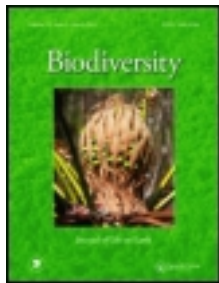


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Publisher: Taylor & Francis

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## Biodiversity

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/tbid20>

### 37. Spirulina - food for the universe

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Available online: 16 Jan 2012

To cite this article: Ernest Small (2012): 37. Spirulina - food for the universe, Biodiversity, DOI:10.1080/14888386.2011.642735

To link to this article: <http://dx.doi.org/10.1080/14888386.2011.642735>



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## BLOSSOMING TREASURES OF BIODIVERSITY

### 37. Spirulina – food for the universe

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#### Introduction

Several crises are endangering the ecosystems, atmosphere and biodiversity of the world. The problems are caused substantially by the current needs to expand food production and to harvest fossil fuels for energy. For several decades, Spirulina species, which include some of the tiniest and most primitive organisms on Earth, have been slowly gaining significance as possible players in mankind's quest to live more sustainably in relation to the planet's finite resources. These species have the potential to produce both food and biofuel far more rapidly and efficiently, and with a much smaller environmental footprint, than conventional crops. The phrase 'food of the future' has become associated with these extraordinary microscopic organisms, and very recently they have been considered as key resources for human colonisation of the universe. As our environmental and associated societal problems continue to deteriorate, it is important that society becomes more familiar with the use of Spirulina to alleviate some of our most pressing issues.

#### What is Spirulina?

Spirulina species are photosynthetic bacteria, commonly called 'blue-green algae'. As detailed below, the word 'Spirulina' refers to two distinct genera, *Spirulina* and *Arthrospira*, but it is mainly *A. platensis* and *A. maxima* that constitute the Spirulina of commerce. These species have cylindrical cells joined to form microscopic unbranched filaments that are usually distinctively helical. The cells are typically 3–5 µm in diameter (a micron, abbreviated µm, is one millionth of a metre, i.e. 0.001 mm, equivalent to 0.00004 inch) and the filaments are up to 500 µm long. Spirulina individuals are too small to see with the naked eye, but a large number together can be observed as 'pond scum', clumps or mats. The filaments are typically free-floating in their usual aquatic environments, and

sometimes they are motile, gliding with a rotation along their axis. Some species have tiny gas vacuoles inside the cells, which contribute to buoyancy. The filaments grow by cellular division (binary fission) occurring crosswise to the axis. The species reproduce by fracture of the filaments into small chains of cells (breakage occurs by a cell sacrificing itself and dying to release the adjacent sections of the filament). Sexual (biparental) reproduction as occurs in higher organisms is unknown, but 'horizontal gene transfer' (acquisition of genes by an organism from an individual that is not its parent) is well known in bacteria, and may occur in Spirulina. Like other photosynthetic, planktonic organisms, Spirulina can grow rapidly to form huge floating populations ('blooms') under the right environmental conditions.

#### Classification

In the last 2 decades, genetic research has greatly clarified how life on Earth has split into major groupings. Although much remains to be examined, the predominant view at present is that (aside from viruses), three fundamental groups (usually termed 'domains') deserve recognition. This has revolutionised thinking about the origin, classification, relationships and nature of living things, and several words referring to large groups of species have undergone revision or have become obsolete. Although the term 'kingdom' is still commonly used, it is increasingly being abandoned. This is related to the difficulty of defining the so-called plant and animal kingdoms. 'Animals', by and large, have been considered to have the power of movement (at some point in their life cycle), and to be heterotrophic (i.e. to acquire energy by consuming other species); 'plants' by contrast, have been considered to be stationary and to be autotrophic, i.e. to acquire energy from the sun by photosynthesis. A third so-called kingdom, the fungi, was typically defined as

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Figure 1. Spirulina (*Arthrospira platensis*). Photo courtesy of D.R. Nobles Jr. and S.O. Peña, UTEX Culture Collection of Algae, University of Texas at Austin.

