Algal Model Systems

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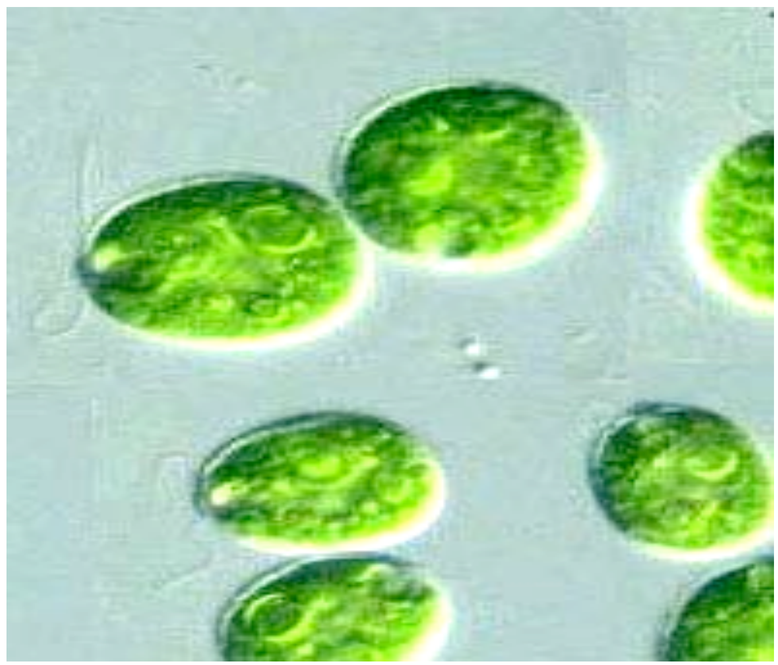
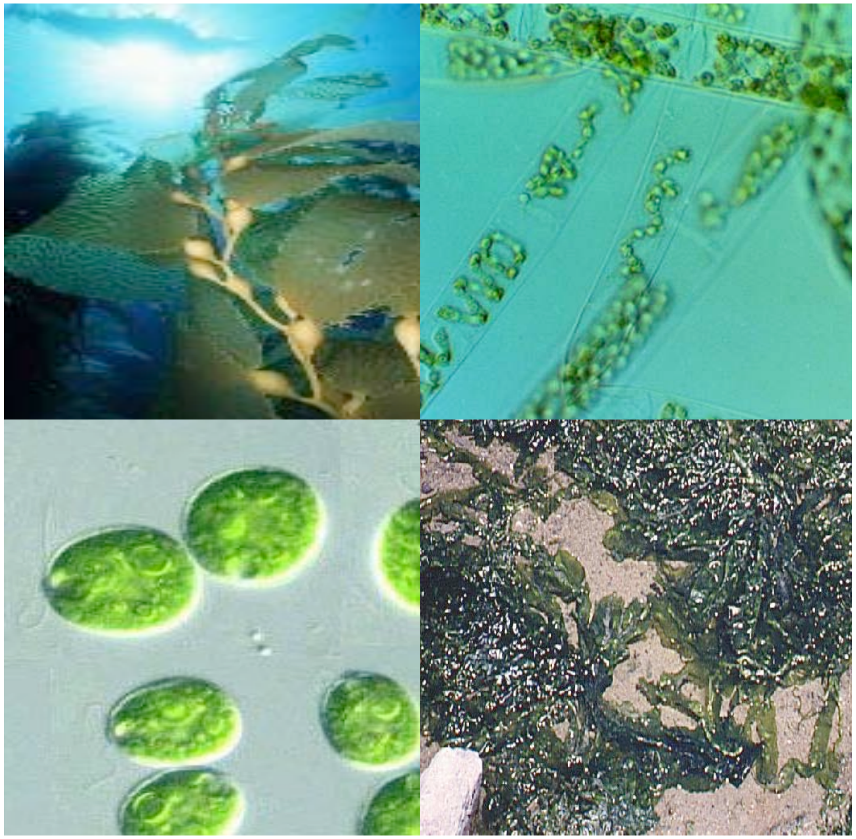


Alga: Latin “Seaweed”

- Aquatic *eukaryotic* organisms that contain chlorophyll and other pigments and can carry on photosynthesis
  - Range from microscopic single cells to very large multicellular structures resembling stems and leaves
  - Further categorized as brown algae, red algae, green algae, also dinoflagellates and diatoms
  - Some prokaryotes are incorrectly called blue-green algae

Why algae as a biofuel platform?



Cost

Scalability

Sustainability

Superior Fuels

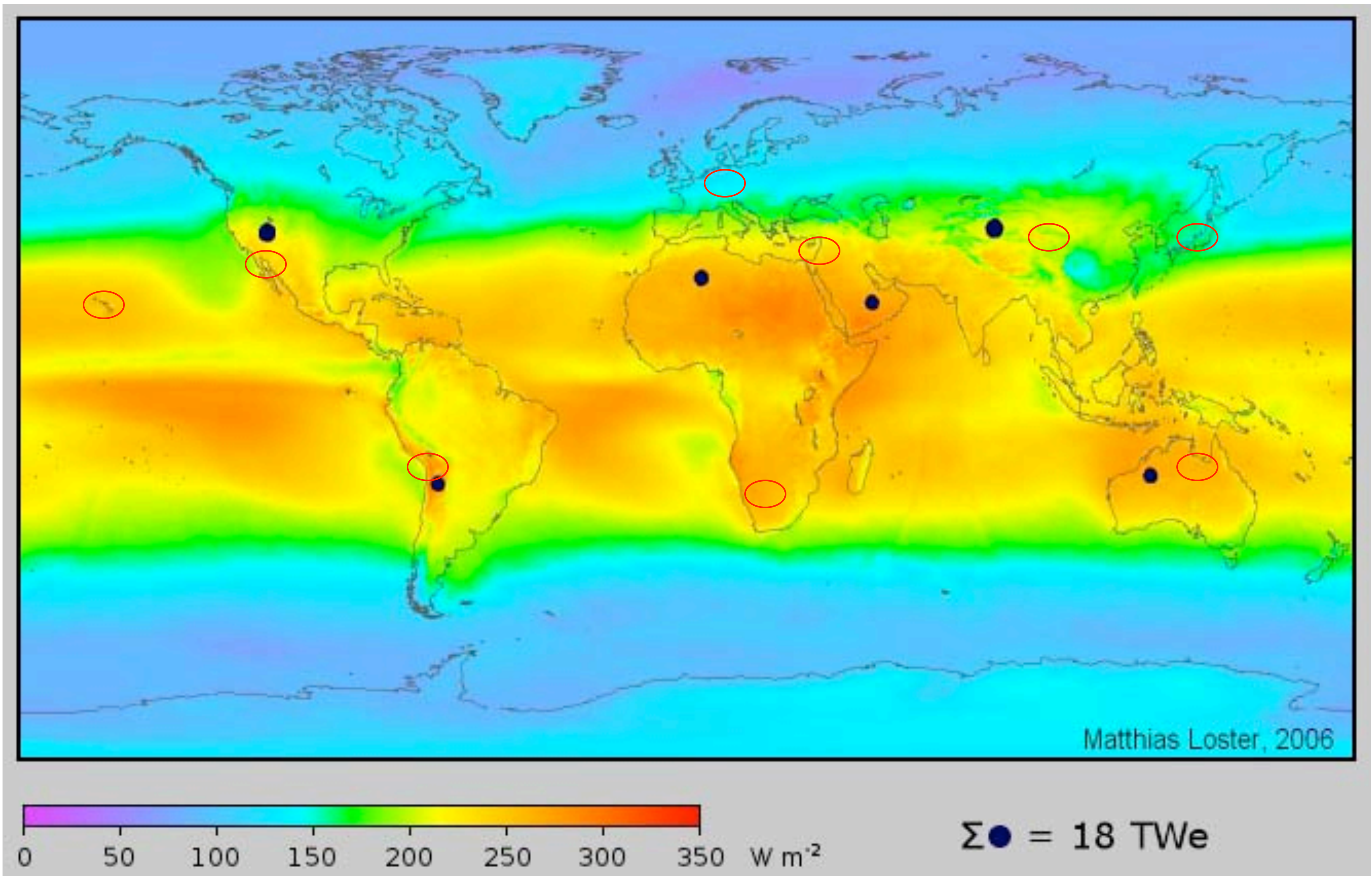
A few numbers to consider for biofuel production from algae

- 140 billion gallons/year of liquid fuel consumed in US
- If algae can produce 50 tons biomass or 1,600 gallon/acre-year
- 90 million acres needed to fill liquid fuel requirements
    - 90 million in corn ($52 B) and 67 million in soybeans ($26 B) in 2008
- Cost of algae oil estimated between $6 and $60 /gallon

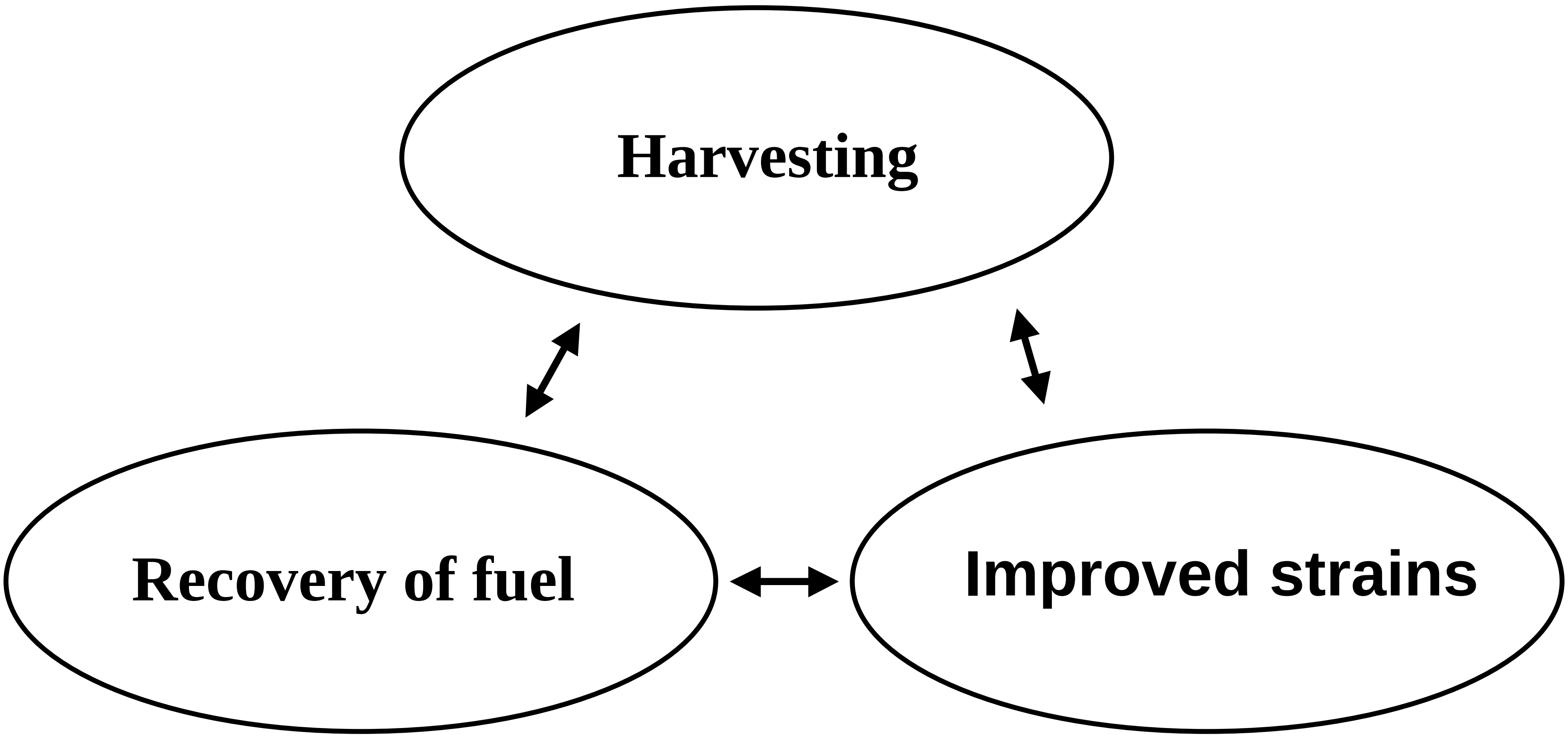
What should an algal biofuel solution look like?

