F., Nozaki, H., Watanabe, M.M., Kawachi, M., Shigyo, M., Nishihiro, J., Washitani,  
694 I., Krienitz, L., and Ito, M. (2009). Taxonomic reexamination of *Chara globularis* (Charales,  
695 Charophyceae) from Japan based on oospore morphology and rbcL gene sequences, and the  
696 description of *C. leptospora* sp. nov. *J Phycol* *45*, 917-927.

697 Schwacke, R., Schneider, A., van der Graaff, E., Fischer, K., Catoni, E., Desimone, M., Frommer, W.B.,  
698 Flugge, U.I., and Kunze, R. (2003). ARAMEMNON, a novel database for Arabidopsis integral membrane  
699 proteins. *Plant Physiol* *131*, 16-26.

700 Scrucca, L., Fop, M., Murphy, T.B., and Raftery, A.E. (2016). mclust 5: Clustering, Classification and  
701 Density Estimation Using Gaussian Finite Mixture Models. *R J* *8*, 289-317.

702 Simao, F.A., Waterhouse, R.M., Ioannidis, P., Kriventseva, E.V., and Zdobnov, E.M. (2015). BUSCO:  
703 assessing genome assembly and annotation completeness with single-copy orthologs. *Bioinformatics*  
704 *31*, 3210-3212.

705 Sorensen, I., Pettolino, F.A., Bacic, A., Ralph, J., Lu, F., O'Neill, M.A., Fei, Z., Rose, J.K., Domozych, D.S.,  
706 and Willats, W.G. (2011). The charophycean green algae provide insights into the early origins of plant  
707 cell walls. *Plant J* *68*, 201-211.

708 Steinbiss, S., Willhoeft, U., Gremme, G., and Kurtz, S. (2009). Fine-grained annotation and classification  
709 of de novo predicted LTR retrotransposons. *Nucleic Acids Res* *37*, 7002-7013.

710 Tan, X., Calderon-Villalobos, L.I., Sharon, M., Zheng, C., Robinson, C.V., Estelle, M., and Zheng, N. (2007).  
711 Mechanism of auxin perception by the TIR1 ubiquitin ligase. *Nature* *446*, 640-645.

712 Theißen, G., Melzer, R., and Rümpler, F. (2016). MADS-domain transcription factors and the floral  
713 quartet model of flower development: linking plant development and evolution. *Development* *143*,  
714 3259-3271.

715 Timme, R.E., Bachvaroff, T.R., and Delwiche, C.F. (2012). Broad phylogenomic sampling and the sister  
716 lineage of land plants. *PLoS ONE* *7*, e29696.

717 Tivendale, N.D., Ross, J.J., and Cohen, J.D. (2014). The shifting paradigms of auxin biosynthesis. *Trends*  
718 *Plant Sci* *19*, 44-51.

719 Trapnell, C., Williams, B.A., Pertea, G., Mortazavi, A., Kwan, G., van Baren, M.J., Salzberg, S.L., Wold,  
720 B.J., and Pachter, L. (2010). Transcript assembly and quantification by RNA-Seq reveals unannotated  
721 transcripts and isoform switching during cell differentiation. *Nat Biotechnol* *28*, 511-515.

722 Van Bel, M., Proost, S., Wischnitzki, E., Movahedi, S., Scheerlinck, C., Van de Peer, Y., and Vandepoele,  
723 K. (2012). Dissecting plant genomes with the PLAZA comparative genomics platform. *Plant Physiol* *158*,  
724 590-600.

725 Vesty, E.F., Saidi, Y., Moody, L.A., Holloway, D., Whitbread, A., Needs, S., Choudhary, A., Burns, B.,  
726 McLeod, D., Bradshaw, S.J., *et al.* (2016). The decision to germinate is regulated by divergent molecular  
727 networks in spores and seeds. *New Phytol* *211*, 952-966.

728 Vriet, C., Lemmens, K., Vandepoele, K., Reuzeau, C., and Russinova, E. (2015). Evolutionary trails of  
729 plant steroid genes. *Trends Plant Sci* *20*, 301-308.

730 Walker, K.L., Muller, S., Moss, D., Ehrhardt, D.W., and Smith, L.G. (2007). Arabidopsis TANGLED identifies  
731 the division plane throughout mitosis and cytokinesis. *Curr Biol* *17*, 1827-1836.

732 Wang, C., Liu, Y., Li, S.S., and Han, G.Z. (2015). Insights into the origin and evolution of the plant  
733 hormone signaling machinery. *Plant Physiol* *167*, 872-886.

734 Wang, W., Esch, J.J., Shiu, S.H., Agula, H., Binder, B.M., Chang, C., Patterson, S.E., and Bleecker, A.B.  
735 (2006). Identification of important regions for ethylene binding and signaling in the transmembrane  
736 domain of the ETR1 ethylene receptor of Arabidopsis. *Plant Cell* *18*, 3429-3442.  
737 Wass, M.N., Kelley, L.A., and Sternberg, M.J. (2010). 3DLigandSite: predicting ligand-binding sites using  
738 similar structures. *Nucleic Acids Res* *38*, W469-473.  
739 Wickett, N.J., Mirarab, S., Nguyen, N., Warnow, T., Carpenter, E., Matasci, N., Ayyampalayam, S., Barker,  
740 M.S., Burleigh, J.G., Gitzendanner, M.A., *et al.* (2014). Phylotranscriptomic analysis of the origin and  
741 early diversification of land plants. *Proc Natl Acad Sci U S A* *111*, E4859-4868.  
742 Wilhelmsson, P.K.I., Muhlich, C., Ullrich, K.K., and Rensing, S.A. (2017). Comprehensive Genome-Wide  
743 Classification Reveals That Many Plant-Specific Transcription Factors Evolved in Streptophyte Algae.  
744 *Genome Biol Evol* *9*, 3384-3397.  
745 Xiong, W., He, L., Lai, J., Dooner, H.K., and Du, C. (2014). HelitronScanner uncovers a large overlooked  
746 cache of Helitron transposons in many plant genomes. *Proc Natl Acad Sci U S A* *111*, 10263-10268.  
747 Yang, Z. (2007). PAML 4: phylogenetic analysis by maximum likelihood. *Mol Biol Evol* *24*, 1586-1591.  
748 Zeng, J., Dong, Z., Wu, H., Tian, Z., and Zhao, Z. (2017). Redox regulation of plant stem cell fate. *EMBO*  
749 *J* *36*, 2844-2855.

750

751

752

753 **Figure titles and legends**

754

755 **Figure 1: Evolution of charophytic algae and land plant features**

756 Cladogram symbolizing streptophytic evolution shows gain/expansion (green lines) and loss  
757 (red lines) of features; topology as in (Wickett et al., 2014) with phytohormone-related terms  
758 in blue and transcription factors (TF) and transcriptional regulators (TR) in brown. Expansions  
759 (and gains/losses) detected in the *Chara* lineage are shown by asterisk. See text for  
760 abbreviations. Modes of cytokinesis: a cleavage furrow with persistent telophase spindle as  
761 seen in *Klebsormidium*, and a phragmoplast seen in *Chara* that differs from that of land plants  
762 as the cell plate in *Chara* shows little centrifugal growth but is formed simultaneously across  
763 the cell's equator.

764

765 **Figure 2: Life cycle and habit of *Chara braunii***

766 Meiosis occurs just prior to germination. At germination, a positively gravitropic rhizoid and a  
767 protonema that develops into the thallus are formed. The shoot-like thallus (phototropic and  
768 negatively gravitropic) comprises stem-like structures (axes) and whorls of branchlets (lateral  
769 organs appended to the main axes having adaxial-abaxial differentiation) at axial nodes. Growth  
770 of the axis/stem is axial from the terminal (apical) cell. Internodal cells, up to 5 cm long, are  
771 multinucleate. Internodal cells and branchlets are connected *via* specialized nodes or central  
772 cells connecting the internodes. Nodal cells can serve asexual propagation as they can form  
773 apical cells *de novo*. Female (oogonia) and male (antheridia) gametangia are borne on branchlet  
774 nodes of the monoicous thalli and generate female (egg cell) and male (sperm cell) gametes.  
775 The oogonial complex is comprised of egg cell and associated corona, jacket (five spiral tube  
776 cells), and basal cells. Sperm cells arise from filaments produced on the inner surfaces of  
777 antheridial shield cells. Upon fertilization the only diploid cell of the life cycle, the dormant  
778 zygote or oospore, is formed. Charasomes are plasmamembrane invaginations that allow carbon  
779 concentration *via* local acidification. Cells are connected by plasmodesmata. Actin-myosin  
780 based cytoplasmic streaming provides a fast transport mechanism. *C. braunii* is ecorticate, other  
781 species develop cortical cells (filaments with spine cells) from the nodes that cover the axis and  
782 branchlet internodal cells. LS: longitudinal section.

783

784 **Figure 3: Gene and transposon length and density in selected plant and algal genomes.**

785 Comparative box and whisker plots depicting distributions of feature lengths (A) and densities  
786 in 100 kbp windows (B). Organisms are ordered top-down by decreasing genome size; x-axes  
787 are logarithmic scale. Features are color-coded (legend on the right) and comprise predicted  
788 genes, helitrons, intact full-length long terminal repeat elements (fLTRE) and potentially  
789 fragmented copies (LTREs).

790

791 **Figure 4: Overview of predicted presence of factors in phytohormone biosynthesis and**  
792 **signaling pathways of *C. braunii*.**

793 Shown are biosynthesis enzymes (rectangles), receptors (pentagons), signal transduction  
794 components (hexagons), and TFs (ovals). Elements for which no orthologs were found (light  
795 green dashed boxes) and for which putative orthologs were identified (dark green boxes) (*cf.*  
796 Table 1, S10/11). Abbreviations as in Table 1.

797

798 **Figure 5: Land plant heritage genes present in the *C. braunii* genome**

799 (A) Growing repertoire of retrograde signaling components as well as PAPs along the  
800 streptophyte trajectory. Potential retrograde signaling orthologs are marked with colored dots  
801 (see species key). PEP-associated proteins (PAPs) are shown in the bottom inset. XRN2/XRN3  
802 were not distinguished due to paralogy; faded dots mark the paralogy of *Chlamydomonas* FSD2  
803 and the detection of *P. patens* PTAC7 ortholog with  $E < 10^{-4}$ ; mosses encode the cyanobacterial  
804 (i.e. non-PAP) version of MurE (Garcia et al., 2008), potentially applying for algal MurEs, too.  
805 (B) Bayesian inference phylogenetic tree of plant MADS-box genes. Posterior probabilities  
806 ( $\geq 0.6$ ) of main branches are depicted next to the tree. Insert shows the exon-intron structures of  
807 representatives of MIKC<sup>C</sup>-type genes together with the *Chara* MIKC-type genes. (C)  
808 Condensed ML tree of the LysM-RLK family. The Charales sequences form a single clade (blue  
809 branches) encompassing 7 *C. braunii* sequences. Duplication (red circle) leading to the LYK  
810 (orange) and LYR (green) subclades occurred at the base of the embryophytes. The moss and  
811 liverwort clades are clustered. (D, E) GO enrichment word clouds (biological process). Word  
812 clouds of genes down-regulated (D) or up-regulated (E) in oogonia as compared to antheridia.  
813 Font size correlates with significance; red terms are depleted, green terms enriched; top three  
814 terms each are shown. See also Fig. S5, S6, related to Table S2-S4.

815

816 **Figure 6: Expression of the ROS gene network during sexual reproduction.**

817 ROS-related gene abundance expressed in transcripts per million (TPM) was transformed to  
818 log scale and represented as heatmap in zygotes, oogonia and antheridia. Gene distance was  
819 calculated using the Euclidean method and genes were clustered using complete linkage. DEGs  
820 ( $p < 0.01$ ) between zygotes and oogonia / oogonia and antheridia are depicted: green up arrow,  
821  $\log_2(\text{fold-change}) > 0$ ; red down arrow,  $\log_2(\text{fold-change}) < 0$ . The expanded family of class  
822 III peroxidases is shown in bold. See also Fig. S4, S6, S7, related to Table S2-S4.