non-motile organisms that acquired energy from decaying creatures or by parasitism. Still another term, 'protists' or 'protozoans' (terms that are now obsolete), referred to unicellular creatures with the animal-like abilities to move and consume materials in their surroundings. 'Algae' referred to photosynthetic organisms with quite primitive characteristics compared to the flowering plants and their near-relatives. 'Bacteria' as traditionally understood have been shown to be made up of unrelated groups. All of these terms have proven to be inadequate in their traditional senses. However, most of the difficulties have arisen because biologists have re-assessed the relationships of the 'primitive' mostly microscopic species that are quite unfamiliar to most people; accordingly, it seems certain that words like plant and animal will continue to be used. Are the Spirulina species highlighted in this article plants? Strictly no, they are photosynthetic bacteria, but in the context of food production, they serve the same purpose as familiar food plants. (Indeed, the unicellular alga *Chlorella*, which certainly is a plant, is cultivated very much like Spirulina.)

It is widely accepted that the cells of modern animals and plants contain organelles that arose from

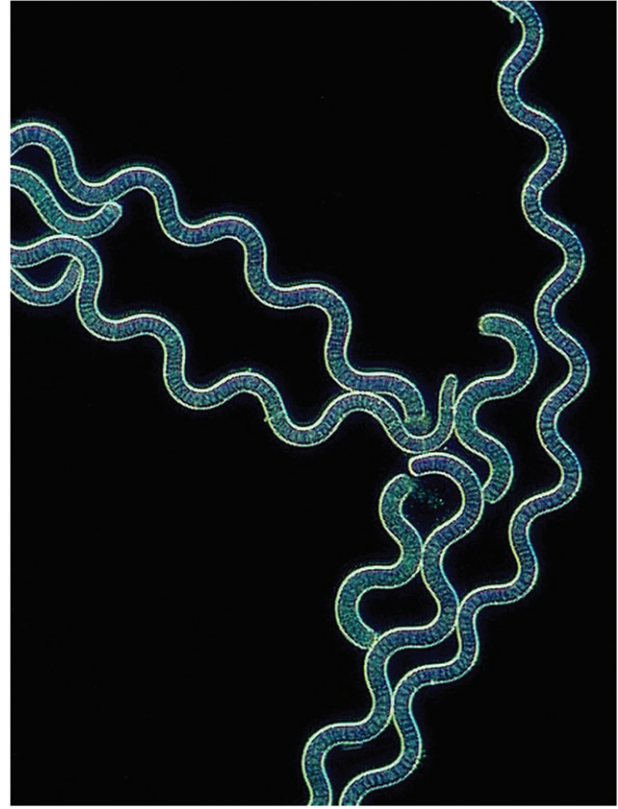


Figure 2. Spirulina (*Arthrospira maxima*), photo taken with dark ground illumination. Image by D. Patterson and R.A. Andersen, courtesy of microscope.mbl.edu.

bacteria in the very early evolution of life. By this 'endosymbiotic theory', photosynthetic plastids (in plants) were once cyanobacterial species (discussed below) that were engulfed by non-photosynthetic bacteria, the resulting symbiotic relationship proving advantageous for the evolution of more advanced multicellular species. (A bacterial origin is also postulated for mitochondria, the energy-producing organelles in advanced species, but the kind of species involved is unclear). Thus almost all cells of modern plants and animals (including humans) contain modified bacteria which are essential for life. Philosophically (or at least semantically) this makes it problematical to define plants and animals as distinctive from bacteria.

Spirulina species were until about 1970 considered to belong to a group of algae called (1) Cyanophyceae (the suffix 'phyceae' is the conventional way that botanists designate plant families); (2) Cyanophyta (the suffix 'phyta' designates a very large division of plants that usually contains several families); or (3) colloquially, the 'blue-green algae'. Over 4000 species have been described to date. Although most of the species are photosynthetic (like almost all plants), after it became evident that they are bacteria, the term

