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Biofuels, facts, fantasy, and feasibility

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Abstract It is frequently claimed that green algae are intrinsically more productive, often by orders of magnitude, than higher plants commonly grown as crops for food. There is no firm evidence for this belief. On the contrary, there is much experience which shows that algae are not more but less productive. Under optimal conditions, all green organisms photosynthesize at the same rate in low light and, whilst commonly cultivated 'sun' species show some differences in rate in full light, these do not translate into widely different rates of accumulation of biomass. Accordingly, irrespective of crop, one acre of land, pond or bioreactor, can annually yield about enough biomass to fuel one motor vehicle or meet the calorific requirement of several people. This amount of biomass is not sufficient to make other than a very small contribution to our present road transport requirements and yet contributes significantly to global food shortages and rising prices. Reliable evidence also suggests that, if all of the inputs are taken into account, the net energy gain of liquid biofuels, derived either from algae or terrestrial crops, is either very modest or non-existent and will therefore bring about little or no sparing of carbon dioxide emissions.

Keywords Algae · Biofuels · Energy balance · Photosynthesis · Productivity

Photosynthetic efficiency

Zhu et al. (2008) state that "A key starting point for identifying and evaluating biotechnology targets for improving photosynthetic solar conversion efficiency is a critical re-examination of the maximum efficiency of photosynthetic solar energy conversion that could theoretically be achieved in managed ecosystems". What then is the greatest amount of light energy that could, in theory, be converted into chemical energy by photosynthesis?

If, for purposes of calculation, we take the absorption of solar energy by chlorophyll to be maximal at about 680 nm and the chemical end-product of the Z-scheme and the Benson–Calvin Cycle, to be a carbohydrate, the first starting point is as follows. The Z-scheme calls for four electrons to be propelled by four photons through each of two photosystems for every molecule of O_2 released from water and every molecule of CO_2 incorporated into 'CH_2O' (Fig. 1).

A photon mole of red light, with a wavelength of about 680 nm, has an energy content (Walker 2000) of about 42 kcal (176 kJ). Burn one gram molecule of $C_6H_{12}O_6$ in a calorimeter and 672 kcal is released as heat. The formation of one 'CH_2O' therefore requires an input of at least $672/6=112$ kcal (468 kJ) and, when this is supplied by eight photons of red light, the arithmetic becomes $112/(8\times42)\times100=33\%$. However, rather less than 50% of sunlight is photosynthetically active radiation (PAR). The energy content of an average photon mole of visible light in this range is about 50 kcal (209 kJ) and, using the leaf-disk electrode (Delieu and Walker 1981), the mean quantum requirement for thirty seven C3 species was found to be 9.4 (Bjorkman and Demmig 1987). This has been repeatedly confirmed (see, e.g., Walker 1987, Walker 1989, Walker and Osmond 1986, Seaton and Walker

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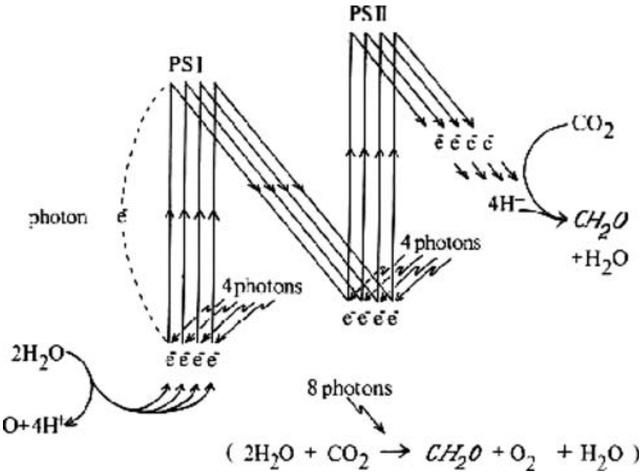

Fig. 1 From Walker (1992b)

1990). So, introducing these values, we can arrive at 112/(9.4×50)×0.5×100=11.9%.

