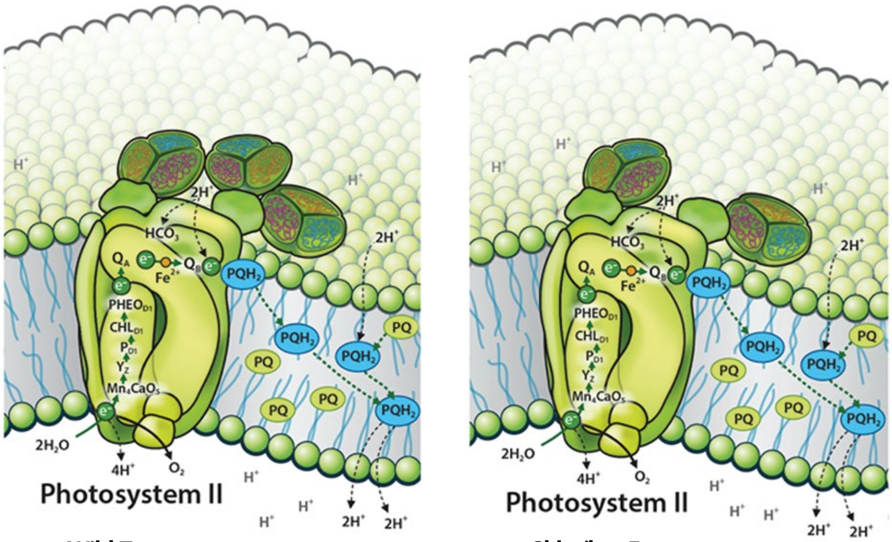
Optimising the photosynthetic efficiency in plants and green algae for biomass production

Algae and plants use photosynthesis to harvest the light energy from the sun, allowing them to trap gaseous carbon dioxide and convert it into biomass. One of the major constraints limiting biological carbon capture and biomass production in plants and algae is the low thermodynamic efficiency of photosynthesis. Dr Richard Sayre and his team from the New Mexico Consortium have shown that the thermodynamic efficiency of photosynthesis can be increased in bio-engineered photosynthetic organisms by altering the size of the light-harvesting antenna complex (LHC).

During photosynthesis, plants and green algae will absorb light at a very fast rate, but the apparatus responsible for converting the solar energy into a stream of electrons will work at a considerably slower pace. Eventually, some of the light energy absorbed will be harvested during this process of electron transfer, but up to 75% of the energy captured at full sunlight intensity will be wasted in the form of heat or fluorescence. This loss occurs when the electron transport chain is saturated, contributing to the low thermodynamic efficiency of photosynthesis. Dr Richard Sayre from the New Mexico Consortium has an extensive publication record in the production of genetically modified plants and microalgae that are optimised for maximum photosynthetic efficiency.

Dr Sayre and his team have shown that the efficiency of photosynthesis in microalgal cultures can be increased by partially reducing the cross-section of the light-harvesting antenna complex (LHC). The LHC consists of proteins and photosynthetic pigments, including chlorophyll b (Chl b) and chlorophyll a (Chl a). In a paper published in 2012, Dr Sayre and his collaborators demonstrated that there is an inverse relationship between Chl a/b ratios and the size of the LHC. A reduction in Chl b content relative to Chl a content yielding a Chl a/ Chl b pigment ratio of 5 is optimal for photosynthetic efficiency. Higher or lower Chl a/ Chl b ratios are less efficient.



