

HALOPHYTES ENERGY FEEDSTOCKS: BACK TO OUR ROOTS

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ABSTRACT

Of the Earth's landmass, ~43% is arid or semi-arid, and 97% of the Earth's water is seawater. Halophytes are salt-tolerant plants (micro and macro) that can prosper in seawater or brackish waters and are common feedstocks for fuel and food (fuel-food feedstocks) in depressed countries. Two types, broadly classed as coastal and desert, can be found in marshes, coastal planes, inland lakes, and deserts. Major arid or semi-arid halophyte agriculture problems include pumping and draining the required high volumes of irrigation water from sea or ocean sources. Also, not all arid or semi-arid lands are suitable for crops. Benefits of halophyte agriculture include freeing up arable land and freshwater resources, cleansing the environment, decontaminating soils, desalinating brackish waters, and carbon sequestration. Sea and ocean halophyte agriculture problems include storms, transport, and diffuse harvesting. Benefits include available nutrients, ample water, and Sun.

Careful attention to details and use of saline agriculture fuel feedstocks are required to prevent anthropogenic disasters. It is shown that the potential for fuel-food feedstock halophyte production is high; based on test plot data, it could supply 421.4 Quad, or 94% of the 2004 world energy consumption and sequester carbon, with major impact on the Triangle of Conflicts.

INTRODUCTION

With a growing gap between petroleum production and demand, and with mounting environmental regulations, industry is investigating candidates for alternative (nonpetroleum-based) fuels and improved fuel efficiency. Bioderived fuels are being considered to replace or supplement conventional distilled petroleum fuels. Most of these alternative fuels present designers with safety, logistical, and performance challenges. For

example, airplanes are not as fuel-flexible as ground vehicles, and jet fuel (which is about 6 to 8% of global oil consumption) requires high-performance characteristics.

Current biofuel feedstocks and human existence are highly dependent on the familiar glycophytes rice, corn, wheat, potatoes, soy beans, palm oil, and nut plants, which cannot tolerate salt. There is some probability that plants started as halophytes, moving from the sea to the shores and marshes. The not-so-familiar halophytes are highly specialized plants with a great tolerance to salt (see also app. D). They can germinate, grow, and reproduce in areas of high-saline solutions, coastal shorelines, marshes, inland lakes (coastal-halophytes), huge potential irrigation areas such as desert regions with subterranean brackish water aquifers (desert-halophytes), and directly in oceans or seas (e.g., Sargasso Sea). These plants provide shoreline erosion protection and feeding areas for birds, fish, and animals. They are coming to the foreground as the salinity of freshwater-irrigated systems continues to rise as does the population demand for food and energy biofuel feedstocks. Selectivity and nurturing of both micro and macro halophytes to provide proteins, oils, and biomass while enduring a wide range of environmental conditions may provide human needs as limits to freshwater food and energy are reached (Khan and Weber, 2006). Harvesting ocean halophytes such as seaweed, algae, and kelp from the Sargasso Sea becomes more difficult because of storms, conversion, and transport, yet the oceans are vast reservoirs of both CO₂ and nutrients (nearly 80% of required plant nutrients (Bushnell, 2006a). Halophyte agriculture is not that well understood, yet has potential to provide yields similar to glycophytes (alfalfa) (Glenn et al., 1998) with even larger projected yields. Micro-halophytes (algae) that demonstrate small ponding and bioreactor yields produce 10 times more glycophytes, yet

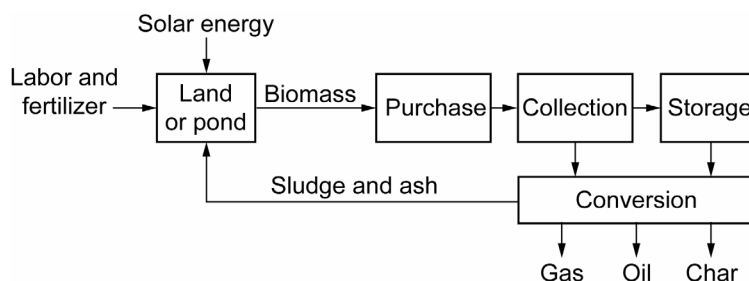


Figure 1.—Diagram showing overall system for conversion of biomass.

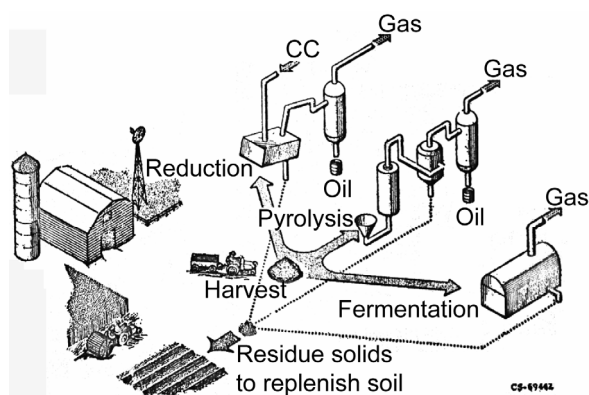


Figure 2.—Methods of converting crops to fuel.

It is this potential of halophytes to provide both sources of food and fuel feedstocks (without affecting current sources) that excites our interest. In this paper, we pay more attention to the lesser known macrohalophytes. A few differences and similarities between the photosynthesis of more common plants and that of halophyte plants are found in appendices A and B.