- Sunlight energy converted directly to fuel
- No use of agricultural land or products
- Highly scalable process to meet demand
- Commodity energy prices
- Carbon neutral process

Sunlight is the original source of crude oil and all biofuels



Challenges of producing fuels from algae



Biofuels produced by algae

Biodiesel, triglycerides and fatty acids

Lipids, long chain hydrocarbons - botryococcene

Carbohydates: sugars and starches

Ethanol or other alcohols

Cellulose or other biomass

Production of each of these is likely form a different species

Guesses* about how to realize biofuel production from algae

- Identify strains with desired traits
  - **one strain unlikely to have everything we want**
  - **one strain unlikely to grow ever where we need it to**
- Need to modify those strains
  - to produce high levels of desired molecule
  - to fit harvest and fuel recovery requirements
  - Probably not naturally occurring traits
  - **Require genetic modification on an accelerated time frame**

*To predict without sufficient information

Need an accelerated time frame for “domestication” of algae

Corn Domesticated 4000 B.C.

Steel plow, large scale agriculture 1837

Corn “varieties” 1863

Green Revolution 1944

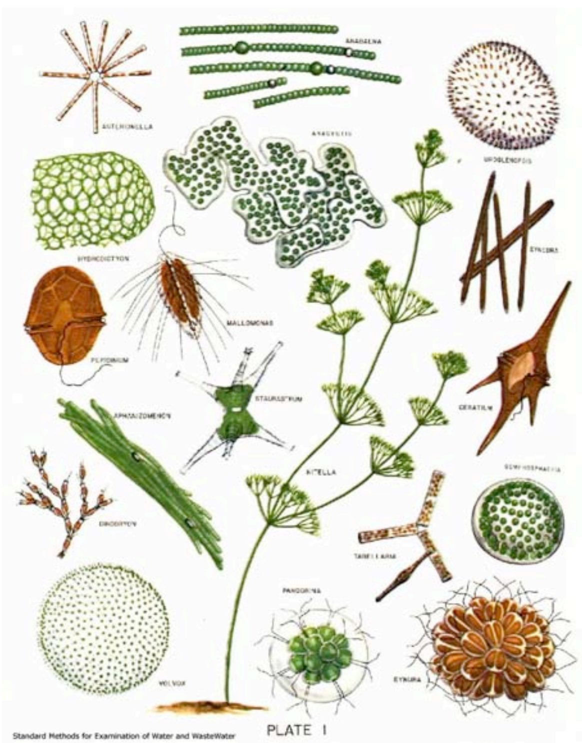
Genetically modified corn 2000

- Need the same for algae only quicker

What do we need to achieve rapid domestication of algae for biofuels?

- We need a much bigger and better knowledge base on algae
- We need to identify and characterize a large number of diverse algal species
  - Genomic, proteomic and metabolic profiles
- *We need to develop genetic tools for breeding*
- *We need to develop molecular tools for engineering*
- *We need to develop agricultural practices for algal growth, harvesting and processing*

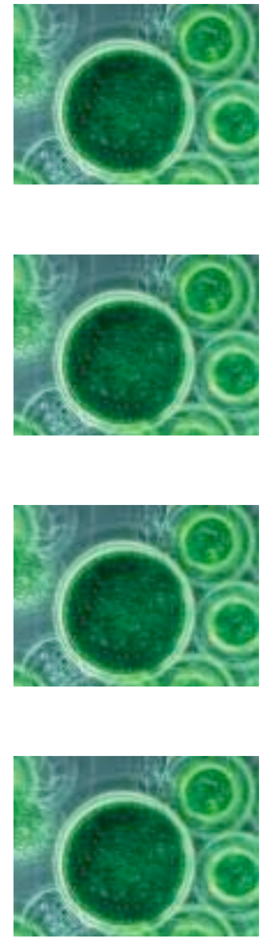
Domestication will require source genes, engineering and hosts strains



