RESEARCH ARTICLE

Conserved cobalamin acquisition protein 1 is essential for vitamin B_{12} uptake in both *Chlamydomonas* and *Phaeodactylum*

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Short title: Identification of a B_{12} uptake protein in algae

One sentence summary: Knockout mutants and physiological studies demonstrate that vitamin B_{12} uptake in both *Chlamydomonas reinhardtii* and the unrelated *Phaeodactylum tricornutum* requires cobalamin acquisition protein 1.

Keywords: cobalamin, *Chlamydomonas reinhardtii*, *Phaeodactylum tricornutum*, insertional mutagenesis, CLiP mutants, CRISPR-Cas9, riboswitch

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Abstract

Microalgae play an essential role in global net primary productivity and global biogeochemical cycling. Despite their phototrophic lifestyle, over half of algal species depend for growth on acquiring an external supply of the corrinoid vitamin B_{12} (cobalamin), a micronutrient produced only by a subset of prokaryotic organisms. Previous studies have identified protein components involved in vitamin B_{12} uptake in bacterial species and humans. However, little is known about its uptake in algae. Here, we demonstrate the essential role of a protein, cobalamin acquisition protein 1 (CBA1), in B_{12} uptake in *Phaeodactylum tricornutum* using CRISPR-Cas9 to generate targeted knockouts and in *Chlamydomonas reinhardtii* by insertional mutagenesis. In both cases, CBA1 knockout lines could not take up exogenous vitamin B_{12}. Complementation of the *C. reinhardtii* mutants with the wild-type *CBA1* gene restored B_{12} uptake, and regulation of *CBA1* expression via a riboswitch element enabled control of the phenotype. When visualised by confocal microscopy, a YFP-fusion with *C. reinhardtii* CBA1 showed association with membranes. Bioinformatics analysis found that CBA1-like sequences are present in all major eukaryotic phyla. In algal taxa, the majority that encoded CBA1 also had genes for B_{12}-dependent enzymes, suggesting CBA1 plays a conserved role. Our results thus provide insight into the molecular basis of algal B_{12} acquisition, a process that likely underpins many interactions in aquatic microbial communities.

INTRODUCTION

Microalgae are a diverse group of eukaryotic organisms that thrive in all aquatic environments. They form the basis of most aquatic food chains and are major contributors to global primary productivity, with marine microalgae responsible for an estimated 30% of total carbon fixation (Field et al., 1998). Understanding the drivers that support algal growth is thus of considerable ecological importance. Despite their photoautotrophic lifestyle, a widespread trait in algae is dependence on an external source of an organic micronutrient, vitamin B_{12} (cobalamin), a complex cobalt-containing corrinoid molecule. Approximately half of algal species surveyed across the eukaryotic tree of life require B_{12} for growth (Croft et al., 2005). However, the proportion of B_{12}-dependent species differs between algal groups, from 30% (n=148) of Chlorophytes to 96% (n=27) of algal species that participate in harmful algal blooms (Tang et al., 2010). Within algal lineages, there is no evidence that any can produce B_{12} *de novo*, so this auxotrophy is not due to loss of one or more biosynthetic genes. Rather, the requirement for B_{12} stems from the fact that it is an essential cofactor for methionine synthase (METH), and species that can grow without supplementation have an alternative, B_{12}-independent, isoform of this enzyme called METE (Croft et al., 2005; Helliwell et al., 2011). Many microalgae, including the green alga *Chlamydomonas reinhardtii* and the unrelated diatom *Phaeodactylum tricornutum*, encode both forms of methionine synthase and utilise METE in the absence of exogenous B_{12}, but take up and utilise the compound if it becomes available (Helliwell et al., 2011). Under those conditions, the expression of *METE*, which has been found to have a lower catalytic rate than METH (Gonzalez et al. 1992), is repressed, and cells rely on METH activity.

The biosynthetic pathway for B_{12} is confined to prokaryotes (Warren et al., 2002) and indeed only a subset of bacteria encode the entire set of 20 or so enzymes required to synthesise corrinoids from the common tetrapyrrole precursor (Shelton et al., 2019), with many eubacterial species also reliant on an external source. In some cases, this is due to the loss of one or a few enzymes of the biosynthetic pathway, but in many bacteria the pathway is absent altogether and auxotrophy is the consequence of relying on one or more B_{12}-dependent enzymes, such as METH. In microalgae, supplementation of cultures of *P. tricornutum* with B_{12} increases its growth rate subtly (Bertrand et al., 2012) and in *C.*

reinhardtii use of METH confers thermal tolerance (Xie et al., 2013). More direct evidence for a selective advantage is demonstrated by the fact that an experimentally-evolved *metE* mutant of *C. reinhardtii* predominates in mixed populations with wild-type cells over tens of cell generations, as long as B_{12} is included in the medium (Helliwell et al., 2015). This is despite the fact that in the absence of B_{12}, the *metE* mutant is non-viable within a few days (Bunbury et al., 2020).

The minimum levels of B_{12} in the medium needed to support growth of laboratory cultures of algal B_{12}-auxotrophs are in the range of 10-50 pM (Croft et al., 2005), whereas B_{12} concentrations have been reported to be just 5-13 pM in freshwater systems (Ohwada, 1973). A similar value of 6.2 pM is the average value in most marine environments, although up to 87 pM could be detected in some coastal waters (Sañudo-Wilhelmy et al., 2014), which may be linked to the higher cobalt concentrations measured there (Panzeca et al., 2009). Given the limiting levels of B_{12} in the environment, its relatively short half-life (in the order of days) in surface water (Carlucci et al., 2007; Sañudo-Wilhelmy et al., 2014), and that as a large polar molecule it is unlikely to simply diffuse across cellular membranes, it is clear that algae must have an efficient means to take up B_{12}. In bacteria, the molecular mechanisms for B_{12} uptake have been extensively characterised. The B_{12} transport and utilisation (*btu*) operon is perhaps the best known (Kadner, 1990), comprising BtuB, a TonB-dependent transporter in the outer membrane, a B_{12}-binding protein, BtuF, located in the periplasm, and BtuC and BtuD, components of an ATP-binding cassette (ABC) transporter that sits in the inner membrane (Borths et al., 2002). In mammals, dietary B_{12} is bound to intrinsic factor in the ileum and taken up from the gut via receptor-mediated endocytosis (Nielsen et al., 2012). It is then transported between and within cells via multiple B_{12} transport proteins (Banerjee et al., 2021; Choi and Ford, 2021). These include lipocalin-1 interacting membrane receptor domain-containing protein 1 (LMBD1), ATP-binding cassette subfamily D member 4 (ABCD4), the latter being an integral membrane ABC transporter in the lysosomal membrane of gut epithelial cells, which facilitates delivery of B_{12} into the cytosol, and multidrug resistant protein 1 (MRP1, also known as ABCC1), another ABC transporter that has sequence similarity to BtuCD and is involved in export of free B_{12} into the plasma where it binds to the main B_{12} transport protein, transcobalamin (Beedholm-Ebsen et

al., 2010). Mice *mrp1* mutants were still able to transport a small amount of cobalamin out of cells, indicating redundant mechanisms for this function that have not yet been identified. Cobalamin circulating in the plasma bound to transcobalamin can then be taken up by other cells via receptor-mediated endocytosis (Nielsen et al., 2012).

In contrast to these well-studied processes in bacteria and mammals, the understanding of B_{12} acquisition in microalgae is more limited. A survey of microalgal species, including marine and freshwater taxa and those that require B_{12} (for example *Euglena gracilis, Thalassiosira pseudonana*) and non-requirers (such as *P. tricornutum, Dunaliella primolecta*), found that many released a 'B_{12}-binder' into the medium, likely a protein, that appeared to sequester B_{12} from solution and thereby inhibited growth of B_{12}-dependent algae (Pintner and Altmeyer, 1979). Its role was unknown, but it was postulated that it might be involved in competition for resources between microalgal species in the environment. Subsequently, a protein was purified from the medium of cultures of *T. pseudonana* with a high affinity binding constant of 2 pM for B_{12} (Sahni et al., 2001). In its native state it was an oligomer of >400 kDa, with subunits of ~80 kDa and the amino acid profile was determined, but it was not possible to obtain sufficient amounts to characterise further. A different approach was taken by Bertrand et al. (2012), who conducted a transcriptomics and proteomics study of *P. tricornutum* and *T. pseudonana* grown under low or sufficient B_{12} conditions. This led to the identification of a gene highly upregulated at the transcript and protein level in the absence of B_{12}. Overexpression of this protein in *P. tricornutum* resulted in an increase in the rate of B_{12} uptake, and the protein was named CoBalamin Acquisition protein 1 (CBA1) although no direct role was established. In this study we have taken a mutagenesis approach to identify genes responsible for B_{12} uptake in both *P. tricornutum* and *C. reinhardtii*, including extending the work on CBA1. In addition, we have determined the extent to which candidate proteins are conserved throughout the algal lineages, making use of recent increases in algal sequencing data.

RESULTS

P. tricornutum CBA1 knockout lines do not take up B_{12}

Previous work showed that overexpression of CBA1 in *P. tricornutum* conferred enhanced B_{12} uptake rates (Bertrand et al., 2012) but the study did not demonstrate whether it was essential for this process. To address this question, *CBA1* knockout lines were generated in *P. tricornutum* strain 1055/1 (Supplemental Table S1) by CRISPR-Cas9 editing, using a homologous recombination repair template that included a nourseothricin resistance (*NAT*) cassette (Figure 1a). CRISPR-Cas9 lines were cultured on selective media and screened for the absence of WT alleles at the *PtCBA1* locus (Phatr3_J48322) using PCR (Figure 1b). When the *PtCBA1* gene was amplified (top panel, Figure 1b) from ΔCBA1-1 with primers flanking the homologous recombination regions, two bands were detected; the larger of these corresponded to the WT amplicon, whilst the smaller band corresponded to a replacement of *CBA1* by *NAT*, suggesting that this strain is a mono-allelic knockout. For ΔCBA1-2, the *PtCBA1* gene primers amplified a single smaller product, suggesting that this was a bi-allelic knockout, whereas the *PtCBA1* ORF primers (bottom panel of Figure 1b) did not amplify anything, indicating a disruption specifically in this region. Similarly, no band was detected with primers that amplify across the 5' end of the NAT knock-in (HR primers), which might indicate further disruptions upstream of the 5'HR region of ΔCBA1-2. Although a larger band than for WT was amplified in ΔCBA1-3 using the *PtCBA1* gene primers, those for the *PtCBA1* ORF amplified a smaller product; in both cases a single band was observed indicating a bi-allelic deletion at the sgRNA target sites.