It cannot be too strongly emphasized that 11.9% (cf. Radmer and Kok 1977) is an unequivocal theoretical maximum that will never be realized by a growing crop of whatever nature even when all adverse factors such as disease, predation, inadequate inorganic nutrients and sub-optimal water are disregarded. This is because the actual quantum yield (i.e., the reciprocal of the quantum requirement) invariably decreases as the photon flux density approaches light saturation (at about one fifth of full sunlight for C3 species) and the fact that environmental factors such as temperature (Spalding et al. 1980) vary during daylight hours and are rarely optimal. We can however approach a rather more realistic maximum figure of photosynthetic efficiency (photon energy converted into biomass energy) of about 4.5% for C3 plants or microalgae by using "educated guesswork" (Boardman 1980, Edwards and Walker 1983, Walker 1992a, Benemann and Oswald 1996) and detailed consideration of the partial reactions involved (Walker 2000, Barber and Archer 2004, Zhu et al. 2008). Uncritical acceptance of uncorrected photosynthetic efficiencies of about 10% or even higher (Pirt 1986) inevitably leads to exaggerated estimates of present and future biofuel productivity. For example Huntley and Redalje (2007) state that "the annually averaged rate of achieved microbial oil production from *Haematococcus pluvialis* is equivalent to >420 GJ ha^{-1} y^{-1}, which exceeds the most optimistic estimates of biofuel production from plantations of terrestrial "energy crops". Yet, if 500 J is taken as an arbitrary value for the PAR of "full sunlight" (Edwards and Walker 1983 and see below) and a crop utilizes 1% of this energy this equates to about 630 GJ ha^{-1} y^{-1} .This suggests that the annual biofuel production of >420 GJ ha^{-1} by *H. pluvialis* is less rather than greater than the best terrestrial crops. Similarly, it makes untenable the often-cited conclusion by Longhurst et al. (1995) that "the productivity of photosynthetic microbes in nature, on an areal basis, exceeds that of terrestrial plants by approximately one order of magnitude". Indeed if this were correct, it would imply an efficiency of about 20%.

As important in this context is how to relate about 4.5% for C3 plants (and 6% for C4 plants, Zhu et al. 2008) to grams of biomass per square meter per day. Assuming a mean wavelength of 575 nm for the PAR component of solar radiation Edwards and Walker (1983) took an arbitrary value of 500 J (= 500 W s=0.119 kcal m^{-2} s^{-1}) for the photosynthetically active component (PAR) of "full sunlight" for the U.K. This is equivalent to 0.119×60×60×12=5141 kcal m^{-2} for a 12-h day.

According a nominal value of 4.25 kcal g^{-1} for plant material (rather than 3.7 for carbohydrate) 5,141/4.25=1,210 g/12-h day. One percent of this is 12.1 g and 4.5% is 54.45, and for carbohydrate it would be 62.5 g m^{-2}/12-h day. The corresponding figure for PAR for the United States, based on a more accurate 48.7% of total incident solar radiation (Zhu et al. 2008) would be equivalent to 0.1164×60×60×12=5028 kcal m^{-2} for a 12-h day and this, in turn, equates to 5,028/4.25=1183 g/12-h day and values of 11.83 and 54.4 for 1% and 4.6% respectively.

Very similar values can be derived from calculations based on the actual light received during a growing season. Thus, solar radiation in Tucson, Arizona from 1988 to 2001 occurred in May and June near the summer solstice and was "as much as 1,110 Watts" (J s^{-1}) per square meter (Kania and Giacomelli 2000). This would equate to about 13 g day^{-1} for 1% light utilization efficiency at the peak of the Tucson growing season. It also points up the limitations of attempting to read too much into yields calculated on the annual values of insolation for an entire continent. Thus, on June 21st in Tucson (latitude 32°) the day length is not 12 but 14 h and 15 min whereas where I live, in England's most northern county (latitude 55°) the day length on June 21st is about 18 h. This would increase the theoretical 1% value (based on a 12-h day) from 12 to 18 g if it were not for the fact that, in earliest light and after the sun has set, the incident photon flux density (PFD) might well be below the light compensation point at which photosynthetic carbon dioxide gain is matched by respiratory loss (see also "Temperature limitations" section below).