Biomass Fuel-Food Feedstocks

NASA's early biomass interests included algae for spacecraft oxygen generation. In the early 1970s, clean fuels from biomass were the subject of NASA Lewis studies in response to the fuel crisis and published by Hsu (1974) and Graham et al. (1976). Basically all biomass is based on nutrients, water, and solar energy input (fig. 1).

Glycophyte Feedstocks

Hsu discussed reduction, pyrolysis, and fermentation as methods of converting glycophyte biomass to fuels (fig. 2).

To determine crop yields (ton/acre-yr) and power equivalent (W/m^2), Hsu investigated the effects of solar flux, photoefficiency, location, and crop. Napier grass was among the highest yields (table 1).

Hsu cites that in 1970 each person in the United States required 3.5×10^8 Btu/yr of fuel. Fuel crops at 10 tons/acre supplied 10^8 Btu/acre, requiring 6.5 acre/person, and thus could support a population of 250 million.

The 2006 U.S. demand for energy at 0.271 Quad/day^* (equivalent to 50 million bbl/day or 580 bbl/s) of oil outstrips our ability to sustain it with current glycophyte biofuel crops. We need alternate biomass fuel-food feedstocks in order to meet demand.

Halophyte Feedstocks

Recent halophyte advocacy by Bushnell (2006a and b) and the International Center for Biosaline Agriculture¹ has revived the visions of Glenn et al. (1998) and Hodges et al. (1993) of halophytes as a large-scale industry within a decade and with it the prospects of sustainable fuel-food supply along with increasing carbon flow from the atmosphere into the soil via seawater-based communities <http://www.seawaterfoundation.org/swKino.htm>.

Table 1.—Representative Biofeedstock Yields of Dry Mass^{a,b}

Crop	Location	Yield, ton/acre-yr
Napier grass	Puerto Rico	21.6
Napier grass	India	15.5
Congo grass	Puerto Rico	22.4
Buffelgrass	-----	28.0
Dallis grass	Taiwan	10.7
Kikuyu grass	Taiwan	23.3
Canary grass	United States and Canada	3.6 to 8.3
Ryegrass	Great Britain	10.0
Sugarcane	United States	9.5 to 10.7
Corn	United States	10.0
Sugar beets	United States	9.5

^aFrom Hsu (1996).

^bValues from Ohio Agricultural Research and Development Center survey.

they are nearly 10 times more costly. Ponding is less expensive than reactor systems, yet uses more water and is subject to control by indigenous algae. In either case, the challenges of harvesting and oil production must be addressed to lower the current high production cost (Sheehan et al., 1998, Ryther et al., 1987, <http://www.montana.edu/wwwpb/univ/CO2scrub.html>).

* 1 Quad (Q) is 10^{15} Btu.

How Halophytes Work to Survive

Some halophyte plants have rooting systems that function as semipermeable membranes to pass water and filter out salt. Others have developed salt bladders in the leaves that store salt and can burst, spreading a reflective layer to cool the leaf. The anatomy of the halophyte *atriplex* (saltbush) is graphically illustrated, after Glenn et al. (1998), in figure 3.[†]

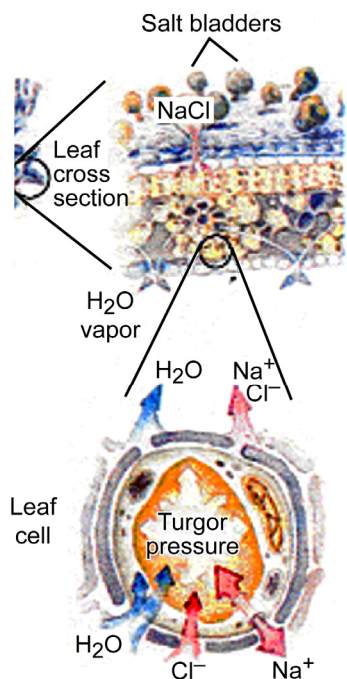


Figure 3.—Leaf structure of halophytes. From Glenn et al. (1998). Permission applied for, 1 Feb 2007.

Internally, halophytes have cells that transport sodium ions Na^+ that attract Cl^- ions, which in turn attracts water. Any salt absorbed by the plant is handled by these specialized cells. Halophytes absorb sodium ions and

transport them to vacuoles via a protein called sodium-proton antiport,[‡] which is highly active in halophytes, causing a reversal in osmotic pressure so water and nutrients are absorbed into the cells rather than desorbed. The resulting turgor pressure enables these cells (turgid plant cells) to hold more water, which maintains plant stiffness through neighboring cell interaction and is a key factor in microbial growth.

Water vapor escapes from the underside of the leaf. Plants, especially arid and semi-arid plants, minimize water losses (Glenn et al., 1998).[§]

Halophyte Selection

To assist in the selection of potential crops for different regions, a computer program was developed by Edwin Ongley, Sarah Dorner, and Nicholas Yensen with the Food and Agriculture Organization of United Nations (Yensen, 2002, 2006).

Benefits

Halophytes may be used to reclaim the ground for freshwater plants. Halophytes can leach soil salt through enhanced percolation and, to some extent, through storing salt in their leaves that are harvested and removed from the fields to the point where halophytes do not grow well. Then the cleansed soils can be used for conventional crops. Plants use these principles to cleanse contaminated soils. The native perennial grain plant *Distichlis* (*NyPa*)⁴ excretes salt from bicellular-salt glands, the foliage (similar to that of alfalfa) has enhanced salt, yet the grain is not salty (Yensen, 1998 and Glenn et al., 1988).