To test whether the ΔCBA1 lines were affected in their ability to take up vitamin B_{12} we developed a standardised B_{12}-uptake assay, detailed in Materials and Methods. In brief, algal cells were grown to the same growth stage and adjusted to the same cell density, then incubated in media containing a known amount of cyanocobalamin for one hour. Thereafter, cells were pelleted by centrifugation and the amount of B_{12} determined in the cell pellet and the media fraction using a *Salmonella typhimurium* bioassay (Bunbury et al., 2020). For each sample, the B_{12} measured in the cellular and media fractions were added to provide an estimated 'Total' and compared to the amount of B_{12} added initially (Figure

1c, dashed line), to determine the extent of recovery. For the WT strain, most of the added B_{12} was found in the cellular fraction. The mono-allelic knockout line ΔCBA1-1 consistently showed ~20-30% B_{12} uptake relative to the WT strain. This suggested that a single copy of *PtCBA1* is sufficient to confer B_{12} uptake in *P. tricornutum*, but not to the same extent as the WT strain. In contrast, for the two bi-allelic knockout lines (ΔCBA1-2 and ΔCBA1-3) no B_{12} was detected in the cellular fraction in any experiment, indicating that vitamin B_{12} uptake was fully impaired in the absence of a functional *PtCBA1* copy, at least at the limit of detection of the B_{12} bioassay (of the order of 10 pg). These results expand our understanding of *PtCBA1* by demonstrating that its presence is essential for B_{12} uptake and indicates that there is no functional redundancy to *PtCBA1*.

Insertional mutagenesis identified the *C. reinhardtii* homologue of *CBA1*

Bertrand et al. (2012) reported that there were no detectable *CBA1* homologues in algal lineages outside the Stramenopiles, so to investigate B_{12} uptake in *C. reinhardtii*, we decided to take an insertional mutagenesis approach. We took advantage of the fact that B_{12} represses expression of the *METE* gene at the transcriptional level via the promoter (P_{METE}), and that reporter genes driven by this genetic element respond similarly (Helliwell et al., 2014), to develop a highly sensitive screen for lines no longer able to respond to B_{12}. We hypothesised that, since P_{METE} is likely to respond specifically to intracellular B_{12}, P_{METE} would not be repressed in strains unable to take up B_{12} from the media, so the reporter would be expressed and functional. If the reporter were an antibiotic resistance gene, this would allow identification of B_{12} uptake mutants in a more high-throughput manner than the B_{12}-uptake assay. The background strain for insertional mutagenesis was made by transforming *C. reinhardtii* strain UVM4 (Neupert et al., 2009) with plasmid pAS_R1 containing a paromomycin resistance gene (*aphVIII*) under control of P_{METE} (Figure 2a, top construct; Supplemental Table S2). Lines of this strain were tested for their responsiveness to B_{12} and paromomycin. One line, UVM4-T12, showed the appropriate sensitivity with increasing repression of growth in paromomycin as B_{12} concentrations were increased, the effect being more marked at 15-20 $\mu g \cdot ml^{-1}$ paromomycin than at 5-10 $\mu g \cdot ml^{-1}$ (Figure 2b). This line thus allowed for an easily quantifiable growth phenotype that was proportionally related to B_{12} concentration.

Insertional mutagenesis was carried out by transforming UVM4-T12 with a plasmid (pHyg3) containing a hygromycin resistance gene (*aphVII)* under the control of the constitutively expressed β2-tubulin promoter (Figure 2a, bottom construct), generating a population of UVM4-T12::pHyg3 lines with the cassette randomly inserted into the nuclear genome. By plating the products of the transformation on solid TAP media supplemented with a range of paromomycin, hygromycin and vitamin B_{12} concentrations (see Methods), 7 colonies were obtained. This was estimated to be from approximately 5000 primary transformants, determined by plating the same volume on TAP plates with the antibiotics but without B_{12}. These 7 putative insertional mutant (IM) lines were then assessed for their ability to take up B_{12} using the B_{12} uptake assay. For UVM4, UVM4-T12 and insertional lines from the plate without B_{12} (labelled Control 1-3), similar amounts of B_{12} were recovered from the cellular and media fractions (Supplemental Figure S1). This was also the case for 6 of the IM lines, suggesting that they could still take up B_{12} and were likely false positives of the initial screen. However, no B_{12} could be detected in the cellular fraction of UVM4-T12::pHyg3 #IM4 (hereafter referred to as IM4), indicating that this mutant line did not take up B_{12}.

To obtain independent corroboration that IM4 was impaired in B_{12} uptake, cells of this mutagenized line were incubated with a fluorescently-labelled B_{12} derivative, B_{12}-BODIPY (Lawrence et al., 2018), and then imaged using confocal microscopy. *C. reinhardtii* cells were incubated in TAP medium without B_{12}-BODIPY or with 1 µM B_{12}-BODIPY for 1 hour, washed with fresh media and subsequently imaged. There was no signal detected in the channel used for B_{12}-BODIPY (589 nm excitation; 607-620 nm detection) in samples without B_{12}-BODIPY added (Supplemental Figure S2, top two rows), indicating that the imaging protocol was specific to this compound. When B_{12}-BODIPY was added, UVM4-T12 showed the B_{12}-BODIPY signal located within the algal cell (Supplemental Figure S2, third row), indicating that this signal could be effectively detected by the imaging protocol and that B_{12}-BODIPY was being transported into the cells. In contrast, there was no B_{12}-BODIPY signal in IM4 cells, supporting the hypothesis that B_{12} uptake was impaired in this mutant (Supplemental Figure S2, bottom row). In addition, the response of the *METE* gene to B_{12} in

IM4 was assessed by RT-qPCR. UVM4 and IM4 cultures were grown in media with or without addition of B_{12} for 4 days in continuous light, after which the cultures were harvested for RNA extraction and cDNA synthesis. As expected, *METE* was repressed in UVM4 in the presence of B_{12} compared to no supplementation (Figure 3a), whereas IM4 showed similar *METE* expression in both conditions. This provided further support for disrupted B_{12} uptake in this line.

To identify the genomic location of the causal mutation in IM4, short-read whole genome sequencing was performed on DNA samples from UVM4, UVM4-T12 and IM4. The location of the pHyg3 cassette in IM4 was identified as described in Methods and found to have disrupted the *Cre12.g508644* locus (Supplemental Figure S3a), an unannotated gene. To corroborate that disruption of the *Cre12.g508644* was responsible for the uptake-phenotype, two independent mutant lines of the gene (LMJ-119922 and LMJ-042227) were ordered from the Chlamydomonas library project (CLiP) collection (Li et al., 2016) and verified to be disrupted at this locus by PCR (Supplemental Figure S3a). However, when these knockout lines were tested for the ability to take up B_{12} using the B_{12} uptake assay, they were both found to be able to do so to a similar extent as their parental strain, cw15 (Figure S3b). This suggested that *Cre12.g508644* did not encode a protein essential for B_{12} uptake.

We therefore examined the genome sequence data more closely to determine the genetic cause for the B_{12}-uptake phenotype of IM4. We had identified putative homologues of human proteins involved in receptor-mediated endocytosis of B_{12}, such as ABCD4, LMBD1 (Rutsch et al., 2009; Coelho et al., 2012) and MRP1 (Beedholm-Ebsen et al., 2010), in the *C. reinhardtii* genome by BLAST. However, given the widespread percentage of SNPs in the IM4 genome compared to UVM4, it was not possible to identify any candidate causal mutations with confidence. Instead, manual inspection of the DNA sequencing reads mapped to the reference strain revealed one locus, *Cre02.g081050,* annotated as flagella-associated protein 24 (FAP24), where there was a unique discontinuity, suggesting that there was an insertion at exon 2 in IM4 (Figure 3b; Supplemental Figure S4a). The sequence was bordered by a genome duplication of 8 bp (shown in blue in Figure S4a) and exhibited imperfect inverted repeats at the terminal regions (TIRs), indicative of a transposable element. Reads could not be

assembled across the discontinuity to obtain the complete sequence of the insertion, but using the left and right junction sequences as queries, three regions encoding two very similar genes were identified (Supplemental Figure S4b).

Remarkably, when the *Cre02.g081050* protein was used as a query in a BLAST search, one of the hits recovered was the PtCBA1 protein (22.9% sequence identity), even though the reciprocal sequence search had not picked up the *C. reinhardtii* gene (Bertrand et al., 2012). Predicted 3D structures of PtCBA1 and the *C. reinhardtii* protein encoded by *Cre02.g081050* were obtained from the AlphaFold2 protein structure database and overlaid (Supplemental Figure S5). The modelled proteins showed a high degree of structural similarity to one another (root mean squared deviation (RMSD) = 1.688), particularly with respect to the arrangement of alpha helices and a lower cleft. Due to the sequence similarity and predicted structural similarity, these proteins appeared to be homologous to one another and Cre02.g081050 is hereafter referred to as CrCBA1.

To determine whether disruption of *CrCBA1* in IM4 was responsible for the impaired B_{12} uptake, we investigated whether it was possible to restore its ability to take up B_{12} by transforming IM4 with the wild-type *CrCBA1*. Construct pAS_C2 was designed with the *CrCBA1* promoter, *CrCBA1* open reading frame (ORF) and terminator and included a 3' mVenus tag attached by a poly-glycine linker (Figure 3c). IM4 was transformed with pAS_C2, and resulting lines were tested for the ability to take up B_{12} using the B_{12} uptake assay. As observed previously, UVM4 was able to take up B_{12} whilst IM4 was unable to do so (Figure 3d). The CBA1 complementation line IM4::pAS_C2 showed B_{12} in the cellular fraction at similar levels as in UVM4, thereby indicating that the mutant phenotype had been complemented.

CrCBA1 CLiP mutant is unable to take up B_{12} and is complemented by the WT _CrCBA1_ gene

Given the many genetic changes in line IM4 compared to the parental UVM4-T12 strain caused by the mutagenesis, it was essential to have independent corroboration that mutation of *CrCBA1* caused the inability to take up B_{12}. Accordingly, we obtained two further CLiP mutants (LMJ-135929 and

LMJ-040682) with disruptions in intron 2 and introns 6/7 respectively of *CrCBA1* (Supplemental Figure S6a) and assessed them for their ability to take up B_{12} (Supplemental Figure S6b). No B_{12} was detected in cells of LMJ-040682, indicating complete inhibition of B_{12} uptake. Although LMJ-135929 cells accumulated some B_{12}, this was less than half the amount of its parent strain cw15, suggesting partial impairment in uptake, similar to the phenotype of the monoallelic *PtCBA1* knockout line (Figure 1c). However, heterozygosity cannot be the explanation for *C. reinhardtii*, which is haploid, and instead indicates that LMJ-135929 was likely to have just partial knockdown of the gene, probably because the insertion is in an intron.