Additionally, although at low light there is a linear relation between 'light intensity' (PFD) and rate of photosynthesis, this is not so above about one fifth of full sunlight. This in itself diminishes the usefulness of attempted comparisons between crop yields in areas of high- and low light intensity. Moreover, even in augmented CO$_2$, many C3 higher plants (Edwards and Walker 1983, Walker 1992a, Ort and Long 2003, Long et al. 2006,) and microalgae (Vonshak et al. 1989) become 'light saturated' well below one quarter of full sunlight (Fig. 2).

Moreover, it is becoming increasingly clear (below) that green plants are even more able, than is sometimes recognized, to adjust both their photosynthetic capacity and their growth to what is optimal in a given environment (Walker 1995, Noctor and Foyer 1999, Edwards and Walker 2004).

Temperature limitations

The maximum conversion efficiency of solar energy to biomass of 4.6% for C3 photosynthesis determined by Zhu et al. (2008) was specified to be at 30°C and "today's 380 ppm atmospheric [CO_2]". It is a matter of common observation that no 'higher' plants or microalgae grow much when it is cold but the responses of photosynthesis and respiration to temperature (Labate et al. 1990) are more complex. Respiration increases with temperature in an exponential manner within the 0–50°C range until a ceiling is imposed by genetic and environmental constraints. Photosynthesis by algae (Emerson 1929) and spinach chloroplasts (Baldry et al. 1966) is characterized by high Q_{10}s at low temperatures so that its rate, over the 0°C to 20°C range, increases with temperature in a linear rather than an exponential fashion. Most leaves equilibrate with ambient temperature very quickly. Conversely, because of their greater heat capacity, when open algal ponds are situated in places where low night temperatures are combined with relatively abrupt transition from darkness to full light, photosynthesis is slow to start in the morning and respiration slow to diminish in the evening.

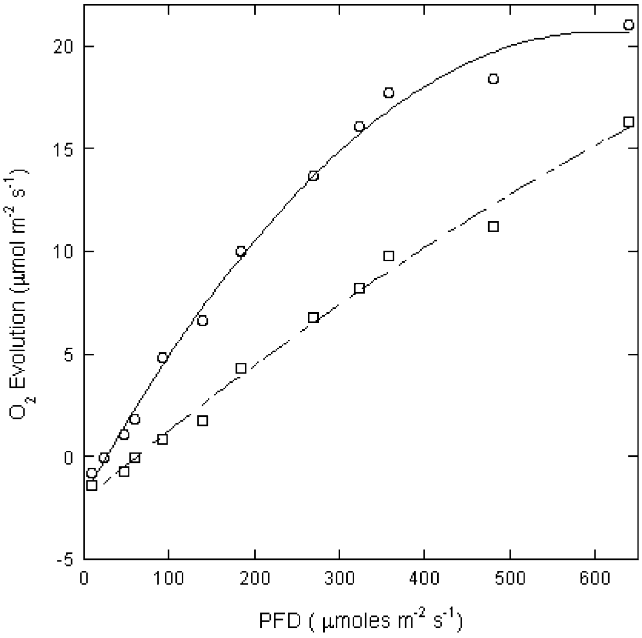

Fig. 2 Photoinhibition in *Spirulina platensis*

This again emphasizes the fact that, while a value of about 60 g m^{-2} day^{-1} (and an annual value often half this) may constitute the absolute maximum rate of accumulation of biomass in the field, this value will rarely, if ever, even be approached in practice.

Nonsensical calculations far beyond reality?

There are obvious dangers in attempting to extrapolate (to tons of biomass/ha/year) from rates of photosynthesis measured in μmol m^{-2} s^{-1} or from growth measured in g m^{-2} day^{-1}. For example, remarkable statements have been issued by, or on behalf of companies such as GreenFuels Technologies, who claimed (Pulz 2007) that they "were able to successfully grow algae at APS' Redhawk natural gas power plant at levels 37 times higher than corn and 140 times higher than soybeans—the two primary crops used for biofuels … an average productivity of 98 $g.m^{-2}.d^{-1}$ (ashfree, dry weight basis) and reaching a high peak value of 174 $g.m^{-2}.d^{-1}$ surpassed previous lab growth rates and exceeded all expectations going into the project. The results provide evidence of the financial viability of using the emissions of a power plant to grow algae for the exclusive purpose of creating biofuels" (see, e.g., GreenFuels Online 2007)