PRODUCTION

Although halophyte agriculture is not that well understood, saltwater-irrigated shrublike species of halophytes such as *Salicornia* (glasswort), *Suaeda* (sea blite), and *Atriplex* (saltbush) can provide yields similar to alfalfa that is grown with freshwater irrigation (2 kg/m² dry mass) as seen in figure 4.

Salicornia bigelovii seeds (fig. 5) are 30% oil and 35% protein and of a fatty acid composition similar to that of safflower oil. The raw seeds are bitter and inedible.

[†]Academician Karl Biel and Professor Nicholas Yensen suggest that photohalosynthesis may enable energy storage without chlorophyll. Yensen and Biel (2006) also speculate that photo-halosynthesis does not use chlorophyll or pigments in the energy conversion but uses sodium-ion-electron transport. Yensen and Biel (2006) hold that halosynthesis enables halophytes to produce more than glycophytes (in energy terms) under salty soil conditions. Although it is known that in C4-type photosynthesis plants (1) are more efficient in their uptake of CO_2 (see apps. A and B), (2) lose less water and energy in respiration, and (3) with different cell anatomy (Kranz Anatomy) seem to have high tolerance to incident light intensity, the question becomes, “how do they do this?”

[‡]The gene for this protein was isolated by Dr. Eduardo Blumwald, University of California at Davis² from a thale cress plant, which is related to the mustard plant and introduced through the nucleus of the tomato seed thereby providing a multiplicity of copies of the protein.³

[§]The salt crystal may serve as a lens altering the incident energy through Compton scattering. The scattered energies are less destructive forms (longer wavelengths) than the incident UV in plants through respiration and in animals where salts are transported through perspiration. Thus the combination of water and salts on the surface protect nuclear acids, membranes, proteins, and biochemical pathways against destruction.

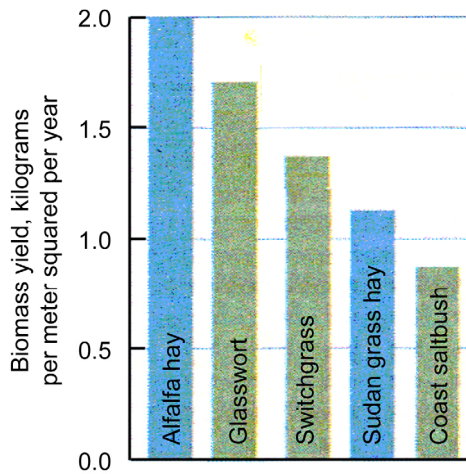


Figure 4.—Halophyte and glycophyte yields. Adapted from Glenn et al. (1998). Permission applied for, 1 Feb 2007.



Figure 5.—*Salicornia bigelovii* (glasswort species) From Glenn et al. (1998). Permission applied for, 1 Feb 2007.

Experimental farms yield 1.7 kg/yr-m² total biomass and 0.2 kg/yr-m² oil, similar to soybean seed oil yields. To support these yields, *Salicornia* needs to mature over 100 days at cool temperatures before flowering (subtropics) (fig. 6), and by recycling algae-nourished shrimp, fish, or other farm effluent, the halophyte crop can recover nutrients that otherwise create problems (Glenn 1998 and Hodges, 1993) <http://www.seawaterfoundation.org/swKino.htm>. See also figure 1-Hsu where residue is returned to the fields.

In contrast, seed oil from soybeans (a glycophyte) is about 19% oil and 48% protein.⁵ There are about 10.9 lb/bushel (bu), 468 lb/acre, or 61 gal/acre of oil with an average crop of 43 bu/acre and specific gravity of 0.92.⁶ Daggett et al. (2006) used 60 gal/acre (148 gal/ha, 1135 lb/ha, 516kg/ha, or 0.516 tonne/ha), with good agreement with the soy seed oil content.

Halophyte seeds provide 30% oil, and yields are 0.2 kg/m² (2000 kg/ha or 2 tonne/ha). “These yields equal



Figure 6.—Potential coastal and inland biosaline plant sites. From Glenn et al. (1998). Permission applied for, 1 Feb 2007.



Figure 7.—World inland areas that are salt-affected (Yensen (2006)). Permission applied for, 2 Feb 2007.

or exceed the yields of soybeans and other oil seeds using freshwater irrigation” (Glenn et al., 1998). At 30% oil, this implies 6.67 tonne/ha seed. This is nearly 4 times that produced by the U.S. average crop of soybeans.^{**}

As shown in appendix C, the rooting system of switchgrass and alfalfa can be several meters and capable of storing large quantities of carbon. Assuming 145 t/ha carbon sequestration, plant roots can potentially store over a century of carbon production.

Yensen (2002) cites, “several tons per hectare” as a NyPa cereal grain food source.^{4,7} As dry weight forage, for a 4-month period, the yield was 13.9±3.5 tonne/ha (Yensen, 2006), and for the cereal grain halophyte, Yensen cites yields over 4 tonne/ha (small test plots). In other test plots green matter yields up to 25 tonne/ha were produced, and NyPa *Distichlis* cultivars tolerated up to 1.5 times ocean salt conditions with a dry matter yield reduction from 1444 to 817 kg/ha (Leake et al., 2002).