Source genes

Identification
Annotation
Cloning
Optimization
Engineering
Transformation

Engineering

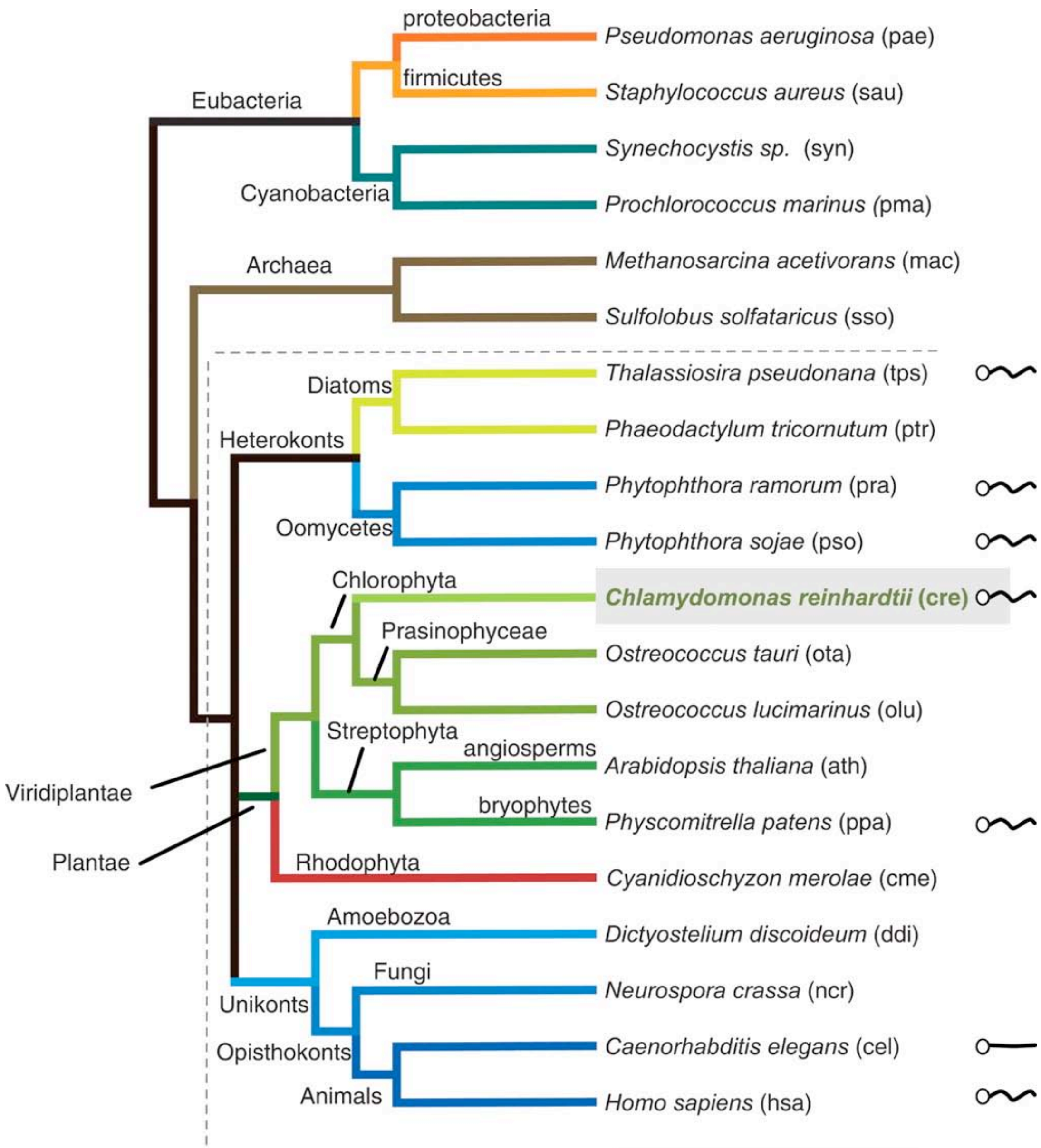


Production strains

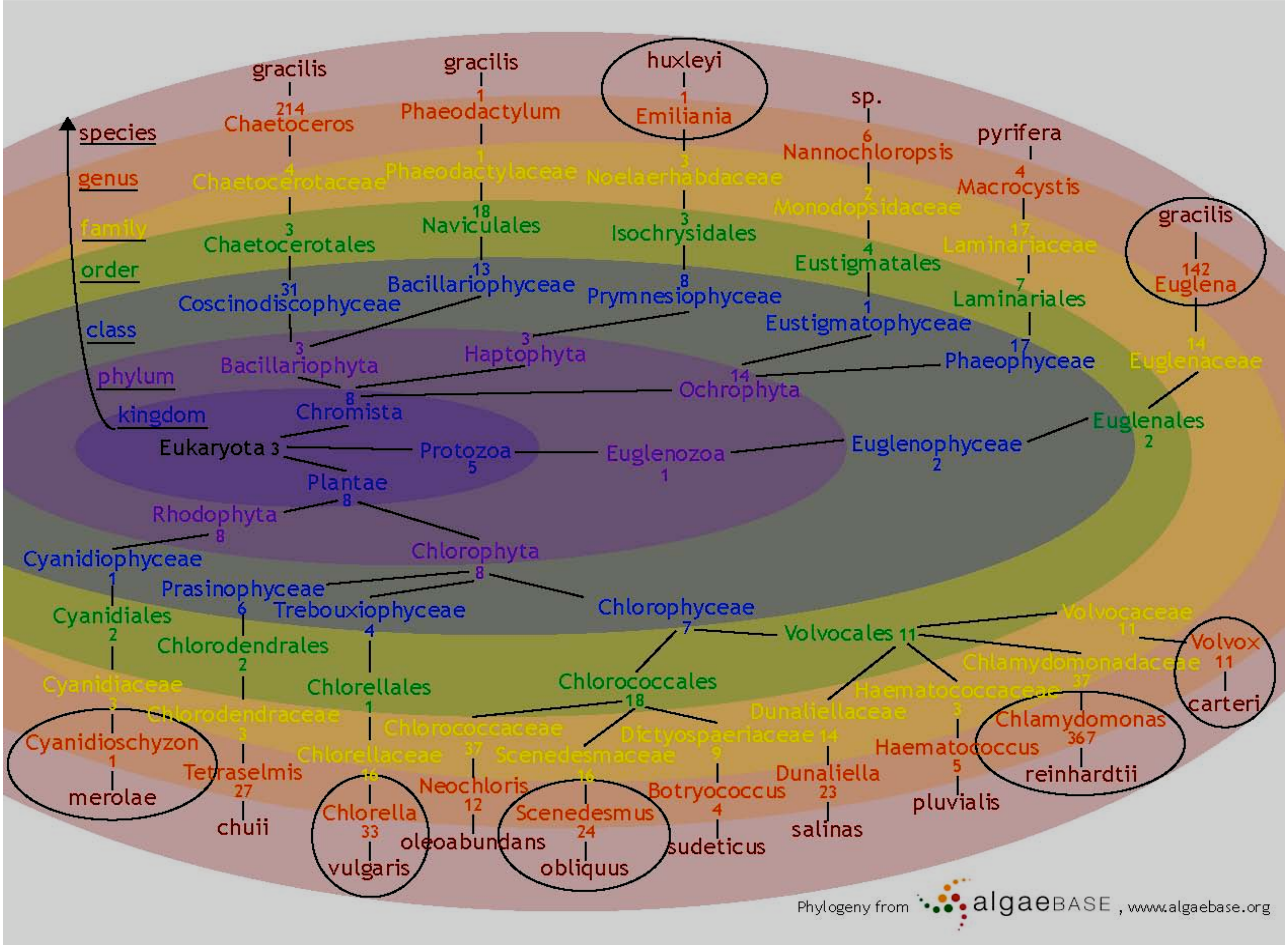
What do we have so far?

- We have many species identified with limited characterization, but showing the potential
- We know how to grow algae at a modest scale
- We have a few algal genomes sequenced and annotated
- We have nuclear and chloroplast transformation for a handful of species

Phylogenetic tree



Algae are the most diverse organisms in the world



Completely sequenced chloroplast genomes (as of 10/07)

	organism		strain	GenBank	size (bp)
chlorophyta	*Chlamydomonas*	*reinhardtii*		BK000554	203828
chlorophyta	*Chlorella*	*vulgaris*	C-27	AB001684	150613
rhodophyta	*Cyanidioschzon*	*merolae*	10D	AY286123	149987
rhodophyta	*Cyanidium*	*caldarium*	RK1	AF022186	164921
glaucocystophyceae	*Cyanophora*	*paradoxa*	Pringsheim strain LB 555	CPU30821	135599
haptophyceae	*Emiliania*	*huxleyi*	CCMP 373	AY741371	105309
euglenozoa	*Euglena*	*gracilis*	Pringsheim strain Z	X70810	143171
rhodophyta	*Gracilaria*	*tenuistipitata*	liui	AY673996	183883
chlorophyta	*Leptosira*	*terrestris*	UTEX 333	EF506945	195081
chlorophyta	*Mesostigma*	*viride*		AF166114	118360
chlorophyta	*Nephroselmis*	*olivacea*		AF137379	200799
stramenophiles/diatom	*Odontella*	*sinensis*		Z67753	119704
chlorophyta	*Oltmannsiellopsis*	*viridis*		DQ291132	151933
chlorophyta	*Ostreococcus*	*tauri*		CR954199	71666
stramenophiles/diatom	*Phaeodactylum*	*tricornutum*		EF067920	117369
rhodophyta	*Porphyra*	*purpurea*	avonport	U38804	191028
rhodophyta	*Porphyra*	*yezoensis*		AP006715	191952
chlorophyta	*Pseudendoclonium*	*akinetum*		AY835431	195867
cryptophyta	*Rhodomonas*	*salina*	CCMP1319	EF508371	135854
chlorophyta	*Scenedesmus*	*obliquus*	UTEX 393	DQ396875	161452
chlorophyta	*Stigeoclonium*	*helveticum*	UTEX 441	DQ630521	223902
stramenophiles/diatom	*Thalassiosira*	*pseudonana*		EF067921	128814

How do we choose the species to isolate the source genes

Oil content of selected algae species

Species	Oil content (% dw)	Reference
Ankistrodesmus TR-87	28-40	Ben-Amotz and Tornabene (1985)
Botryococcus braunii	29-75	Sheehan et al. (1998); Banerjee et al. (2002); Metzger and Largeau (2005)
Chlorella sp.	29	Sheehan et al. (1998)
Chlorella protothecoides (autotrophic/ heterothrophic)	15-55	Xu et al. (2006)
Cyclotella DI-35	42	Sheehan et al. (1998)
Dunaliella tertiolecta	36-42	Kishimoto et al. (1994); Tsukahara and Sawayama (2005)
Hantzschia DI-160	66	Sheehan et al. (1998)
Isochrysis sp.	7-33	Sheehan et al. (1998); Valenzuela-Espinoza et al. (2002)
Nannochloris	31 (6-63)	Ben-Amotz and Tornabene (1985); Negoro et al. (1991); Sheehan et al. (1998)
Nannochloropsis	46 (31-68)	Sheehan et al. (1998); Hu et al. (2006)
Nitzschia TR-114	28-50	Kyle DJ, Gladue RM (1991) Eicosapentaenoic acids and methods for their production. International Patent Application, Patent Cooperation Treaty Publication WO 91/14427, 3 October 1991.
Phaeodactylum tricornutum	31	Sheehan et al. (1998)
Scenedesmus TR-84	45	Sheehan et al. (1998)
Stichococcus	33 (9-59)	Sheehan et al. (1998)
Tetraselmis suecica	15-32	Sheehan et al. (1998); Zittelli et al. (2006); Chisti (2007)
Thalassiosira pseudonana	(21-31)	Brown et al. (1996)

Photosynthetic efficiency and yield

Plant system	Photosynthetic efficiency of PAR (%)	Typical productivity range (g m^{-2} day^{-1})	Typical productivity (t ha^{-1} y^{-1}) (Maximum)	Comment	Reference
Land plants					
C3 land plants	< 6.6 (theor.)	Not applicable	10 – 18 (24) 8 -10 (30)	Sugarbeet (temperate climate) Willow (max. on test plots)	Kenter et al. (2006) Keoleian and Volk (2005)
C4 land plants	< 13.4 (theor.)	Not applicable	10 – 30 (72) 10 – 20 (50) 15 – 20 (40)	Sugarcane Sorghum Miscanthus	Muchow et al. (1994), Samson et al. (2005) Habyarimana et al. (2004), Clifton-Brown et al. (2001), Heaton et al. (2004),
Macro-algae				Biomass yield difficult to determine in the absence of sustained harvests	
Laminaria offshore	Not reported	1 – 5	7 - 16	Natural populations and commercial harvesting	Mann (1973); Chynoweth (2002), page 39
Macrocystis, *Gracilaria*, *Laminaria* and *Chondrus* in culture chambers	Not reported	3 – 10	10 – 34 (127)	"probably not achievable on a commercial scale" (Chynoweth 2002)	Chynoweth (2002), page 11-15
Laminaria in offshore farm	Not reported	Not reported	28 – 46 (expected values, prevented by storm!)	High values can only be obtained by supplying nutrients at excessive costs	Brinkhuis and Levin (1987)
Uncultivated brown algae	Not reported	Not reported	10 - 36	Review	Gao and McKinley (1994)
Micro-algae in open ponds					
Micro-algae in commercial raceway ponds	Not reported	3 - 8	10 – 30	*Chlorella*, *Arthrospira*, and *Dunaliella* sp.	Jimenez et al. (2003)
Algae in experimental raceway ponds (Aquatic Biomass Program)	< 10	3 – 40 (winter to summer)	30 – 50	Summary of ABP-program run from 1978 – 1996	Benemann and Oswald (1996); Sheehan et al. (1998)
Heamatococcus pluvialis	3 – 4.4	10 – 15 (uncorrected)	20 – 30	Annual yield corrected for space occupied by PBRs	Huntley and Redalje (2007)
Arthrospira (*Spirulina*)	Not reported	2 – 15	30	450 m^2	Jimenez et al. (2003)

Outputs from the EPOBIO project September 2007 Prepared by A Carlsson, J van Beilen, R Moller and D Clayton

Photosynthetic efficiency and yield

Table 4 continued.

Plant system	Photosynthetic efficiency of PAR (%)	Typical productivity range (g m^{-2} day^{-1})	Typical productivity (t ha^{-1} y^{-1}) (Maximum)	Comment	Reference
Dunaliella salina	Not reported	2	Not reported	Small outdoor photo-bioreactor, 55l, 2.2 m^2	García-González et al. (2005)
Pleurochrysis carterae	Not reported	3 – 33 (winter to summer)	60	Small system (1 m^2), 13 months 21.9 t/ha/y lipids 5.5 t/ha/y $CaCO_3$	Moheimani and Borowitzka (2006) (see Table 3 for a list of similar experiments)
Scenedesmus obliquus	Not reported	48 (3 months in summer)	Not applicable	20 m^2 raceway pond unpublished results	Grobbelaar (2000)
Tetraselmis suecica	6 – 7 average 13 – 18 max	20 60 – 70	Not applicable	Duration less than 1 month Single day result	Laws et al. (1986)
Micro-algae in photobioreactors					
Chlorella vulgaris	Not reported	Not reported	130 – 150 (claimed)	Tubular PBR (700 m^3) in 1.2 hectare greenhouse	Moore (2001); Pulz (2001)
Phaeodactylum tricornutum	15 - 20	61 – 73 (depending on tube diameter) 14 – 17 (calculated for total area)	Not applicable	PBR with optimised dilution rates, extrapolated yields	Acien Fernandez et al. (1998)
Chlorella vulgaris	5.1 – 6.4	0.57 – 0.97	Not applicable	Helical bioreactor, artificial light	Scragg et al. (2002)
Chlorella sp.	7.1	43	Not applicable	Low level artificial light Turbulent culture	Tamiya (1957)
Chlorella sp.	< 47	Not reported	Not applicable	Value obtained under extremely low light with alternative photosystems	Pirt et al. (1980); Richmond (2000)
Arthrospira (Spirulina)	5.45	5.44	Not applicable	Helical bioreactor, artificial light	Watanabe et al. (1995)
Arthrospira (Spirulina)	2 - 5	7 – 25	33	215 days outdoor cultivation period in central Italy	Torzillo et al. (1986)

What are essential criteria for selecting hosts strains?