## 823 Tables

Gene/ Gene family	<i>K. nitens</i>	<i>C. braunii</i>	<i>P. patens</i>	<i>A. thaliana</i>
AUX biosynthesis				
Tryptophan aminotransferase-related proteins (TAA/TAR)	1	0	6	5
YUCCA (YUC)	1	0	8	11
AUX signaling				
Transport inhibitor response 1/AUX signaling F-box (TIR1/AFB)	0	0	5	5
AUX response factor (ARF)	0	1	15	22
Indole-3-acetic acid inducible (Aux/IAA)	1/0 <sup>a</sup>	2	4	29
AUX metabolism				
Gretchenhagen (GH)	4	1	2	20
AUX transport				
ATP-binding cassette B (ABCB)	7	5	10	22
AUX resistance 1 (AUX1/LAX)	1	0	9	4
PIN-formed 1 (PIN)	1	6	4	8
PIN-likes 1 (PILS)	3	0	3	7
CK Signaling				
CHASE domain containing histidine kinase (CHK)	6	2	11	3
Histidine-containing phosphotransfer proteins (HPT)	1	1	2	5
Response regulator type B (RRB)	1	0	5	11
Response regulator type A (RRA)	1	2	7	10
ETH biosynthesis				
1-aminocyclopropane-1-carboxylate synthase (ACS)	1	2	2	12
1-aminocyclopropane-1-carboxylate oxidase (ACO)	0	0	0	5
ETH signaling				
ETH response/ETH response sensor (ETR/ERS)	5	4	8	5
Constitutive triple response1 (CTR1)	1	2	1	1
ETH insensitive2 (EIN2)	0	1	2	1
ETH insensitive3 (EIN3)	1	4	2	6
EIN3 binding F-box protein (EBF1)	1	1	2	2

ABA biosynthesis				
Phytoene synthase1 (PSY1)	1	1	3	1
Phytoene desaturase (PDS)	2	1	2	1
Lutein deficient (LUT)	1	1	1	3
Zeaxanthin epoxidase (ZEP/ABA1)	1	1	1	1
9-Cis-epoxycarotenoid dioxygenase (NCED)	0	0	2	5
Abscisic aldehyde oxidase3 (AAO3)	1	0	2	1
ABA signaling				
Pyrabactin resistance (PYR)	0	0	4	14
Protein phosphatase 2C (PP2C - Group A)	1	0	2	9
SNF related kinase (SnRK)	1	1	4	5
CBL-interacting protein kinase (CIPK)	1	0	7	25
Calcium-dependent protein kinase (CPK)	1	2	30	34
SL synthesis				
Beta-carotene isomerase (D27)	2	1	1	1
Carotenoid cleavage dioxygenase (CCD7)	2	0	1	1
Carotenoid cleavage dioxygenase (CCD8)	2	0	1	1
SL signaling				
Alfa beta hydrolase (D14)	0	0	0	1
D14-like/ Karrikin insensitive2 (KAI2)	2	1	11	2
More axillary branching 2 (MAX2)	0	0	1	1

824

825 **Table 1: Comparison of gene families operating in the biosynthesis and signaling networks**  
826 **of phytohormones.**

827 A specific set of individual genes or gene families encoding steps in the phytohormone  
828 biosynthesis/signaling/metabolism/transport networks have been analysed in *K. nitens*, *C.*  
829 *braunii*, *P. patens* and *A. thaliana* (Table S1J).

830 a, kf100094\_0070 features Aux/IAA domains but also a B3 domain (see text for details).

831

832

Commented [SR5]: Character count from start to here;  
must be <= 60,000

833 **Supplemental Figure Titles and Legends**

834

835 **Figure S1, related to STAR methods: Chromosomes in an antheridial filament of *C.***  
836 ***braunii* (n=14, strain S276).**

837 The chromosomes during cell division in young antheridial filaments of strain S276 were  
838 observed after Feulgen staining. The chromosome number n=14 was confirmed by counts made  
839 on chromosomes during metaphase or anaphase. Most Chara species have either n=14 or n=28  
840 chromosomes, Nitella and the other genera have different base numbers. There are numerous  
841 examples of monoecious/dioecious species pairs in the family, with the dioecious species  
842 always displaying half the number of chromosomes than their monoecious counterpart. For  
843 Chara typically dioecious=14, monoecious=28 (or other multiples of 14). *C. braunii* is  
844 monoecious, but is unique in having the dioecious chromosome number of 14. There are no  
845 known dioecious sister taxa to *C. braunii*, perhaps due to the already reduced genome. Scale  
846 bar = 2  $\mu$ m.

847

848 **Figure S2, related to STAR methods: Assembly characteristics and decontamination**

849 A) k-mer frequency analysis of the S276 paired end read data with k=25. Number of 25-mers  
850 at frequency 3 to 200 are shown with the solid line. Circles shows the points from 16 to 80 as  
851 what was recognized the major peak, presumably representing the single copy region in *C.*  
852 *braunii*. B) Scatter plot of mapped reads of two *C. braunii* strains on each scaffold. Blue and  
853 light blue points are scaffolds with GC content of at least 55% and less than 55%, respectively.  
854 C) Frequency distribution of scaffold wise GC content compared between putative *C. braunii*  
855 derived scaffolds (blue) and other scaffolds (green).

856

857 **Figure S3, related to STAR methods: Ks-based analysis of *C. braunii* paralogs**

858 Paraname-based WGD signature prediction. (A) Ks frequency plot highlighting mixture model  
859 components mean and standard-deviation (top: #component, bottom: mean Ks) based on raw  
860 Ks value classification. (B) Ks frequency plot highlighting mixture model components mean  
861 and standard-deviation (top: #component, bottom: mean Ks) based on log-transformed Ks value  
862 classification. (C) Ks group assignment for raw Ks classification. (D) Ks group assignment for  
863 log-transformed Ks classification. (E) Significant zero crossing (SiZer) plot. (F) Significant  
864 convexity (SiCon) plot. (G-J) Significant features of kernel density estimates using indicated  
865 bandwidths, highlighting significant gradient regions in blue and significant curvature regions  
866 in green using a significance level of 0.05. Red vertical lines represent Ks value of 0.1 and 2.0,  
867 dotted red vertical line represents Ks value of 0.235 corresponding to 12.5 Ma ago (these events  
868 might be no WGDs but only more or less recent local duplication events). For *C. braunii* no  
869 single predicted WGD signature was supported by three different bandwidth kernel densities  
870 (cf. STAR Methods).

871

872

873 **Figure S4, related to Figure 6: Expression profiles during sexual reproduction.**

874 Expression profile of trihelix TF genes based on RNA-seq evidence (Table S4) was visualized  
875 as A) a Venn diagram using venny (<http://bioinfogp.cnb.csic.es/tools/venny/>) and B) as a  
876 heatmap showing gene expression and DEGs from reproductive organs with RPKM > 1 in  
877 minimum two samples. C) Shows expression of differentially expressed TFs/TRs during sexual  
878 reproduction. D) Expression of DEGs associated with seeds during sexual reproduction.  
879 Transcripts per million (TPM) were transformed to log<sub>2</sub> scale and clustered using the euclidean  
880 distance method and the complete clustering method (B, C, D).

881

882 **Figure S5, related to Figure 5: Exon-intron structure comparison of MIKCC-type,  
883 MIKC\*-type and charophyte MIKC-type genes.**

884 (A) Exon-intron structures of representatives of MIKCC-type and MIKC\*-type genes together  
885 with the charophyte MIKC-type genes *CbMADS1*, *CbMADS2* and *KnMADS1*. The exons  
886 encoding MADS-, I-, K- and C-domains are color coded in black, red, blue and green,  
887 respectively. Among the three Type II genes that were identified in the *C. braunii* genome only  
888 *CbMADS1* shows a canonical MIKC-type gene sequence. In contrast *CbMADS2* lacks most  
889 (but not all) introns and thus probably evolved via a retrotransposition and recombination event.  
890 *CbMADS3* lacks the conserved K-box that encodes for the protein-protein interacting K-domain  
891 (data not shown). (B and C) Analysis of exon-intron structures suggest that *CbMADS1* directly  
892 descends from an ancestral MIKC-type gene that was a common ancestor of MIKCC- and  
893 MIKC\*-type genes. (B) It was previously suggested that the N-terminal part of the K-domain  
894 of MIKC\*-type proteins evolved through a duplication of two K-domain exons of an ancestral  
895 MIKC-type gene (Kwantes et al., 2012). The aligned amino acid sequences encoded by exon 2  
896 of *CbMADS1*, and by the first K-domain exons of *KnMADS1*, *MpMADS1*, *PPM3*, *SmMADS4*  
897 and *AGL30* indeed strongly support this hypothesis. (C) In addition, striking similarities  
898 between the aligned amino acid sequences encoded by exon 5 of *CbMADS1*, exon 6 of  
899 *KnMADS1* and exons 5 and 6 of *MpMADS2*, *PPM1*, *SmMADS3* and *SEP3*, respectively, suggest  
900 that also the K-domain of MIKCC-type proteins evolved through an exon duplication of an  
901 ancestral MIKC-type gene. This is especially intriguing considering the fact that, based on  
902 structural data, the last two K-domain exons of most if not all MIKCC-type genes encode for a  
903 protein-protein interaction interface that facilitates tetramer formation of MIKCC-type proteins  
904 (Puranik et al., 2014). It has already been suggested that the ability of MIKCC-type proteins to  
905 tetramerize was an important precondition to evolve and diversify efficient developmental  
906 switches that facilitated the transition to land and the evolution of complex body plans of land  
907 plants (Theißen et al., 2016). Thus it is tempting to speculate that an exon duplication of an  
908 ancestral MIKCC-type gene in the MRCA of extant land plants created the molecular  
909 prerequisites for this evolutionary novelty.

910

911

912

913

914 **Figure S6, related to Figures 5/6: Transcriptome analyses of reproduction and early**  
915 **development.**

916 GO enrichment word clouds (category biological process); genes down-regulated (A) or up-  
917 regulated (B) in oogonia as compared to antheridia, genes down-regulated (C) or up-regulated  
918 (D) in zygotes as compared to oogonia. Antheridia are strongly enriched with the GO category  
919 GO:0015074 “DNA integration” (A). 349 gene models expressed in antheridia were classified  
920 in this category; of these, 324 genes were found to be overlapping with a TE to at least 50 %  
921 (Table S4). Most of these genes were annotated as “integrase”, “ribonuclease H-like”, “reverse  
922 transcriptase”, and “aspartyl protease” by homology-based approach, terms typical of  
923 Ty3/Gypsy pol gene composition (Havecker et al., 2004). Ty3/Gypsy elements represent 20 %  
924 of the *C. braunii* genome. These results might indicate mobilization of retrotransposons and  
925 other mobile elements during male gametogenesis. This could be a consequence of genome  
926 rearrangement during male gamete formation. One could also imagine that mobilization and  
927 integration of retrotransposons might enhance genomic diversity during sexual reproduction.

928

929 **Figure S7, related to Figure 6: Major reactive oxygen species scavenging pathway in**  
930 **plants.**

931 Proteins associated with ROS scavenging are in bold. Number of genes found for *A. thaliana*  
932 and *C. braunii* (in green) are indicated in brackets. APx: Ascorbate peroxidase, Asn: ascorbate,  
933 DHA: Dehydroascorbate, DHAR: Dehydroascorbate reductase, GPx: Plant glutathione  
934 peroxidase, GR: Glutathione reductase, Grx: Glutaredoxins superfamily, GSH: reduced  
935 glutathione, GSSH: oxidized glutathione. Kat: Catalase, MDAR: Monodehydroascorbate  
936 reductase, PrxR: Peroxiredoxins family, RBOH: Respiratory burst oxidase homolog also called  
937 NADPH oxidase, SOD: Superoxide dismutase, Trx: Thioredoxins, MDA:  
938 Monodehydroascorbate, adapted from (Inupakutika et al., 2016).

939

940

941 **STAR Methods**

942

943 **CONTACT FOR REAGENT AND RESOURCE SHARING**

944 Further information and requests for resources and reagents should be directed to and will be  
945 fulfilled by the lead contact Stefan A. Rensing ([stefan.rensing@biologie.uni-marburg.de](mailto:stefan.rensing@biologie.uni-marburg.de)).