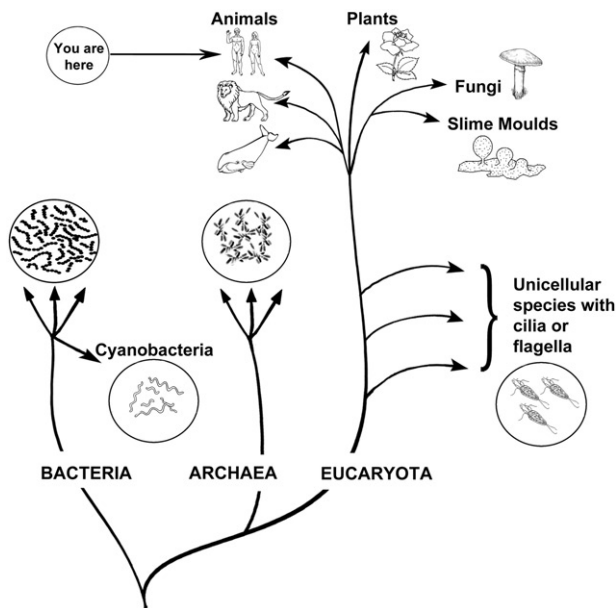


Figure 3. A simplified interpretation of the majority view of the evolution of non-viral life into three 'domains': Bacteria, Archaea and Eucaryota. The three groups are best defined by their biochemicals. The Archaea were recently split off from the Bacteria; individuals of both groups are microscopic and frequently are merely single cells. Only species of the Eucaryota possess a membrane-bound nucleus; although some of these organisms are microscopic, virtually every species visible to the unassisted eye belongs to this group. Photosynthetic species occur in some species of all three domains. Figure prepared by B. Brookes.

'Cyanobacteria' became standard (less frequently, the phrase 'blue-green bacteria' is employed). The colour is indeed often cyan or blue-green, but species that are red, green and brown are also known. The photosynthetic pigments that produce the colour are diffused throughout the cells, not in plastids as in the true or higher plants. Some of the species occur as independent cells (i.e. they are unicellular), and others are colonial, particularly in the form of filaments (i.e. attached end-to-end like the cars of a train).

The Cyanobacteria as well as other bacteria are thought to represent the first life forms to inhabit Earth, from which all of the world's biodiversity arose. Many of the species seem to be virtually unchanged from fossils dating back 3.5 billion years, which represent the oldest known life on Earth. It has been speculated that Cyanobacteria arrived as extraterrestrials billions of years ago, and founded life on our planet. The Cyanobacteria were the first organisms capable of converting atmospheric carbon dioxide into carbon compounds using water in the process and producing oxygen. Thus they are responsible for having produced the present oxygen-rich atmosphere of the world that permits animals, including humans,



Figure 4. Intertwined filaments of a *Spirulina* species. The very tightly coiled helix indicates this is a *Spirulina*, not an *Arthrospira* species. Photo taken with phase contrast microscopy. Image by D. Patterson, courtesy of microscope.mbl.edu.

to exist. It has been argued that, because Cyanobacteria occupy a wider variety of habitats than any other group, they are the most successful microorganisms on Earth.

In 1932, the Austrian biologist Lothar Geitler combined all cyanobacterial species that formed helical trichomes into one genus, *Spirulina*. However, it has been shown that there are two distinct genera with helical trichomes, *Spirulina* and *Arthrospira*. Unfortunately the common name 'Spirulina' has persisted for species of both *Spirulina* and *Arthrospira*. The important economic *Spirulina* species belong to *Arthrospira*, not *Spirulina*, and so it is important to distinguish species called by the vernacular name *Spirulina* from species called by the scientific name *Spirulina*. Species of both genera are more or less helical (but occasionally have just straight filaments), and often occur together. In *Spirulina* species the cross walls separating the cells are very difficult to see under a light microscope, while in *Arthrospira* species they are readily apparent, and there are more or less pronounced constrictions of the filament at the cross walls. *Arthrospira* tends to have more loosely coiled spirals or



Figure 5. Lesser Flamingos (*Phoenicopterus minor*) in the Ngorongoro Crater, Tanzania. Carotenoids in the *Spirulina* species that the birds eat are responsible for the pink coloration of their feathers. Photo (online at Wikipedia) by C.J. Sharp, GNU Free Documentation License.

a merely sinuous form in comparison with *Spirulina*. The number of species in these genera is uncertain, and indeed so is the separability of the two principal economic species, *A. platensis* and *A. maxima*, from other species currently recognised in *Arthrospira*.