Kelp

Euglena

Cyanobacteria

Should commercial algae be the host species

Species/group	Product	Application areas	Prod. facilities	References
Spirulina (*Arthrospira platensis)* / Cyanobacteria)	Phycocyanin, biomass	Health food, cosmetics	Open ponds, natural lakes	Lee (2001); Costa et al. (2003)
Chlorella vulgaris / Chlorophyta	Biomass	Health food, food supplement, feed surrogates	Open ponds, basins, glass-tube PBR	Lee (2001)
Dunaliella salina / Chlorophyta	Carotenoids, β-carotene	Health food, food supplement, feed	Open ponds, lagoons	Jin and Melis (2003); Del Campo et al. (2007)
Haematococcus pluvialis / Chlorophyta	Carotenoids, astaxanthin	Health food, pharmaceuticals, feed additives	Open ponds, PBR	Del Campo et al. (2007)
Odontella aurita / Bacillariophyta	Fatty acids	Pharmaceuticals, cosmetics, baby food	Open ponds	Pulz and Groß (2004)
Porphyridium cruentum / Rhodophyta	Polysaccharides	Pharmaceuticals, cosmetics, nutrition	Tubular PBR	Fuentes et al. (1999)
Isochrysis galbana / Chlorophyta	Fatty acids	Animal nutrition	Open ponds, PBR	Molina Grima et al. (1994); Pulz and Gross (2004)
Phaedactylum tricornutum / Bacillariohyta	Lipids, fatty acids	Nutrition, fuel production	Open ponds, basins, PBR	Yongmanitchai and Ward (1991); Acien-Fernandez et al. (2003)
Lyngbya majuscule / Cyanobacteria	Immune modulators	Pharmaceuticals, nutrition		Singh et al. (2005)
Muriellopsis sp. /Chlorophyta	Carotenoids, Lutein	Health food, food supplement, feed	Open ponds, PBR	Blanco et al. (2007); Del Campo et al. (2007)

Could macro-algae be a host species

Seaweed genus	**Remarks**
Alaria	Possesses floating structure, occurs in arctic waters
Corallina	Calcareous, spread widely, small, can possibly be grown together with other species
Cystoseira	Moderate climate zone, floating reproduction structures
Ecklonia	Subtropical and moderate climate zone, one floating species
Egregia	Moderate climate zone, floating structure, very robust species
Eucheumia	Already cultivated in tropical areas, relatively small size
Gracillaria	Widely occurring, often cultivated, high productivity
Laminaria	Extensively grown in moderate climate zones
Macrocystis	In semi-culture, seasonal harvest, moderate climate zone
Pterygophora	Moderate climate zone, very robust species
Sargassum	Widely occurring (including Sargasso Sea), many species, floating structures, in moderate and tropical climate zones

What model species for engineering?

Do we take one strain and devote substantial resources to develop it faster? The *E. coli* paradigm

Do we bet on several horses and see who wins?

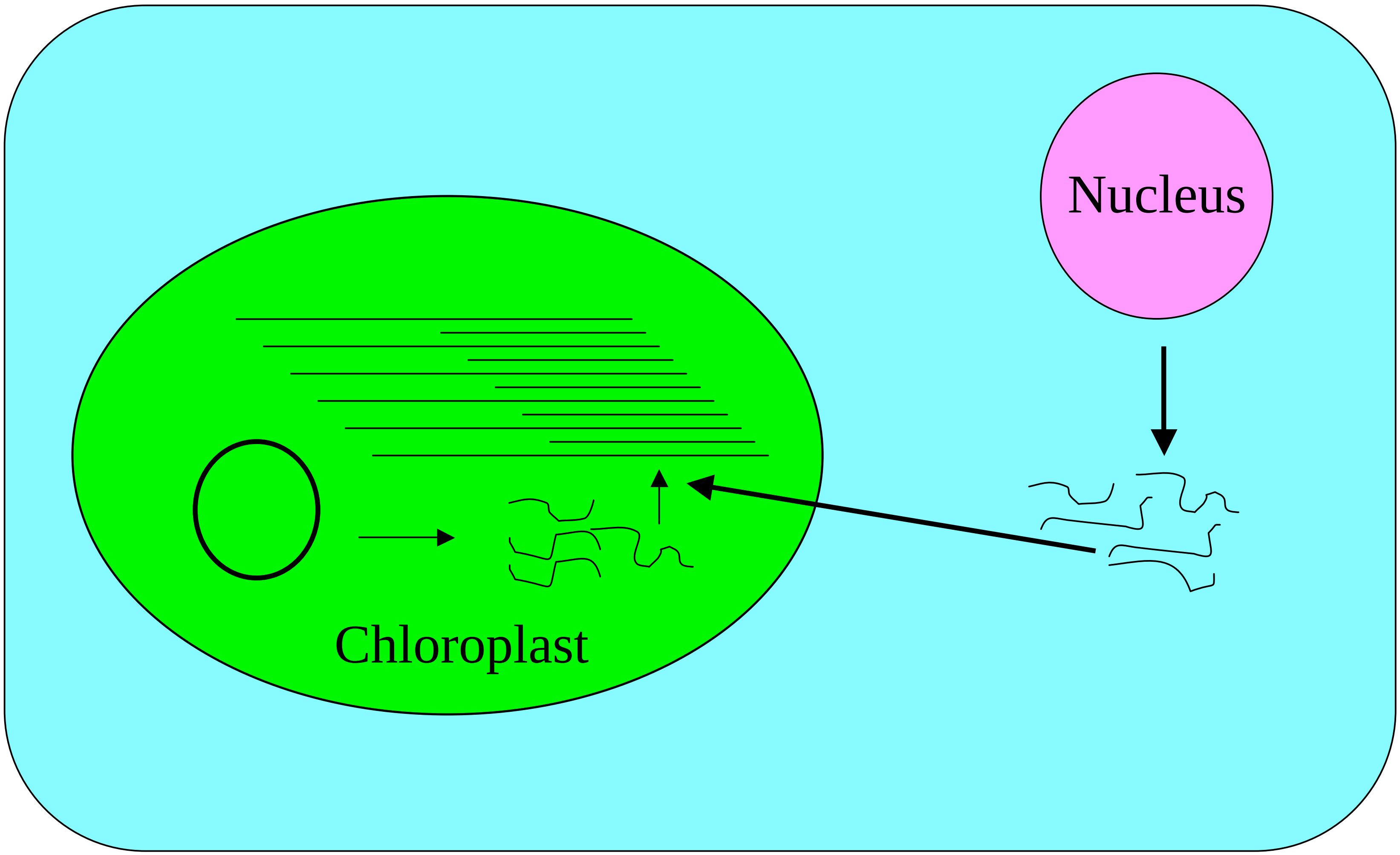
Do we already have the model organisms we need?

Model Algal Species by Citation

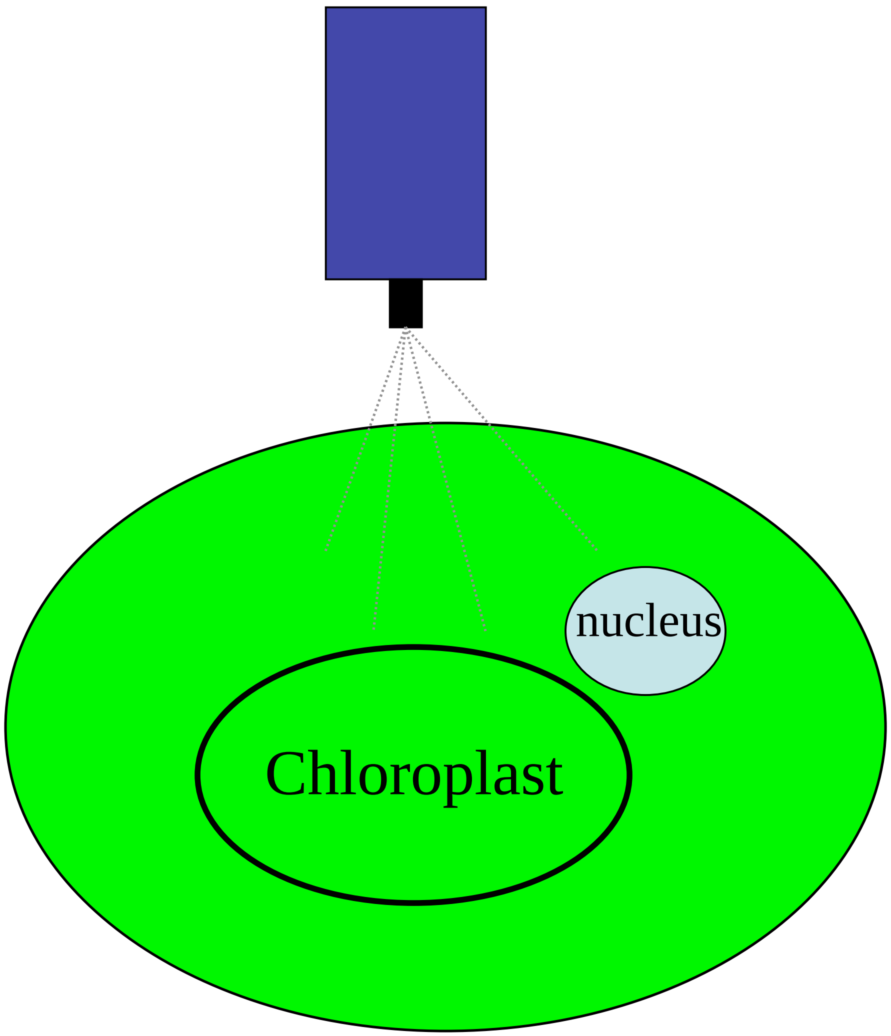
Genus species	Nuclear Genome	Chloroplast Genome	Transformation	Papers
Chlamydomonas reinhardtii	complete	complete	Nuc/Ct (269)	4611
Chorella vulgaris	in progress	complete	Nuc (1)	2901
Euglena gracilis	In progress	complete	Ct (1)	2291
Scenedesmus obliquus	none	complete		642
Laminaria japonica	none	complete	Nuc (1)	623
Dunaliella salina	minimal	partial	Nuc (3)	499
Volvox carteri	draft	complete	Nuc (8)	257
Porphyra sp.	none	complete	Nuc (1)	221
Phaeodactylum tricornutum	minimal	complete	Nuc (3)	192
Porphyridium sp.	minimal	minimal	Ct (1)	184
Thalassiosira pseudonana	complete	complete	Nuc (1)	158
Cyanidium caldarium	none	complete		155
Cyanophora sp.	none	complete		129
Haematococcus pluvialis	some	minimal	Nuc (1)	119
Tetraselmis chuii	minimal	minimal		93
Isochrysis galbana	none	none		90
Cyanidioschyzon merolae	complete	complete	Nuc (1)	71
Emiliania huxleyi	complete	complete		70
Chaetoceros gracilis	minimal	minimal		67
Nannochloropsis sp.	minimal	minimal		48
Macrocystis pyrifera	none	none		56
Rhodomonas sp.	none	complete		40
Botryococcus braunii	minimal	minimal		36
Ostreococcus tauri	draft	complete		33
Nannochloris oculata	minimal	minimal		29
Odontella sinensis	none	complete		18
Leptosira sp.	none	complete		4
Neochloris oleoabundans	none	none		3
Arabidopsis	complete	complete	880	23564
Saccharomyces	complete		3077	84960
E. coli	complete		7407	220222