946

947 **EXPERIMENTAL MODEL AND SUBJECT DETAILS**

948 Two strains of *C. braunii* (S276 and S277) were used. The strain S276 was isolated from the  
949 thallus, which germinated from the bottom soil of Lake Kasumigaura (Ibaraki, Japan) and was  
950 maintained at Kobe University. The unialgal isolation of this strain was achieved as follows.  
951 First, collected oospores were surface sterilized for 5 to 8 min in 20% (v/v) NaClO (aq) with  
952 0.05% (v/v) Tween20. The sterilized oospores were then transferred into autoclaved soil-water  
953 medium for the Charales (SWC-3), containing distilled water and two layers of substrate: a  
954 mixture of black soil and river sand on top of a layer of leaf mould. In the present study, strain  
955 S277 was newly collected from a pond at Saijo (Ehime, Japan) on October 18, 2011. Newly  
956 collected specimens of *C. braunii* were identified based on their *rbcL* DNA sequences. The  
957 methods employed for field collection and DNA barcoding followed (Sakayama et al., 2009).  
958 The thalli were collected using a handmade anchor. Total DNA was extracted from field-  
959 collected samples using the Qiagen DNeasy Plant Mini Kit. Partial *rbcL* DNA sequences were  
960 amplified using the primers CHAR-RF-1 (5'-ATGTCACCACAGACAGAACTAA-3') and  
961 CHAR-RR-4 (5'-GCTCCTGGAGCATTTCCTCAAG-3'). PCR conditions were 95 °C for  
962 5min; 32 cycles at 95 °C for 40s, 55 °C for 40s, and 72 °C for 1.5min; and 72 °C for 7 min  
963 using Ex Taq (Takara Bio). PCR products were sequenced using the primers CHAR-RF-1,  
964 CHAR-RR-4, CHAR-RF-2 (5'-GAGCTGTATATGAATGTCTTCG-3') and CHAR-RR-3 (5'-  
965 GTTTCTGCTTGAGATTTATA-3'). The sequences obtained were aligned with published *rbcL*  
966 DNA sequences of the genus *Chara* downloaded from GenBank. Sequence alignment was  
967 performed using MUSCLE (Edgar, 2004) with default options. The aligned dataset of the *rbcL*  
968 DNA sequences was subjected to the Neighbour-Joining (NJ) method with Jukes-Cantor  
969 distances and 1,000 bootstrap replicates, using MEGA 6.0. Based on NJ trees, field-collected  
970 samples were identified at the species level. The unialgal culture of S277 was established  
971 following the same procedure as outlined for S276. The pressed specimens of S276 and S277  
972 (TNS-AL 209137 and 209138) were deposited at the Herbarium, Department of Botany,  
973 National Science Museum (TNS), Tsukuba, Japan. Routine culture was essentially performed  
974 at 23 °C with a 16-h light: 8-h dark cycle with 24.5  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$  illumination provided  
975 by fluorescent lamps using soil-water medium for the Charales (SWC-3).

976

977 **METHOD DETAILS**

978 **DNA extraction**

979 Thalli of strain S276 were harvested in SWC-3 medium, washed with distilled water, frozen in  
980 liquid nitrogen, and stored at -80 °C until DNA extraction. High molecular weight DNA was  
981 prepared by the CTAB method followed by purification with Qiagen Genomic Tip. The frozen  
982 powder was weighed and poured on 6 volumes of 2X CTAB buffer (2%

983 hexadecyltrimethylammonium bromide [CTAB], 1.4M NaCl, 100 mM Tris-Cl pH 8, 20 mM  
984 EDTA, 1% Polyvinylpyrrolidone, 1% 2-mercaptoethanol) on a hotplate stirrer at 60 °C. After  
985 two rounds of Chloroform:IAA 25:1 extraction, the supernatant was mixed with 3 vol of CTAB  
986 precipitation buffer (1% CTAB, 50 mM Tris-Cl pH 8, 10 mM EDTA). The precipitate was  
987 recovered by centrifugation and dissolved in NaCl solution (1 M NaCl, 10 mM Tris-Cl pH 8, 1  
988 mM EDTA), then precipitated with 0.6 vol of 2-propanol. The precipitate was dissolved in TE  
989 and further purified with a Qiagen Genomic Tip according to the manufacturer's instruction.  
990 The integrity of the DNA was confirmed with pulsed field electrophoresis using CHEF DR-II  
991 (Bio-Rad). Alternatively, genomic DNA from harvested thalli was isolated by grinding the flash  
992 frozen material, adding 15 mL extraction buffer (100mM Tris, 50mM EDTA, 500mM NaCl,  
993 10mM 2-mercaptoethanol; pH8) and 2 mL 10% SDS, and incubating for 10 min at 65 °C with  
994 mild agitation. Subsequently, 5.4 mL 5M potassium acetate were added and incubated 20 min  
995 on ice. After centrifugation at 13,000 g for 20 min at 4 °C the DNA is precipitated by adding  
996 14 mL 2-propanol, incubation for 30 min at -20 °C and centrifugation at 13,000 g for 15 min at  
997 4 °C. After the isopropanol precipitation the air dried pellet was dissolved in 700 µl 1x TE  
998 buffer (pH 8), 1-3µl RNaseA (10mg/ml) was added and incubated for 10 min at 37 °C. To purify  
999 the DNA 600 µl phenol/chloroform 1:1 were added, mixed, centrifuged at 10,000 g for one  
1000 minute and the aqueous phase extracted. To this phase 600 µl chloroform/isoamylalcohol 24:1  
1001 were added, mixed, centrifuged at 10,000 g for one minute and the aqueous phase extracted. To  
1002 precipitate the DNA 70 µl 3M Na-acetate and 500 µl isopropanol were added, mixed and  
1003 centrifuged at 10,000 g for ten minutes. The pellet was washed with one ml 70% ethanol, dried  
1004 and afterwards was dissolved in deionized water. Quality was controlled using Nanodrop, Qubit  
1005 measurement and agarose gel electrophoresis.

#### 1006 **Chromosome observation**

1007 The thalli with young antheridia were collected within the first hour of the dark period and fixed  
1008 in ethanol:acetic acid (3:1). Fixed material was stored at 4 °C until used. Chromosome  
1009 preparations were made using the Feulgen squash method (Fig. S1). Fixed samples were  
1010 rehydrated by passing through a graded series of ethanols and rinsed gently in distilled water.  
1011 The samples were treated with 1N HCl for 5 min at room temperature, then treated with 1N  
1012 HCl for 8 min in a water bath at 60 °C, and rinsed gently in distilled water. Afterwards, the  
1013 samples were transferred into Schiff's reagent (Merck Millipore) for 60 min at room  
1014 temperature. After rinsing the samples in distilled water, they were squashed and observed.

#### 1015 **Genome sequencing and assembly**

1016 Genomic DNA of the uni-algal strain S276 isolated from Lake Kasumigaura (Ibaraki, Japan)  
1017 was sequenced as the reference genome using Illumina technology and sequences were  
1018 compared with those of the strain S277 that was isolated from the pond at Ehime (Japan).  
1019 Approximately 0.25 Gbp of scaffolds were present in only one of the datasets and found to be  
1020 of bacterial origin. After removal of these prokaryotic sequences, 1.75 Gbp of scaffold data  
1021 (N50 size of 2.26 Mbp at #234) were obtained, of which 1.43 Gbp were assembled into contigs.  
1022 This corresponds to ~74% of the *C. braunii* genome as measured by flow cytometry (1.89-1.96  
1023 Gbp) and to ~61% of the 2.35 Gbp estimated by k-mer analysis. The plastid and mitochondrial  
1024 genome were assembled separately to recover 187,771 and 67,059 bp circular genomes,  
1025 respectively.

1026 **Genome sequencing of *C. braunii* strain S276**

1027 A paired-end library with insert size of 250 bp was constructed using an S2 ultrasonicator  
1028 (Covaris) and a TruSeq DNA PCR-Free LT Sample Prep Kit (Illumina) according to the  
1029 manufacturer's protocols. The products were size-selected on an agarose gel and purified using  
1030 the Qiagen MinElute Gel Extraction Kit. Nucleotide sequences were determined for 150 bp  
1031 from both ends with an Illumina HiSeq 2500. Sixteen Mate-pair libraries were constructed using  
1032 a Nextera Mate-pair library construction kit with standard and modified input DNA of 5.6, 8,  
1033 and 20 µg in the reaction. The first set, four libraries were constructed using the standard  
1034 protocol, a gel-free method starting with 1 µg DNA (one library), and gel-excision starting with  
1035 4 µg DNA (three libraries). In the Gel-free protocol tagmented DNA was purified with AMPure  
1036 XP resulting in a broad size with a peak at 2.7 kbp. In the Gel (+) protocol, the size range was  
1037 3-5 kbp, 5-8 kbp, and larger, resulting in a peak of 4.5, 5.8, and 9 kbp, respectively, as measured  
1038 with a Bioanalyzer after purification with a Zymoclean Large Fragment DNA Recovery Kit.  
1039 After circularization, fragmentation with Covaris S2, end-repair, A-tailing and adapter ligation,  
1040 gel-free and 4.5 kbp library were amplified for 10 cycles, whereas 5.8 kbp and 9 kbp libraries  
1041 were amplified for 15 cycles. After purification and quantification, the libraries were further  
1042 subjected to 8, 6, 6, and 8 cycles of PCR, for gel-free, 4.5, 5.8 and 9 kbp libraries, respectively  
1043 (Table S1A).

1044 In the second set, two libraries were constructed using 20 µg DNA instead of the standard 4 µg  
1045 DNA to obtain larger fragment size distribution after tagmentation. In this sample, though the  
1046 large molecules were not well separated on the agarose gel, three fractions, thick band at high  
1047 molecular weight above all marker bands, below the band to 12 kbp, and a 8-12kbp fraction  
1048 were recovered. The size of the recovered DNA could not be measured accurately using a  
1049 Bioanalyzer, though the peak was around the 17kbp marker. The final amplification was done  
1050 for 21 cycles and additional 8 cycles. The lowest 8-12 kbp fraction did not amplify well and  
1051 was not used in further analysis.

1052 In the third set, five libraries were constructed using 5.6 µg of starting DNA (1.4-fold of  
1053 standard) and an additional five libraries using 8.0 µg of starting DNA (2-fold of standard);  
1054 pulsed field electrophoresis on a CHEF-DRII (Bio-Rad) was used for the separation after the  
1055 tagmentation. The electrophoretic conditions were 6 V/cm, 11 hours, switch time 1-6 s, on 1%  
1056 agarose gel, in 0.5 X TBE buffer. The gel was stained with SYBR Gold and the gel slices were  
1057 recovered in five fractions each. The lower limit of each slice was 5.0, 7.5, 10.0, 15.0, and 23.5  
1058 kbp. After purification, the DNA was immediately subjected to circularization without  
1059 measuring its size. The final amplification was conducted for 15 cycles. Of these (Table S1A),  
1060 15 had good insert size distribution when mapped to a preliminary version of the assembly, but  
1061 one (S276MP3 xk) had not and thus excluded for further analysis.

1062 Another two mate pair libraries were constructed by GATC (3-4 kbp fragment size) and  
1063 sequenced on an Illumina HiSeq 2000. One library was constructed using Crelox with an insert  
1064 size of 3 kbp. DNA was fragmented using the Covaris S2 AFA instrument and sequencing was  
1065 performed on an Illumina HiSeq 2000 at 2 x 100 bp.

1066 **K-mer frequency analysis**



1067 *K*-mer frequency with  $k = 25$  in the paired end reads were counted with JELLYFISH (Marcais  
1068 and Kingsford, 2011), applying the min-quality=20 option. A clear peak at 51 was observed  
1069 with a valley at 16 (Fig. S2A). The peak at 51 was interpreted as the single copy genomic  
1070 sequence and those less than 16 were mostly *k*-mers containing sequencing errors. The  
1071 cumulative *k*-mer count from 16 upto 10,000 (which was the default upper limit of JELLYFISH)  
1072 divided by 51 suggested the genome size be 2.355 Gbp. Note that this number includes *k*-mers  
1073 derived from organellar and bacterial sequences and supposed to be overestimate for the nuclear  
1074 genome size. With the peak at 51, the amount of paired-end reads are supposed to be sufficient  
1075 for the assembly. The region from 16 to 80 as the putative single copy region comprised 0.95  
1076 Gbp.

#### 1077 **Assembly**

1078 The raw sequences were assembled with ALLPATHS-LG (Gnerre et al., 2011). Initially the  
1079 assembly started with R48517 on a machine having 768 GB of memory and 32 CPU cores.  
1080 After running a month this process stopped at UnipathPatcher phase. Continuation was tried  
1081 with the settings: PATCH\_UNIPATHS=False FIX\_LOCAL=False  
1082 PATCH\_SCAFFOLDS=False FIX\_SOME\_INDELS=False; unfortunately this failed again.  
1083 The run directory was copied to a machine having 2 TB of memory and 80 cores and the  
1084 assembly was continued with R48777 and completed after another twenty days (with 48  
1085 slots=threads), with reported peak memory usage of 1,756 GB. The assembly resulted in 28,091  
1086 scaffolds with a total length of 1.99 Gbp, comprised of 250,979 contigs with a total length of  
1087 1.65 Gbp. The library information is summarized in Table S1B.