Nonetheless, to provide further confirmation that mutations in *CrCBA1* were responsible for the observed impaired B_{12} uptake, we again tested whether the phenotype could be complemented with the wild-type *CrCBA1* gene using both plasmid pAS_C2 (Figure 3b) and an additional construct pAS_C3 (Figure 4a), in which expression of *CrCBA1* can be controlled by a thiamine pyrophosphate (TPP) repressible riboswitch, RS_{THI4_4N} (Mehrshahi et al., 2020). In the absence of thiamine supplementation of the cultures, the riboswitch is not active and the gene containing it is transcribed and translated as normal; with thiamine addition, alternative splice sites are utilised, leading to inclusion of an upstream ORF containing a stop codon in the mRNA, preventing translation from the downstream start codon. LMJ-040682 was transformed with both pAS_C2 and pAS_C3, and representative transformant lines selected via antibiotic resistance were obtained. These, together with their parental strains were grown in the presence or absence of 10 µM thiamine for 5 days, and then used in the B_{12} uptake assay. Transformants of both LMJ-040682::pAS_C2 and LMJ-040682::pAS_C3 were found to take up B_{12} to a similar extent as their parental strain cw15 when grown in the absence of thiamine (Figure 4b). However, when 10 µM thiamine was included in the culture medium, LMJ-040682::pAS_C3 showed virtually no B_{12} uptake. This riboswitch-mediated conditional complementation of the phenotype in LMJ-040682::pAS_C3 demonstrated conclusively that B_{12} uptake in *C. reinhardtii* is dependent on the presence of CrCBA1.

CrCBA1 shows an association with membranes and is highly upregulated under B_{12}-deprivation

To investigate the subcellular location of CrCBA1, we used several bioinformatic targeting prediction tools. CrCBA1 is annotated as a flagella-associated protein in the Phytozome v5.6 *C. reinhardtii* annotation. However, both DeepLoc (Almagro Armenteros et al., 2017) and SignalP (Almagro Armenteros et al., 2019), as well as AlphaFold2, indicated a hydrophobic sequence with the characteristics of a signal peptide at the N-terminus of CrCBA1 and predicted it would be targeted to the endoplasmic reticulum (ER). Additionally, it was predicted to contain a transmembrane helix at its C-terminus by InterPro (Mitchell et al., 2019) and AlphaFold2.

We next investigated the subcellular location of CrCBA1 *in vivo* by imaging two lines of LMJ-040682::pAS_C2, where the CBA1 is tagged with mVenus, with confocal microscopy. No mVenus was detected in the parental LMJ-040682 cells, whereas a clear fluorescent signal was observed in LMJ-040682::pAS_C2 #A10 and LMJ-040682::pAS_C2 #D10 (Figure 5). In these complemented lines, the mVenus signal was absent from the chloroplast, nucleus and flagella, but instead could be seen within the cell localising both to the plasma membrane and to regions that may be endomembranes such as the ER. This is consistent with findings from *P. tricornutum* showing a similar distribution (Bertrand et al., 2012). Together these data indicate that CBA1 is likely to be associated with membranes, and therefore, may have a conserved role in the B_{12} uptake process.

Further evidence for the role of CBA1 in B_{12} uptake was obtained by taking advantage of a B_{12}-dependent mutant of *C. reinhardtii*, metE7 (Helliwell et al., 2015; Bunbury et al., 2020). We tested the effect of B_{12}-deprivation over time on the expression of the *CrCBA1* gene by RT-qPCR in the mutant and determined the rate of B_{12} uptake over a similar period. Within 6h of B_{12} removal, there was a ~250-fold induction of the *CrCBA1* transcript, followed by a slow decline over the next 60h (Figure 6a). After resupply of B_{12} there was then a rapid ~100-fold decline within 8h. The B_{12} uptake capacity of metE7 followed a similar profile, increasing 3-fold over the first 12 hours of B_{12} depletion,

from ~6.5 x 10^5 molecules B_{12}/cell/hour to 1.86 x 10^6 molecules B_{12}/cell/hour (Figure 6b), then declining slowly. This induction profile is characteristic of a nutrient-starvation response shown by many transporters, including in *C. reinhardtii* those for Fe (Allen et al., 2007), and for *CBA1* in the B_{12}-dependent diatom, *Thalassiosira pseudonana* (Bertrand et al., 2012).

Widespread distribution of CBA1 in algae

Having shown the importance of *PtCBA1* and *CrCBA1* for B_{12} uptake in their respective species, we re-examined how prevalent CBA1-like proteins are in Nature. Searches with BLASTP using *PtCBA1* were reported to result in no significant hits in species outside the Stramenopiles (Bertrand et al., 2012). Instead, we created a hidden Markov model (HMM), using the *C. reinhardtii* CBA1 amino acid sequence and CBA1 sequences from *P. tricornutum*, *T. pseudonana*, *Fragilariopsis cylindrus*, *Aureococcus anophagefferens* and *Ectocarpus siliculosus* (Bertrand et al., 2012), to identify more accurately CBA1-like proteins in other organisms. The EukProt database of curated eukaryotic genomes (Richter et al. 2022) includes representatives from the Archaeplastida (designated by EukProt as Chloroplastida), which encompass green algae, red algae, glaucophytes and all land plants, as well as phyla that include algae with complex plastids, namely Stramenopiles (which include diatoms), Alveolata (including dinoflagellates), Rhizaria and Haptophyta, and the animals (both Metazoa and the Choanoflagellates, the closest living relatives of the animals), the fungi and Amoebozoa. This database was queried with the CBA1 HMM model, using a cutoff e-value of 1e-20, and 277 hits were obtained (Supplemental Figure S7; Supplemental Table S4). No candidates were found in the Metazoa, but CBA1 homologues were identified in all other phyla, including all photosynthetic groups, fungi and amoebozoa and in choanoflagellates, unicellular and colonial flagellated organisms considered to be the closest living relatives of animals (King et al., 2008).

Given that vascular plants have no B_{12}-dependent enzymes, the presence of a putative B_{12}-binding protein in several angiosperms, both monocot and dicot, and the gymnosperm *Ginkgo biloba*, was somewhat surprising. To address this conundrum, we investigated to what extent CBA1 was associated with vitamin B_{12} dependence by determining the distribution of the different isoforms of

methionine synthase, METH and METE. Using the same HMM approach as before, the protein sequences were searched against the EukProt database and the combination of presence and absence of CBA1, METH and METE across eukaryotic species groups was compiled (Figure 7; Supplemental Table S5). What is immediately apparent is that the combination of the three proteins is quite different in the various lineages. In the major algal groups, the Chlorophyta and the SAR clade (Stramenopiles, Alveolata and Rhizaria), METH sequences were found in the majority of genomes analysed and their presence was associated with CBA1. In the genomes of the Chlorophyta and the SAR clade that encoded METE only (7 taxa in total), CBA1 was absent in all but one, the diatom *Thalassionema nitzschiodes*. Equal numbers of Alveolata species encoded METH and CBA1, or METH only; interestingly, the latter were all non-photosynthetic lineages. Grouping the data from these 4 algal groups, a Chi Square test was significant for CBA1 and METH being more often both present or both absent (*X2 (1, N = 86) = 9.2, p = 0.00240).* The association could be due to linkage, although in neither *C. reinhardtii* nor *P. tricornutum* are the two genes on the same chromosome, making this unlikely. Alternatively, there is a fitness advantage in both genes being acquired or lost together.

Most fungal taxa lacked both METH and CBA1, but we found examples of 6 species that were predicted to be B_{12} users (METH present) and 5 of these were also predicted to contain CBA1-like sequences: *Allomyces macrogynus, Spizellomyces punctatus, Rhizophagus irregularis, Rhizopus delemar* and *Phycomyces blakesleeanus*. CBA1-like sequences were identified in the Opisthokonta and Amoebozoa, although were less prevalent, with ~23% of choanoflagellates and 8% of amoeboid species being like algae in having both METH and CBA1. CBA1 was entirely absent from the Metazoa. In contrast, in the Streptophyta, which include multicellular green algae and all land plants, the majority lack METH, but almost 80% of species were found to contain CBA1-like sequences. This implies that Streptophyta CBA1 sequences may have gained a different function, which would be consistent with the lack of B_{12}-dependent metabolism in these organisms. In summary, these data suggest that CBA1 is associated with vitamin B_{12} use to different degrees in different eukaryotic groups, with there being a greater association in obligate and facultative B_{12} users than in those organisms that do not utilise B_{12}.

The many putative CBA1 homologues in algal lineages and their strong association with B_{12} uptake provided an opportunity to identify conserved, and thus likely functionally important, residues. Accordingly, a multiple sequence alignment of proteins matching the CBA1 HMM query was generated (Supplemental Figure S7). Highlighted in green in the similarity matrix at the top are nine conserved regions with several almost completely conserved residues; these are shown in more detail in Figure 8a for selected taxa representing different algal groups. Further insight came from inspection of the model of the 3D structure of CrCBA1 generated by the AlphaFold2 protein structure database. The analysis showed that regions of CrCBA1 showed similarity to bacterial periplasmic binding proteins, including the B_{12}-binding protein BtuF. A structure is available of *E. coli* BtuF in complex with B_{12} (Borths et al., 2002), so we compared this to the modelled CrCBA1 structure. Although there is little sequence similarity, alignment of the two structures resulted in an RMSD of 3.362 and enabled the relative position of B_{12} to be placed in the lower cleft of CrCBA1, shown in red in Figure 8b. Mapping of the highly conserved residues onto this structure found that four (W255, W394, F395 and E396) were in a cluster around the relative position of B_{12}. Another cluster of highly conserved residues were located at the end of the upper alpha helix (K78, P118, L136, F214, F215, N216 and E218). Both clusters represent promising mutational targets to investigate CrCBA1 function.

DISCUSSION

In this study we have shown experimentally that a conserved protein, CBA1, is required for the uptake of the micronutrient B_{12} in two taxonomically distant algae, the diatom *P. tricornutum* (Figure 1) and the chlorophyte *C. reinhardtii* (Figures 3 & 4). Strains with knockouts of the gene were unable to take up $B_{12,}$ demonstrating that there is no functional redundancy of this protein in either organism. As well as providing evidence that CBA1 is present outside the Stramenopiles, we found widespread occurrence of CBA1 homologues with considerable sequence conservation across eukaryotic lineages (Figures 7 and Supplemental S7). The strong association of CBA1 with the B_{12}-dependent methionine synthase, METH, in algal lineages, provides evidence that CBA1 is a key component of the B_{12}

uptake process in evolutionarily distinct microalgae, and the structural similarities between CBA1 and BtuF (Figure 8b) suggest it may operate as a B_{12}-binding protein. The highly conserved residues identified in the algal homologues (Figure 8a) offer the means to establish which are functionally important, facilitated by the uptake assay we established.