Developing the tool for algal engineering

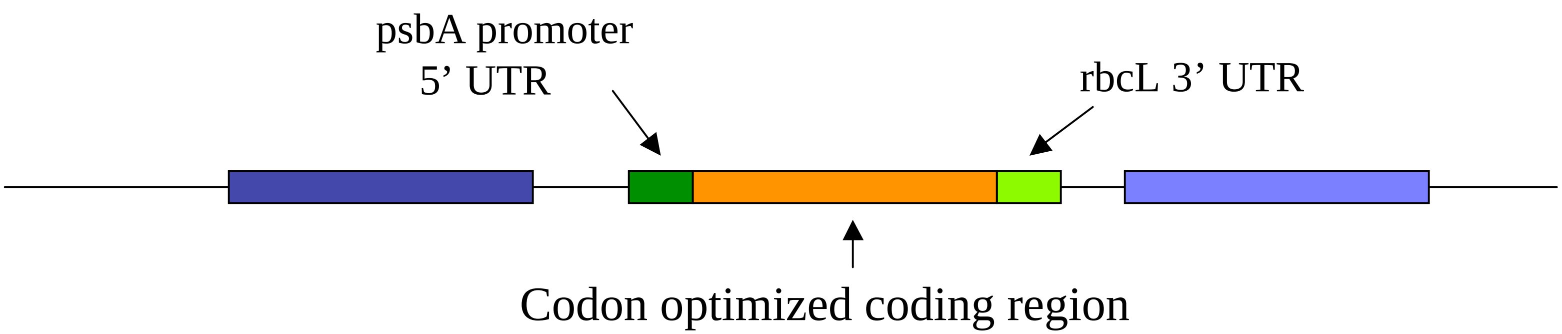
Biofuels are all made in the chloroplast from photosynthesis
- most of enzymes responsible are nuclear encoded



Genetic transformation of algae is relatively easy
Although you need selectable markers for each species

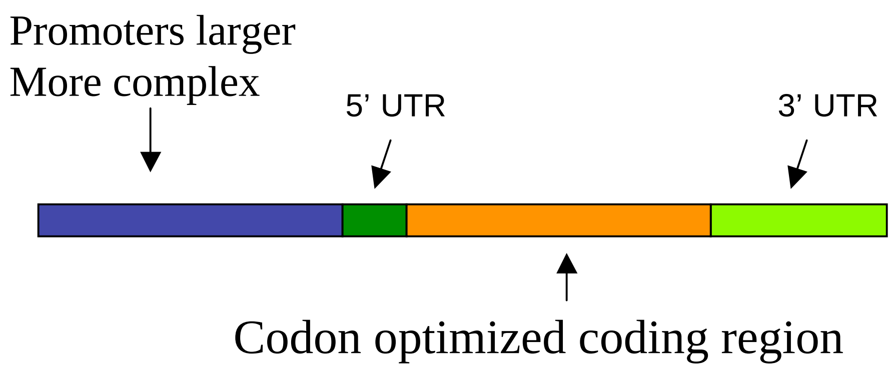


Chloroplast transformation proceeds by homologous recombination

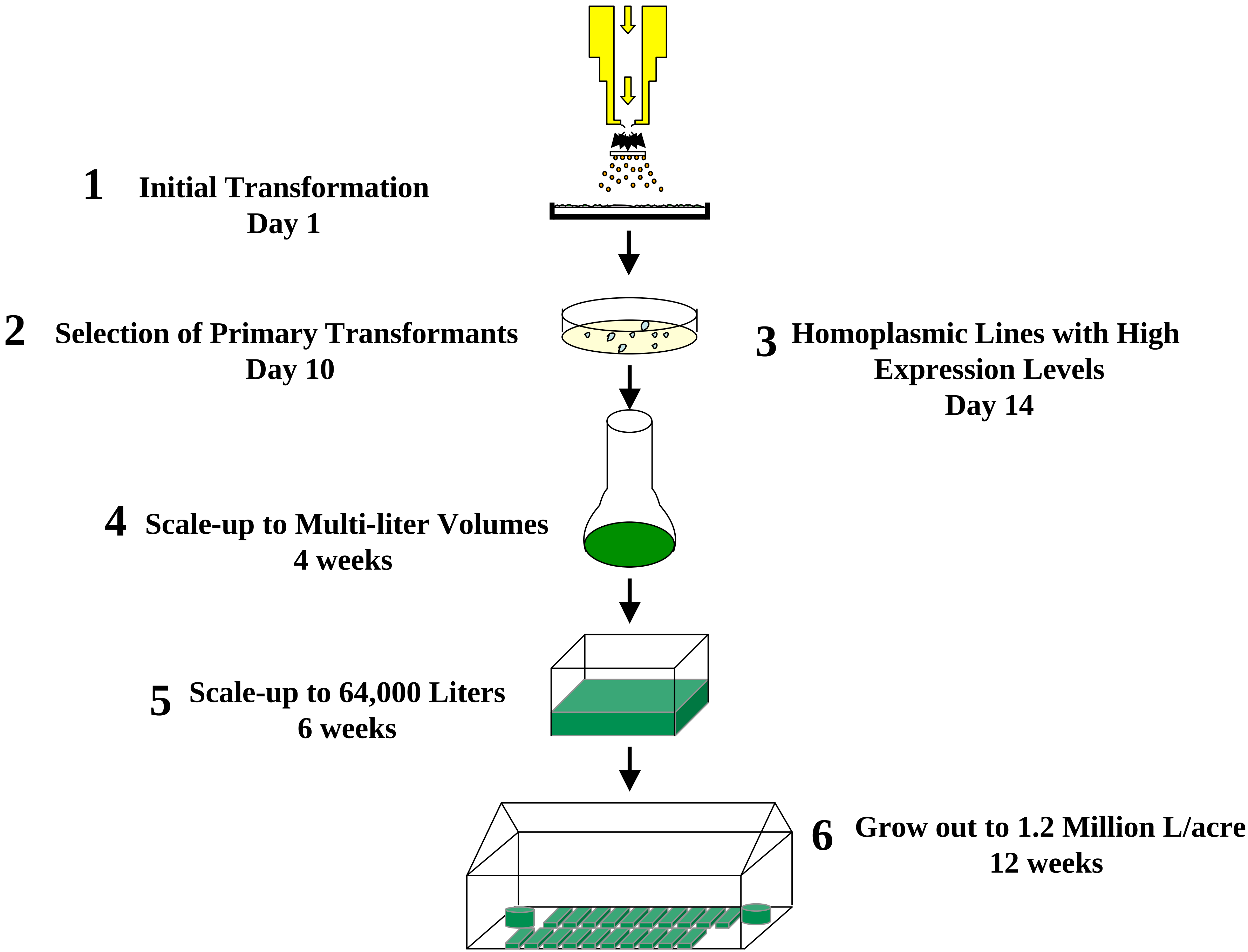


- need promoter and UTRs flanking region of homology
- recombinant proteins can accumulate to very high levels
- chloroplast can express complex proteins
- less sophisticated gene regulation in plastids

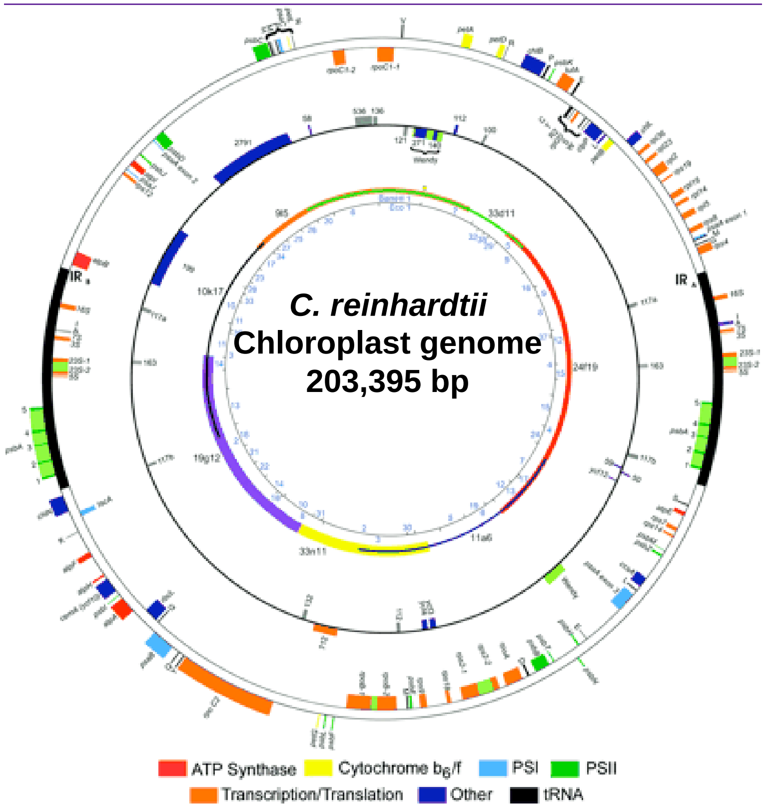
Nuclear transformation proceeds by random integration



- Need more transformation events to get good expression
- Gene expression more complex, regulation potential greater
- Can target proteins to plastids, cytoplasm or export
- Gene silencing is presently a limiting factor

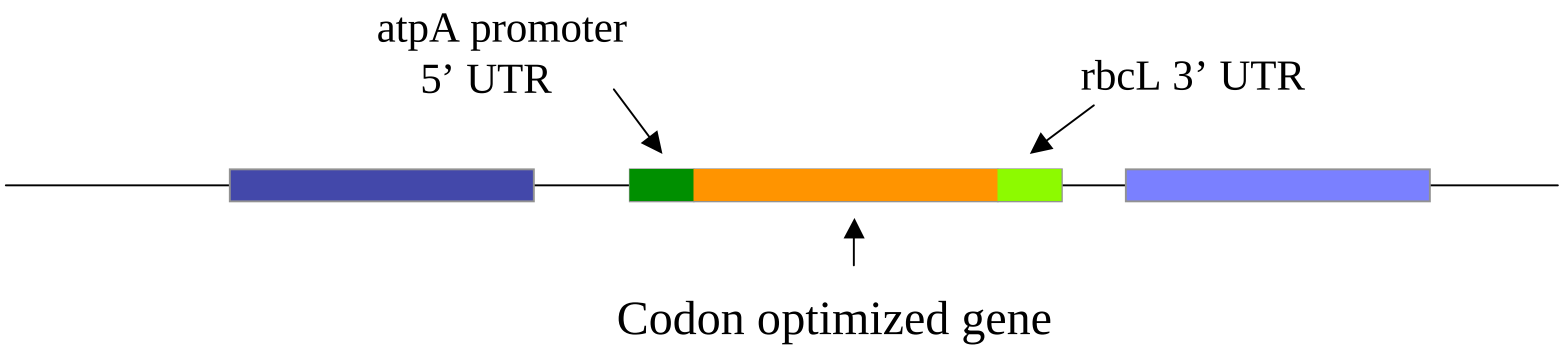

1 Initial Transformation
Day 1
2 Selection of Primary Transformants
Day 10
3 Homoplasmic Lines with High
Expression Levels
Day 14
4 Scale-up to Multi-liter Volumes
4 weeks
5 Scale-up to 64,000 Liters
6 weeks
6 Grow out to 1.2 Million L/acre
12 weeks