#### 1088 **Genome sequencing of *C. braunii* strain S277**

1089 Thalli of strain S277 were harvested in SWC-3 medium, washed with distilled water, frozen in  
1090 liquid nitrogen, and stored at -80 °C until DNA extraction. Total DNA was extracted as  
1091 described above. A paired end library was constructed using a TruSeq DNA PCR-free library  
1092 preparation kit (Illumina) and sequenced with HiSeq (DRA accession: DRR054048). 1.1 µg  
1093 of DNA was fragmented with Covaris S2, using micro tube, duty cycle 10%, intensity 4, 200  
1094 cycles/burst and total time of 80 s. The fragments were size selected using a bead-based method  
1095 following the 350-bp protocol.

#### 1096 **PacBio sequencing of fosmid clones for quality control**

1097 *C. braunii* S276 genomic DNA was cloned into the pNGS fosmid vector using the aNxSeq 40  
1098 kbp Mate-Pair Cloning Kit (Lucigen). Six fosmid clones with verified end sequence and one  
1099 96 well plate of undetermined clones were pooled and shotgun sequenced on a PacBio SMRT  
1100 cell (608 Mbp, 63,768 reads post-filtering). The resulting reads were assembled into contigs  
1101 using HGAP (Chin et al., 2013) in smrtanalysis (PacificBiosciences). The contig sequences  
1102 were further polished with two rounds of Quiver. Bacterial contamination was removed using  
1103 MEGAN, and comparative mapping of S276 and S277 reads, resulting in 22 probable *C.*  
1104 *braunii* contigs. All but one of those could be BLAST-mapped to the assembly. One clone  
1105 appeared to be chimeric based on mapping Illumina mate-pair library data on the clone. Of the  
1106 remaining 20, 14 were mapping to single scaffolds, the other 6 to 2-4 scaffolds. 10 of the 22  
1107 contigs were found to map with  $\geq 95\%$  identity and  $\geq 90\%$  coverage to the assembly, the  
1108 remaining 12 did not meet these parameters, probably due to assembly gaps. In summary, 45%

1109 of the assembled fosmid clones had high quality representations in the assembly, and 91% could  
1110 be mapped, demonstrating the good quality of the assembly.

#### 1111 **Distinction of bacterial sequences**

1112 Paired end sequences of S276 and S277 were mapped to the assembly with bwa mem (Burrows-  
1113 Wheeler Aligner) (Li and Durbin, 2010) and the number of mapped sequences were counted on  
1114 each scaffold (Fig. S2). Number of tags of both samples on each scaffold was plotted and we  
1115 found two groups. The two groups were separated by a line in which S277 had 1/100 of S276  
1116 tags (Fig. S2B). The GC content of each scaffold was calculated and compared between the two  
1117 groups. The group showing less tags in S277 had a higher GC content distribution (Fig. S2C).  
1118 Thus, these scaffolds were presumed to be derived of different organisms, which were probably  
1119 bacteria that survived autoclaving. In addition, scaffold\_64 was found to be of bacterial origin  
1120 in manual inspection during gene prediction. Further, the genomic scaffolds were split into 1  
1121 kbp fragments. Using tera-BLASTn 9.0.0 on DeCypher 9.0.0.25  
1122 (<http://www.timelogic.com/catalog/757/tera-blast>) each fragment was BLASTed against the  
1123 NCBI nt database. The BLAST output was analysed by MEGAN 6 (Huson et al., 2016) and  
1124 bacterial hits assigned to the 1 kbp fragments. All scaffolds containing more than 50 % of  
1125 bacterial hit fragments were extracted. If no non-bacterial hits were contained on the scaffold  
1126 and the bit score of the bacterial contamination exceeded 50 per hit the scaffold was removed  
1127 as contamination. This affected 153 scaffolds with a total length of 312 kbp (Table S5),  
1128 containing 120 gene models (marked in Table S4). Thus, 11,655 scaffolds totaling  
1129 1,751,225,565 bp, comprised of 234,221 contigs totaling 1,429,911,168 bp were recovered as  
1130 representing the *C. braunii* nuclear genome. N50 scaffold size, and N50 contig size were  
1131 2,261,426 bp (at #234) and 10,124 bp (at #41,610), respectively.

#### 1132 **Microbiome analysis**

1133 The diversity of microorganisms is expected to be low due to lab-culturing conditions and DNA  
1134 sequence extraction protocols. To isolate the microorganisms remaining in the bulk of data, we  
1135 mapped reads to the eukaryotic genome and only analyzed reads left unmapped. Given that  
1136 S276 and S277 were reared at different geographical locations, analyzes were done on both sets  
1137 separately. The two separate sets of remaining reads were assembled into contigs and analyzed  
1138 from a meta-genomics point of view. Two separate assemblies have been generated using CLC-  
1139 assembly cell using the larger word-size (kmer) of 50 nt to force more specificity (CLC bio,  
1140 Aarhus, Denmark). These assemblies resulted in respectively 322685 contigs with a total size  
1141 of 76.7 Mbp (N50 242 bp, max size 167358 bp, min size 100 bp) and 325720 contigs with a  
1142 total size of 90.1 Mbp (N50 373 bp, max size 172440 bp, min size 100 bp). The obtained contigs  
1143 represent a mixture of microorganisms that where clustered using CONCOCT (Alneberg et al.,  
1144 2014) according to the manual, using BEDtools (Quinlan, 2014), Picard-tools and R, to create  
1145 and format the needed input files. Several runs were done, aiming at providing the minimal  
1146 number of differentiated clusters. In some cases large clusters were isolated and submitted again  
1147 for a new round of clustering. The clusters (or bins) were calculated based on read coverage  
1148 and sequence tetramer composition of the contigs following an iterative fitting of mixture-of-  
1149 Gaussian models on the available data; each group is supposed to represent an organism that  
1150 was further characterized to establish the species. Taxonomic assignment of the bins was  
1151 performed using a similarity-based labeling of the fragments with MEGAN5. A first assessment

1152 of the quality and completeness of the bins was done by monitoring the presence of 36 COG  
1153 single copy genes. 16S rRNA genes were isolated from the sequences using online RNAmmer  
1154 1.2 Server (Lagesen et al., 2007) and provided to SINA Alignment Service within Silva database  
1155 for classification (Pruesse et al., 2012). Not all clusters could be identified up to species level,  
1156 but for those for which we could find a reference genome, we show also a level of completeness  
1157 by comparing to the respective reference genomes using nucmer from the MUMmer (Delcher  
1158 et al., 1999) v3.23 package (Table S1T, S1U).

#### 1159 **Transcriptome sequencing**

1160 Thalli of strain S276 were harvested in SWC-3 medium under controlled laboratory conditions  
1161 at 23 °C with a 16-h light: 8-h dark cycle with 24.5  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$  illumination provided  
1162 by fluorescent lamps. Two and seven different samples, for full-length cDNA and RNA-seq  
1163 analyses, respectively, were collected, frozen in liquid nitrogen, and stored at -80 °C until  
1164 further processing. Frozen samples were ground in liquid nitrogen. Total RNAs were then  
1165 extracted with ISOGEN (Nippon Gene, Tokyo, Japan), and purified using the Qiagen RNeasy  
1166 Plant Mini Kit. For the extraction of total RNA in oospores and rhizoids, Fruit-mate (Takara  
1167 Bio, Shiga, Japan) was used prior to the extraction by ISOGEN. Full-length cDNA libraries  
1168 were constructed using the oligo-capping method. Total RNA was treated with bacterial  
1169 alkaline phosphatase (BAP; Takara) at 37°C for 40 min with RNasin (Promega). After  
1170 extraction with phenol:chloroform (1:1) twice and ethanol precipitation, the RNA was treated  
1171 with tobacco acid pyrophosphatase (TAP; in house purified) with RNasin at 37°C for 45 min.  
1172 The BAP-TAP treated RNA were ligated with 5'-oligo (5'-AGC AUC GAG UCG GCC UUG  
1173 UUG GCC UAC UGG-3') using T4 RNA ligase (Takara). The first strand cDNAs were  
1174 amplified using 5' (5'-AGC ATC GAG TCG GCC TTG TTG-3') and 3' (5'-GCG GCT GAA  
1175 GAC GGC CTA TGT-3') PCR primers. The amplified cDNAs were digested with SfiI and  
1176 cloned into DraIII-digested pME18S-FL3-3 (AB009864). Clones were picked and sequenced  
1177 with ABI sequencers at National Institute of Genetics, Japan. After filtering for vector, synthetic  
1178 oligonucleotides, and low-quality sequences 73,388 reads were left in total (Table S1D). RNA-  
1179 seq libraries were constructed via the Illumina mRNA-Seq Sample Prep Kit using RNA  
1180 extracted from various tissues (Table S1E). 76 or 101 bp paired end sequencing was performed  
1181 on an Illumina HiSEQ 2000. Additionally, a late reproductive phase thalli (harvested 2-3 weeks  
1182 after appearing of the gametangial primordia) library was constructed as RNA-ligation based  
1183 stranded library using the combined method of mRNA-Seq Sample Prep Kit and Small RNA  
1184 Sample Preparation Kit (Illumina), following the manufacturer's instructions. This library was  
1185 sequenced by 76 bp single end sequencing performed on a GAIIx (Illumina).

#### 1186 **Quantitative transcriptome comparison of antheridia, oogonia, and zygotes**

1187 Antheridia and oogonia were hand-dissected in Qiagen RNA<sub>later</sub> from *C. braunii* thalli (strain  
1188 S276) grown under a 14:10 hours light:dark cycle at 22 °C. Zygotes were collected once  
1189 detached from mother plants grown in identical conditions. Samples were flash frozen in liquid  
1190 nitrogen then kept at -80 °C until further processing. Approximately 20 mg of starting material  
1191 was ground in liquid nitrogen then total RNA was extracted using Ambion mirVana kit  
1192 following manufacturer's recommendations. DNA was digested from RNA extracts using  
1193 Promega RQ1 DNase and RNA was cleaned using a Qiagen RNeasy MinElute Cleanup Kit.  
1194 RNA was then amplified using an Ovation RNA-Seq System V2 (NuGEN) amplification kit

1195 following manufacturer's protocol. Final amplified cDNAs were cleaned using the Qiagen PCR  
1196 cleanup kit. Three biological replicates were obtained for antheridia, oogonia and zygotes. One  
1197 sample containing vegetative and reproductive tissues was similarly prepared, except for the  
1198 amplification step. 20 µg of RNA from each replicate was paired-end sequenced on an Illumina  
1199 HiSeq 2000 platform at the Beijing Genomics Institute in China; at least 2 x 10 million reads  
1200 were obtained per sample. Reads were processed to remove low quality sequences, PCR  
1201 adapters, foreign sequences introduced by the amplification procedure and any detectable bias  
1202 using Trimmomatic v0.36 (Bolger et al., 2014) and Perl scripts. Transcript were inferred from  
1203 the reads pooled and aligned to the *C. braunii* genome sequence using Tophat v2.1.0 (Kim et  
1204 al., 2013) and Cufflinks v2.0.2 (Trapnell et al., 2010). Both programs were given the *C. braunii*  
1205 genomic structure as a guide. A custom Perl script was then used to clean Cufflinks predictions  
1206 from spurious gene fusions and other detectable problems. Unaligned reads were further  
1207 normalised, assembled and scaffolded into transcripts. Both reference guided and *de novo*  
1208 assemblies were merged. Coding sequences were predicted, and sequence annotation and GO  
1209 terms were obtained from transcripts using a pipeline based on BLAST v2.2.29 (Altschul et al.,  
1210 1997) and TransDecoder v2.0.1 (Haas et al., 2013). A summary of assembly and read mapping  
1211 statistics is presented in Table S1W. Read counts were obtained by mapping reads onto the  
1212 inferred transcriptome with RSEM v1.2.11 (Li and Dewey, 2011). Differential expression was  
1213 tested between zygotes and oogonia samples and between oogonia and antheridia samples and  
1214 was conducted in R using DESeq2 v1.14.1 (Love et al., 2014). Genes were considered  
1215 differentially expressed between two conditions with an adjusted p-value < 0.01 and a log2  
1216 fold-change (logFC) > 2. Differentially expressed genes are listed in Table S2. GO terms  
1217 enrichment analysis was conducted in R using topGO v2.22.0. Enriched GO terms and  
1218 associated genes are listed in Table S3. Heatmaps were generated using R and the package  
1219 pheatmap v1.0.8. Visualization of the GO terms was implemented using word clouds via the  
1220 <http://www.wordle.net> application. The weight of the given terms was defined as the -log10(q-  
1221 values) and the color scheme used for the visualization was red for down-regulated GO terms  
1222 and green for those up-regulated. See Table S2 for DEGs and Table S3 for GO analyses.