POTENTIAL FOR SUSTAINABLE PRODUCTION LAND

The Earth’s salt-affected land mass is large (fig. 7). Yensen (2006) cites there are nearly 1×10⁹ ha of salt-affected land with another 1×10⁹ ha desert lands above

^{**}For reference, a 40-acre, carefully monitored and watered Missouri field of soybeans produced 139 bu/acre (Fischer, 2006). Soybeans weigh 49 to 56 lb/bu and at 43 bu/acre provide 958 to 1095 kg/acre or 2.37 to 2.7 tonne/ha.

brackish aquifers and $(1.5 \text{ to } 7) \times 10^9$ ha of salt-affected arable lands of reduced productivity with 5 million hectares of reduced-productivity lands added annually. Salt-affected soils of the United States alone amount to over 8.5×10^6 ha, with 10 times that in Argentina and 20 times that in the former USSR (Yensen, 2006). These areas do not respect national boundaries or political issues and require international cooperation to develop into sources of forage and food.

FUEL LAND FRACTIONS

In terms of total U.S. land mass and at rates of fuel-food feedstocks production cited by Glenn et al. (1998), U.S. oil demand replacement would require some 70% (of total land) and oil and gas demand replacement would require 120%, assuming all feedstocks are converted at 100% efficiency to biodiesel of the same density and heating value. At projected production rates using genetically modified plants and new production methods, these percentages decrease over an order of magnitude (Bushnell, 2006a) as illustrated in table 2.

The fractions of table 2 are based on U.S. total land of nearly 0.92 billion hectares (10^9 ha, 19.13% of which is arable) and yearly petroleum demand of about 7.4 billion barrels (7.4×10^9 bbl) per year. 2000 kg/ha of halophyte seed oil translates to 5.53 bbl/acre or 13.65 bbl/ha and is equivalent to 11.4 bbl/ha No. 2 diesel oil.

The land fractions for fresh water and microhalophyte agriculture (algae) are even more impressive, requiring between 0.08% and 5.6% of total U.S. land to replace oil or oil and gas consumption. With large arid land fractions

(43% of Earth), halophyte agriculture appears promising as a food and fuel resource.

For comparison, other feedstocks are cited based on current production rates. The values of table 3 refer to the more familiar glycophyte fuel feedstocks.

Limitations

Just as arable land is not suitable for all crops, neither are all nonarable or desert soils suitable for irrigated halophyte crops; nor is high-yielding algae ponding or bioreactors a viable option in various climates and environments. For all fuel-food biomass, suitable water resources are a necessity.

Some 43% of the Earth's land is arid or semi-arid and 97% of the Earth's water is in its oceans, Glenn et al. (1998). Worldwide estimates of coastal lands and inland salt deserts suitable for growing halophytes are set at 130 million hectares (fig. 4), of which perhaps 10% resides in the U.S. West and Southwest. Assuming that 13×10^6 ha U.S. desert soils can produce *Salicornia bigelovii* (glasswort species) oil at the rates given by Glenn et al. (1998) of 0.2 kg/m^2 (2000 kg/ha or 13.65 bbl/ha), the zero-loss conversion would supply 2% of 2005 U.S. (~20.3 Mbbbl/day) oil usage. For energy comparisons, No. 2 diesel fuel was used as the basis where the heating value of biodiesel B100 is about 0.83 that of the No. 2 diesel. At the projected production rate of 60 bbl/acre of oil (148 bbl/ha or 2.17 kg/m^2) this percentage jumps to nearly 22%, providing of course that one could supply the necessary irrigation water, soil, weather, nutrients, and disease-free environment.

Table 2.—Fuel Feedstock Production Relative to U.S. Land Fractions^a

[Assumes no conversion losses in processing or land use.]

Feedstock crop	Fuel	Production rate, kg/ha	U.S. total land		U.S. arable land	
			Oil fraction	Oil and gas fraction	Oil fraction	Oil and gas fraction
Halophyte ^b	Biodiesel	2 000	0.711	1.202	3.741	6.324
		Projected 21 685	0.066	0.111	0.345	0.583
Algae ^c	Biodiesel	43 090	0.033	0.056	0.174	0.294
		Upper limit 172 360	0.008	0.014	0.043	0.073
Jatropha (India)	Biodiesel	3 000	1.066	0.801	2.494	4.216
Palm oil (Malaysia)	Biodiesel	5 000	0.284	0.481	1.496	2.529
Switchgrass ^d	Ethanol	2 375	0.543	0.918	2.857	4.829
Sugarcane ^e	Ethanol	2 790	0.461	0.780	2.428	4.105
Miscanthus giganteus ^f	Ethanol	11 290	0.114	0.193	0.601	1.016
Seashore dropseed ^g	Ethanol	6 970	0.145	0.245	0.764	1.292
Saltgrass ^h	Ethanol	6 020	0.168	0.284	0.884	1.496

^aEnergy ratio to No. 2 diesel: B100, 0.82 to 0.85; ethanol, 0.63 to 0.67.

^bGlasswort species of *salicornia bigelovii*.

^c $(5000 \text{ to } 20000 \text{ gal/acre-yr}) \times (0.92 \times 8.34) / (0.4047 \times 2.2) = \text{kg/ha}$

^d $1236 \text{ gal/ha} \times 0.645 \text{ energy conversion} = 798 \text{ gal/ha} \times (0.785 \times 8.34) \text{ lb/gal} / 2.2 \text{ lb/kg} = 2374 \text{ kg/ha}$

^e $1454 \text{ gal/ha} \times 0.645 \text{ energy conversion} \times (0.785 \times 8.34) \text{ lb/gal} / 2.2 \text{ lb/kg} = 2793 \text{ kg/ha}$

^f $5878 \text{ gal/ha} \times 0.645 \text{ energy conversion} \times (0.785 \times 8.34) \text{ lb/gal} / 2.2 \text{ lb/kg} = 11289 \text{ kg/ha}$