These and similar claims, by some proponents of algae mass culture, would appear to go far beyond exaggeration into the realms of science fantasy. There is in fact no credible evidence to support the contention that algae produce much more biomass per unit area per unit time than any other green organism. On the contrary, when compared on the same basis, just as all plants (under optimal conditions) photosynthesize at identical rates in limiting light (Bjorkman and Demmig 1987), they photosynthesize at relatively similar rates in high light. For example, sunflower (*Helianthus annulus*) has a reputation for fast photosynthesis but, at the Robert Hill Institute at Sheffield, *P* vs. *E* recordings of oxygen evolution were not merely similar but identical to those made on spinach (*Spinacea oleracea*) when leaves were taken from plants grown side by side in the same glasshouse (Walker 1995). Similarly, many hundreds of measurements (see, e.g., Walker 1995, Walker and Osmond 1986) have been made with the leaf-disk electrode (Delieu and Walker 1981, Walker 1987, 1989, 1997 on a miscellany of C3 species), in Australia, Europe, and South East Asia by myself and students who participated in UNEP courses; created and inspired by the late David Hall (Rao 1999, Larson 2000). These showed relatively moderate differences in the rate of photosynthesis (at 25°C) around a mean of about 20 μmol

m^{-2} s^{-1}, but never varied by an order of magnitude nor exceeded about 60 µmol m^{-2} s^{-1}. When taken from the same sites, on the same day, broadly similar categories, such as C3 grasses or deciduous trees, showed considerably less variation than corresponding measurements from environmentally different sites in the same neighborhood (Walker 1995). The extent to which such generalizations can be usefully extended from higher plants to algae is, of course, questionable. Oxygen evolution by *Spirulina* can be as high as 700 µmol O_2 mg^{-1} chlorophyll h^{-1} (Vonshak et al. 1996) but there are long recognized problems (Nielsen 1957) in relating µmol mg^{-1} chlorophyll h^{-1} (by algae in aqueous media) to µmol m^{-2} s^{-1} (by higher plants grown in soil) which, like comparing chalk with cheese, are neither merely a matter of arithmetic nor easily resolved by experiment. Thus, in Fig. 2, the maximum rate for *Spirulina* measured in a leaf-disk electrode was only about 20 µmol O_2 m^{-2} s^{-1} but, whereas leaf disks retain the advantages of complex internal architecture, algae (necessarily packed closely together on an artificial support for this type of measurement) will not, for example, enjoy the advantages of short diffusion paths that they experience in aqueous suspension.

Photosynthesis by single leaves and the growth of the parent plant (Sachs 1887) are not, of course, synonymous (see, e.g., Walker 1995). Nevertheless, while the annual yields of conventional crops such as wheat, oats, barley and potatoes grown in N. America, the United Kingdom and Continental Europe differ in consequence of the considerable differences in altitude, latitude insolation, and daily temperatures to which they are exposed, these differences in yield are not large (cf. Walker 1995), possibly implying some degree of homeostasis (cf. Noctor and Foyer 1999). On average, the lowest main-crop potato yield in these countries is about 35 t ha^{-1}, the highest about 65 and the great majority in the 40 to 55 t ha^{-1} range. (Haverkort 1990, British Potato 2007, Potatoes 2007) This of course is not to discount local differences in biomass consequent upon the supply of water, nitrogenous fertilizers, informed agronomy, selection of favorable varieties and advances wrought by conventional plant breeding or other forms of genetic manipulation (Rosenberg et al. 2008). It does, however, suggest that the attention that has been given to this, the world's fourth most important food crop, over the last half century has not resulted in the huge changes in yield of the sort that are implicit in statements such as "37 times higher than corn and 140 times higher than soybeans" (above). Mindful of the constraints imposed by the laws of physics, it also suggests that the much-celebrated threefold increases in the yields of rice (Bullard 2004), to what might be regarded as the norm, are exceptional, that further doubling is unlikely, and that there is little possibility of further increases of one, let alone two, orders of magnitude.