#### 1223 **Identification of repeat sequences with RepeatModeler/RepeatMasker**

1224 A species-specific repeat model was constructed using RepeatModeler Version open-1.0.7 with  
1225 ncbi engine. Repeats were identified using RepeatMasker version open-4.0.5 with Search  
1226 Engine: NCBI/RMBLAST [2.2.27+] and RepeatMaskerLib.embl (Complete Database:  
1227 20140131), resulting in masking 46% of the genome. The breakdown is shown in Table S1F.

#### 1228 **Gene prediction**

1229 High throughput cDNA sequencing (RNA-seq) was conducted on several libraries representing  
1230 vegetative and reproductive stages, including thallus, gametangia and zygotes. These data were  
1231 used together with full-length cDNA sequences to annotate the genome with AUGUSTUS.  
1232 35,445 putatively protein-coding genes were identified, of which 63% could be annotated using  
1233 similarity-based approaches. A total of 13,331 gene models overlap to at least 50% with TE  
1234 evidence and thus might not represent canonical protein-coding genes, bringing the number of  
1235 protein-encoding genes down to 23,546. In total, the expression of 12,388 of those (53%) was  
1236 supported by RNA-seq data (Table S4). Reciprocal best BLAST (Altschul et al., 1997) hit  
1237 analysis of the *C. braunii* protein set revealed a high percentage presence of core gene sets:

1238 96.43% of eukaryotic benchmarking universal single-copy orthologs (BUSCO, (Simao et al.,  
1239 2015)), 98.65% CEGMA core eukaryotic genes (Parra et al., 2007), and 93.96% core gene  
1240 families for green plants (Van Bel et al., 2012).

1241 Gene prediction with Augustus (Keller et al., 2011) was performed following  
1242 [https://computationalbiology.wordpress.com/2013/07/25/incorporating-rnaseq-tophat-to-](https://computationalbiology.wordpress.com/2013/07/25/incorporating-rnaseq-tophat-to-augustus/)  
1243 [augustus/](https://computationalbiology.wordpress.com/2013/07/25/incorporating-rnaseq-tophat-to-augustus/). Initial models were created based on the CEGMA output. RNA-seq data was mapped  
1244 to the RepeatMasker masked *C. braunii* genome. Each accepted\_hits.bam was sorted and  
1245 processed with filterBam --uniq (--paired for paired data). Evidence of introns was extracted  
1246 using bam2hints --intronsonly to obtain intron\_hints.gff. The first round of Augustus was run  
1247 with this as hints. An exon-exon junction database was constructed based on this output and  
1248 bowtie was used to map the reads to the junctions. These mappings were further merged to the  
1249 first intron hints and the second round of augustus was run. Gene prediction at this phase was  
1250 manually investigated and confirmed genes on scaffold\_0 and scaffold\_2 were chosen and  
1251 adjusted for the 5' and 3' ends of UTR based on RNA-seq mapping on Web Apollo (Lee et al.,  
1252 2013). Thus, 120 manually inspected gene models were used to retrain Augustus. Construction  
1253 of exon-part hints through wig file were performed according to  
1254 <http://augustus.gobics.de/binaries/readme.rnaseq.html>. For the stranded RNA-seq data, forward  
1255 and reverse mapped reads were separated with samtools and assigned the strand accordingly.  
1256 Repeat hints were prepared by processing the gff file created by the RepeatMasker with "sed -  
1257 e s/similarity/nonexonpart/ -e 's/Target.\*/src=RM/'". Amino acid sequence of *A. thaliana*  
1258 (TAIR10\_pep\_20110103\_representative\_gene\_model\_updated) and *P. patens*  
1259 (P.patens.V6\_filtered\_cosmos\_proteins.fas) were mapped to the genome using exonerate and  
1260 converted as hint data. The full-length EST sequences were mapped using blat (Kent, 2002)  
1261 with -minIdentity=92 -extendThroughN parameters and converted to EST hints. All these hints  
1262 were merged to a single hints file and the final run of Augustus was run with --gff3=on --  
1263 UTR=on --alternatives-from-evidence=true --allow\_hinted\_splicesites=atac with a merged  
1264 hints file. The output was collected and gene models predicted on the 11,808 scaffolds that were  
1265 treated as *C. braunii* genome. Thus, we obtained 36,877 transcripts from 35,883 loci. For  
1266 annotation see Table S4.

#### 1267 **Assembly of organellar genomes**

1268 Organellar genomes were assembled using NOVOPlasty (Dierckxsens et al., 2017) v2.5.3. For  
1269 chloroplast genome, two lanes of paired end data were processed using the *Chara vulgaris*  
1270 chloroplast genome (NC\_008097.1) as seed. This resulted in 4 possible reconstructions, two in  
1271 187 kbp and the remaining two in 200 kbp, i.e. contig arrangement 01+02+03+04+06,  
1272 01+04+05, 01+02+03+04+05, or 01+04+06. The differences are on whether 02 and 03 are  
1273 inserted and whether the end is 05 or 06. 02 and 03 is contained in 01 and seems to represent  
1274 an inverted repeat region and insertion of them would be excess. The 05 and 06 contain 27,447-  
1275 bp common sequence, which is the small single copy region. Given there are about equal  
1276 number of molecules that is flipped at the inverted repeat region, both reconstructions are  
1277 equally valid and one is arbitrarily chosen. The mitochondrial genome was assembled using the  
1278 *C. vulgaris* mitochondrial genome (NC\_005255.1) as seed input and specifying the chloroplast  
1279 genome obtained as above. This resulted in a single circularized assembly of 67,059 bp, which  
1280 is very close to 67,737 of the *C. vulgaris* mitochondrial genome.

1281 **Repeat/TE annotation**

1282 Repetitive elements collectively contribute approximately 1.1 Gbp of the genome assembly.  
1283 This estimate is probably low, given that highly similar repeats are challenging to assemble and  
1284 that there is ~0.5 Gbp size difference between the ungapped (1.43 Gbp) assembly and C-value  
1285 estimates (1.9 Gbp). Transposable elements (TEs) and unclassified repeats are abundant (61%  
1286 and 37% of repeat annotation, respectively), with Gypsy-type LTR retrotransposons  
1287 representing 24% (343 Mbp) of the ungapped assembly (Table S1G).

1288 We have used the REPET package v2.4 to perform *de novo* identification, classification and  
1289 annotation of repetitive elements in the *C. braunii* assembly as described in (Jouffroy et al.,  
1290 2016). We first launched the TEdenovo pipeline on a sub-genome comprising contigs of size  
1291 above 20 kb and representing a total of 362 Mb (12,655 contigs). We used default settings  
1292 except that the minimum number of copies per group was set to 5 (minNbSeqPerGroup: 5),  
1293 resulting in a library of 3,140 consensus sequences. This library was subsequently filtered by  
1294 using the TEannot pipeline against the whole assembly and discarding consensus sequences  
1295 without a single full length match, resulting in a library of 2,161 sequences. This filtered library  
1296 was used to annotate the whole genome assembly using the TEannot pipeline. Threshold  
1297 annotation scores were determined for each consensus as the 99th percentile of the scores  
1298 obtained against a randomized sequence (whole genome reversed, not complemented and  
1299 masked with TRF). Consensus sequences were then classified using the features detected with  
1300 PASTEC followed by semi-manual curation. In addition to the HMM comparison against  
1301 PFAM implemented in PASTEC, we have also used RPS-BLAST (-F T -e 1e-2) to search for  
1302 more remote homologies against a library of CDD domains identified in the repbase library.

1303 Several unclassified consensus sequences have been classified in putative retrotransposons  
1304 because they contain at least one of the following domains: cd00024 Chromatin organization  
1305 modifier, cd00303 Retropepsins, cd01650 RT nLTR, cd01651 RT G2 intron, cd05482  
1306 Retropepsins, cd06095 Retropepsin, cd06222 RNase H, pfam00385 Chromo, pfam00552  
1307 Integrase, pfam00665 Integrase, pfam02093 Gag P30, pfam03708 Avian retrovirus envelope  
1308 protein, pfam03732 Retrotransposon gag protein, pfam07727 Reverse transcriptase,  
1309 pfam10536 Plant mobile domain, pfam13966 zinc-binding in reverse transcriptase, pfam13975  
1310 gag-polyprotein putative aspartyl protease, pfam13976 GAG-pre-integrase domain, and  
1311 smart00298 Chromatin organization modifier domain.

1312 Based on the REPET results, percentage overlap of protein coding gene models with TEs was  
1313 assessed and added to Table S4. Gene models overlapping to 100% with TE evidence are  
1314 considered true TE genes, while those overlapping to at least 50% (but less than 100%) might  
1315 be protein-coding genes present in TE regions, or might encode TE-based proteins. All genes  
1316 were kept in the gene catalog so that individual evaluation (e.g. based on the homology-based  
1317 annotation) is possible.

1318 **Screening for whole genome duplication events**

1319 To identify whole genome duplication (WGD) events we employed the KeyS software (Rensing  
1320 et al., 2007) to obtain Ks (synonymous substitution) distributions of paralogous genes for *C.*  
1321 *braunii*. In brief, paralogous genes were defined by a self-BLAST retaining only BLAST hits  
1322 that showed at least 50% query and subject coverage and an alignment length according to the

1323 twilight zone *sensu* (Rost, 1999). Gene pairs with a BLAST identity of 98% or higher were  
1324 further tested at the nucleic acid level to remove nearly identical sequences using optimal global  
1325 alignments and a threshold of 98% identity. For nearly identical gene pairs only the longer  
1326 sequence was kept and all gene pairs containing the shorter sequence were discarded (Rensing  
1327 et al., 2007). The paralogous genes were further clustered using a minimal connectivity  
1328 threshold of 50% (half linkage) and Ks values were calculated at the cluster nodes (representing  
1329 duplication events rather than gene pairs) using the maximum likelihood method of CODEML  
1330 implemented in PAML v4.7 (Yang, 2007).

1331 The following procedure has been described recently (Lang et al., 2018), please see there for  
1332 related citations. Briefly, we employed mixture modeling to find WGD signatures using the  
1333 *mclust* v5.1 R package (Scrucca et al., 2016) to fit a mixture model of Gaussian distributions to  
1334 the raw Ks and log-transformed Ks distributions. All Ks values  $\leq 0.1$  were excluded for analysis  
1335 to avoid the incorporation of allelic and/or splice variants and to prevent the fitting of a  
1336 component to infinity, while Ks values  $> 5.0$  were removed because of Ks saturation. Further,  
1337 only WGD signatures were evaluated between the Ks range of 0.235 (12.5 Ma ago) to account  
1338 for recently duplicated gene pairs to Ks of 2.0 to account for misleading mixture modeling  
1339 above this upper limit. Because model selection criteria used to identify the optimal number of  
1340 components in the mixture model are prone to over fitting we also used SiZer and SiCon as  
1341 implemented in the *feature* v1.2.13 R package (Duong et al., 2008) to distinguish components  
1342 corresponding to WGD features at a bandwidth of 0.0188, 0.047, 0.094 and 0.188  
1343 (corresponding to 1 Ma, 2.5 Ma, 5 Ma and 10 Ma ago) and a significance level of 0.05.

1344 Deconvolution of the overlapping distributions that can be derived from paranome-based Ks  
1345 values without structural information shows that using mixture model estimation based on log-  
1346 transformed Ks values mimics structure-based WGD predictions better than using raw Ks  
1347 values, and can predict young WGD signatures and can pin point older WGD signatures (Lang  
1348 et al., 2018). Since WGD signature prediction based on paranome-based Ks values can be  
1349 misleading and is prone to over prediction we only considered Ks distribution peaks in a range  
1350 of 0.235 to 2.0 as possible WGD signatures, thus excluding young paralogs potentially derived  
1351 from tandem or segmental duplication and those for which accurate dating cannot be achieved  
1352 due to high age (Fig. S3).

### 1353 **Genome comparison**

1354 *C. braunii* was compared with eight further Viridiplantae genomes. In addition to the genome  
1355 length, GC content and the number of annotated genes, the mean intergenic and the mean intron  
1356 length were calculated. The intergenic length was performed by extracting the genome regions  
1357 not covered by the gff3 annotation file with bedtools complement (Quinlan, 2014) version  
1358 2.25.0. The intron length was calculated by extracting the distance between the annotated CDS  
1359 regions. Both mean length and the corresponding standard deviation were calculated using awk  
1360 (Table S1L). The gene density of the *C. braunii* genome is relatively sparse as compared to e.g.  
1361 *A. thaliana*, *O. sativa* (rice) or two algae (*K. nitens* and *Chlamydomonas reinhardtii*), but similar  
1362 to other Gbp-sized genomes like *Z. mays* or *H. vulgare* (Fig. 3 and Table S1L); the distance  
1363 between genes is comparable to the approximately equal-sized *Z. mays* genome.