Wild Type **Chl a/b = 5**

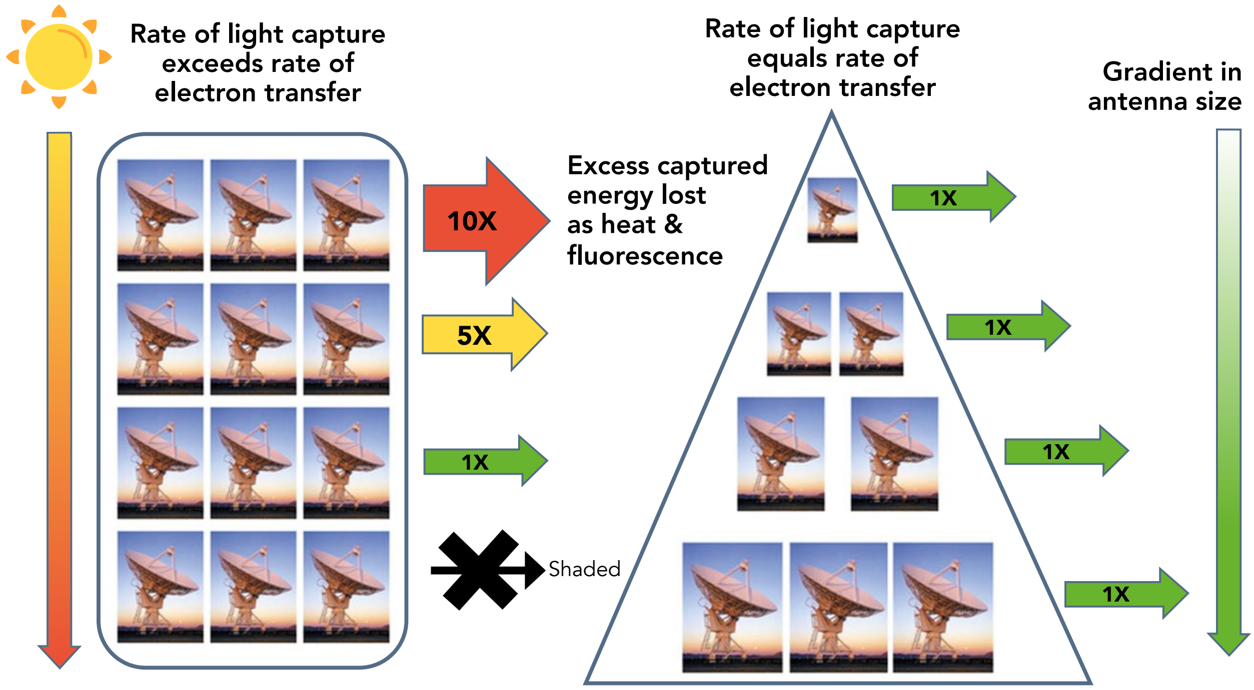
At a Chl a/b ratio of 5, the reduction in LHCII content corresponds to the loss of one PSII-LHCII trimer lines based on analysis of relative Chl content in LHCII supercomplexes.

ENGINEERING ALGAE TO MAXIMISE LIGHT UTILISATION

Higher energy prices and increasing emissions of CO_2 in the atmosphere have driven the scientific community to develop renewable sources of energy by using photosynthetic systems capable of converting CO_2 into biomass. By using varying levels of light intensity to regulate Chl b levels, Sayre's lab demonstrated that it is possible to adjust LHC sizes so that they are smaller when algae are grown in high light intensity conditions and larger when grown in low light, increasing the dynamic light range for efficient light harvesting and utilisation.

The team found that the dynamic control of the LHC size in algae can be achieved by a protein, NAB1, that acts as a gene expression repressor which effectively regulates the synthesis of Chl b. The abundance and activity of NAB1 correlate positively with light intensity. At higher levels of light intensity, NAB1 downregulates the expression of Chl b, which in turn decreases the size of the LHC, optimising the photosynthetic efficiency. Vice versa, in conditions of low

Optimal light-harvesting antenna sizes for enhanced fitness in differing environments



light intensity, the low activity of NAB1 results in increased Chl b levels and an increase in the size of the light-harvesting antenna complex, increasing culture productivity at low light conditions.

These findings have important implications for producers of algal biofuels. Engineering algae to be able to adjust their light-harvesting antenna size continuously to maximise light utilisation efficiency can lead to improved photosynthetic rates and greater yields in biomass accumulation. This means that biofuels could be priced competitively when compared with other products obtained with petroleum-based finite resources.