Algae are no better than the next in this regard and, often yield less, rather than more, than terrestrial crops. (Radmer and Kok 1977) For example, in respect of conventional open-pond cultivation of algae, Avigad Vonshak (personal communication 2008) states that "The highest numbers that I have seen based on large scale long production periods for *Spirulina* are in the range of 4 t per 1,000 m^{-2}. This is an equivalent to a daily productivity of 12–14 g m^{-2} d^{-1} and a total of about 300 days of operation. Most of the production facilities are actually doing only 3 t" (see also Belay 1997). This is about 1% 'efficiency', (see "Photosynthetic efficiency" section above) and possibly comparable to sugarcane.

It is frequently contended that much better yields can be obtained by using closed 'photobioreactors'. However, these claims have still to be substantiated and Benemann (2007) states that "Over the past few years, several companies have issued press releases about technologies they have developed to produce biofuels from algae. The claims in these stories are that algae yield 'enormous' amounts of biomass that can be turned into liquid fuels at low cost. Most of the projects involve the use of closed photobioreactors, in which the microorganisms are grown in a controlled manner by feeding them CO_2 and nutrients. Sadly, after decades of development, none of those projects have ever demonstrated the technology on a large scale, let alone over long periods of time".

Benemann (2008) adds that photobioreactors are worse (than open-ponds) "in almost all respects. Good enough (in an economic sense) to produce an inoculum (seed, starter culture), in small amounts (or at most ~1% of production)" (see also Benemann 2008, 2009)

Feeding motor vehicles or people

The concept of using 'bioethanol' to fuel road transport has been around as long as there have been motor vehicles to use it. Nikolaus Otto, the German inventor of the combustion engine, conceived his invention to run on ethanol. The Ford Model T, produced between 1903 and 1926 used ethanol. Even before World War II, Germany sold a blend of gasoline with alcohol from potatoes called Reichskraftsprit. This latter blend is particularly apt in the present context because it permits a ready comparison between the competing demands on biomass as food or fuel. Because algae are not directly used as food by all but a small minority of the world's population, they could be excluded from this competition if it were not for the fact that, like all green crops, they require both water and space in which to grow. It has been reported, for example Hodge (2008) reports, that "enough algae can be grown to replace all transportation fuels in the U.S. on only 15,000 $miles^2$, or

4.5 million acres of land". Similarly Briggs (2004) writing about the same 15,000 miles^2, now grown to 9.5 million acres, for producing enough biodiesel to meet the same national requirement", adds that "even if we are only able to sustain an average yield of 5,000 gal/acre year in algae systems spread across the US, the amount of land required would still only be 28.5 million acres". No doubt both Hodge and Briggs have written in good faith and are quoting potential rather than actual yields. Moreover, the arithmetic, involving such imponderables as hectares, acres, long tons, short tons, metric tons, US gallons, and Imperial gallons is both tiresome and tedious. Nevertheless, having attempted much of the same, I can say with confidence that these and similar, much reproduced figures (see, e.g., Gressel, 2008), frequently exaggerate the actual yields (cf. Johnston et al. 2009), often by an order of magnitude. For example Avigad Vonshak's figure (above) of about 14 g m^{-2} day^{-1}=about 4 t 1,000 m^{-2} is equivalent to=about 40 t ha^{-1}=16.2 tons acre^{-1}. Assuming a carbohydrate content of 21%=this is about 3.4 tons carbohydrate/acre in 300 days. "Factoring in maximum obtainable yield and realistic plant operations, the expected actual recovery would be about 141 US gal (ethanol) per ton" (Salassi 2007) and (141×3.4)/1.2=400 U.K gal/acre/300 days=400×2/3= 267 gal petrol equivalent/acre