Chloroplast Genome



- Complete set of genetic material
- Simple prokaryotic promoters
- Stable uncapped non-polyA mRNAs
- Bacteria-like ribosomes
- Easily transformed

Expression of recombinant protein in *C. reinhardtii* chloroplasts

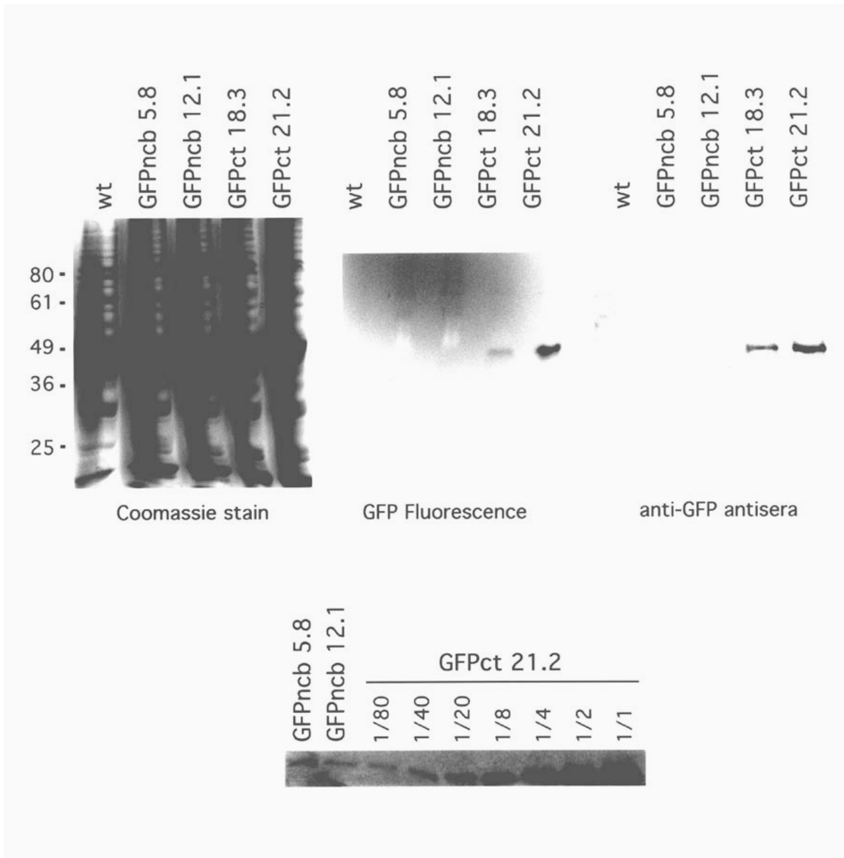


Synthetic codon optimize chloroplast GFP gene

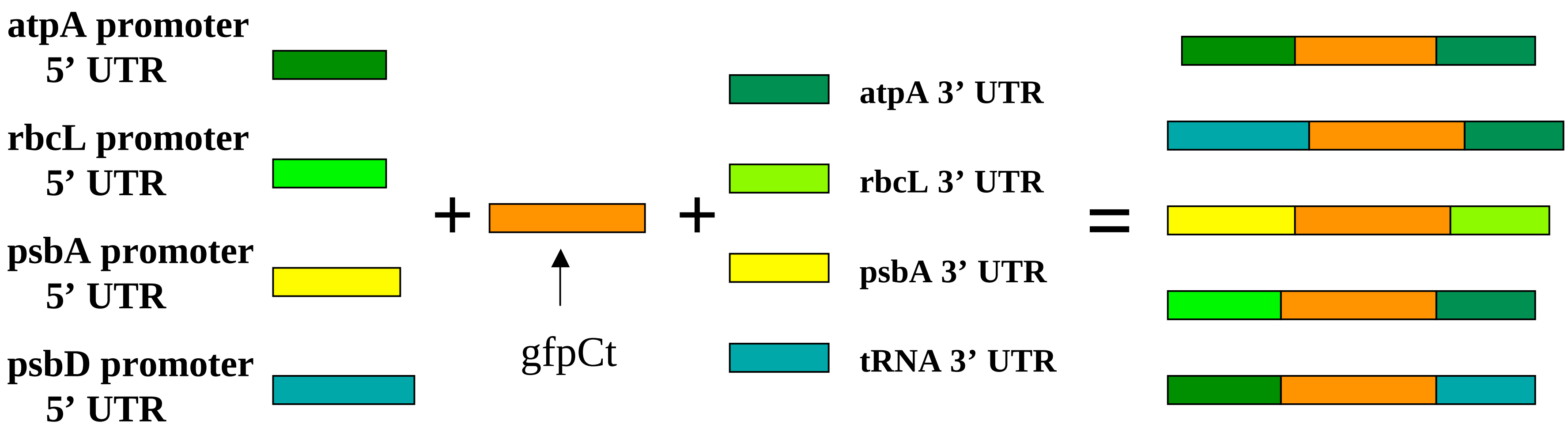
GFP Codon Alignment

ct	ATG	GCT	AAA	GGT	GAA	GAA	TTA	TTC	ACA	GGT	GTT	GTA	CCT	ATT	TTA	GTA	GAA	
ncb	ATG	AGT	AAA	GGA	GAA	GAA	CTT	TTC	ACT	GGA	GTT	GTC	CCA	ATT	CTT	GTT	GAA	
	M	A*	K	G	E	E	L	F	T	G	V	V	P	I	L	V	E	17
ct	TTA	GAC	GGT	GAT	GTA	AAC	GGT	CAC	AAA	TTT	TCA	GTT	TCT	GGT	GAA	GGT	GAA	
ncb	TTA	GAT	GGT	GAT	GTT	AAT	GGG	CAC	AAA	TTT	TCT	GTC	AGT	GGA	GAG	GGT	GAA	
	L	D	G	D	V	N	G	H	K	F	S	V	S	G	E	G	E	34
ct	GGT	GAC	GCA	ACT	TAT	GGT	AAA	TTA	ACA	CTT	AAA	TTC	ATT	TGT	ACT	ACA	GGT	
ncb	GGT	GAT	GCA	ACA	TAC	GGA	AAA	CTT	ACC	CTT	AAA	TTT	ATT	TGC	ACT	ACT	GGA	
	G	D	A	T	Y	G	K	L	T	L	K	F	I	C	T	T	G	51
ct	AAA	TTA	CCA	GTA	CCT	TGG	CCA	ACT	TTA	GTT	ACA	ACT	TTT	ACA	TAC	GGT	GTA	
ncb	AAA	CTA	CCT	GTT	CCA	TGG	CCA	ACA	CTT	GTC	ACT	ACT	TTC	TCT	TAT	GGT	GTT	
	K	L	P	V	P	W	P	T	L	V	T	T	F	T*	Y	G	V	68
ct	CAA	TGT	TTC	AGT	CGT	TAC	CCT	GAT	CAC	ATG	AAA	CAA	CAT	GAC	TTT	TTC	AAA	
ncb	CAA	TGC	TTT	TCA	AGA	TAC	CCA	GAT	CAT	ATG	AAA	CGG	CAT	GAC	TTT	TTC	AAG	
	Q	C	F	S	R	Y	P	D	H	M	K	Q	H	D	F	F	K	85
ct	TCT	GCT	ATG	CCA	GAA	GGT	TAT	GTT	CAA	GAA	CGT	ACT	ATT	TTT	TTC	AAA	GAT	
ncb	AGT	GCC	ATG	CCC	GAA	GGT	TAT	GTA	CAG	GAA	AGA	ACT	ATA	TTT	TTC	AAA	GAT	
	S	A	M	P	E	G	Y	V	Q	E	R	T	I	F	F	K	D	102
ct	GAC	GGT	AAT	TAT	AAA	ACA	CGT	GCT	GAA	GTA	AAA	TTT	GAA	GGT	GAT	ACT	TTA	
ncb	GAC	GGG	AAC	TAC	AAG	ACA	CGT	GCT	GAA	GTC	AAG	TTT	GAA	GGT	GAT	ACC	CTT	
	D	G	N	Y	K	T	R	A	E	V	K	F	E	G	D	T	L	119
ct	GTT	AAC	CGT	ATT	GAA	TTA	AAA	GGT	ATT	GAC	TTC	AAA	GAA	GAT	GGT	AAT	ATT	
ncb	GTT	AAT	AGA	ATC	GAG	TTA	AAA	GGT	ATT	GAT	TTT	AAA	GAA	GAT	GGA	AAC	ATT	
	V	N	R	I	E	L	K	G	I	D	F	K	E	D	G	N	I	136
ct	TTA	GGT	CAC	AAA	CTT	GAA	TAT	AAC	TAC	AAT	TCA	CAT	AAC	GTA	TAT	ATT	ATG	
ncb	CTT	GGA	CAC	AAA	TTG	GAA	TAC	AAC	TAT	AAC	TCA	CAC	AAT	GTA	TAC	ATC	ATG	
	L	G	H	K	L	E	Y	N	Y	N	S	H	N	V	Y	I	M	153
ct	GCA	GAC	AAA	CAA	AAA	AAT	GGT	ATT	AAA	GTA	AAC	TTT	AAA	ATT	CGT	CAT	AAT	
ncb	GCA	GAC	AAA	CAA	AAG	AAT	GGA	ATC	AAA	GTT	AAC	TTC	AAA	ATT	AGA	CAC	AAC	
	A	D	K	Q	K	N	G	I	K	V	N	F	K	I	R	H	N	170
ct	ATC	GAG	GAT	GGT	TCT	GTA	CAA	TTA	GCT	GAC	CAC	TAT	CAA	CAA	AAC	ACA	CCA	
ncb	ATT	GAA	GAT	GGA	AGC	GTT	CAA	CTA	GCA	GAC	CAT	TAT	CAA	CAA	AAT	ACT	CCA	
	I	E	D	G	S	V	Q	L	A	D	H	Y	Q	Q	N	T	P	187
ct	ATT	GGT	GAT	GGT	CCT	GTT	TTA	CTT	CCA	GAC	AAT	CAT	TAT	TTA	AGT	ACT	CAA	
ncb	ATT	GGC	GAT	GGC	CCT	GTC	CTT	TTA	CCA	GAC	AAC	CAT	TAC	CTG	TCC	ACA	CAA	
	I	G	D	G	P	V	L	L	P	D	N	H	Y	L	S	T	Q	204
ct	TCT	GCT	TTA	TCA	AAA	GAT	CCT	AAC	GAA	AAA	CGT	GAC	CAC	ATG	GTA	TTA	CTT	
ncb	TCT	GCC	CTT	TCG	AAA	GAT	CCC	AAC	GAA	AAG	AGA	GAC	CAC	ATG	GTC	CTT	CTT	
	S	A	L	S	K	D	P	N	E	K	R	D	H	M	V	L	L	221
ct	GAA	TTT	GTT	ACA	GCA	GCT	GGT	ATT	ACT	CAC	GGT	ATG	GAT	GAA	TTA	TAC	AAA	
ncb	GAG	TTT	GTA	ACA	GCT	GCT	GGG	ATT	ACA	CAT	GGC	ATG	GAT	GAA	CTA	TAC	AAA	
	E	F	V	T	A	A	G	I	T	H	G	M	D	E	L	Y	K	238
ct	TAA																	
ncb	TAA																	
	Och																	