Table 3.—Common Crop (Glycophyte) Fuel Feedstock Production Relative U.S. Land Fractions^a

Feedstock crop	Fuel	Yield		Production ^b		Fuel ratio, ^d bio:oil	Land ratio, ^e bio:arable
		Crop	Biofuel	Acres ^c	Gallons		
Soybeans	biodiesel	40 bu/acre	1.5 gal/bu	7.50×10 ⁷	4.50×10 ⁹	0.014	12.24
Corn	ethanol	140 bu/acre	2.5 gal/bu	8.00×10 ⁷	2.80×10 ¹⁰	0.088	2.10
Corn stover	ethanol	2.7 ton/acre	80–90 gal/ton	8.00×10 ⁷	1.84×10 ¹⁰	0.058	3.14
Switchgrass ^f	ethanol	5 ton/acre	75–100 gal/ton	7.88×10 ⁸	3.49×10 ¹¹	1.1	1.66

^aSources accessed for table values:

Yields and bio-energy: <http://bioenergy.ornl.gov/papers/misc/farmerfactsheet.pdf>

Land arable and total use: <http://www.cia.gov/cia/publications/factbook/geos/us.html>

Oil use: <http://www.eia.doe.gov/emeu/ipsr/t17.xls>

Switchgrass yields: <http://bioenergy.ornl.gov/reports/tvareg/supply3.html>

Corn stover yields: <http://ianrpubs.unl.edu/fieldcrops/nf310.htm>

Crop land planted: http://www.westernwatersheds.org/watmess/watmess_2002/2002html_summer/article6.htm

<http://www.ers.usda.gov/Briefing/LandUse/majorlandusechapter.htm>

^bAssumes that all planted acres produce the same and are converted to biofuels.

^cU.S. 2002 cropland was about 350 million acres (about 80% was corn (80 million acres), soybeans (75 million acres), wheat (62 million acres), or alfalfa hay (61 million acres) of which most, except wheat, feed livestock); range and pasture land, 788 million acres; and vegetables, 3 million acres.

^dAssumes U.S. oil usage at 20.731 Mbbl/day (318 Bgal/yr).

^eRatio of bio-cropland required for U.S. oil usage replacement to U.S. arable land. Assumes U.S. arable land at 19.13% total land or 4.331×10⁸ acres (50 states and District of Columbia); for example, $7.5 \times 10^7 / (0.014 \times 4.331 \times 10^8) = 12.24$ U.S. arable land required for fuel replacement from soybeans.

^fAssumes all range and pasture lands are planted and capable of producing switchgrass at 5 ton/acre.

Irrigating large tracks of desert land with salt water can have one unintended anthropomorphic effect, namely turning adjacent desert into farmland. The evaporating water from these plants will change the local weather pattern, resulting in condensation, and change dry climates to wetter climates. This is the exact reverse effect that is happening in large tracks of land next to the Sahara desert where the desert soaks up the moisture and expands into the adjacent farmlands. Such an event has been a critical issue in Beijing for the last few decades. Due to rampant deforestation, the Gobi desert has been creeping towards Beijing for the last few decades and persons returning after several decades have noted it is now much drier and sandier than it used to be. Putting large amount of water into the desert for the water to vaporize can potentially make places like Beijing a little wetter and promote vegetation growth, which will in turn put more water in the atmosphere. Ultimately, it has the possibility of halting or outright reversing the desert growth.

FUEL VERSUS FOOD: ADVERSARY FEEDSTOCKS

The major issue is choosing between producing food or oil because there is a limited amount of arable land. That is why saline agriculture—an undeveloped source of both food and fuel—is so interesting. Saline agriculture, when combined with aqua culture, as accomplished in the Manzanar Project,¹¹ provides food, fuel feedstocks, habitat, and redistribution of fresh water resources. Seawater irrigation requires a lot of water, some 4 ft/yr for each acre.

Yet seawater irrigation also provides some 80% of the nutrients needed for plant growth and requires only additions of phosphorous, iron and nitrogen, suggesting the need for genetically modified nitrogen-fixing halophytes (Bushnell, 2006a). Soybeans and alfalfa are good arable-crop (glycophyte) nitrogen-fixing fuel feedstocks, and if we can learn and develop those same characteristic in halophytes, combine with aquaculture as in tilapia farming, we are on the road to both food and feedstocks for oil independence. However it is important to combine these efforts with metrology and global climate modeling to ensure that redistribution of seawater to arid and semi-arid regions (terra forming) provides a favorable climate balance and avoids adverse and unintentional consequences, such as anthropogenic global warming (Bushnell, 2006a).

The point is that through research in diverse plant development and processing, engineered to produce higher yields and more efficient use of these oils, biofuel feedstocks could provide a larger and larger portion of the transportation fuel demand. For example, Bushnell (2006a) cites genomic-derived halophyte production of tomatoes, eggplant, rice, wheat, and rapeseed, which appear quite successful. Irrigation agriculture is diverse, producing a large portion of fruits, nuts, and vegetables and also contributing to forage, fiber, industrial (paper, rubber, resins, solvents, and others), medicine, and ornamental products.¹² When it is combined with aquaculture, such as fish or shrimp farming, there are benefits to both in terms of long-term sustained production¹³ <http://www.seawaterfoundation.org/swKino.htm>.