Comparing the yield of one plant crop (or biofuel) to another becomes increasingly complex. For example, oil palms (Wikipedia 2008) are perennial crops with a growing season of 7 months, and an annual biomass of about 10 t ha^{-1} yielding about 4.2 t of palm oil (US Department of Agriculture 2005). One tonne of palm oil would be expected to replace about 0.850 t of mineral diesel and, if 1 gal is taken to weigh 7.15 pounds, 4.2 t of palm oil would be equivalent to 4.2×2,000/7.15=1,175 U.S. gal (4,465 L) or 978 U.K gal/ha=978/ 2.47=396 U.K. gal/acre. Accordingly, if we wish to lay to rest misleading statements such as "Algae are the fastest-growing organisms on the planet, and can produce 100 times more oil per acre than conventional soil-tilled crops that are now being grown for biofuel use" (Sears 2006), we should (in terms of biofuels) perhaps compare the amount of bioethanol that algae currently yield in 300 days (i.e., 400 U.K gal/acre) with what the oil palm yields in a year (also about 400 U.K gal/acre).

It may be concluded that bioethanol figures are, in general, about 400 U.K gal per acre (270 petrol/gasoline equivalent) for algae, potatoes, and sugarcane and probably for most major crops, which have benefited from man's attempts to maximize yields for many centuries. These values (and see also Johnston et al. 2009) whose results "show overestimates of biofuel yields by 100% or more for many crops") constitute about 1% theoretical light use efficiency at best and the possibility of doubling them to 2% on a large-scale sustainable basis by better agronomy, genetic intervention, or whatever, is perhaps as much as could be reasonably aspired to in the foreseeable future. This means that, in terms of land usage, one acre only yields sufficient fuel (400 U.K gal) to propel one motor vehicle about 8,000 miles, i.e., rather less than the U.K average of 12 to 15,000 miles per annum (Walker 2008). There is no doubt that aircraft can also fly on biofuels but, however desirable this might become as fossil oil reserves shrink, procuring sufficiently large quantities to meet this need would involve a major diversion of land and water resources (Squatriglia 2008) Thus, according to Boeing (2009)), a "747-400 that flies 3,500 statute miles (5,630 km) and carries 126,000 pounds (56,700 kg) of fuel will consume an average of 5 gal (19 L) per mile". If this aircraft were fuelled by biofuel from palm oil and we accept the generous (cf. Johnston et al. 2009) yields of 4.2 t of palm oil/ha cited above, each flight would consume the annual output of about 15 ha To put this in context, the proposed expansion of London's main airport "would put an initial cap on additional flights from the new runway of 125,000 a year" (BBC News Channel 2009). The new third runway alone would therefore gobble the output of about 1.875 million hectares (4.6 million acres) year^{-1}, an area large enough to meet the annual calorific food requirement (Walker 1992a) of a population as large as that of the U.K.

The impact of biofuels on food supply

Pimentel and Pimentel (1990) have written that "to produce food for each person in the United States, a total of 1.9 ha [4.7 acres] of cropland and pasture land is used, whereas in China only 0.4 ha/person is used". This latter figure is near enough one acre (i.e., one acre to produce food for one person) and, while increasing population and diversion of agricultural land to industry in China may well have diminished this ratio over the last eighteen years, it undoubtedly remains more representative of global requirements (than the corresponding figure for the United States). For those who have no alternative but to survive on a subsistence diet, one acre of land (0.404 ha) can easily support 12 people (Walker 1992a). This of course was why a million or more people died in Ireland when a switch from traditional agricultural practices (to reliance on the potato) was followed, in 1845, by the devastation wrought by *Phytopthora investans*. "Turning to the unexceptional, it was not unusual for an Irish farmer and his wife, to raise a family of five and maintain several milking cows and a couple of horses, on a thirty acre farm as recently as the early 1960s" (Walker 1992a).

The present rapid increases in affluence in China and India are making more demands on the N. American grain crop. Hitherto, this has kept pace with or, arguably even made possible, much of the increases in world population over the last 50 years but obviously it cannot continue indefinitely. World food reserves are shrinking and there can be little doubt that this decline is exacerbated by the diversion of crops such as corn from food into biofuels (Dyer 2006). Ostensibly, the use of algal biofuels should not contribute to this decline although, even here, the use of energy land and water for this purpose (Bullard 2004) would not be without significance. As always, there are dangers in generalization. For example there is much to be said for algal treatment of sewage (Benemann 2008) as in Israel where the byproducts are mostly put to better use than fueling motor transport. In small, densely populated countries, like the U.K., with 33 million registered motor vehicles, even the proponents of biofuels (National Farmers Union U.K. 2006) admit that it would take 20% of its arable land (1.2 million hectares of 5.9 million hectares) to meet the present European Community requirement to derive 5% of its motor transport fuel from biomass.