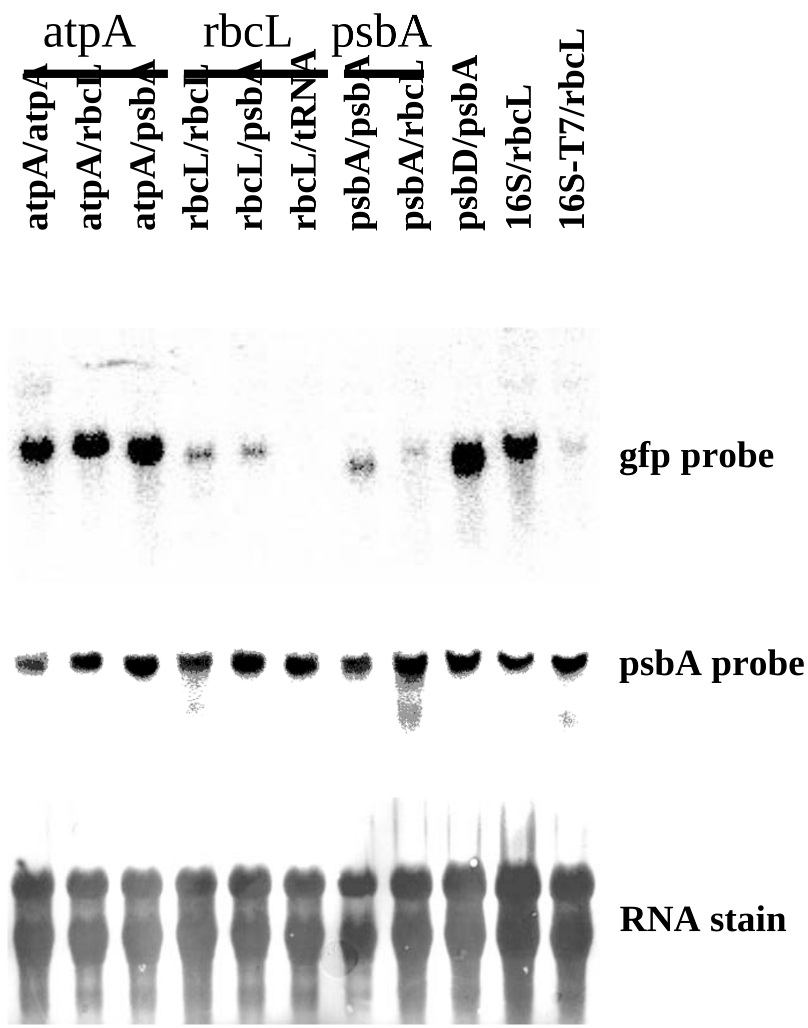
Analysis of codon optimized gfp expression in transgenic chloroplast