### Geography and ecology

*Arthrospira platensis* is widely distributed, especially in Asia, Africa and South America; *A. maxima* is thought to be native to California, Mexico and Central America. *Spirulina* species have been found in various environments, including soil, sand, marshes, saline lakes, brackish water, sea water and fresh water. *Arthrospira* filaments may be solitary and free-floating (planktonic), or grouped into slimy sea-bottom (benthic) clumps. The species grow particularly well in soda lakes (which have high levels of sodium carbonate and sodium bicarbonate) that are astonishingly alkaline (the pH up to 11), in tropical and subtropical regions of the world. *Spirulina* is an alkaliphile (adapted to alkaline conditions), a thermophile (adapted to extremely hot conditions), a halophile (adapted to salty water) and an extremophile (adapted to conditions too extreme for most life forms). The harsh chemistry of soda lakes prevents the growth of most other organisms, so that *Spirulina* often grows in more or less pure cultures. The photosynthetic output of some *Spirulina* lakes has been reported to be among the most

productive natural systems on Earth. *Spirulina* grows normally in sunlight, but like many Cyanobacteria, the species have been found to be capable of growing in the dark when supplied with certain organic nutrients (glucose for some species, fructose for others). Like most unrooted, submersed aquatic plants, *Spirulina* absorbs carbon dioxide and minerals dissolved in the water, along with the water itself, as the raw chemicals with which, through photosynthesis and other biochemical pathways, it constructs itself. Many bacteria (especially Cyanobacteria) are capable of fixing nitrogen from the air or dissolved in water (i.e. converting the inert gas to nitrogenous compounds that can be metabolised), but not *Spirulina* species. Nitrogen-fixing microorganisms provide most of the nitrogenous compounds that are essential for growth of higher plants and animals (and *Spirulina* as well).

In Africa, huge populations of flamingos often consume most of the *Spirulina* in soda lakes, and rely on it for sustenance. The Lesser Flamingo is so dependent on *Spirulina* that when the supply becomes disastrously reduced so does the bird. Carotenes (especially  $\beta$ -carotene, i.e. provitamin A, a precursor of vitamin A) are required for development of pink colour of plumage in the birds. Without consumption of the carotenes that are abundant in *Spirulina*, the feathers of the birds would be white. Flamingos are filter-feeders; complex rows of horny plates line the beaks, and are used to strain food items from water. The Lesser Flamingo's filtration apparatus is divided



Figure 6. A raceway pond for the production of photosynthetic microorganisms. A paddlewheel circulates the water, exposing the microorganisms to uniform light and promoting rapid growth. Photo (online at Wikipedia) by JanB46, Creative Commons Attribution-Share Alike 3.0 Unported License.

so finely that it can sieve single-celled organisms from water. Certain cultured crustaceans (e.g. the red-bodied Black Tiger Prawn, *Penaeus monodon*) and Koi species (ornamental varieties of the Common Carp, *Cyprinus carpio*) can also convert  $\beta$ -carotene to reddish pigments that are admired by people, and Spirulina is an extraordinarily rich source of the needed carotenes. Carotenoids also enhance the yellow colouration of commercial eggs, and the flesh of broiler poultry. Humans can develop yellowish skin by excessive intake of carotenoids, for example by consuming huge amounts of carrots or carrot juice (a normally harmless condition called carotenosis), but Spirulina is eaten in such small quantities by people that this does not occur.

#### Wildcrafting (harvest from nature)

Spanish conquistadors in 1521 observed *Arthrospira maxima* being harvested from Lake Texcoco in the Valley of Mexico, and sold for human consumption in markets in Mexico City. The Spanish reports are regarded as the first recorded use of Spirulina as food. Curiously, the first modern commercial production of Spirulina was from the same lake in the 1970s. In the 1940s, native peoples in the Republic of Chad in Africa were reported to be harvesting *A. platensis* from lakes.