Energy balance

Nothing so distinguishes those who advocate the use of biofuels, from those who voice skepticism, than their reactions to statements such as this: "At first sight they (biofuels) "appear to be carbon-neutral (the carbon they emit to the atmosphere when burned is offset by the carbon that plants absorb from the atmosphere while growing" (Roy Soc Policy 2008).

No one questions the fact that some energy must be expended in the production of biofuels. It follows that, if an appreciable amount of fossil fuel is used (Pimentel and Patzek 2005), there will be no significant sparing of carbon dioxide released to the atmosphere. In other words, if the use of a biofuel is to be justified on the basis of diminished carbon dioxide release it should exhibit more than a very modest "net energy gain" (Wikipedia 2009).

What follows exemplifies the views of the skeptics and the advocates of bioethanol from sugar cane (which conserves at least as much light energy as biomass as any other crop). Thus, Pimentel and Patzek (2007) are skeptical and conclude that: "Based on all the fossil energy inputs in U.S. sugarcane conversion process, a total of 1.12 kcal of ethanol is produced per 1 kcal of fossil energy expended. In Brazil a total of 1.38 kcal of ethanol is produced per 1 kcal of fossil energy expended. Some pro-ethanol investigators have overlooked various energy inputs in U.S. and Brazilian sugarcane production, including farm labor, farm machinery, processing machinery, and others. In other studies, unrealistic low energy costs were attributed to such energy inputs, as nitrogen fertilizer, insecticides, and herbicides".

Conversely, in a recent letter to the Guardian (a U.K, national newspaper), Felipe Costa (of the Embassy of Brazil) wrote "Sugarcane ethanol allows for a 90% reduction in emissions, compared with petrol, and its energy balance is 8.3 to one, i.e. for every unit of energy used in production eight units of energy are created (sic)". To my mind, this from a country with a vested interest in sugarcane ethanol, invites the time-honored response that "he would (say that), wouldn't he?" (Rice-Davies 1963).

Why do I number myself amongst the skeptics? In 'Energy Plants and Man' (Walker 1992a) I quoted Leach (1975) who wrote that "The industrialized food systems of the West have raised food yields and quality and cut labor usage, but have done so by heavy consumption of—and dependence on—fossil fuels. Most developed societies now use 7 to 8 units of fossil fuel energy for each food energy unit consumed, or an annual 0.8 tons of oil equivalent per person." In short, industrialized ('Western') agriculture, which is unquestionably essential if most of us are not to starve (Walker 1995) is nevertheless an in inefficient way of "turning oil into potatoes" (Walker 1992a). It returns more carbon dioxide to the atmosphere than it extracts This is not to say that the energy balance is as unfavorable for biofuels (as Leach considered it to be for food in 1975), or that all of the inputs are necessarily the same, but the energy costs of transporting relatively light biomass from field to processing plant are similar and then there are the considerable additional energy costs (distillation and such) of conversion to usable motor transport fuel.