Promoter and UTR combinations for increased chloroplast expression

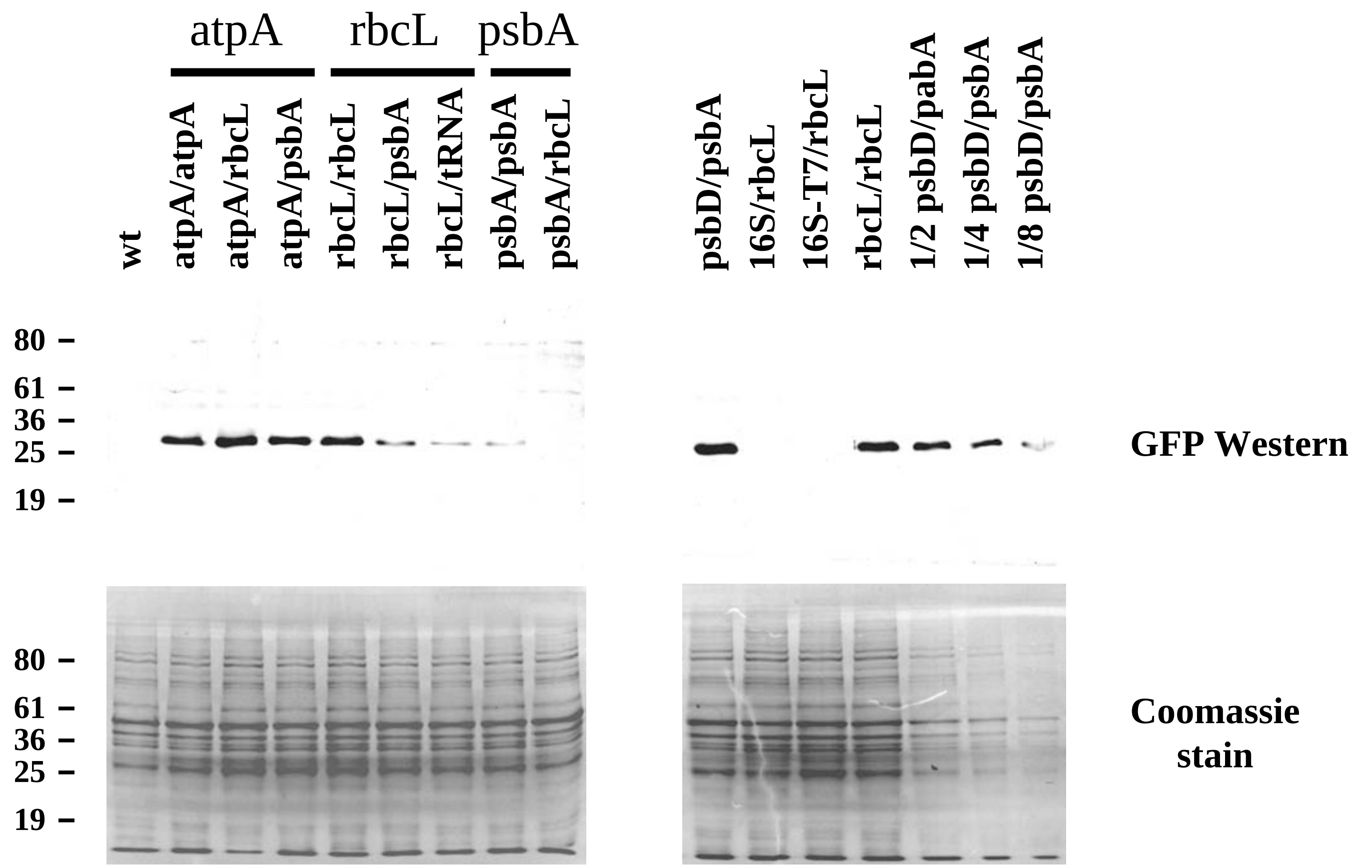


Accumulation of chimeric gfp mRNAs in *C. reinhardtii* chloroplast

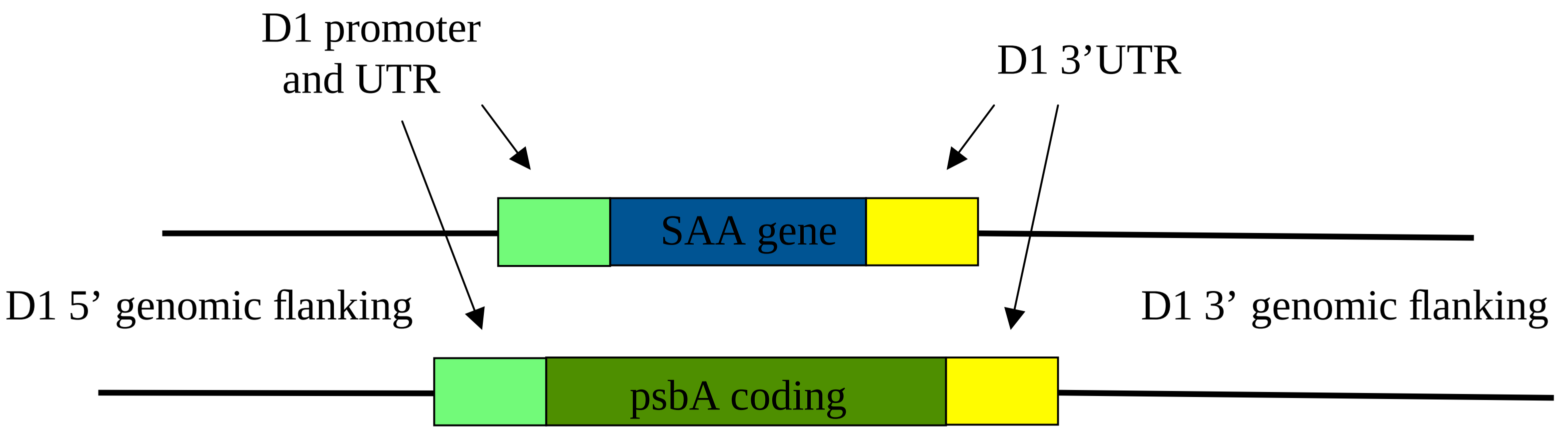


Northern blot

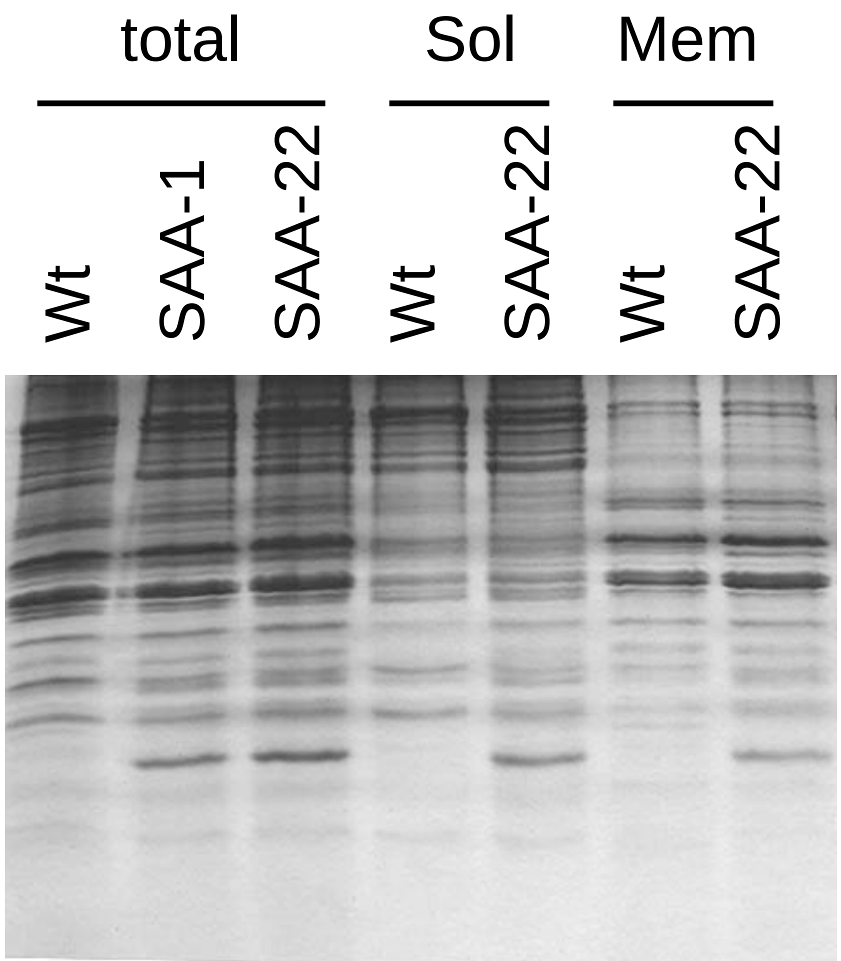
GFP accumulation in transgenic lines



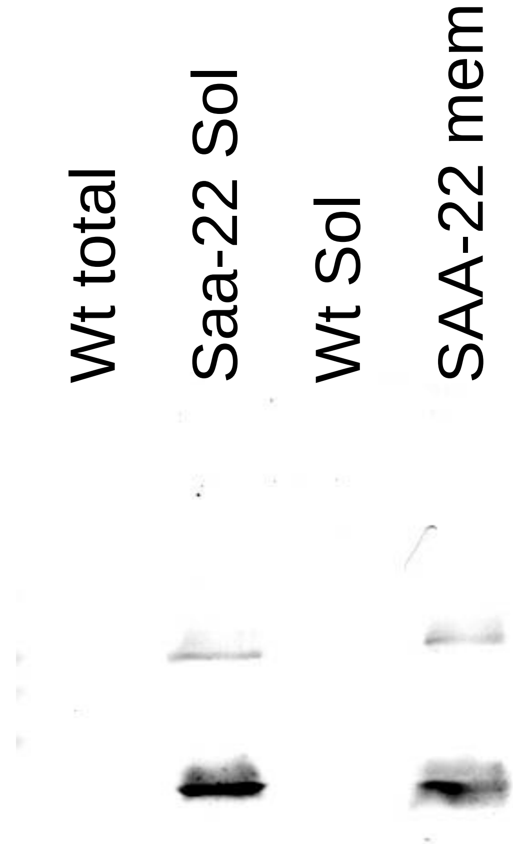
Gene replacement vector for improved Recombinant protein expression



Expression of SAA from *psbA* KO vector

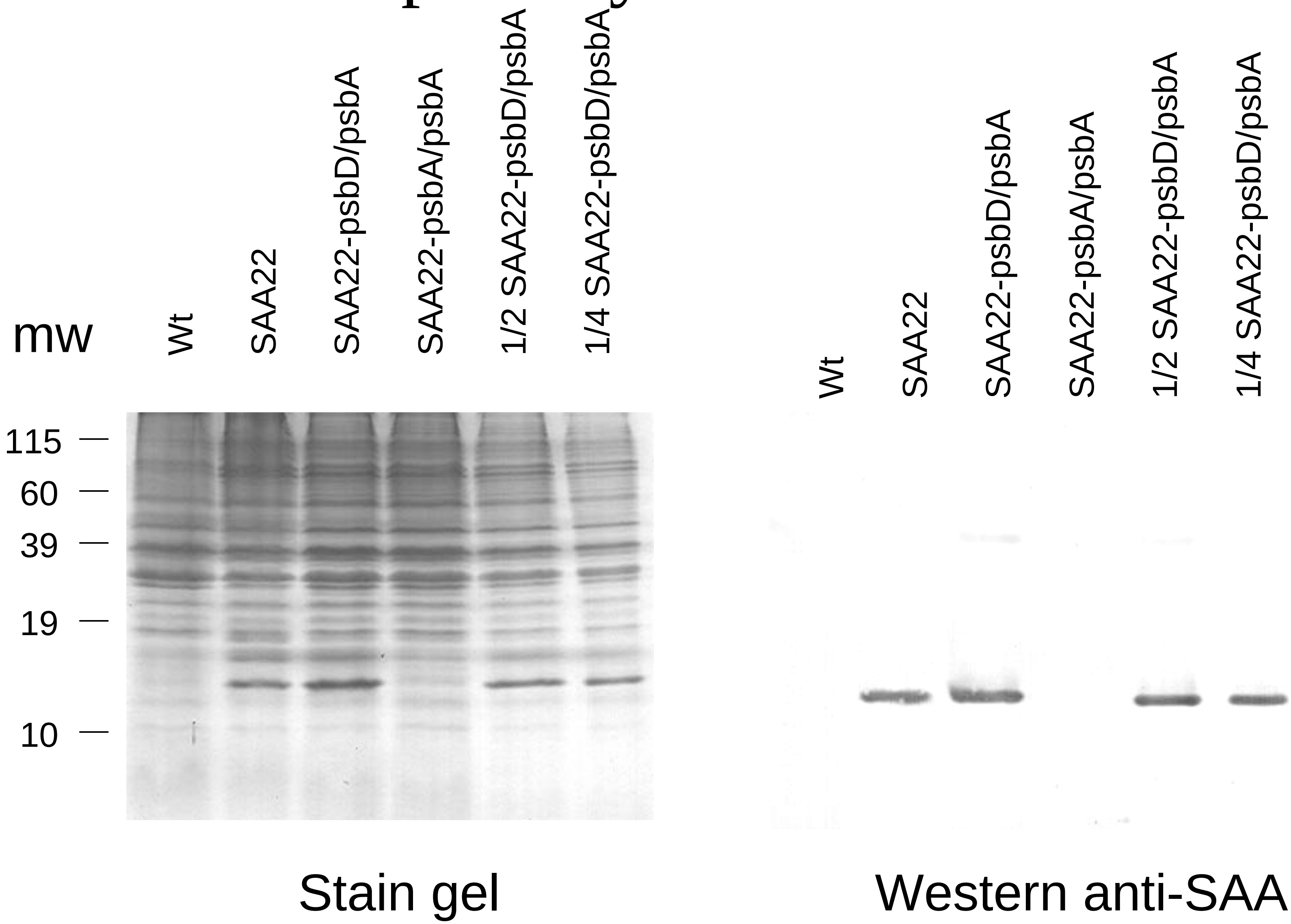


Coomassie stain gel

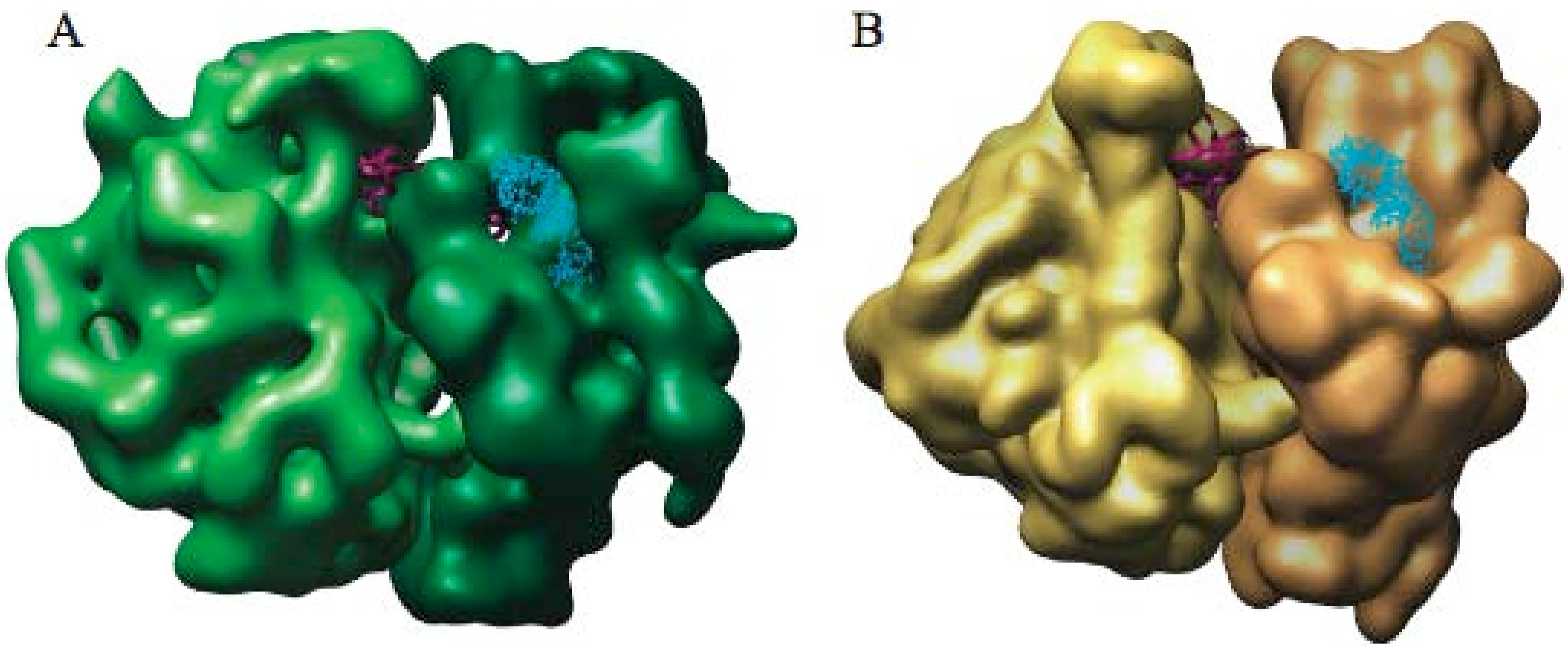


Western anti-SAA3

Robust expression of recombinant proteins in a photosynthetic strain



C. reinhardtii and *E. coli* mRNA binding site



Chloroplast Bacteria

Where do we go from here?

- We need a national center for algal research
- Develop the knowledge base of algal
- Develop the molecular tools to make algae a biotechnology platform
- Develop strains of algae for economic biofuel production
- Develop industrial practices for growth harvest and recovery of biofuel