### 1364 **Comparative analysis of gene and transposons in selected plant and algae species**

1365 The genome sequences and annotations of *K. nitens*, *C. reinhardtii*, *A. thaliana*, *M. polymorpha*,  
1366 *Oryza sativa*, *P. patens*, *C. braunii*, *Z. mays*, *H. vulgare* were downloaded and processed with  
1367 GAG and the genome tools gff3 validator, to obtain consistent annotation files. For each  
1368 annotated gene, intronic regions were inferred using the GenomeTools gff3 program. The *K.*  
1369 *nitens* annotation file was manually curated for consistency with the other annotations and the  
1370 GFF3 data standard.

1371 Subsequently, intact full-length long terminal repeat transposon elements (LTREs) were  
1372 predicted using the GenomeTools LTRharvest and LTRdigest software (Steinbiss et al., 2009)  
1373 utilizing a set of TE-associated PFAM domains and a compilation of eukaryotic tRNAs. The  
1374 pipeline was implemented as a BASH/PBS shell script (run\_LTR\_harvest\_digest.sh). The  
1375 resulting set of candidate LTREs was filtered to contain 2 LTRs,  $\geq 1$  protein domain match and  
1376 2 target site duplications. These filtered elements were considered to represent intact full-length  
1377 LTREs whose nucleotide sequences were extracted and searched against the genome using  
1378 Vmatch requiring  $\geq 80\%$  sequence identity and 100 bp alignment length. Depending on the  
1379 repeat content and genome size, genomes were either split at gap boundaries into preferably  
1380 100 Mbp stretches using the UCSC toolkit faSplit (A: Snakemake workflow: split\_approach),  
1381 or directly processed as a whole FASTA file (B: Snakemake workflow: vmatch\_mask) (Köster  
1382 and Rahmann, 2012). Resulting putative LTRE fragments were merged into non-redundant,  
1383 non-overlapping regions using the reduce function implemented in the R/Bioconductor package  
1384 GenomicRanges (A) (Lawrence et al., 2013) or the bedtools merge program (B).

1385 Helitrons were predicted using the HelitronScanner software using the parameters reported for  
1386 element inference and copy number prediction in plant genomes reported in the initial  
1387 manuscript (Xiong et al., 2014). Additional fragments were inferred by matching 50 bp from  
1388 the 3' terminus of each full-length helitrons against the respective genome utilizing Vmatch  
1389 (Abouelhoda et al., 2004) following the same approach as described for LTREs. Resulting  
1390 matches and full-length helitrons were merged into non-redundant, non-overlapping regions  
1391 using the bedtools merge program. The pipeline was implemented in the Snakemake workflow  
1392 in folder helitrons/.

1393 Gene-to-gene, gene-to-LTRE, LTRE-to-gene and LTRE-to-LTRE distances were inferred using  
1394 an R script utilizing the distanceToNearest function from the R/Bioconductor GenomicRanges  
1395 package (get\_distances.R/get\_distances.sh). Subsequent data analysis and plotting was carried  
1396 out and documented in the R Jupyter Notebooks: folder analysis/: analyseWindows.ipynb,  
1397 Distances.ipynb, Introns.ipynb, Lengths.ipynb. All described, generated materials and software  
1398 needed to reproduce this analysis are available from the accompanying Mendeley Data  
1399 repository (doi:10.17632/9hzzf9m4kh.1), arranged as an archive  
1400 ("ComparativeTE\_and\_genes.Lang.tar.gz") that contains input, output and scripts.

#### 1401 **In-depth analyses of specific gene families**

##### 1402 *Cell wall biosynthesis*

1403 Glycosyltransferases in the *C. braunii* genome assembly were initially identified via BLAST,  
1404 using the Carbohydrate Acting enZYme database (CAZY) as of 2016-06-01 as query and a cut-  
1405 off value of  $10^{-25}$ . The sequences were manually verified by alignment with known cell wall  
1406 biosynthetic glucosyltransferases and deposited in Table S1H. Phylogenetic trees were



1407 constructed using Phylogeny.fr with standard settings, starting with muscle alignment, curation  
1408 of alignment by deletion of positions with gaps, and finally PhyML maximum likelihood tree  
1409 construction (Guindon et al., 2010). The phylogenetic trees (Data S1A, B) were statistically  
1410 supported by approximate likelihood-ratio tests using default settings and values between 0 and  
1411 1 were obtained, as with bootstrap values. Approximate likelihood-ratio-test (aLRT) values  
1412 were included when values were under 0.7 where *C. braunii* sequences are present.

#### 1413 **Cell division**

1414 In order to compare the mode of cell division of algae and land plants we compiled a list of 221  
1415 *Arabidopsis* genes involved in cytokinesis (Table S1C), focusing on genes required for  
1416 phragmoplast and PPB function. With these 221 *A. thaliana* proteins, a BLASTp (version  
1417 2.6.0+) search was performed against published plant and algal genomic/transcriptomic  
1418 datasets (key resource table), including *C. braunii* and *K. nitens*. The e-value cutoff was set to  
1419 1E-4 and the number of database sequences to show alignment for was set to 3,000. The BLAST  
1420 result was filtered according to (Rost, 1999) to keep homologous sequences only. Multiple  
1421 sequence alignments for phylogenetic trees of protein families were conducted using MAFFT  
1422 (Katoh and Standley, 2013) in the automatic mode, and manually curated. The best fitting  
1423 evolutionary model based was determined using ProtTest (Darriba et al., 2011) and applied in  
1424 Bayesian phylogenetic inference using MrBayes (Ronquist et al., 2012) with two hot and two  
1425 cold chains (Data S1Q-U) until the standard deviation of split frequencies dropped below 0.01  
1426 or for 6 mio generations (actin and cyclin).

1427 Using the amplification score that shows potential gene expansion between *K. nitens* and *C.*  
1428 *braunii* (Table S1C) we performed phylogenetic analyses as outlined above and found cyclin  
1429 genes to be amplified in *C. braunii*, suggesting a more intricate regulation of the cell cycle as  
1430 compared to *K. nitens*. While there is a single A1-type cyclin in both algae, the *C. braunii*  
1431 genome encodes three B1-type cyclins (like *A. thaliana*), whereas *K. nitens* encodes only one  
1432 (Table S1C, Data S1Q). We also found evidence that membrane trafficking is more elaborate;  
1433 there are three genes coding for EXOCYST 70A in *A. thaliana*, two in *C. braunii* (and in the  
1434 transcriptomes of several Zygnematomyceae), and a single gene in *K. nitens* (as in *Mesostigma*  
1435 *viride* and Chlorophyta; Data S1R). With regard to the SNARE complex, we find that the *A.*  
1436 *thaliana* NOVEL PLANT SNARE (NPSN) 11/12/13 clade contains two *C. braunii* (and two  
1437 *Nitella mirabilis*) and a single *K. nitens* (and *M. viride*) protein (Data S1S).

#### 1438 **Phytohormones: ETH**

1439 For the identification of putative homologs for ETH biosynthesis and signaling genes,  
1440 BLASTp/tBLASTn searches were carried out against the *C. braunii* gene models and genome  
1441 assembly using representative *A. thaliana* protein sequences as queries [ACS1 (AT3G61510),  
1442 ACO1 (AT2G19590), ETR1 (AT1G66340), CTR1 (AT5G03730), EIN2 (AT5G03280), EIN3  
1443 (AT3G20770); Table S1J]. Translated sequences of putative ETH biosynthesis/signaling genes  
1444 from *C. braunii* were then used as queries in reciprocal BLASTp searches to the *A. thaliana*  
1445 protein database. Multiple ACO homologs were found in the *C. braunii* genome, however, the  
1446 reciprocal BLASTp search suggests that these homologs are likely to be other oxidases. The  
1447 other candidate *C. braunii* ETH biosynthesis/signaling protein sequences were manually  
1448 verified and screened for essential protein domains [ACS (PR00753), ETR/ERS (ETH Binding

1449 Domain), CTR1 (PF14381 and CD13999), EIN3 (PF04873 and C-terminal Signaling Domain),  
1450 EBF (IPR001810)]. An additional search with BLASTP 2.8.0+ using the representative *A.*  
1451 *thaliana* proteins as queries and the putative homologs as the subjects was performed.

1452 ***Phytohormones: ABA***

1453 For the identification of putative homologs for ABA biosynthesis and signaling genes,  
1454 BLASTn/BLASTp searches were carried out against the *C. braunii* gene models and genome  
1455 assembly using representative *A. thaliana* genomic/protein sequences as queries (Table S1J).  
1456 An additional search with BLASTP 2.8.0+ using the representative *A. thaliana* proteins as  
1457 queries and the putative homologs as the subjects was performed. The obtained *C. braunii*  
1458 protein sequences were manually verified and screened for essential protein domains [PSY  
1459 (PF00494), PDS (PF01593), GTG1 (PF12537), SnRK/CPK (PF00069)].

1460 ***Phytohormones: SL***

1461 For the identification of putative homologs for SL biosynthesis and signaling genes,  
1462 BLASTn/BLASTp searches were carried out against the *C. braunii* gene models and genome  
1463 assembly using representative *A. thaliana* genomic/protein sequences as queries (Table S1J).  
1464 An additional search with BLASTP 2.8.0+ using the representative *A. thaliana* proteins as  
1465 queries and the putative homologs as the subjects was performed. The obtained *C. braunii*  
1466 protein sequences were manually verified and screened for essential protein domains [CCD  
1467 (PF03055)].

1468 ***Phytohormones: Jasmonates (JA), Salicylates (SA), Gibberellins (GA), Brassinosteroids***  
1469 ***(BR)***

1470 For the identification of putative homologs for JA, SA, GA and BR biosynthesis and signaling  
1471 genes, BLASTn/BLASTp searches were carried out against the *C. braunii* gene models and  
1472 genome assembly using representative *A. thaliana* genomic/protein sequences as queries (Table  
1473 S1J). Canonical (land-plant like) signaling pathways for JA, SA, GA and BR have been shown  
1474 to have arisen in land plants [JA - (Han, 2017); SA - (Wang et al., 2015)], vascular plants [GA  
1475 - (Gao et al., 2008; Wang et al., 2015)] and seed plants [BR - (Vriet et al., 2015)] respectively.  
1476 Consistent with these findings, none of the genes encoding steps in the biosynthesis or signaling  
1477 pathways for GA, JA, SA or BR appear to be present in the *C. braunii* genome (Table S1J).  
1478 However, JA was found in *C. australis* (Beilby et al., 2015), JA and SA were detected in *K.*  
1479 *nitens* (Hori et al., 2014), and GA was detected in *Chara tomentosa*, suggesting a different  
1480 synthesis than known in land plants as in the case of AUX and ABA (Table 1, Fig. 4).

1481 ***Phytohormones: AUX transport***

1482 For the identification of putative homologs for AUX transporter genes, tBLASTn/BLASTp  
1483 searches were carried out against the *C. braunii* gene models and genome assembly using  
1484 representative *A. thaliana* genomic/protein sequences as queries (Table S1J and S11).

1485 Predicted coding sequences of PIN proteins were manually aligned with representative PIN  
1486 sequences from previously published alignments, PIN sequences from charophyte algae were  
1487 obtained from the NCBI database. The PIN sequence of *K. nitens* (GAQ81096.1) originated  
1488 from the complete genome assembly, other algal sequences were obtained from the SRA  
1489 database (Leinonen et al., 2011) of individual sequencing project by using the BLASTn

1490 algorithm, using the sequence from *K. nitens* as a query. The resulting hits were assembled with  
1491 CAP3 (Huang and Madan, 1999) and repeatedly BLASTed against respective SRA databases  
1492 to increase sequence length. Maximum-likelihood phylogenetic analysis was performed in  
1493 MEGA 7.0 software using amino acid representation of highly conserved N- and C-terminal  
1494 part of PIN sequence, LG+G+I substitution model and 500 bootstrap replicates (Data S1C, D).