Nonetheless, the mechanistic role of CBA1 in the process of B_{12} acquisition in algae is not yet clear. Previous physiological studies of B_{12} uptake by microalgae, such as the haptophyte *Diacronema lutheri* (Droop, 1968), indicated a biphasic process: firstly rapid irreversible adsorption of B_{12} to the cell exterior, followed by a slower second step of B_{12} uptake into the cell, consistent with endocytosis. CBA1 is unlikely to be associated with the binding of B_{12} in the cell wall, however. This is because the *C. reinhardtii* strains used in this study, UVM4 and CW15, were cell wall deficient, and therefore likely also deficient in cell wall proteins that bind B_{12}; the lack of a B_{12}-BODIPY signal from the cell surface in IM4 (Supplemental Figure S2) supports this hypothesis. Further use of this fluorescent probe offers the possibility to monitor the localisation of B_{12}-BODIPIY over time to gain insights into the stages of B_{12} uptake, as has been done in other organisms (Lawrence et al., 2018). In addition, confocal microscopy of CBA1-mVenus fusion protein in *C. reinhardtii* (Figure 5) showed an apparent association of CrCBA1 with the plasma membrane and endomembranes, which is similar to that for ER-localised proteins (Mackinder et al., 2017). Moreover, in a proteomics study of lipid droplets (which form by budding from the ER) CBA1 was in the top 20 most abundant proteins (Goold et al., 2016). Bertrand et al. (2012) found that PtCBA1 had a signal peptide and fluorescently tagged PtCBA1 was also targeted to the ER. Nonetheless, based on its predicted 3D structure and the fact that it has at most one transmembrane helix, CBA1 does not appear to be a transporter itself. Instead, given its structural similarity to BtuF, a distinct possibility is that CBA1 is the soluble component of an ABC transporter, either at the plasma membrane or an internal membrane, and likely will interact with one or more other proteins to allow B_{12} uptake to occur, at least some of them being those involved in receptor-mediated endocytosis, as is the case for B_{12} acquisition in humans (Rutsch et al., 2009; Beedholm-Ebsen et al., 2010; Coelho et al., 2012). In this context, there are known similarities between endocytosis in *C. reinhardtii* and humans (Denning and Fulton, 1989; Bykov et al., 2017),

447 and several putative homologues have been identified by sequence similarity in the alga. Testing the
448 B_{12}-uptake capacity of mutants of these proteins would be one approach to investigate whether their
449 roles are also conserved.
450
451 In contrast to the situation in algae, the Streptophyta live in a B_{12}-free world, neither synthesising nor
452 utilising this cofactor. This is exemplified by the fact that in our analysis only one species, the
453 charophyte alga *Cylindrocystis brebissonii*, encoded METH. Despite this, more than three-quarters of
454 this group encode a CBA1 homologue (Figures 7 & S7). Since the majority of the conserved residues
455 (Figure 8a) are also found in putative CBA1 sequences in the angiosperms such as *Arabidopsis*,
456 including those around the potential binding pocket, it is possible that the streptophyte protein has
457 acquired a new function that still binds a tetrapyrrole molecule. Intriguingly, the reverse is observed in
458 the Metazoa, where METH is almost universal, but CBA1 is entirely absent. However, some
459 Choanoflagellates and some species of fungi do appear to encode both METH and CBA1, suggesting
460 that they utilise B_{12}, a trait recognised to occur in fungi only recently (Orłowska et al., 2021). It will
461 be of interest therefore to test whether CBA1 is involved in B_{12} uptake in these organisms, for
462 example by gene knockout studies.
463
464 The importance of B_{12} availability for phytoplankton productivity has been demonstrated across
465 several marine ecosystems by amendment experiments (e.g. Bertrand et al., 2011; Koch et al., 2012;
466 Joglar et al., 2021), where addition of B_{12} led to algal blooms and affected the composition and
467 stability of microbial communities. The mode of acquisition of this micronutrient is thus likely to be
468 highly conserved and subject to substantial ecological and evolutionary selection pressure to be
469 retained. Moreover, the role of B_{12} at the cellular level may well provide a direct connection between
470 environmental conditions and the epigenetic status of the genome: methionine synthase is the key
471 enzyme in C1 metabolism, linking the folate and methylation cycles and thus responsible for
472 maintaining levels of S-adenosylmethionine (SAM) the universal methyl donor (Hanson & Roje
473 2001; Mentch & Locasale, 2016). In this context, it is noteworthy that the knockout of *CBA1* in the
474 IM4 line was the result of insertion of a class II transposable element into the gene. This mobilization

is likely to reflect epigenetic alterations of the autonomous element, presumably as a result of cellular stress either from the antibiotic selection, or the transformation procedure, or both. Recent classification of the transposons in *C. reinhardtii* indicate that the transposon inserted into *CBA1* in IM4 is a member of the KDZ superfamily of class II TIR elements named Kyakuja-3_cRei (Craig et al. 2021). If the phenomenon of inactivation of a gene that is deleterious (in this case allowing B_{12} to be taken up and repress the antibiotic resistance gene) via transposition is a general response in *C. reinhardtii*, repeating the screen for CBA1 mutants might allow observation of further transposition events, and enable characterisation of this group of elements at the functional level. Moreover, it could be adopted as a more general methodology to identify candidate genes involved in other physiological processes, by tying their expected effects to deleterious outcomes through synthetic biology constructs and screening surviving mutants by sequencing.

MATERIALS AND METHODS

Organisms and growth conditions

Strains, media and growth conditions used in this study are listed in Table S1. If required, antibiotics, vitamin B_{12} (cyanocobalamin) and thiamine were added to the medium at concentrations indicated. Algal culture density was measured using a Z2 particle count analyser (Beckman Coulter Ltd.) and optical density (OD) at 730 nm was measured using a FluoStar OPTIMA (BMG labtech) plate reader or a CLARIOstar plate reader (BMG labtech). Bacterial growth was recorded by measuring OD_{595}.

Algal B_{12}-uptake assay

Algal cultures were grown to stationary phase and cyanocobalamin salt (Sigma) was added (*Phaeodactylum tricornutum*: 600 pg; *Chlamydomonas reinhardtii*: 150 pg) to 5 x 10^6 cells in a final volume of 1 ml in f/2 or TAP medium respectively. The samples were incubated at 25°C under continuous light with shaking for 1 hour and inverted every 30 minutes to aid mixing. Samples were centrifuged and the supernatant (media fraction) transferred into a fresh microcentrifuge tube. The cell

pellet was resuspended in 1 ml water. Both samples were boiled for 10-20 minutes to release any cellular or bound B_{12} into solution, and then centrifuged to pellet debris. The supernatant was used in the *S. typhimurium* B_{12} bioassay as described in Bunbury et al. (2020). The amount of B_{12} in the sample was calculated by comparison to a standard curve of known B_{12} concentrations fitted to a 4 parameter logistic equation f(x) = c + (d-c)(1+exp(b(log(x)-log(e)))) (Ritz et al., 2015). This standard curve was regenerated with every bioassay experiment.

Generating *P. tricornutum* CBA1 knockout lines using CRISPR-Cas9

CRISPR/Cas9 genome editing applied the single guide RNA (sgRNA) design strategy described in Hopes et al., (2017). Details are provided in the Supplemental methods. *P. tricornutum CCAP 1055/1* cells were co-transformed with linearised plasmids pMLP2117 and pMLP2127 (Supplemental Table 2) using a NEPA21 Type II electroporator (Nepa Gene) as previously described (Yu et al., 2021). After plating on 1% agar selection plates containing 75 $mg \cdot l^{-1}$ zeocin and incubation for 2-3 weeks, zeocin resistant colonies were picked into 96 well plates containing 200 µl of f/2 media with 75 $mg \cdot l^{-1}$ zeocin. After seven days strains were subcultured into fresh media either containing 75 $mg \cdot l^{-1}$ zeocin or 300 $mg \cdot l^{-1}$ nourseothricin, and genotyped with a three-primer PCR using PHIRE polymerase (Thermo Fisher Scientific) with primers gCBA1.fwd, gCBA1.rv and NAT.rv (Supplemental Table S3). Five promising colonies resistant to nourseothricin and with genotypes showing homologous recombination or indels were re-streaked on 75 $mg \cdot l^{-1}$ zeocin f/2 plates to obtain secondary monoclonal colonies. Twelve secondary colonies were picked for each primary colony after 2-3 weeks and again genotyped with a three-primer PCR. Promising colonies were genotyped in further detail with primer pairs gCBA1.fwd/gCBA1.rv, gCBA1.fwd/NAT.rv and gCBA1in.fwd/gCBA1in.rv (Supplemental Table S3).

Construct assembly and *C. reinhardtii* transformation

Constructs were generated using Golden Gate cloning, using parts from the *Chlamydomonas* MoClo toolkit (Crozet et al., 2018) and some that were created in this work. All parts relating to *Cre02.g081050* were domesticated from UVM4 genomic DNA, with BpiI and BsaI sites removed

from the promoter, ORF and terminator by PCR-based mutagenesis using primers listed in Supplemental Table S3. A list of plasmids used in this study is shown in Supplemental Table S2. Transformation of *C. reinhardtii* cultures with linearised DNA was carried out by electroporation essentially as described by Mehrshahi et al. (2020) before plating on TAP-agar plates with the appropriate antibiotics.

Insertional mutagenesis was performed as above, however, cultures were grown to a density of approximately $1x10^7$ cells/ml and were incubated with 500 ng transgene cassette. After allowing the cells to recover overnight in TAP plus 60 mM sucrose at 25°C in low light (less than 10 µmol photon $m^{-2}.s^{-1}$ at 100 rpm), between 200 - 250 µl of transformants were plated on solid TAP media (square 12x12 cm petri dishes) containing ranges of 15-20 µg/ml hygromycin, 20-50 µg/ml paromomycin and 48-1024 ng/l vitamin B12, and the plates were incubated in standing incubators.

Confocal laser scanning microscopy

C. reinhardtii transformants carrying the pAS_C2 construct were imaged in a confocal laser scanning microscope (TCS SP8, Leica Microsystems, Germany) with an HC PL APO CS2 40x/1.30 aperture oil-immersion lens. Images were taken using the sequential mode provided by the Leica LAS software, with the channel used for mVenus and brightfield detection being taken first and the channel used for chlorophyll detection taken second. The first image was acquired with excitation from a white light source at 486 nm at 7% power and emissions were detected between 520 - 567 nm; mVenus settings included 100% gain, gating between 0-8.24 ns and a reference line at 486 nm. Brightfield imaging used 610% gain and a 0% offset. Frames were captured with a line average of 4 and a frame accumulation of 2. The second image was acquired with excitation from a white light source at 514 nm at 2% power and emissions were detected between 687 - 724 nm with 50% gain. Frames were captured with a line average of 4 and a frame accumulation of 1. The overlay images were produced automatically by the Leica LAS software. Inkscape was used to increase the lightness and decrease the contrast of all the images in the same manner.