However, African use of Spirulina likely dates to very old times. Although ancient documents recording this are unavailable, it is thought that Spirulina harvesting by aboriginal peoples occurred in North Africa at least since the ninth century. In modern times, collection of *Spirulina* from natural lakes is uncommon.

#### Cottage industry (small-scale) production

Small-scale Spirulina cultivation by rural poor people of tropical and subtropical developing nations has been advocated as a way to produce a nutritional supplement to alleviate hunger and reduce infectious disease. Recycled village wastes and industrial effluent are often employed for the purpose, and cultivation may be as simple as growing the bacterium in clay pots. Spirulina cultivation can be established quickly under emergency famine conditions. Of course, such non-commercial production poses an increased risk of introduction of toxic materials, but properly carried out it has proven to be effective.

#### Commercial Spirulina production

Spirulina is now grown on an industrial scale. It is adapted to high light intensity and high temperatures (ideally 35–38°C, or 95–100°F). Most cultivation is in



Figure 7. Dried Spirulina. Photo (online at Wikipedia) by Music4thekids, Creative Commons Attribution-Share Alike 3.0 Unported License.

outdoor, open ponds (closed bioreactor production is also possible), and such production is best conducted in areas with minimal precipitation (i.e. in dry climates, especially deserts) to allow close control of water chemistry. Spirulina is usually grown in large, open-channel, shallow 'raceway ponds' (so-named for their resemblance to equestrian raceways), a system developed in the 1950s for outdoor mass cultivation of photosynthetic microorganisms. Such systems typically are 15–40 cm (6–100 inches) in depth, with a paddle-wheel forcing the water around a track. Spirulina is produced in many countries, including several African countries, Argentina, Burma, Chile, China, Cuba, Greece, India, Israel, Japan, Mexico, Myanmar, Pakistan, Spain, Taiwan, Thailand, the US (California and Hawaii) and Vietnam. At present commercial production is most successful in areas of the world with very warm or hot, long-season climates that permit production to continue for all or most of the year. Current world production is uncertain – published estimates ranging from 2000 to 40,000 metric tons annually in China alone, and perhaps as much in the remainder of the world.

#### Food usage

Among the varied products in which dried, flaked, or powdered Spirulina is now incorporated are: baked desserts, beer, breakfast cereals, confectionary, corn chips, crackers, doughnuts, food bars, frozen desserts, juice smoothies, muffins, pasta, popcorn, salad dressing, snack foods, and soups. Several cookbooks dedicated to Spirulina have been published. Usually Spirulina's taste does not justify serving it as a

stand-alone item, and it is normally used in relatively small amounts at meals, and mixed with other foods. Normally when Spirulina is employed as a nutritional supplement, no more than 15 g (0.5 ounce) per day is recommended or consumed.

So-called 'functional foods' are food preparations fortified with exceptionally nutritional additives; 'nutraceuticals' are nutritional additives or supplements, and are typically plant extracts. Spirulina is a legitimate material for both nutraceuticals and functional foods. Dried Spirulina alone has been sold both as a nutraceutical and as a functional food. Several nutritional extracts from Spirulina are marketed as nutraceuticals. For example, the fatty acid gamma linolenic acid can be extracted from Spirulina, and is known to be beneficial for treatment of several human deficiency diseases. The photosynthetic pigment phycocyanin can also be obtained readily from Spirulina, and is commonly employed in the food industry as a food colorant, emulsifier, thickener and gelling agent.

Spirulina differs from virtually all land crops harvested for human consumption in that the entire crop is edible, not just fruits, or seeds, or leaves, or underground storage organs as in conventional crops. Moreover, the cell wall is not constructed of indigestible cellulose as in true plants: it is typically composed of more than 60% protein (dry weight basis), as well as carbohydrates and fats, and is easily digested. The protein has a good balance of amino acids, but reduced amounts of methionine, cysteine and lysine; the amino acid balance is superior to most plant protein (which is usually quite deficient in one or more amino acids) but inferior to the complete protein of animals.



Figure 8. Spirulina tablets. Photo (online at Wikipedia) by Perdita, released into the public domain.