FUEL-FOOD FEEDSTOCK POSSIBILITIES

Consider the possibilities:^{††} Since 43 to 44% of the Earth landmass is arid or semi-arid, there is the potential for developing a multiplicity of seawater-irrigated regions to produce halophyte crops and combine them with aquaculture. Now suppose that the size of these diverse, multiple regions is that of the Sahara desert,¹⁶ or 8.6×10^8 ha, and these diverse regions produce 100 bbl/ha-yr of bio-oil. The total equivalent energy produced would be 421.4 Q, or 94% of the 2004 world energy consumption.¹⁵ Currently, halophyte agriculture could free up freshwater supply and arable lands for food production. Freeing up freshwater with its abundance of energy and food drastically impacts the Triangle of Conflicts (energy, water, and food), which are the resources that spawn conflicts (even fighting) among people and nations.

Supposing that the production, logistics, and political issues could be overcome, the total energy from such arid land sources scattered over the Earth would be sufficient to meet the world's energy demands (Hsu, 1974 and Bushnell, 2006b). As such, if humanity chose and if we became committed, it could be accomplished.

C3 plants are better suited for arable soils, while C4 and Crassulacean Acid Metabolic (CAM) plants adapt to arid conditions. These plant characteristics and some examples are given in appendix B.

SUMMARY

The U.S. 2006 demand for energy at 0.271 Q/day (equivalent 50M bbl/day of oil or 580 bbl/s) outstrips our ability to sustain it.

Most engine systems run on fuels of some nature. For biomass fuels, as alcohols or diesel, the availability of arable land is a major problem and limits biomass use as a fuel resource, and it competes with food production. We need alternate biomass fuel-food feedstocks.

This paper deals with the prospects of one biomass fuel-food feedstock, halophytes, which can supply a considerable quantity of fuel or food and sequester carbon.

Halophytes are salt-tolerant plants that can prosper in seawater or brackish waters. Two types, broadly classed as coastal and desert, can be found in marshes, coastal planes, inland lakes, and deserts.

Improperly watered, irrigated croplands build up salt residues. If uncorrected, fertile soils hosting glycophytes crops (conventional soybeans, corn, wheat, and others)

^{††}Earth land size 148.9391×10^6 km² (148.9391×10^8 ha), 29.2% of its surface.¹⁴ The size of the Sahara Dessert is 8.6×10^6 km² (8.6×10^8 ha), envelopes nearly all of Northern Africa, and is about the same size as the total U.S. landmass ($9,161,923$ km²). A barrel of oil equivalent to a barrel of bio-oil, corrected for energy content to No. 2 diesel, is 5.4×10^6 Btu/bbl \times 0.91 (bio-oil to oil equivalent conversion) = 4.9×10^6 Btu/bbl of bio-oil. If production were 100 bbl/ha-yr of bio-oil, then total energy = $8.6 \times 100 \times 4.9 \times 10^{14}$ = 42.14×10^{16} Btu = 421.4×10^{15} Btu = 421.4 Q. World energy consumption¹⁵ (year 2004) = 446.4 Q. U.S. energy consumption = 98 to 99 Q.

become wastelands and eventually deserts. In general, halophyte agriculture productivity increases with increases in light and temperature (subtropics). As the salinity of arable lands producing conventional crops continues to increase, crop productivity decreases.

Genetic modification and synthetic biology have the potential to increase yields of halophyte crops, and in some cases the yields are much better than soybeans by a factor of 4 of the U.S. average production.

Considering that ~43% of the Earth's landmass is arid or semi-arid, and 97% of the Earth's water is seawater, the potential for fuel-food feedstock halophyte production becomes very large. As an example, if the Sahara desert (8.6×10^8 ha) were made capable to support halophyte agriculture, and if production were increased to 100 bbl/ha-yr of bio-oil, it alone would supply 421.4 Q, or 94% of the 2004 world energy consumption.

Major problems stem from pumping and draining of the required high volumes of irrigation water from sea or ocean sources. Coastal and ocean areas are better suited for saline-agriculture-nurtured plants such as mangroves, salicornia, algae as seaweed, kelp, sargassum (Sargasso Seas), as they enhance aquaculture.

Not all arable, arid, or semi-arid lands are suitable for crops, yet even if as little as 0.5% (7.5×10^8 ha) of the world's arid or semi-arid lands were capable of supporting halophyte agriculture, at 15 bbl/ha-yr of bio-oil, this fuel feedstock would supply 55 Q or 12.3% of 2004 world energy consumption (oil energy equivalent to nearly $\sim 10^{10}$ bbl/yr of oil, or 4/3 of U.S. oil consumption). More importantly, this would either free up arable food-producing land or itself become a source of food where the demand for food outpaces that for fuel. Most importantly, it would free up the use of freshwater (only ~3% of Earth's water) for other purposes.

Halophytic plants are used in cleansing the environment whether controlled by man or not. In phytoremediation specialized plants are used to cleanse contaminated soils where urgency is not a primary factor. These plants can cleanse and "make" soil as well as desalinate brackish waters. In addition, the roots of both glycophytes and halophytes store carbohydrates and can sequester with potential nearly two decades of CO₂ production.

It is important to remember that not all anthropogenic endeavors are in consort with nature, and careful attention to details of saline agriculture are required to prevent an anthropogenic disaster as is inherit in continued unabated, business-as-usual use of hydrocarbon fuels.