Accurate and meaningful determination of energy inputs is difficult (Benemann and Oswald 1996) and deciding what might, or might not, be put into the balance can be as subjective as deciding what constitutes a work of art. It has also been confounded by statements reminiscent of those who wished to deny climate change (see, e.g., Dale 2007). Even so, the work of independent and disinterested scientists might be thought to carry more credence than statements by some politicians, farmers or others with vested interests. In the end, the total energy inputs depend on where you stop counting. If, as I walk through nearby forests, and pick up fallen branches (as do millions, the world over, every day), I have in my hand a biofuel as "carbon-neutral" as it is possible to imagine. It is said that wood warms you five times; once when you fell it, once when you saw it, once when you carry it home, once when you chop it and once when you burn it. So, even in these circumstances, there is a modest energy input. However, if I wished to produce and sell wood chips to my neighbors, I would need to surround land with a 2-m tall fence to keep out the deer and shoot every gray squirrel that I could see. I would perhaps plant fast-growing willows and do my best to provide them with water and inorganic nutrients. After a few years, I might borrow a large machine (which had taken an unthinkable number of calories to construct) and use it to drag my trees from the ground Then I would need a 'shredder', also fueled by diesel, to render them into small pieces which could be dried, at the expense of some significant part of my crop, so that they become 'chips' which could be transported by road to where they are needed. Seemingly, Matthew Carse (2007) chief executive of 'Prenergy', has said of these: "Using wood chip from independently certified sustainable forestry, which ensures harvested trees are replanted, means that generation is carbon-neutral and sustainable". Personally, I feel bound to conclude that this is wishful thinking but please don't misunderstand me. I commend wood chips as a fuel just as I commend potato chips (of the sort that the British combined with fish as a staple diet during the last world war) as an item of diet. If wood chips help to keep our power stations running for an hour or two when imported gas is shut off that is fine, But let's not pretend that they, or any other biofuel, will ever spare as much carbon dioxide released to the atmosphere as a handful of low energy electric lights or not be bettered by any other modest degree of fuel economy.

Why grow biomass as a source of road transport fuels?

It is suggested that because biofuels recycle newly fixed CO_2 they do not add to existing concentrations of atmospheric CO_2 (cf. Felipe Costa above). If, as Pimentel and Patzek claim, the energy ratio is 1 to 1.38 at best and, for many terrestrial crops there would be no net gain at all, it seems that any overall sparing of emissions would be negligible. A general lowering of legal speed limits by 5 mph might well have a much larger effect as would any number of alternative energy conservation measures (Walker 1992a).

Reducing dependence on imported oil (Sheehan et al. 1998) would no doubt be very welcome (not only to the United States) but a large reduction is scarcely feasible on the basis of proven yields. Large scale switching of N. American grain from food to biofuels has already caused, or added to, world food shortages. There are yet no authenticated figures for microalgae grown for prolonged periods in large-scale 'photobioreactors' (Benemann and Oswald 1996; Weissman et al. 1988) and, although these would not affect conventional food supplies directly, they would compete for fossil-based fertilizers, land, and water (Bullard 2004; Walker 2008). In view of the findings of Pimentel and Patzek, it can be reasonably concluded that the best that can be expected from industrial production of biofuels in general is energy neutrality, i.e., near equality of energy inputs (mostly from fossil fuels, etc.) and outputs (energy content of the biofuels produced). It is difficult to imagine therefore that the degree of industrialization implicit in the use of 'photobioreactors' could be achieved with a positive energy balance.

Summary and Conclusions

Re-examination of the relevant literature confirms that there is general agreement that maximal, theoretical light utilization by C3 plants and algae is about 4.5%. An increase in actual light utilization by crops, from present values (of about 1%) to as much as 3%, remains a goal to be aspired to rather than one which is likely to be achieved in the foreseeable future. There is no credible evidence that cultivated algae are currently able to accumulate substantially more biomass, during a period of sustained growth, than other green organisms. When comparisons of crop yields are based on their normal period of growth, the yields of biomass are relatively similar, regardless of species or locality. Intensive agricultural practice of any sort rarely uses less fossil fuel energy than the light energy that it conserves as biomass. Biofuels do not, at present, lead to any appreciable sparing of carbon dioxide emissions that could not be better accomplished by the most modest means of energy conservation. Moreover, diversion of crops from food to biofuels makes a significant contribution to increasing food shortages and rising prices. This is not to say that biofuels in general, or algal biofuels in particular, have no place in substituting for fossil oil where there is, as yet, no practical alternative. Western agriculture is, after all, an inefficient but inescapable means of converting fossil fuels into food (Walker 1992a). 'Retro-agriculture' (the use of biomass for transport fuels) may, despite its intrinsic drawbacks of low density and distillation or other processing costs, may still be judged to have a role in energy security and conservation. As such, its purpose will not, however, be best served by exaggeration of the yields that might be achieved per unit area, unrealistic estimates of the energy that it is necessarily expended in its utilization of failure to recognize the constraints imposed by the laws of physics.

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