#### **Treatment of waste and contaminated water**

Spirulina has been demonstrated to absorb some heavy metals. Even dried but rehydrated Spirulina has been experimentally shown to be capable of effectively removing copper and cadmium from water. Accordingly Spirulina is considered to be potentially useful for treating water contaminated by metals. Also, like many aquatic plants, Spirulina can utilise a variety of elements and compounds that occur in wastewater, and so can also reduce the presence of these materials.

#### **Health benefits**

Spirulina in the form of tablets and capsules is widely marketed as a dietary supplement, with an extremely wide range of alleged medical and health benefits. For example, it has been described as anti-inflammatory, antioxidant, hypolipidemic (cholesterol-reducing), protective against some cancers, and able to enhance the immune system, increase intestinal lactobacilli, reduce kidney toxicity from heavy metals and drugs, and reduce obesity. Unfortunately as is so often the case with new or unfamiliar products, exaggerated nutritional and medical claims have been made by marketers, and indeed sometimes also by scientists with

interests in the success of the product. Spirulina does have excellent nutritional properties: high content of protein, and good content of vitamins, minerals, fatty acids, and antioxidants. It is a good, but not a 'wonder food' (a misleading marketing phrase). The numerous claims of medical benefits are largely based on animal studies, but Spirulina has not been established to be useful for treating most human illnesses in comparison with current standard treatments. However, Spirulina has been fed extensively to malnourished children, and has proven to be an excellent supplement for restoring them to nutritional health. Intriguingly, Africans living close to soda lakes where Spirulina has been naturally available have shown less malnutrition than those without this special nutritional source. Following a world food conference that declared Spirulina to be the 'best food for the future', in 1974 the United Nations established IIMSAM (The Intergovernmental Institution for the Use of Micro-Algae Spirulina Against Malnutrition).

#### **Health cautions**

As with all products marketed as food or dietary supplements in technologically advanced nations, safety standards have to be satisfied. Because some



species of Cyanobacteria are extremely toxic, *Spirulina* species have been carefully examined for toxicity. *Spirulina* has not been found to be toxic, but care needs to be exercised in production to ensure that toxic organisms are not introduced, and that potentially poisonous materials, such as heavy metals, are kept out of the water used for culture. Thus it is critical that *Spirulina* be obtained from reliable sources. The safety of *Spirulina* to date has been established using laboratory animals, not humans. Nevertheless there is a high degree of confidence that its use by humans and animals is safe, based both on the animal studies and on anecdotal observations of human consumption over the last several decades. The US Food and Drug Administration has categorised *Spirulina* as GRAS (Generally Recognised as Safe). As with all foods and food supplements that have not been consumed before, consumers should be cautious when first sampling *Spirulina* to ensure that they do not experience a negative reaction.

#### **Livestock feed usage**

*Spirulina* is widely used as an animal feed supplement. About 30% of world production is fed to livestock. *Spirulina* is also often fed to aquarium and aquaculture creatures (e.g. fish, abalone, shrimp and prawns), especially those that consume algae in the wild. It has also proven to be a useful feed addition for poultry, and has been shown to be healthy for mammalian livestock. As noted above, the carotenoids in *Spirulina* contribute to yellowish or reddish pigmentation that consumers admire in several seafood and poultry species.

#### **Biofuel production**

There has been enormous interest in the last decade in employing renewable, land-based biofuels to replace fossil fuels. Unfortunately there are two major and very controversial problems with the use of terrestrial crops as energy sources: (1) most current biofuel crops are agricultural food crops, and even if not they usually utilise agricultural lands that could be used for food production; the resulting diversion from food to fuel production has contributed to a rise in food prices; (2) natural ecosystems are being cleared to provide land on which biofuel crops are grown, endangering biodiversity.

Cyanobacteria (and also unicellular algae) can be high-yield sources of lipids usable as biodiesel, fermentable biomass (starch and other carbohydrates) usable as ethanol, and even hydrogen which can be used directly as a fuel. Photosynthetic production

(i.e. 'solar energy yield') is much more efficient (typically 6–12 times higher) in Cyanobacterial and unicellular algal crops than in conventional crops. Most importantly, arable land is not sacrificed for the production of biofuel, and when species that grow naturally in seawater are used, precious freshwater is not sacrificed. There is considerable technological development occurring to make biofuel production employing Cyanobacteria and unicellular algae profitable.