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APPENDIX A: PHYTOREMEDIATION

Four basic types of phytoremediation are (i) phytoextraction, where specialized plants extract and accumulate high-biomass metal in above the ground shoots; this is most common and cost effective. The plants are harvested by conventional methods; (ii) rhizofiltration, similar to hydroponic gardening where plant roots are grown in aerated water and precipitate and concentrate toxic metals from polluted effluents; (iii) phytostabilization, a less researched discipline that uses plants to stabilize and neutralize soil pollutants; and (iv) phytovolatilization, also a less-supported discipline, uses plants to extract volatile metals (e.g., mercury and selenium) from soil and volatilize them from the foliage. Plants are also used to clean up organics as polychlorinated biphenyls (PCBs), pesticides, and explosives.¹⁷

Metals: green to clean.

Specialized plants are used to cleanse contaminated soils where urgency is not a primary factor at a cost 70 to 100 times less than conventional soil cleanup.^{17,18} Poplar trees, mustard crops, and turfgrass are but a few such plants. Turfgrass can accumulate lead concentrations up to 5000 ppm in the blades.¹⁸ Yensen and Biel (2006) provide an estimate of salts removal for *Distichlis* (a C4 grass) of 2 to 150 tonne/ha-yr. Some plants can remove up to 1% or more of their drymass weight.¹⁷ Other targeted metals include arsenic, chromium, cadmium, and various radionuclides.¹⁷ Sunflower plants were effective in decontaminating 100 to 400 ppb uranium in ground and pond water at a DOE site in Ashtabula, Ohio.

Atmosphere: green to clean.

Glenn et al. (1992) reports that halophytes could be grown on 0.13×10^9 ha in coastal and inland salt deserts and secondary salinization irrigation areas with a potential to sequester 0.7×10^9 tonne of carbon. Spencer (1991) estimates that 1.3×10^6 km² (0.13×10^9 ha) of inland and coastal deserts and marshlands could sequester 0.5×10^9 ton (0.45 tonne) of carbon and estimates cost of dry ton delivered at \$150 to \$250. See also appendix C.

Maintaining the balance of CO₂, CH₄, H₂, and water is significant for planetary atmospheric stability, and the Hansen's (2006) "business as usual scenario" indicates that Earth has already entered into the criticality zone and humanity must respond.^{‡‡}

Space travel: green to clean.

A similar scenario will become paramount in space travel and colonization, where in order to survive the human must become an essential part of the environment, regeneration of oxygen is critical. The studies that NASA and others have and will conduct can become essential lessons for survival (e.g., Salisbury, 1991; Anker, 2004; and Loyeva et al., 2006).

Genetics.

Chinese seawater agriculture is reporting genetically modified plants, tomatoes, eggplant, pepper, wheat, rice, and rapeseed grown on beaches using seawater,¹⁹ (Bushnell, 2006c). Professor Lin of Hainan University, Hainan Island, used the "pollen tube method," whereby the total DNA from salt-resistant plants such as mangrove is transferred through the tube to the ovary producing a transgenic plant that may or may not be stable and useful. The Hainan group added some fertilizer and irrigated their stable transgenic plants with seawater. The plants have survived four generations with yield and nutritional levels about the same as freshwater grown crops, but with better taste.¹⁹

Professor Xia Guangmin of Shandong University claims the development of a special species of halophytic wheat with a reported yield of nearly 400 kg/mu^{§§} with the taste of conventional wheat.¹⁹

Of the many sources of plant matter, some have been wiped out by fungi—a potential problem with genetically modified plants (GMO), and careful monitoring of crop

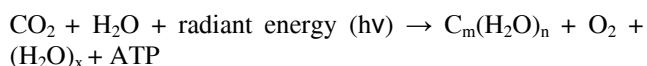
‡‡See also Climate Change Scenarios for the United Kingdom Hadley Centre report UK: Met Office, April 2002/UKCIP02 Report.

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^{§§}400 kg/mu is 6000 kg/ha, 5342 lb/acre, or 89 bu/acre, where 1 ha = 15 mu). China's average is 3910 kg/ha²⁰. As a controlled yield (very good soil, drainage, fertilizer, seed, weather, and planting conditions), a 120 bu/acre yield is possible, yet the U.S. 2005 wheat crop average was 42 bu/acre^{21,22}, or 189 kg/mu (256 kg/mu (Missouri yield))²¹, well below the UK yield 780 kg/ha, or 115 bu/acre²⁰. The key issue is that yield can vary an order of magnitude or even be nothing, entirely dependent on environment.

and growth needs to be accomplished. As an example of halophytes, eelgrass was at one time prevalent throughout the world, yet in the 1930s as slime mold attacked the leaves, eelgrass nearly became extinct and waterfowl depending on eelgrass starved. Culturing, while proving quite resistive, has shown progress.²³ The advances in synthetic biology may enable researchers to determine more accurately how to construct rather than modify plants and cells to produce what is needed for food and oil.²⁴

APPENDIX B: C3, C4, AND CAM PLANTS

Plants produce carbohydrates through the metabolic process of photosynthesis, in which radiant energy is used to convert inorganic carbon into organic carbon:²⁵



where ATP is adenosinetriphosphate.

C3 plants fix CO₂ (one carbon) with ribulose 1,5-diphosphate (five carbons) to form two molecules of 3-phosphoglyceric acid (three carbons each). Examples include Kentucky bluegrass, bentgrass, sugar beets, barley, and oats.²⁶

C4 plants fix CO₂ (one carbon) by combining with phosphoenolpyruvic acid (three carbons) forming oxaloacetic acid (four carbons). Examples include Bermudagrass, crabgrass, sorghum, millet, and corn.²⁶

Under high light intensity and high temperatures, C4 and CAM photosynthesis is faster than C3 plants because the CO₂ is delivered directly to Rubisco, thus inhibiting photorespiration with less transpiration water loss by not keeping stomata open as long. Rubisco is a common protein involved in catalyzing the conversion of inorganic carbon to organic carbon.