559 **Reverse transcription quantitative PCR**

560 Quantification of steady state levels of transcripts was carried out according to Bunbury et al. (2020),
561 using random hexamer primers for cDNA synthesis. The RT-qPCR data was analysed using the
562 ΔΔCT method with an assumed amplification efficiency of 2. Log2(2-ΔCT) values were plotted in the
563 resulting figures.

564

565 **Whole genome sequencing**

566 Genomic DNA was extracted from *C. reinhardtii* cells by phenol-chloroform extraction and
567 sequenced using the NovaSeq sequencing platform by Novogene (Cambridge, UK) to produce 150 bp
568 paired-end reads. This involved RNase treatment and library preparation with the NEBNext Ultra II
569 DNA Library Prep Kit (PCR-free), which generated 350 bp inserts. The raw sequencing data for this
570 study have been deposited in the European Nucleotide Archive (ENA) at EMBL-EBI under accession
571 number PRJEB58730 (https://www.ebi.ac.uk/ena/browser/view/PRJEB58730). Novogene performed
572 all quality filtering, summary statistics and bioinformatic analysis. The location of the Hyg3 cassette
573 was determined by identifying loci that comprised reads from IM4 that mapped between genomic
574 DNA and pHyg3, and cross-referencing these loci against the parental strains. The TE identification
575 was carried out similarly, full details are provided in Supplemental Methods.

576

577 **Bioinformatics pipeline**

578 The EukProt database was assessed for the presence of METE, METH and CBA1 (Richter et al.,
579 2022). The query used for CBA1 was a hidden Markov model (HMM) generated from the protein
580 fasta sequences: Phatr3_J48322, Thaps3 11697, Fracy1 241429, Fracy1 246327, Auran1 63075,
581 Ectocarpus siliculosus D8LMT1 and Cre02.g081050.t1.2 by first aligning using MAFFT (Katoh and
582 Standley, 2013) version 7.470 with the --auto option, and then building a HMM using hmmbuild
583 (hmmer 3.2.1). Additionally, protein fasta (Cre06.g250902, Cre03.g180750), PFAM (PF02310,
584 PF02965, PF00809, PF02574, PF01717, PF08267) and KO (K00548, K00549) queries were searched
585 against EukProt to identify sequences with similarity to METE and METH. The queries were
586 searched against EukProt using hmmsearch (HMMER 3.1b2). The default bitscore thresholds were

used for KO and PFAM queries. The threshold used for CBA1 HMM, and the CrMETE and CrMETH protein fasta sequences, was a full-length e-value of 1e-20. For each protein, all individual queries were required to be significant to classify the protein as present. The best hit in each species was identified by taking the protein with the greatest geometric mean of full length bitscores for the queries. The dataset was joined with taxonomic information from EukProt and completeness information calculated using BUSCO version 4.1.4 and eukaryote_odb10 (Manni et al., 2021).

Accession Numbers

Sequence data from this article can be found in the GenBank/EMBL data libraries under accession numbers_ PRJEB58730 (https://www.ebi.ac.uk/ena/browser/view/PRJEB58730.

Supplemental Data

Supplemental Figure S1. Characterization of B_{12} uptake in *C. reinhardtii* insertional mutant lines.

Supplemental Figure S2. Visualization of B_{12}-BODIPY uptake in *C. reinhardtii* using confocal microscopy

Supplemental Figure S3. *C. reinhardtii* knockout lines of *Cre12.g508644* are able to take up B_{12}

Supplemental Figure S4. Structure and sequence of a second insertion in the IM4 strain

Supplemental Figure S5. The predicted structures of CrCBA1 and PtCBA1 show a high degree of structural similarity.

Supplemental Figure S6. Independent mutant lines of *CrCBA1* show defective B_{12} uptake

Supplemental Figure S7. Sequences with similarity to CBA1 are found throughout Eukaryota

Supplemental Table S1. Table of strains used in this work

Supplemental Table S2. Plasmids used in this study

Supplemental Table S3. Oligonucleotides used in this study

Supplemental Table S4. Protein sequences with similarity to CBA1 used for tree building in Figure S7.

Supplemental Table S5. Summary of CBA1, METE and METH presence/absence found in organisms within Supergroups with greater than 5 organisms with a completeness greater than 70% and at least one of: METE or METH.

Supplemental Methods

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Author contributions

APS designed and performed research, analysed data and wrote the article with contributions from all the authors. KG and MLP carried out the CRISPR/Cas9 editing of *P. tricornutum* and contributed to writing the article. AH carried out the bioinformatics analysis to identify the putative transposable elements. FB performed the *metE7* RT-qPCR and B_{12} uptake assays. MJW & ADL synthesised the BODIPY-labelled B_{12} and contributed to writing the article. KG, GMO and PM supervised aspects of the project and contributed to writing the article. AGS conceived the project, obtained the funding, supervised the project and wrote the article with contributions from all the authors. AGS agrees to serve as the author responsible for contact and ensures communication.

Figure Legends

Figure 1. Disruption of *Phaeodactylum tricornutum CBA1* (*PtCBA1*) using CRISPR-Cas9 yielded lines with impaired B_{12} uptake. a) Schematic showing CRISPR-Cas9 sgRNA target sites and the homology repair template design used to generate mutant lines in *PtCBA1* (Phatr3_J48322). The homology repair template schematic is annotated with the 5' homology region (HR) and 3'HR, the *FCPB* promoter, nourseothricin resistance gene (*NAT*) and *FCPC* terminator. The *PtCBA1* gene is annotated with the ORF, the 5'HR and 3'HR regions used in the homology template and the regions of the ORF targeted by sgRNA (vertical bars). Primer positions used for the analysis of putative mutant lines are shown with arrowheads. **b)** PCR of regions across and within wild-type (WT) and mutant *PtCBA1* in 3 independent CRISPR-Cas9 lines (ΔCBA1) showing indel mutations in the mutants. PCR products from different sets of primers indicated in panel a are shown. M = marker, - Ctrl = no DNA template. **c)** A B_{12} uptake assay was performed as described in Materials and Methods, to determine the amount of B_{12} in the media and the cells after 1h incubation of *P. tricornutum* cells in 600 pg B_{12}. The 'Total' was inferred by the addition of the cell and media fractions. The dashed line indicates the amount of B_{12} added to the experiment. Standard deviation error bars are shown, n=4. Statistical analysis was performed on the media fraction, and Tukey's test identified the following comparisons to be significantly different from one another: WT vs No Algae ($p<1e^{-12}$); WT vs ΔCBA1-1 ($p<1e^{-10}$); WT vs ΔCBA1-2 ($p<1e^{-12}$); WT vs ΔCBA1-3 ($p<1e^{-11}$); No Algae vs ΔCBA1-1 ($p<1e^{-03}$); No Algae vs ΔCBA1-3 ($p<0.05$); and ΔCBA1-1 vs ΔCBA1-2 ($p<1e^{-02}$).

Figure 2. Generation and use of *C. reinhardtii* reporter strain UVM4-T12 for insertional mutagenesis. a) Schematic of the constructs used for insertional mutagenesis of *C. reinhardtii*. The pAS_R1 construct was designed to control expression of the paromomycin resistance gene (*aphVIII*) via B_{12} mediated repression of the *METE* promoter (P_{METE}). The pHyg3 construct encoded a constitutively expressed hygromycin resistance gene (*aphVII*), to be used for insertional mutagenesis. **b)** Growth of *C. reinhardtii* B_{12} reporter strain UVM4-

T12 bearing pAS_R1 plasmid, in response to vitamin B_{12} and paromomycin concentration in the media according to the algal dose-response assay. The predicted dose-response model is shown in black, with 95% confidence intervals in grey.

Figure 3. *C. reinhardtii* insertional mutant 4 (IM4) is defective in B_{12} response and uptake, and can be functionally complemented with *CrCBA1*. a) Effect of vitamin B_{12} on *METE* gene expression in UVM4 and IM4, determined by RT-qPCR. UVM4 and IM4 were grown in TAP media with or without 1000 $ng \cdot l^{-1}$ vitamin B_{12} for 4 days at 25°C, 120 rpm and in continuous light (90 $\mu E \cdot m^{-2} \cdot s^{-1}$). Boxplots of the log_2 transformed expression level of *METE* relative to that in the control (no B_{12}) sample are shown, n=6. The boxplots show the median (center line), 25th and 75th percentile hinges, and whiskers extending to the value no further than 1.5 times the interquartile range; values beyond this are plotted individually. Significant comparisons were identified using Tukey's test: UVM4 + 1000 $ng \cdot l^{-1}$ vitamin B_{12} from UVM4 No Addition ($p<1e^{-08}$), IM4 No Addition ($p<1e^{-08}$) and IM4 + 1000 $ng \cdot l^{-1}$ vitamin B12 ($p<1e^{-07}$). **b)** Schematic of the Cre02.g081050 gene showing the position of the insertion site (indicated with a black triangle) determined by whole genome sequencing (Figure S4). **c)** Schematic of the pAS_C2 construct designed to express *CrCBA1* fused to the fluorescent reporter mVenus. *CrCBA1-mVenus* was under the control of the *CrCBA1* promoter and terminator. pAS_C2 also contained the spectinomycin resistance gene *aadA*, driven by the *PSAD* promoter and *PSAD* terminator. **d)** B_{12}-uptake assay with UVM4, IM4 and IM4::pAS_C2 (n =4 separate transformants with high mVenus expression). Dashed line indicates the amount of B_{12} added to the assay. Standard deviation error bars are shown. Statistical analysis was performed on the media fraction, and Tukey's test identified the following comparisons to be significantly different from one another: No Algae vs UVM4 ($p<1e^{-05}$); No Algae vs IM4 ($p<0.05$); No Algae vs IM4::pAS_C2 ($p<1e^{-03}$); UVM4 vs 1.G2 ($p<1e^{-09}$); and 1.G2 vs 1.G2::pAS_C2 ($p<1e^{-06}$).

Figure 4. CLiP mutants in CrCBA1 are impaired in their ability to take up B_{12}. a) Schematic of the pAS_C3 construct designed to express *CrCBA1* in a controllable manner using a thiamine repressible riboswitch (RS_{THI4_4N}) to allow repression of *CrCBA1* through the addition of thiamine (Mehrshahi et al., 2020). **b)** B_{12}-uptake assay with cw15, LMJ-040682 (mean of 4 independent transformants) and LMJ-040682::pAS_C2 and LMJ-040682::pAS_C3 (mean of 3 independent transformants). The growth conditions were modified compared to previous assays: lines were grown with or without 10 µM thiamine supplementation for 5 days in a 16/8 light/dark cycle, and 8 hours after the dark to light transition the cultures were used for the algal B_{12}-uptake assay. The dashed line indicates the amount of B_{12} added to the sample. Standard deviation error bars are shown. Statistical analysis was performed on the media fraction. Tukey's test identified the following algal strains to be significantly different from one another in media without thiamine (not reporting comparisons against the No Algae control condition): cw15 vs LMJ-040682 ($p<1e^{-10}$); LMJ-040682 vs LMJ-040682::pAS_C2 ($p<1e^{-09}$); and LMJ-040682 vs LMJ-040682::pAS_C3 ($p<1e^{-09}$). Additionally, Tukey's test found the following strain to show a significant difference due to thiamine addition: LMJ-040682::pAS_C3 ($p<1e^{-07}$).