#### **Environmental advantages**

*Spirulina* production is energy efficient, needs only limited input of petroleum resources, requires much lower land utilisation, does not require arable land and does not require pesticides or herbicides. There is minimal discharge of materials to the environment, and an absence of environmental degradation such as soil erosion, water contamination and deforestation, as commonly encountered in conventional crop production. Also unlike conventional agriculture, *Spirulina* crops are much less dependent on the vagaries of the weather. The range of products potentially produced (food, medicines, industrial extracts, and biofuels) are indispensable for modern human existence, and production of such products in a more environmentally responsible fashion is extremely desirable.

#### **Environmental disadvantages**

On the negative side, when *Spirulina* is grown in open areas in hot, dry climates, evaporation is considerable, and so water is required (although less than for conventional crops when calculated on a protein yield basis). However, some cultivation systems can use sea or brackish water and even water contaminated by industrial wastes. *Spirulina* allows cultivation to occur in areas that are too saline, too alkaline, or simply too arid for conventional agriculture; this is economically desirable, but ecologically could represent a threat to the biodiversity adapted to such 'hostile' environments. However, so little land is required for *Spirulina* cultivation that this is unlikely to be of much concern. Very likely, *Spirulina* will be the subject of intensive genetic transformation, and it is probably impossible to contain such synthetic bacteria when they are grown outdoors; given the controversial nature of genetic engineering, this should be done with due attention to potential problems.



Figure 9. Spirulina as a possible key food for extraterrestrial life. Prepared by B. Brookes.

#### Exporting genetically engineered microbial biodiversity to other planets – introducing alien invaders?

Human colonisation of planets and other celestial bodies is just a matter of time. Perhaps the most daunting technological hurdle is how human needs will be met, particularly for food and energy, since conditions elsewhere are likely to be extremely hostile, and transportation of supplies from Earth is prohibitively expensive. The common conception that

conventional crops could be cultivated on other planets is appealing but probably unrealistic: microscopic photosynthetic species are much easier to employ. In particular, microbes like *Spirulina* that can thrive under conditions much too harsh for traditional crops may be critical for success. So-called 'extremophiles', defined as capable of life in extreme environments, are probably the key to success, because very hostile conditions prevail almost everywhere outside of our unique planet. These organisms are mostly Bacteria and Archaea (as discussed above), and include those that are adapted to freezing temperatures (such as arctic bacteria), very high temperatures (as in hot springs and hydrothermal vents), ionising or ultraviolet radiation (which can damage DNA), very salty water (halophiles), very high or very low pH, high or low pressure, limited water, and extreme gases (such as an atmosphere of carbon dioxide). Microbes like *Spirulina* that can transform human waste to food and energy would certainly be useful. Some might be valuable for generating hydrocarbon fuels (e.g. methanogens, which live on simple compounds and turn their waste into methane gas). Microbes that secrete acid (acidophiles) could be employed for extracting minerals. The possibilities are exciting but also intimidating, because even if there are microbes on Earth like *Spirulina* that could now serve the purposes of space colonisation, they can be enormously improved by genetic engineering. The fear is that such synthetic microbes might result in 'Frankenlife' that could invade and damage biodiversity on Earth and even natural forms of biodiversity on foreign planets. While this possibility is remote, it would seem to merit sober consideration.

#### Prospects

Commercial *Spirulina* cultivation has been increasing slowly since it was established several decades ago. *Spirulina* has become the leading photosynthetic aquatic microorganism cultivated for food, but currently represents only a very small proportion of the world's food. Yeasts (which are fungi) are more important microorganisms for food production, and are often cultivated in water. Macroalgae ('seaweeds') are also cultivated to a large extent in aquatic environments. However, most food crops are terrestrial plants. By comparison with all other food species, *Spirulina* may be the world's most efficient source of cultivated protein, which is indispensable for human nutrition. As a food plant, *Spirulina* is of principal significance today for alleviating hunger and

malnutrition which are still prevalent in many areas of the world. While quite digestible and very nutritious, the taste of *Spirulina* is not particularly attractive. It is quite feasible that genetic engineering could rapidly improve its taste as well as other qualities (particularly the ability to grow in colder climates), and in any event *Spirulina* is an excellent feed supplement for a wide variety of livestock. Economically, the food potential of *Spirulina* is huge, but awaits technological development.