#### 1495 **Phytohormones: AUX signaling**

1496 For charophyte algae, mRNA sequences were downloaded and protein sequences were  
1497 predicted with ESTScan v3.0.3 (Iseli et al., 1999) using the *A. thaliana* matrix [-M  
1498 Arabidopsis\_thaliana.smat]. Subsequently all proteins were screened with *hmmsearch* of the  
1499 HMMer software suite (v3.1b2) for the abundance of the PFAM v30.0 domains: Auxin\_resp  
1500 (PF06507), AUX\_IAA (PF02309), B3 (PF02362), F-box (PF00646) and F-box-like (PF12937)  
1501 using either the gathering threshold [--cut\_ga] option or an E-value of 0.1 for the complete  
1502 sequence [-E 0.1] and an E-value of 0.1 for the domain [--domE 0.1] to account for possible  
1503 sampling bias and cutoff bias of the curated PFAM model.

1504 The obtained results were used to classify the proteins into possible AUX gene families: ARFs  
1505 [mandatory domains: Auxin\_resp + B3; optional: AUX\_IAA], Aux/IAA [mandatory:  
1506 AUX\_IAA - Auxin\_resp] and TIR1/AFB [mandatory: F-box or F-box-like]. For the AUX gene  
1507 family TIR1/AFB an additional BLAST search with BLAST+ (v2.5.0) [-matrix BLOSUM45  
1508 -evalue 1e-5] using representative *A. thaliana* genes as queries [AT3G62980.1 (TIR1),  
1509 AT4G03190.1 (AFB1), AT3G26810.1 (AFB2), AT1G12820.1 (AFB3), AT4G24390.2 (AFB4),  
1510 AT5G49980.1 (AFB5)] and the domain containing proteins as the subjects was performed. Only  
1511 BLAST hits with a query coverage (alignment length / query length) of at least 50% and a  
1512 minimal protein identity according to formula (2) of (Rost, 1999) were retained as possible  
1513 AUX gene family candidates. Maximum-likelihood phylogenetic analysis for each AUX gene  
1514 family was performed on manual curated multiple sequence alignments obtained via MAFFT  
1515 (v7.305b) and the E-INS-i algorithm. *IQ-TREE* (Nguyen et al., 2015) v1.5.3 was applied using  
1516 the standard non-parametric bootstrap option with 1,000 replicates and the best model selected  
1517 by *IQ-TREE* (Table S1K, Data S1E-G).

#### 1518 **Phytohormones: AUX, in silico modeling of *C. braunii* LRR FBPs.**

1519 Leucine-RichRepeat (LRR)-containing F-Box Proteins (FBPs) from *C. braunii* with sequence  
1520 similarity to land plant LRR FBPs were *in silico* modeled using “intensive” modeling mode in  
1521 Protein Homology/analogY Recognition Engine V 2.0 (Phyre2) (Kelley et al., 2015). Various  
1522 PDB molecule templates (coronatine-insensitive protein 1: Chain B (c3ogmB) and Chain D  
1523 (c3og1D); transport inhibitor response 1: Chain E (c2p1nE); f-box/lrr-repeat max2 homolog:  
1524 Chain A (c5hywA), skp2: Chain C (c1fs2C) and Chain K (c1fqvk); and protein toll: Chain A  
1525 (c4lxa)) were selected to model *C. braunii* LRR FBPs based on heuristics to maximize  
1526 confidence, percentage identity and alignment coverage. Structural prediction from regions  
1527 modeled *ab initio* are highly unreliable. The final models (color-coded by the confidence of the  
1528 match to the templates overall) were submitted to 3DLigandSite server (Wass et al., 2010) to  
1529 predict potential binding sites (gray structures cartoon depiction); see Data S1P.

#### 1530 **Phytohormones: CK**

1531 In order to identify putative CK receptors, BLAST searches were carried out against the *C.*  
1532 *braunii* gene models and genome assembly, using PpCHK4 and AHK4 as queries. The detected  
1533 sequences were run against the Interpro and PFAM databases to detect the domains (histidine  
1534 kinase and response regulators) which are found in CK receptors. Two sequences were  
1535 identified containing the domain architecture of CK receptors (CHBRA123g00790 and  
1536 CHBRA19g00270). In order to identify putative histidine phosphor transfer protein (HPT), a  
1537 search with the HPT domain (Interpro IPR008207) was conducted and retrieved one sequence  
1538 (CbHPT1, CHBRA650g00040) (Table S1J). For identification of the response regulators (type-  
1539 A and type-B) we used the PFAM domains Response\_reg (PF00072) and Myb\_DNA-binding  
1540 (PF00249) in an hmmsearch and did not find any gene models. In order to make sure that this  
1541 result is not due to a missing or fragmentary gene model we also screened the available  
1542 transcriptome data (transcripts were translated in all possible frames). While two A-type  
1543 response regulators (RRA) could be detected in the transcriptome (comp31700c0seq1num3,  
1544 comp64895c0seq1/2 rc num2, Table S1J/S1K, Data S1H), no combination of the two domains  
1545 and thus no B-type (RRB) could be detected. All sequences harboring Response\_reg domains  
1546 were aligned with the response regulator domains of the *Arabidopsis* response regulators ARR1  
1547 and ARR14 (RRB) as well as ARR4 and ARR9 (RRA) and ARR 22 (RRC – not known to be  
1548 involved in CK signaling) using the muscle implementation of the MEGA 7.0 suite. Using the  
1549 alignment, a maximum likelihood tree was calculated with the pairwise distances estimated by  
1550 a JTT model and 100 bootstrap samples. Again, two sequences were determined as RRAs. Of  
1551 the *Chara* sequences in the RRB clade, again none contained a MYB domain (Data S1H).

#### 1552 **Photorespiration**

1553 In land plants, the canonical photorespiratory pathway employs 8 enzymes, namely 2PG-  
1554 phosphatase (PGPase), glycolate oxidase (GOX), glutamate:glyoxylate aminotransferase  
1555 (GGT), glycine decarboxylase (GDC), serine hydroxymethyltransferase (SHMT),  
1556 serine/alanine:glyoxylate aminotransferase (SGT), hydroxypyruvate reductase (HPR) and  
1557 glycerate 3-kinase (GLYK) (Bauwe et al., 2010). Particularly, the glycolate oxidation step,  
1558 which is performed by GOX in the plant peroxisomes, is catalysed by glycolate dehydrogenase  
1559 in the mitochondrion of the green algae *C. reinhardtii* (Nakamura et al., 2005) and in the  
1560 cytosol of cyanobacteria. To analyze the photorespiration in the Charophyte algae *C. braunii*,  
1561 the protein sequences of enzymes from *A. thaliana* were used to identify homologue proteins  
1562 in *C. braunii* by a BLASTp similarity search against the Chbra.pep.20151207.orcae database  
1563 (Table S1M). To verify, if *C. braunii* also possess genes to oxidize glycolate via a glycolate  
1564 dehydrogenase like Chlorophytes and cyanobacteria do, the polyphyletic proteins from *C.*  
1565 *reinhardtii* (ABG36932.1) and *Synechocystis* sp. PCC 6803 (Sll0404 and Slr0806) were used  
1566 as templates in similarity searches. To verify, if a putative glycolate oxidase prefers the substrate  
1567 glycolate over lactate, three amino acids in the active site that were shown to be responsible for  
1568 the substrate preference (Hackenberg et al., 2011) were analyzed. To this end, the putative  
1569 glycolate oxidase from *C. braunii* and verified glycolate oxidase proteins of the land plants *A.*  
1570 *thaliana* and *Spinacia oleracea*, the red alga *Cyanidioschyzon merolae* and characterized L-  
1571 lactate oxidase proteins from the cyanobacterium *Nostoc* sp. PCC 7120 and the bacterium  
1572 *Aerococcus viridans* were aligned and the corresponding amino acids in the active sites of the  
1573 proteins compared.

1574 **Retrograde signaling and PAPs**

1575 Protein data from the genomes of *C. reinhardtii*, *K. nitens*, *C. braunii*, and *P. patens* was  
1576 screened for orthologs of the flowering plant-type retrograde signaling pathway or PAPs via a  
1577 reciprocal best BLASTp approach using *A. thaliana* sequences as query. For GUN1, the  
1578 BLASTp analyses were repeated using reciprocal pHMMER surveys. To further pinpoint the  
1579 relation of *Cb*GUN1 to other PPRs, the high similarity *K. nitens* protein GAQ81958.1 was used  
1580 as a query in BLASTP (2.2.26) search to a database comprising the NCBI nr dataset as of  
1581 January 2015 supplemented with *K. nitens*, *Pinus taeda* 1.01, and *P. patens* v3.3 Ppav3.3  
1582 datasets and 912 hit sequences were retrieved through ([http://moss.nibb.ac.jp/cgi-bin/blast-nr-](http://moss.nibb.ac.jp/cgi-bin/blast-nr-Kfi)  
1583 [Kfi](http://moss.nibb.ac.jp/cgi-bin/blast-nr-Kfi)). Two *C. braunii* proteins Cbr\_g9159.t1 (GUN1) and Cbr\_g31394.t1, and a *M. polymorpha*  
1584 protein Mapoly0154s0039.1 were added to this set. From this set, top 500 hits with  
1585 GAQ81958.1 were retrieved and aligned with mafft version 6.811b and converted to nexus  
1586 format file through (<http://moss.nibb.ac.jp/cgi-bin/selectNalign>). The alignment was edited to  
1587 retain 242 aa (others were excluded; further 47 proteins that showed low conservation in the  
1588 retained regions were deleted). The nexus file was subjected to [http://moss.nibb.ac.jp/cgi-](http://moss.nibb.ac.jp/cgi-bin/makenjtree)  
1589 [bin/makenjtree](http://moss.nibb.ac.jp/cgi-bin/makenjtree) to construct a NJ tree based on JTT distance with 1,000 bootstraps using  
1590 PHYLIP 3.695. Sequences identical within the retained 242 aa sites were treated as a single  
1591 OTUs and 381 OTUs remained in the final tree. The organism name the sequence originated  
1592 was recovered using NCBI taxonomydb  
1593 (<ftp://ftp.ncbi.nih.gov/pub/taxonomy/accession2taxid/prot.accession2taxid.gz>,  
1594 <ftp://ftp.ncbi.nih.gov/pub/taxonomy/taxdump.tar.gz>). The subcellular localization of PAPs was  
1595 predicted using three online tools (Table S1N).

1596 **Transcription factors and transcriptional regulators**

1597 Transcription associated proteins (TAPs) comprise transcription factors (TFs, acting in  
1598 sequence-specific manner, typically by binding to *cis*-regulatory elements) and transcriptional  
1599 regulators (TRs, acting on chromatin or via protein-protein interaction. We classified all *C.*  
1600 *braunii* proteins into 122 families and sub families of TAPs by first screening the proteins for  
1601 domains and then applying a domain-based rule set to distinguish the TAPs (Lang et al., 2010;  
1602 Wilhelmsson et al., 2017). We compared this genome-wide classification with genomic protein  
1603 sets from *Cyanidioschyzon merolae*, *C. reinhardtii*, *Cyanophora paradoxa*, *K. nitens* and  
1604 several land plants, as well as with transcriptomic data of Charophyta (Timme et al., 2012), *M.*  
1605 *polymorpha* and ferns (Table S1Q, S1Z). The phylogenetic tree for the trihelix family (Data  
1606 S1J) was inferred as mentioned above for the cell division related families.

1607 For the Homeodomain (HD) and basic Helix-Loop-Helix (bHLH) phylogenetic analyses (Table  
1608 S1O, S1P), the *C. braunii* genome was searched using a BLASTp query that was assembled  
1609 from the previously characterized bHLH and HD protein sequences (Catarino et al., 2016) in  
1610 *At*, *A. thaliana*; *Os*, *O. sativa*; *Sm*, *Selaginella moellendorffi*; *Pp*, *P. patens*; *Mp*, *M.*  
1611 *polymorpha*; *Kf*, *K. nitens*; *Cr*, *C. reinhardtii*; *Ot*, *Ostreococcus tauri*; *Vc*, *Volvox carteri*; *Cm*,  
1612 *C. Merolae* with the addition of bHLH proteins sequences from *Cv*, *Coccomyxa subellipsoidea*  
1613 (previously *Chlorella vulgaris*). The results of the BLASTp search were analyzed manually to  
1614 ensure the presence of the HD or the bHLH conserved domain using SMART and PFAM. All  
1615 protein sequences were aligned using MAFFT (Katoh and Standley, 2013) and further manually  
1616 aligned independently for HD and bHLH. The Maximum likelihood analysis was carried out

1617 using PhyML (Guindon et al., 2010) 3.0, using the JTT amino acid substitution model and a  
1618 predicted gamma distribution. Branch support was tested using a Shimodaira-Hasegawa-like  
1619 approximate likelihood ratio test (SH-like aLRT). The generated unrooted trees were visualised  
1620 using MEGA 6.0.