Figure 5. Confocal microscopy of complemented *C. reinhardtii CrCBA1* knockout lines showing an association between CrCBA1 and membranes. LMJ-040682 and LMJ-040682::pAS_C2 A10 and D10 lines were imaged according to the protocol outlined in the

materials and methods. Channels shown (left to right) are brightfield, chlorophyll, mVenus and an overlay. Microscope settings are described in Methods.

Figure 6. *CBA1* expression and B_{12} uptake capacity in a B_{12}-dependent mutant of C. reinhardtii (metE7) during B_{12} starvation and add-back. a) Log_2 transformed expression level of CBA1 measured by RT-qPCR and presented relative to levels in control conditions (B_{12} replete). Vertical dashed lines denote when B_{12} was removed and added. b) B_{12} uptake capacity of starved metE7 cells (expressed as 10^6 molecules of B_{12} per cell over 1h) at the same 6 time points during B_{12} starvation; it was not possible to perform the uptake assay on cells to which B_{12} had already been added. Cell density measurements were performed by counting plated cells in dilution series, and so included non-viable cells. For CBA1 expression and B_{12} uptake, 3 and 6 biological replicates were used, respectively, with points representing means, and error bars representing standard deviations.

Figure 7. Distribution of CBA1 and methionine synthase sequences across Eukaryotic groups. The EukProt database (Richter et al., 2022) was searched for METE, METH and CBA1 queries, as described in the materials and methods. Organisms were only considered if they contained at least one valid methionine synthase hit (METE or METH) and their genomes were >70% complete, as measured by BUSCO (Manni et al., 2021). Eukaryotic classes were filtered for those with greater than 5 genomes and the numbers of taxa for each class are indicated in brackets. The different combinations of CBA1, METE and METH were calculated for each species (Supplemental Table S4) and summarised as a percentage of the total number of taxa in each class, with gradual shading to show the variation in distribution between the different classes.

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Figure 1

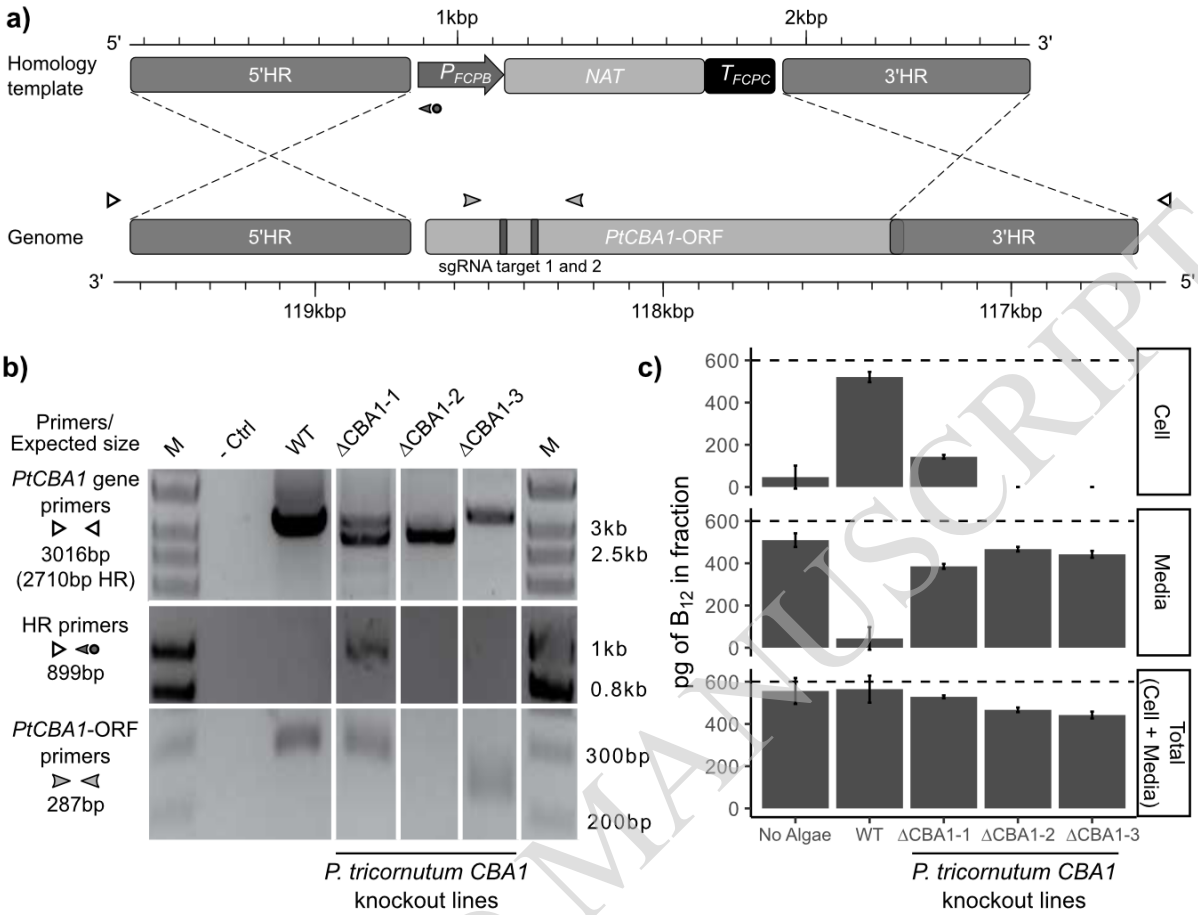

Figure 1. Disruption of *Phaeodactylum tricornutum CBA1* (*PtCBA1*) using CRISPR-Cas9 yielded lines with impaired B_{12} uptake. a) Schematic showing CRISPR-Cas9 sgRNA target sites and the homology repair template design used to generate mutant lines in *PtCBA1* (Phatr3_J48322). The homology repair template schematic is annotated with the 5' homology region (HR) and 3'HR, the *FCPB* promoter, nourseothricin resistance gene (*NAT*) and *FCPC* terminator. The *PtCBA1* gene is annotated with the ORF, the 5'HR and 3'HR regions used in the homology template and the regions of the ORF targeted by sgRNA (vertical bars). Primer positions used for the analysis of putative mutant lines are shown with arrowheads. **b)** PCR of regions across and within wild-type (WT) and mutant *PtCBA1* in 3 independent CRISPR-Cas9 lines (ΔCBA1) showing indel mutations in the mutants. PCR products from different sets of primers indicated in panel a are shown. M = marker, - Ctrl = no DNA template. **c)** A B_{12} uptake assay was performed as described in Materials and Methods, to determine the amount of B_{12} in the media and the cells after 1h incubation of *P. tricornutum* cells in 600 pg B_{12}. The 'Total' was inferred by the addition of the cell and media fractions. The dashed line indicates the amount of B_{12} added to the experiment. Standard deviation error bars are shown, n=4. Statistical analysis was performed on the media fraction, and Tukey's test identified the following comparisons to be significantly different from one another: WT vs No Algae ($p<1e^{-12}$); WT vs ΔCBA1-1 ($p<1e^{-10}$); WT vs ΔCBA1-2 ($p<1e^{-12}$); WT vs ΔCBA1-3 ($p<1e^{-11}$); No Algae vs ΔCBA1-1 ($p<1e^{-03}$); No Algae vs ΔCBA1-3 ($p<0.05$); and ΔCBA1-1 vs ΔCBA1-2 ($p<1e^{-02}$).

Figure 2

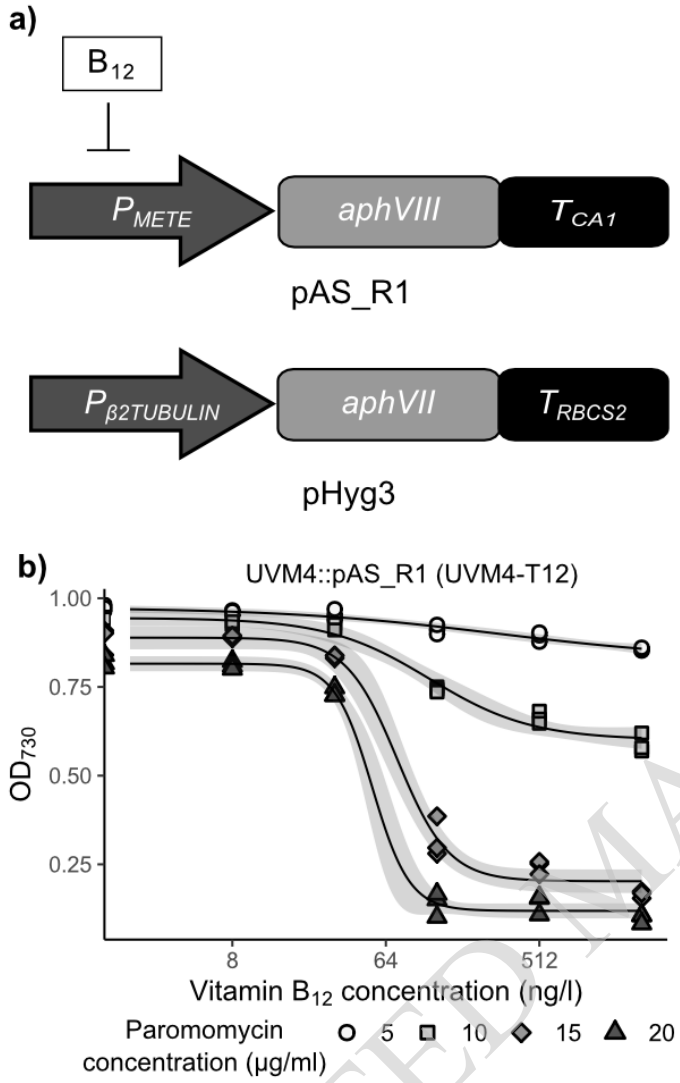

Figure 2. Generation and use of *C. reinhardtii* reporter strain UVM4-T12 for insertional mutagenesis. a) Schematic of the constructs used for insertional mutagenesis of *C. reinhardtii*. The pAS_R1 construct was designed to control expression of the paromomycin resistance gene (*aphVIII*) via B_{12} mediated repression of the *METE* promoter (P_{METE}). The pHyg3 construct encoded a constitutively expressed hygromycin resistance gene (*aphVII*), to be used for insertional mutagenesis. **b)** Growth of *C. reinhardtii* B_{12} reporter strain UVM4-T12 bearing pAS_R1 plasmid, in response to vitamin B_{12} and paromomycin concentration in the media according to the algal dose-response assay. The predicted dose-response model is shown in black, with 95% confidence intervals in grey.