In the context of biodiversity, *Spirulina* has outstanding ecological and environmental advantages that make it much more benign as a food and biofuel source compared to conventional crops. Indeed, as land and water become progressively scarcer for the conventional growth of plants, surely *Spirulina* will become

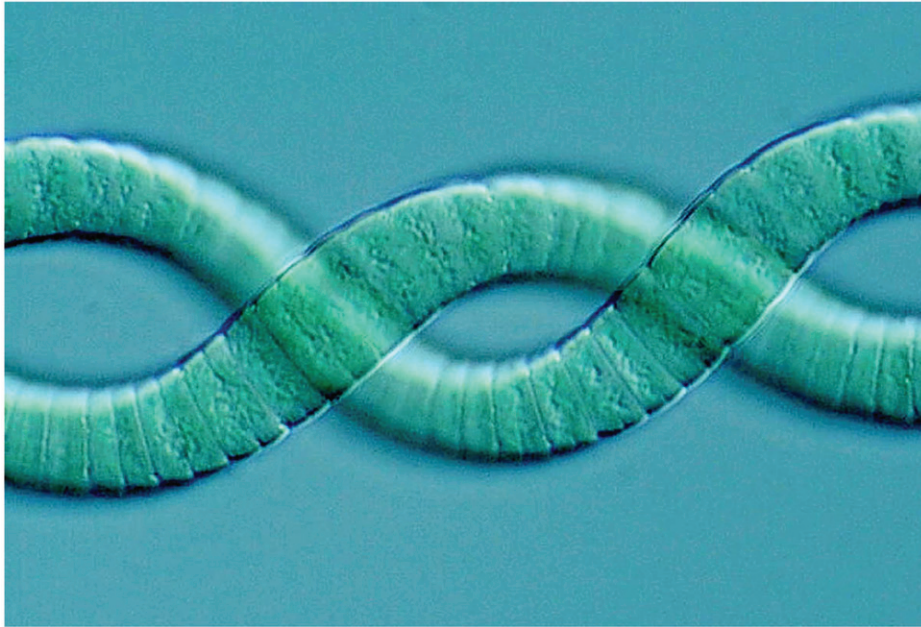


Figure 10. Spirulina (*Arthrospira maxima*), photo taken with differential interference microscopy. Image by D. Patterson and R.A. Andersen, courtesy of microscope.mbl.edu.

much more important. It is ironic that these extraordinarily primitive creatures that billions of years ago gave rise to all living life forms may now play a major role in preserving the quality and variety of modern life.

#### Believe it or not

- The spiral form of Spirulina is a 'left-hand helix', i.e. the helix coils anticlockwise viewed from either end, in contrast to a 'right-hand helix' which coils clockwise.
- Spirulina was employed by NASA (the US National Aeronautics and Space Administration) as a dietary supplement for astronauts on space missions. NASA and MELISSA (the European Space Agency) have proposed Spirulina as one of the primary foods to be cultivated during long-term space missions. It can even be grown in diluted human urine.
- Consistent with Spirulina's reputation for being protective against radiation, it was fed to victims of the Chernobyl nuclear power plant accident, the world's worst such occurrence, which occurred in the Ukraine in 1986.
- Cyanobacteria account for about a quarter of all of the world's photosynthesis.
- In the African country of Chad, pregnant women traditionally eat dried Spirulina in the

belief that its dark colour will screen their unborn baby from the eyes of sorcerers.

- It has been calculated that the amount of land necessary to satisfy the yearly protein needs of one human is about 5 ha (12 acres) for meat from cattle on grassland, slightly less than 1 ha (2.5 acres) for wheat, and about 10 m<sup>2</sup> (108 square feet) for Spirulina.

#### Acknowledgements

I thank Brenda Brookes for assembling the figures presented. The figure legends contain individual acknowledgments.

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