MODIFYING PLANTS TO IMPROVE CROP YIELDS

One of the most significant findings in the work of Dr Sayre is that the same principles described for antenna manipulation in algae hold in plants. Dr Sayre and his team published a study in 2019 reporting their findings on *Camelina sativa*, a member of the *Brasicacee family* of plants. *Camelina sativa* has emerged as a promising biofuel feedstock due to its adaptability to different climates and for its low water, fertiliser, and pesticide requirements. The study revealed that plants having an upper canopy leaf Chl a/Chl b ratio of near 5 had the highest photosynthetic and biomass production yields. Overall, the results were strikingly similar to those observed in algae. Plants with optimised antenna sizes were shown to perform well not only in controlled greenhouse conditions

The efficiency of photosynthesis in microalgal cultures can be increased by partially reducing the cross-section of the light-harvesting antenna complex (LHC).

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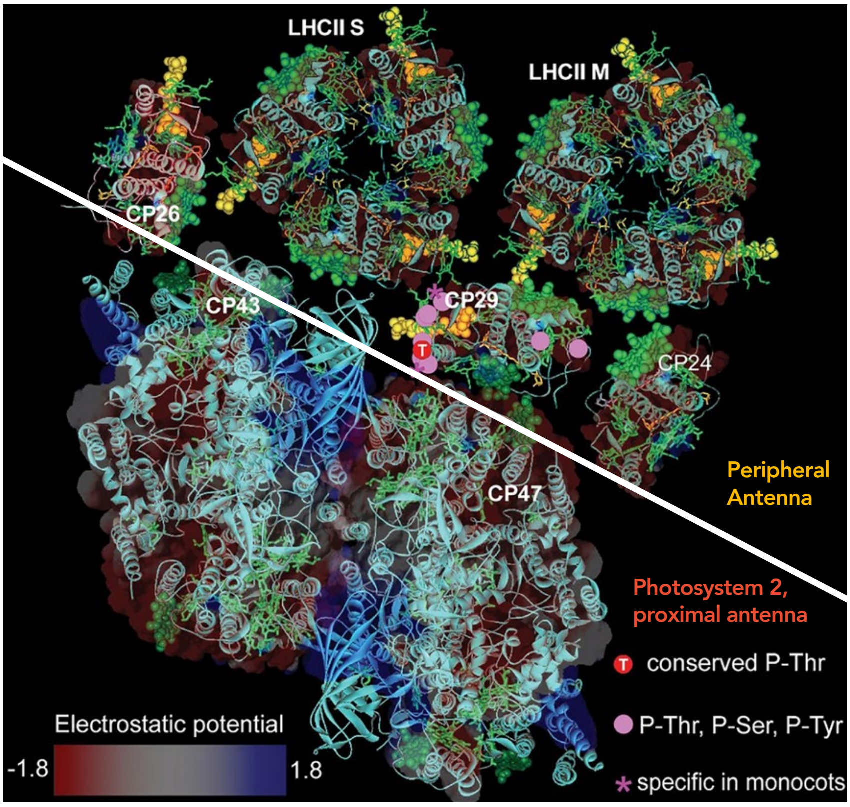
Camelina sativa is a promising biofuel feedstock.



Organisation of the light-harvesting antenna: The peripheral light-harvesting antenna binds 75% of all chlorophyll (Chl a and Chl b) but 100% of the chlorophyll b. Blocking Chl b synthesis destabilises light-harvesting antenna complexes resulting in a reduction in peripheral light-harvesting antenna size.

but also in the field, achieving a 40% increase in biomass yield.

Dr Sayre recently filed a patent after showing that plants can be genetically engineered to artificially modulate their light-harvesting complexes in response to light intensity. The transgenic plants produced following Dr Sayre's method have improved rates of growth and starch accumulation when compared with wild type plants when grown under similar environmental conditions. The patent describes the self-adjusting LHC size system in plants and shows it works the same way as in algae. Biomass yields for engineered *Camelina* plants were double the yields of wild plants grown in the same field. The findings have substantial implications for improving crop yields, reducing the environmental impact of agriculture on the globe, as less land would be required for increased production of crops.