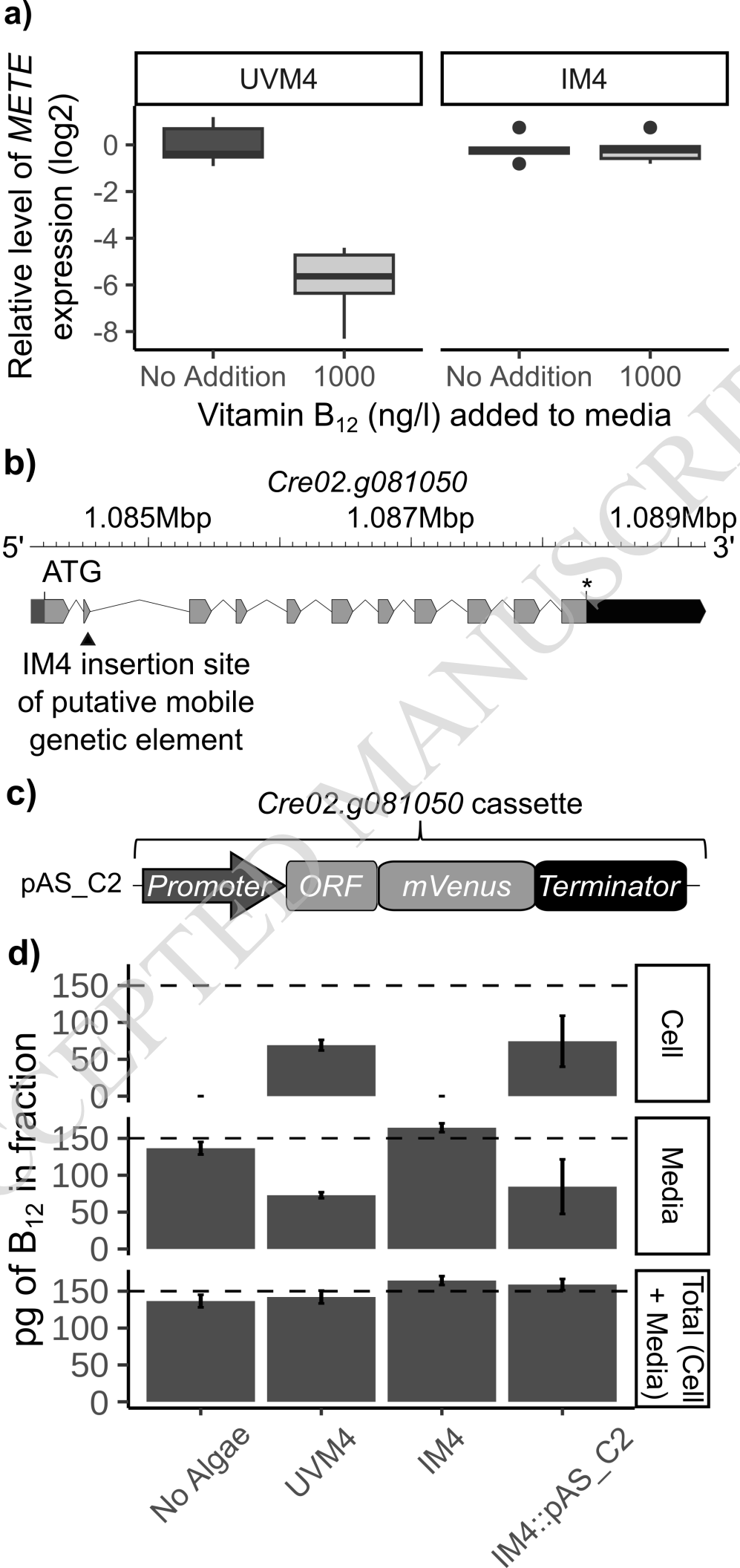

Figure 4

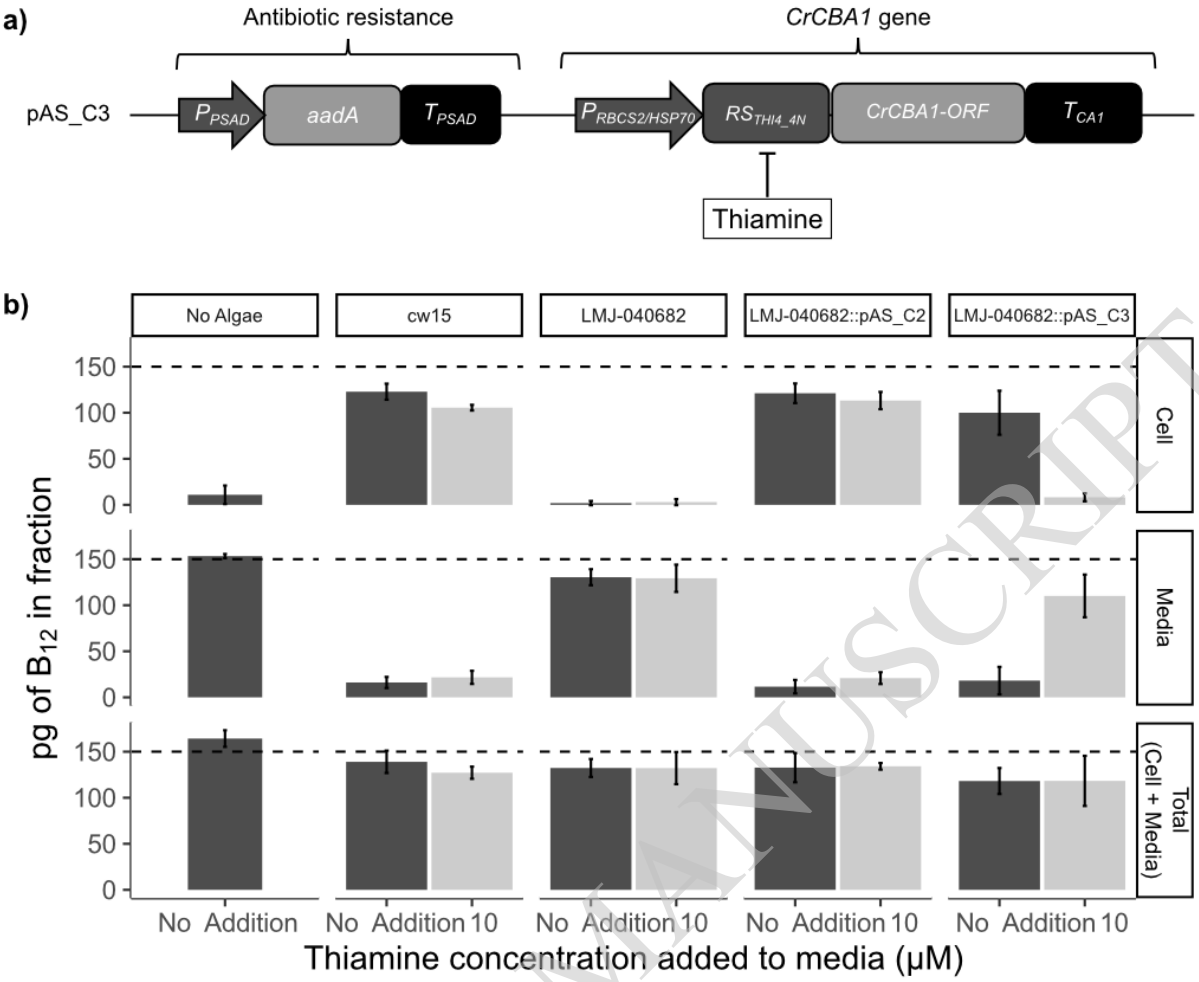

Figure 4. CLiP mutants in CrCBA1 are impaired in their ability to take up B_{12}. a) Schematic of the pAS_C3 construct designed to express *CrCBA1* in a controllable manner using a thiamine repressible riboswitch (RS_{THI4_4N}) to allow repression of *CrCBA1* through the addition of thiamine (Mehrshahi et al., 2020). **b)** B_{12}-uptake assay with cw15, LMJ-040682 and mean of 3 independent transformants of LMJ-040682::pAS_C2 and LMJ-040682::pAS_C3. The growth conditions were modified compared to previous assays: lines were grown with or without 10 μM thiamine supplementation for 5 days in a 16/8 light/dark cycle, and 8 hours after the dark to light transition the cultures were used for the algal B_{12}-uptake assay. The dashed line indicates the amount of B_{12} added to the sample. Standard deviation error bars are shown. Statistical analysis was performed on the media fraction. Tukey's test identified the following algal strains to be significantly different from one another in media without thiamine (not reporting comparisons against the No Algae control condition): cw15 vs LMJ-040682 ($p<1e^{-10}$); LMJ-040682 vs LMJ-040682::pAS_C2 ($p<1e^{-09}$); and LMJ-040682 vs LMJ-040682::pAS_C3 ($p<1e^{-09}$). Additionally, Tukey's test found the following strain to show a significant difference due to thiamine addition: LMJ-040682::pAS_C3 ($p<1e^{-07}$).