For every 10 °C rise in temperature in the range 0 to 35 °C respiration rate increases 2 to 4 times. Storage temperature is critical as parts continue to respire after harvest (catabolic process) and product breakdown releasing heat. C4 plants have better growth during cooler night (5 °C less than day) with less respiration.²⁶

Also C4 plant photosynthetic rate increases with light levels; most C3 plants have a peak threshold indicating that these are better plants for irrigated desert areas (inland, coastal, or aquifer).

CAM plants store CO₂ in the form of an acid before use in photosynthesis. Stomata are open at night when temperatures and wind speeds are lower, prompting water conservation and are even closed at night under extreme arid conditions. Under these conditions, the plant oxygen evolved from photosynthesis is used for respiration and the CO₂ given off is used for photosynthesis, allowing the plant to survive long dry spells and rapidly take up available water. An example of this is a cactus plant.

APPENDIX C: HALOPHYTE AND GLYCOPHYTE ROOT CARBON SEQUESTRATION

While the focus of the work of Samac et al. (2007) is to stem the spread of common alfalfa root rot (*Aphanomyces* and *Phytophthora*); they also compare the root systems of corn, switchgrass and alfalfa, figure C.1.

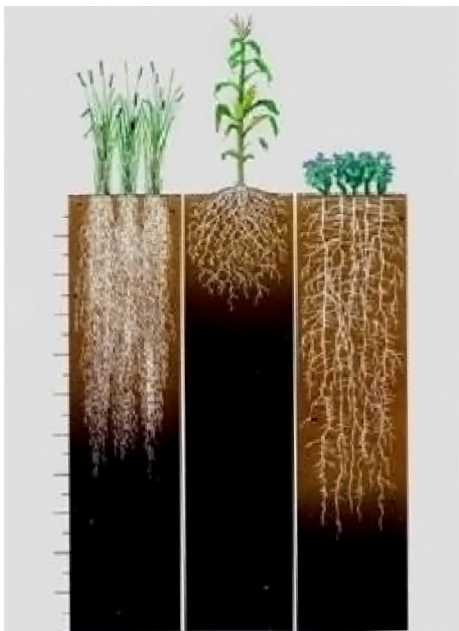


Figure C.1.—Relative root lengths of switchgrass (left), corn (center), and alfalfa (right). <http://www.extension.umn.edu/cropevents/2007/07MNCN14.htm>

Alfalfa roots can grow nearly 2 m/yr in loose soils and have been found 18 m or more below grade. Alfalfa roots symbiotically work with soil bacteria (*Sinorhizobium meliloti*) to fix atmospheric nitrogen and store carbohydrates produced in the leaves enabling rapid regrowth and spring greenup.

For root depths to 6 m, Sommer et al. (2000) cite carbon sequestration for primary forest at 196 t/ha, slash-and-burn 185 t/ha and semipermanent cultures at 146 to 167 t/ha.

Assuming a sequestration of 145t/ha and area the size of the Sahara Desert would sequester (8.6×10^8 ha \times 145t/ha= 1.250×10^{11} t-carbon). With CO₂ production of

2.7×10^{10} t/yr²⁷ such a plant-root system could potentially store $1.25 \times 10^{11} \times [44/12] / 2.7 \times 10^{10} = 17$ yr-carbon. Root carbon sequestration becomes a major benefit of both glycophyte and halophyte food-fuel feedstocks, and it would not be difficult to envision a new energy-system coupled to low-pressure subsoil pipeline networks coupling CO₂ capture with plant root sequestration. System safety becomes paramount as tasteless, odorless CO₂ pockets form in low areas; once into these areas, asphyxiation is eminent; yet the best technique would be natural recycling.

World Feeder Bermuda Grass, is a patented halophyte grass that is similar to switchgrass with a good root system and high salt tolerance. More likely it would be used as a livestock feeder grass rather than a fuel feedstock, but can serve both purposes.²⁸

Kudzu is a rather noxious invasive weed that grows prolifically in the southern United States and could be harvested for fuel. But like *Jatropha*, not as a food source.^{29,30}

APPENDIX D: HALOPHYTE AGRICULTURE

Halophyte agriculture deals with saltwater-tolerant plants. Small saltwater-tolerant algae may be thought of as microhalophytes. They are prolific, and like their freshwater counterparts, can take over salt or brackish water estuaries, ponds, and inland lakes in a matter of days (algae blooms). Some seaweed-algae as kelp and sargassum, can grow to massive mats. (Four main algae types are blue-green, green, brown, and red.) Less well known are macrohalophytes such as *Salicornia*, seashore mallow, and mangroves. Halophytes populate coastal regions and open seas.

Recent halophyte summits discuss challenges of commercialization from seawater farms to photobioreactors and open ponding. For the latter harvesting (skimming, flocculating, and drying) conditioning and extraction in a cost-effective manner are major challenges. Increasing lipid content of cyanobacteria (“blue-green-algae,” unicellular and endosymbiosis with plant cells) and *Chlorella* (single cell freshwater algae) are also a concern. The cost of medical and health food algae (e.g., blue algae) are high, and both the product and algae are not the type to be considered for oil extraction. For the former, investor incentives and territorial land management within and between countries are challenges [Atlanticgreenfuels.com; <http://www.wsgr.com/WSGR/Display.aspx?SectionName=news/emailer/Event141/info.htm>].