Biofuels could be priced competitively when compared with other products obtained with petroleum-based finite resources.

THE USE OF ALGAE FOR CARBON SEQUESTRATION

One advantage of producing algal biomass is the ability of microalgae to capture CO_2 from ponds. Optimising algal biomass production and carbon sequestration has the potential to address the global threat of climate change associated with greenhouse gas emissions. To have the most significant impact on the reduction of greenhouse gas emissions, CO_2 must not only be captured but also sequestered over very long periods of time.

The use of algae is a particularly attractive option not only for their high rates of carbon capture but also for their ability to store carbon as lipids. While not generally considered as a carbon sequestration material, lipids have several advantages over solid CO_2 as a carbon sequestration material.

Triacylglycerol (TAG) extracted from algae using low-energy-harvesting and extraction processes could be injected into geologic formations to 'lock' the carbon in place. Algal lipids stored this way could potentially be used as long-term energy reserves and are easily handled as liquids. Burying TAG does not carry the risk associated with the potential escape of gaseous CO_2 from geologic formations. Also, because TAG does not contain elements other than carbon, hydrogen and oxygen, there is no risk of loss of inorganic nutrients that could threaten the aquatic ecosystems. Moreover, triacylglycerol is 77% carbon by mass and has a density of 0.91 g/cm^3. In contrast, CO_2 is 27% carbon by mass and as a solid has a density of 1.96 g/cm^3. Thus, lipids have a volumetric carbon density that is 32% greater than solid CO_2.

FUTURE PERSPECTIVES

With the ever-increasing challenges posed by global warming, there is a growing need to provide alternatives to fossil fuels that are sustainable and economically viable. Dr Sayre and his team have successfully engineered green algae and *Camelina* plants so that their light-harvesting capabilities can be optimised for maximal growth and biomass productivity. They have shown that the thermodynamic efficiency of photosynthesis can be optimised by modifying the size of the photosynthetic light-harvesting antenna complex. This, in turn, can be achieved by altering the ratio of the photosynthetic pigments, chlorophyll a and b. The team at Dr Sayre's lab has also produced several studies that suggest that capturing CO_2 by algae and storing it in the form of lipids could be a potentially viable strategy for mitigating CO_2 emissions. Dr Sayre suggests that from life cycle analyses, it can be predicted that the costs for capturing carbon and producing liquid biofuels from algae may soon approach the costs of producing petroleum-based fuels.

Behind the Research

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Research Objectives

Dr Sayre is optimising the thermodynamic efficiency of photosynthesis by altering the size of the photosynthetic light-harvesting antenna complex (LHC).

Detail

Richard Sayre
New Mexico Consortium

Bio

Dr Richard Sayre has had a diverse professional career ranging from academics to non-profits, national laboratories, and the private sector. He has also managed a wide range of research consortiums. His current research interests include bioenergetics, plant metabolic engineering, renewable fuels, and plant and animal disease management using RNA interference.

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Collaborators

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Personal Response

How will you further develop this research?

" There is still substantial opportunity to further increase photosynthetic efficiency and biomass yield. The factors limiting the rate of photosynthetic electron transport can potentially be modified to increase light utilisation efficiency. In addition, enhancements in photosynthetic carbon metabolism and storage have the potential to increase biomass yields. Overall, it is possible to increase photosynthetic rates five-fold by combining improvements in light use as well as carbon capture and storage efficiency.

Your findings indicate that reducing the size of the light-harvesting antennae results in increased efficiency of photosynthesis. Could you explain why plants have evolved to increase the size of the antennae, which implies a loss in photosynthetic efficiency?

There are two potential fitness advantages for having a large, less efficient light-harvesting antenna. Plants with a large antenna will compete more efficiently for light and shade, promoting their growth and reproduction. The second potential advantage is the ability to carry out sufficient photosynthesis to reproduce under very low light conditions. In fact, algae living at great depths in the ocean where light intensities are extremely low have the largest light-harvesting antenna of any known algae. "