Figure 5

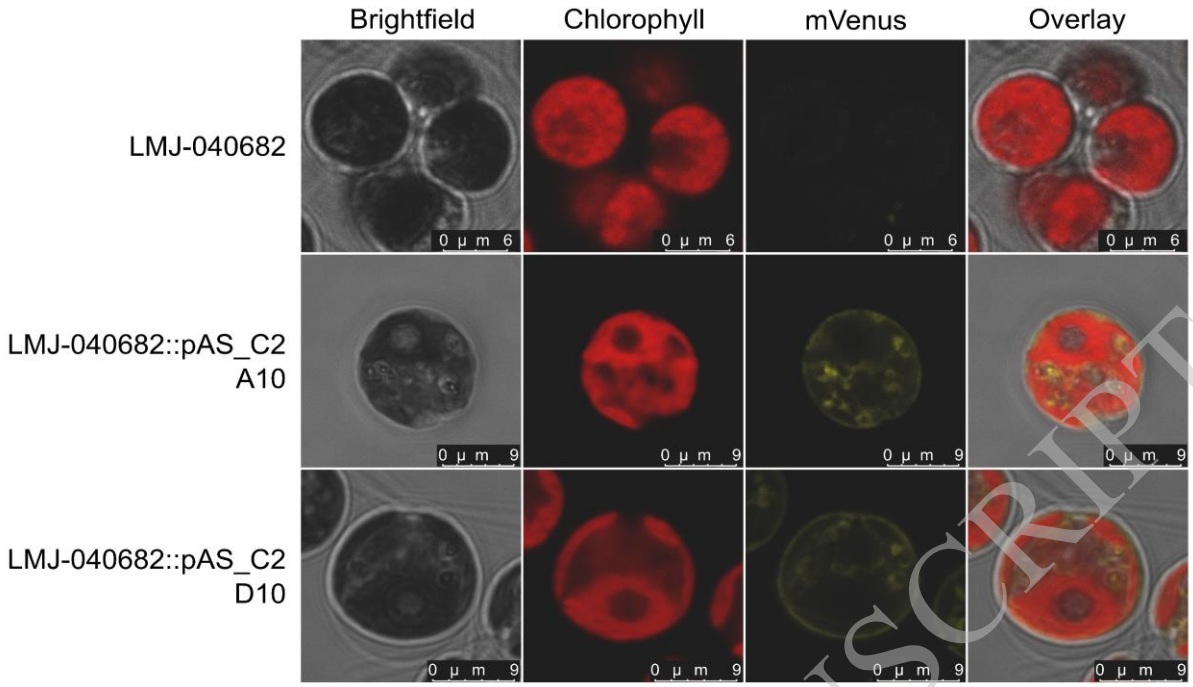

Figure 5. Confocal microscopy of complemented *C. reinhardtii CrCBA1* knockout lines showing an association between CrCBA1 and membranes. LMJ-040682 and LMJ-040682::pAS_C2 A10 and D10 lines were imaged according to the protocol outlined in the materials and methods. Channels shown (left to right) are brightfield, chlorophyll, mVenus and an overlay. Microscope settings are described in Methods.

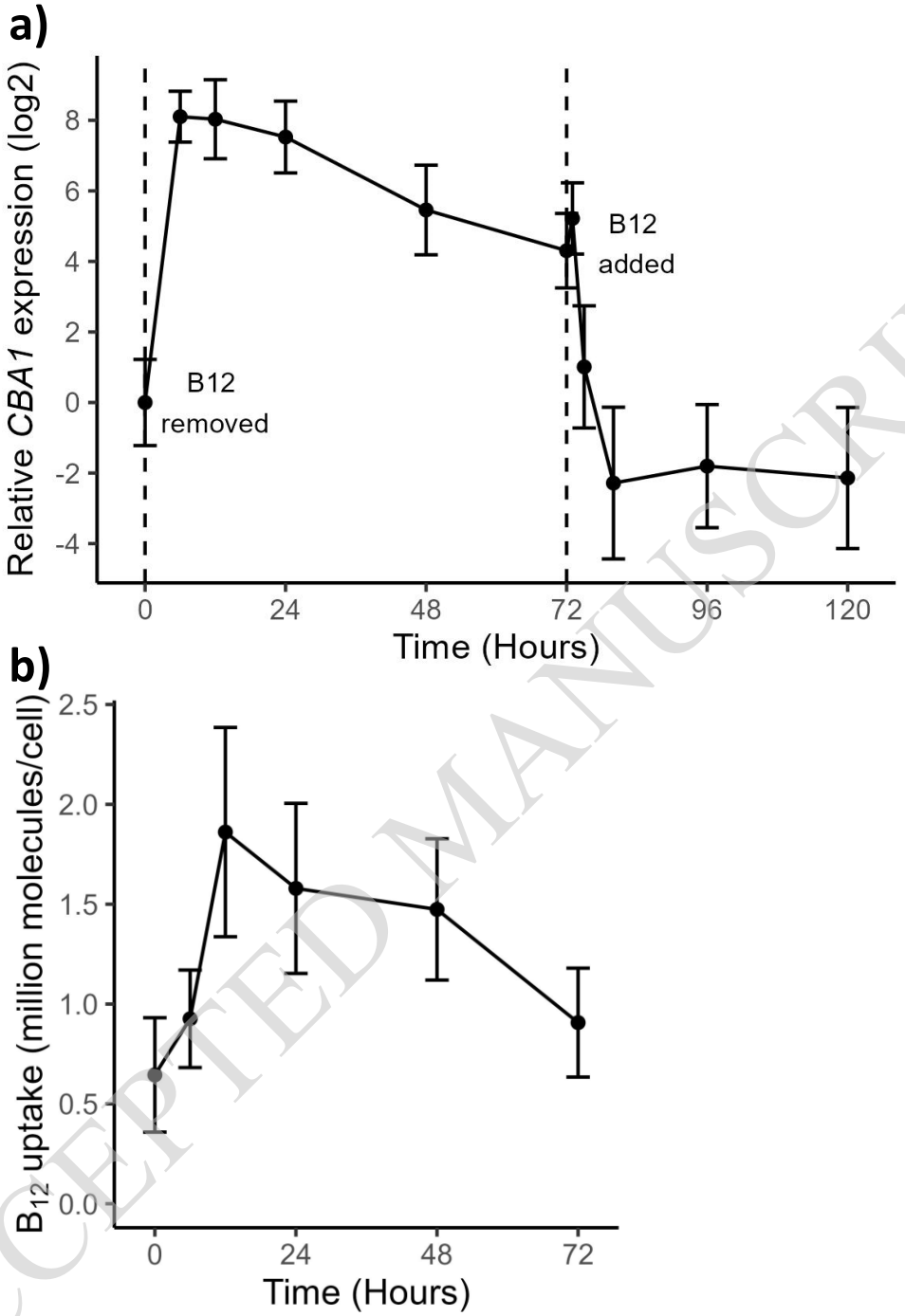

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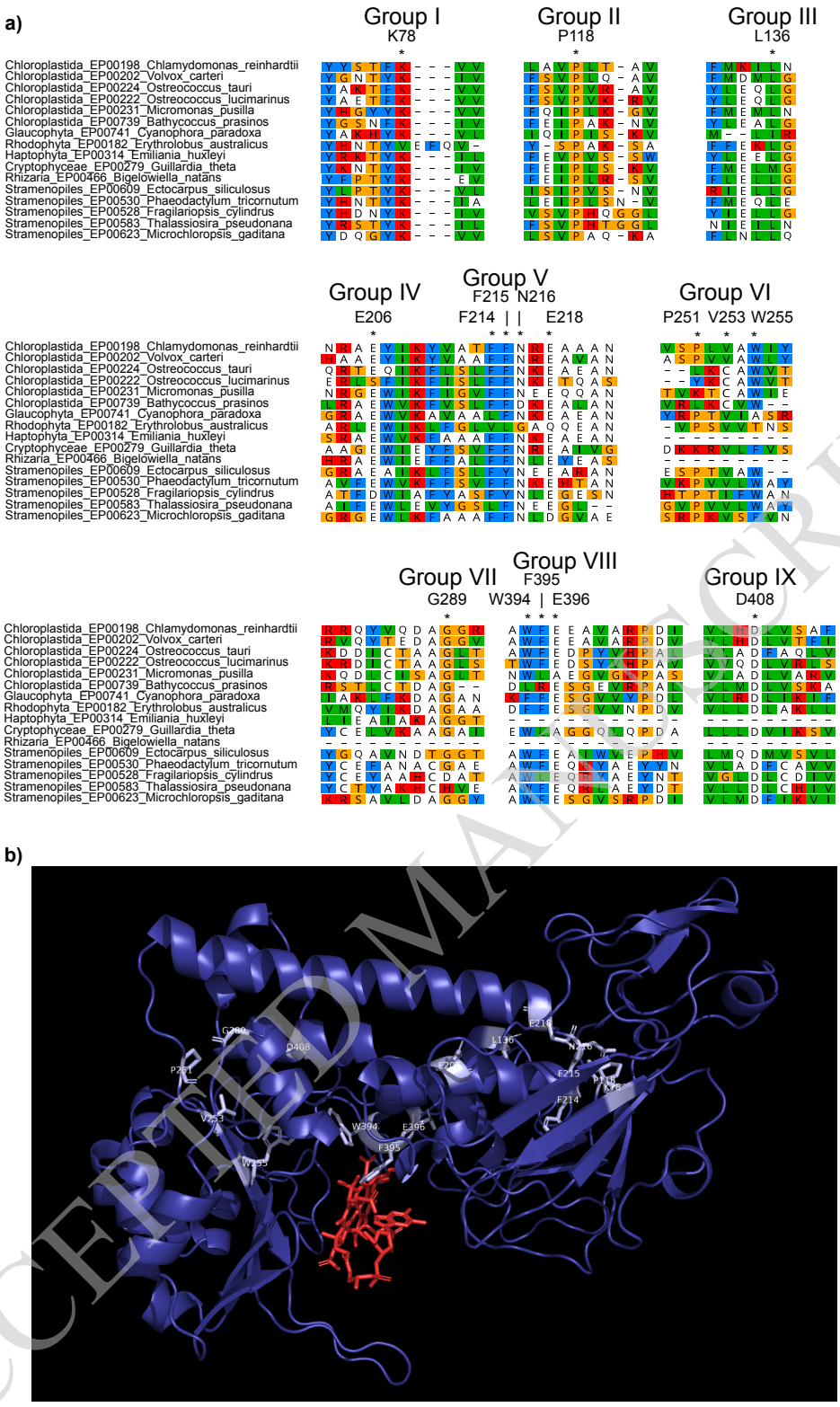
Figure 7

Class (no. of taxa)		% with METH	% with METH+METE	% with METE
Chlorophyta (18)	CBA1	61	17	0
	No CBA1	11	6	6
Stramenopiles (48)	CBA1	48	17	2
	No CBA1	4	21	8
Alveolata (11)	CBA1	45	0	0
	No CBA1	45	0	9
Rhizaria (9)	CBA1	67	0	0
	No CBA1	11	22	0
Streptophyta (22)	CBA1	0	5	73
	No CBA1	0	0	23
Amoebozoa (13)	CBA1	0	8	0
	No CBA1	31	62	0
Choanoflagellata (22)	CBA1	23	0	0
	No CBA1	77	0	0
Metazoa (42)	CBA1	0	0	0
	No CBA1	83	12	5
Fungi (27)	CBA1	0	19	7
	No CBA1	0	4	70

Figure 7. Distribution of CBA1 and methionine synthase sequences across Eukaryotic groups. The EukProt database (Richter et al., 2022) was searched for METE, METH and CBA1 queries, as described in the materials and methods. Organisms were only considered if they contained at least one valid methionine synthase hit (METE or METH) and their genomes were >70% complete, as measured by BUSCO (Manni et al., 2021). Eukaryotic classes were filtered for those with greater than 5 genomes and the numbers of taxa for each class are indicated in brackets. The different combinations of CBA1, METE and METH were calculated for each species (Supplementary Table 4) and summarised as a percentage of the total number of taxa in each class, with gradual shading to show the variation in distribution between the different classes.



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