1621 MADS box sequences were identified using the aforementioned domain-based rule set to  
1622 distinguish the TAPs (Lang et al., 2010). Phylogenies were calculated with MrBayes  
1623 (Huelsenbeck and Ronquist, 2001) applying mixed AA model for 50,000,000 generations based  
1624 on an amino acid alignment of Type I and Type II MADS-domain proteins from a broad set of  
1625 land plants together with MADS-domain proteins from charophytes. Sequences were aligned  
1626 with MAFFT (Kato and Standley, 2013) applying E-INS-i mode. Intron structure was  
1627 determined by using the transcript sequence as query for BLAST searches against the genome  
1628 scaffolds. Subsequently, the genomic region that harbors the gene was extracted and aligned to  
1629 the transcript sequence.

#### 1630 ***Motor proteins***

1631 PFAM domains related to the three classes of motor proteins were retrieved from the whole  
1632 predicted proteomes of *C. braunii*, *C. reinhardtii*, *P. patens*, and *A. thaliana* using Interproscan  
1633 (Table S1S). These selected domain signatures not only include the true motors but also  
1634 domains associated with the tasks the motors have to fulfill in a cell. Since motor proteins are  
1635 comparably long gene prediction on draft genomes can lead to a slight overestimation of domain  
1636 numbers. Thus, retrieved predicted gene structures were examined, whether they reside adjacent  
1637 to another predicted gene encoding for a motor protein part. If the domain structures from  
1638 known complete proteins conformed with a fusion of two or more adjacent gene models in *C.*  
1639 *braunii*, we used this fused gene model for further analysis.

#### 1640 ***Action potential related ion channels and transport proteins***

1641 Ion channels, transporters and pumps predicted to be involved in electrical signaling in plants  
1642 were identified in the *C. braunii* genome via a tBLASTn/BLASTp approach using *A. thaliana*  
1643 sequences as bait as well as on the basis of PFAM domains. Subsequent BLASTp searches of  
1644 retrieved sequences against TAIR10 (<https://www.arabidopsis.org>) and SWISSPROT were  
1645 employed to identify closest homologs. Finally, sequences were classified into respective  
1646 transporter families according to TCDB (Saier et al., 2016) and ARAMEMNON (Schwacke et  
1647 al., 2003) (Table S1R). When partially split models were found, they were manually annotated  
1648 with reference to RNA-seq evidence through a genome browser at [https://chara.asrc.kanazawa-](https://chara.asrc.kanazawa-u.ac.jp/Cbr1/jbrowse/)  
1649 [u.ac.jp/Cbr1/jbrowse/](https://chara.asrc.kanazawa-u.ac.jp/Cbr1/jbrowse/).

1650

#### 1651 ***LysM-RLKs***

1652 The *C. braunii* genome was screened for LysM-RLK genes via tBLASTn using Medicago NFP  
1653 and Rice CERK1 as bait sequences (Table S1V). Hits with E-value < 10<sup>-30</sup> were collected and  
1654 deduplicated. These sequences were aligned using MAFFT (Kato and Standley, 2013) with  
1655 LysM-RLKs from embryophytes and *Nitella mirabilis*. Using MEGA 6.0 the best substitution  
1656 model (JTT+G) was determined and a maximum likelihood tree was inferred using all sites and  
1657 100 bootstrap resamplings (Fig. 5C, Data S1L-N).

#### 1658 ***PPR proteins***

1659 Genomic protein sets were scanned for presence of the PFAM domain PPR  
1660 (<http://pfam.xfam.org/family/PF01535>) using HMMscan. The number of proteins harboring  
1661 two or more PPR domains were considered PPR proteins putatively involved in organellar RNA  
1662 editing (Maier et al., 2008) and are shown in Table S1Y.

#### 1663 **ROS-associated genes**

1664 21 families belonging to the well-known reactive oxygen species (ROS) gene network were  
1665 searched using as a first screen the following PFAM. PF00141 for Class III Prx (CIII) and  
1666 Ascorbate Prx (APx and APx-R), PF00199 and PF06628 for catalases (Kat), PF00255 for  
1667 glutathione Prx (GPx), PF00578 and PF08534 for peroxiredoxin family, PF03098 for  
1668 dioxygenase (DiOx), PF08022, PF01794, PF08030 and PF08414 for NADPH Oxidase (RBOH)  
1669 and Ferric reduction oxidase (FRO), PF02777 and PF00080 for superoxide dismutase family  
1670 (MnSOD, FeSOD, Cu/ZnSOD), PF00462 for Glutaredoxins superfamily, PF01786 for  
1671 Alternative Oxidase (AOX and PTOX), PF02298 for Blue-copper-binding protein superfamily,  
1672 PF00210 for ferritin (FER), PF13417 for dehydroascorbate reductase (DHAR), PF07992 and  
1673 PF02852 for Monodehydroascorbate reductase (MDAR) and Glutathione reductase (GR),  
1674 PF07992, PF02943 and PF00085 for thioredoxin superfamily and PF01070 Glycolate Oxidases  
1675 (GOx). *Arabidopsis* sequences belonging to the “ROS gene network” have been used to confirm  
1676 the *C. braunii* families affiliation.

1677 Only alpha-DiOxygenase (DiOx) and APx-R were not detected in the *C. braunii* assembly. The  
1678 19 other families have been found in *C. braunii* with various conservation rates (Table S1X).  
1679 Among these families, Class III peroxidases (Prx), described as secreted peroxidases, are  
1680 usually members of a large family. The *C. braunii* genome contained 14 homologous sequences  
1681 (Table S1X), which is much lower as compared with flowering plants (73 in *A. thaliana*) but  
1682 higher than in *K. nitens* (3). All the 14 sequences are derived from a single gene in an ancestor  
1683 of *C. braunii* as they form a presumably monophyletic clade (Data S1O). Before these  
1684 duplication events only one or a few initial sequences may have existed, implied by the single  
1685 sequence detected in *Chlorokybus atmophyticus* transcriptome data (Timme et al., 2012) and  
1686 the low number of three sequences found in *K. nitens*. The CIII Prx protein sequences from *K.*  
1687 *nitens* (3 sequences), *C. braunii* (14 sequences), *P. patens* (57 sequences) and *A. thaliana* (73  
1688 sequences) were aligned using MAFFT and the tree constructed using Maximum Likelihood  
1689 implemented in MEGA (Data S1O).

#### 1690 **UBQ proteasome system (UPS)**

1691 *Arabidopsis* genes encoding components of the plant Ubiquitin proteasome system (UPS) were  
1692 manually selected and used as query sequences in a tBLASTn analysis to identify respective  
1693 orthologous genes in the *C. braunii* genome. Hits with E-values  $< 10^{-10}$  were collected and  
1694 annotated following a reciprocal best BLASTp approach using TAIR10 (Table S1I).

1695

#### 1696 **QUANTIFICATION AND STATISTICAL ANALYSES**

1697 All details of the applied statistics (e.g. for RNAseq-based differential gene expression analysis)  
1698 are provided alongside the respective analysis in the Methods Details section. For the  
1699 differential gene expression analysis between antheridia, oogonia, and zygotes, three true

1700 biological replicates were sequenced and used for the statistical analysis (computed using  
1701 DESeq2). No sequencing points, i.e. samples, were removed during the analysis.

1702

### 1703 **DATA AND SOFTWARE AVAILABILITY**

1704 Raw Illumina (DRA004353, DRA006568) and PacBio (DRA006569) genomic sequence data  
1705 have been deposited in the DDBJ Sequence Read Archive (DRA) at the DNA Data Bank of  
1706 Japan (DDBJ) under BioProject PRJDB3348. The main scaffolds are available as entries  
1707 BFEA01000001-BFEA01011654, the accompanying organisms scaffolds as BFBZ01000001-  
1708 BFBZ01016437. The chloroplast genome is available as AP018555, the mitochondrial as  
1709 AP018556. Raw Illumina RNA-seq data used for annotation (DRA006080, DRA002641) have  
1710 been deposited in the DRA at the DDBJ under BioProject PRJDB3228. Raw Illumina RNA-  
1711 seq data of reproductive stages have been deposited to NCBI SRA (PRJNA445548). The  
1712 genome and its annotation is available for human curation *via* the ORCAE interface at the [URL:](http://bioinformatics.psb.ugent.be/orcae/)  
1713 <http://bioinformatics.psb.ugent.be/orcae/>. The data is freely available for browsing as well as  
1714 for bulk downloads and blast searches. Persons who would like to contribute and edit the data  
1715 using the web interface will have to request an account by sending an email. Any change made  
1716 to gene structures will be processed automatically by adding protein domains (running interpro)  
1717 and best-blast hits. These changes will be shared with the community immediately. 69,969 ABI  
1718 reads of a cDNA library (minimum length of 100 bp) have been deposited at the DDBJ under  
1719 the accession numbers LU106825 to LU176793 (Table S1D). Alignments that are the basis for  
1720 the phylogenetic trees as well as the genome comparison datasets resulting in Fig. 3 have been  
1721 deposited as Mendeley Datasets (doi:10.17632/9hzzf9m4kh.1).

1722

1723

1724



1725 **Supplemental Tables and Files**

1726

1727 The supplemental/supporting information is arranged into:

- 1728 • a PDF containing Figures S1-S7;
- 1729 • a PDF containing phylogenetic trees and alignments Data S1A-U;
- 1730 • five Excel spreadsheets containing Tables S1-5 (with indexing of sheets);
- 1731 • alignments and supporting data for the genome comparisons (related to Fig. 3) in  
1732 Mendeley (doi:10.17632/9hzzf9m4kh.1).

1733

1734 **Supplemental Tables**

1735 **Table S1, related to STAR methods: details of assembly, annotation and comparative**  
1736 **analyses, with index in first sheet.**

1737 Table S1A: Genome libraries and accession numbers

1738 Table S1B: Libraries used for assembly

1739 Table S1C: Cell division

1740 Table S1D: EST data deposited in DDBJ

1741 Table S1E: RNA-seq used for annotation

1742 Table S1F: Repeatmasker results

1743 Table S1G: Repetitive elements

1744 Table S1H: Cell wall biosynthesis

1745 Table S1I: UBQ proteasome system

1746 Table S1J: Phytohormones

1747 Table S1K: Auxin signaling and transport

1748 Table S1L: Genome comparison

1749 Table S1M: Photorespiratory pathway

1750 Table S1N: PAP localization prediction

1751 Table S1O: bHLH and HD TFs comparison

1752 Table S1P: bHLH and HD TFs *C. braunii*

1753 Table S1Q: Transcription factors and transcriptional regulators

1754 Table S1R: Ion channels

1755 Table S1S: Motor proteins

1756 Table S1T: Assembled bacterial genomes

1757 Table S1U: Most abundant bacterial genera

1758 Table S1V: LysM RLKs  
1759 Table S1W: Reproductive transcriptome  
1760 Table S1X: ROS network  
1761 Table S1Y: PPR proteins  
1762 Table S1Z: Transcription factors and transcriptional regulators gene Ids  
1763 Table S1AA: genome and transcriptome datasets used for comparative studies  
1764  
1765 **Table S2, related to Fig. 5/6 and STAR methods: Differential gene expression analyses of**  
1766 **reproductive stages, with index in first sheet.**  
1767 Table S2A: zygote versus oogonia  
1768 Table S2B: oogonia versus antheridia  
1769  
1770 **Table S3, related to Fig. 5/6 and STAR methods: Gene Ontology analyses of the**  
1771 **differential expression data in Table S2, with index in first sheet.**  
1772 Table S3A: zygote versus oogonia up GO enrichment  
1773 Table S3B: zygote versus oogonia up genes  
1774 Table S3C: zygote versus oogonia down GO enrichment  
1775 Table S3D: zygote versus oogonia down genes  
1776 Table S3E: oogonia versus antheridia up GO enrichment  
1777 Table S3F: oogonia versus antheridia up genes  
1778 Table S3G: oogonia versus antheridia down GO enrichment  
1779 Table S3H: oogonia versus antheridia down genes  
1780  
1781 **Table S4, related to Fig. 5/6 and STAR methods: *C. braunii* protein coding gene annotation**  
1782 **(Gene Ontology, best blast hits, trihelix TFs, expression data, overlap with TE evidence,**  
1783 **decontamination).**  
1784  
1785 **Table S5, related to STAR methods: Decontamination analyses.**  
1786 S5A summary  
1787 S5B underlying data  
1788  
1789 **Data S1, related to STAR methods: phylogenetic trees and alignments.**  
1790