Thermodynamics of Energy Production from Biomass

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Abstract

With high quality petroleum running out in the next 50 years, the world governments and petrochemical industry alike are looking at biomass as a substitute refinery feedstock for liquid fuels and other bulk chemicals. New large plantations are being established in many countries, mostly in the tropics, but also in China, North America, Northern Europe, and in Russia. These industrial plantations will impact the global carbon, nitrogen, phosphorus, and water cycles in complex ways. The purpose of this paper is to use thermodynamics to quantify a few of the many global problems created by industrial forestry and agriculture. It is assumed that a typical tree biomass-for-energy plantation is combined with an efficient local pelleting facility to produce wood pellets for overseas export. The highest biomass-to-energy conversion efficiency is afforded by an efficient electrical power plant, followed by a combination of the Fischer-Tropsch diesel fuel burned in a 35%-efficient car, plus electricity. Wood pellet conversion to ethanol fuel is always the worst option. It is then shown that neither a prolific acacia stand in Indonesia nor an adjacent eucalypt stand is "sustainable." The acacia stand can be made "sustainable" in a limited sense if the cumulative free energy consumption in wood drying and chipping is cut by a factor of two by increased reliance on sun-drying of raw wood. The average industrial sugarcane-for-ethanol plantation in Brazil could be "sustainable" if the cane ethanol powered a 60%-efficient fuel cell that, we show, does not exist. With some differences (ethanol distillation vs. pellet production), this sugarcane plantation performs very similarly to the acacia plantation, and is unsustainable in conjunction with efficient internal combustion engines.

KEY WORDS: biomass, biofuel, ecosystem, sustainability, renewability, cycle, thermodynamics, energy, exergy, acacia, eucalypt, sugarcane, solar

Musst du nicht längst kolonisieren?
(Hasn't colonizing been your business?)
Mephisto to Faust, Part II, V, line 11274
by Johann Wolfgang von Goethe, 1832

1 Introduction

It is not uncommon for the researchers involved in biomass processing for fuels to claim[1] that there are billions of tonnes of "biowaste" out there[2], ready to be picked up each year, and processed,

[1] "...we can convert organic wastes to fuels that would supplant 10% of fossil fuels now, and in the long run we might create "energy plantations" to replace fossil fuels across the board." (Johnson, 1975).

[2] The total volume of forest woody matter on the earth was estimated by FAO (2001) as 500 Gm^3, equivalent to ~350 Gt of woody mass. Then, it is claimed, about 5 Gt of agricultural and forestry "waste" are created each year

providing – in effect – an almost free, abundant and environmentally benign source of energy for humanity. We will argue that ecosystems (the Earth Households) are the intricately linked webs of life that know of no waste, see e.g., (Capra, 1996; Patzek, 2004). Therefore, "biowaste" is an engineering classification of plant (and animal) parts unused in an industrial process. This dated human *concept* is completely alien to natural ecosystems, which must recycle their matter *completely* in order to survive (Odum, 1998; Patzek, 2004). Excessive "biowaste" removal robs ecosystems of vital nutrients and species, and degrades them irreversibly, see (Georgescu-Roegen, 1971; Odum, 1998; Patzek, 2004) for a more detailed discussion.

This paper is intended for anyone interested in the supply of energy to humanity and the preservation of the global environment to the fullest extent possible. When plants supply fossil energy on the global scale, their cultivation impacts many large and important ecosystems, and may not be the single silver bullet sought by the environmentalists and governments alike to lessen the greenhouse gas emissions and decrease the rate of global warming. We suggest that energy conservation[3] through increased efficiency (Pimentel et al., 2004), as well as increased reliance on solar energy[4] may lessen the human influences on the global environment more than all other schemes of "renewable energy" supply considered today.

1.1 Important Renewable Energy Definitions

The magic words "sustainability" and "renewability" are ubiquitous in agriculture and forestry literature. Unfortunately, these words are not defined rigorously, and have almost arbitrary meanings when used by different authors. In this paper, sustainability is an *ideal* conceivable only for cyclic processes[5], and defined as follows (Patzek, 2004):

Definition 1 [**Sustainability**] A *cyclic* process is *sustainable* if and only if

1. It is capable of being *sustained*, i.e., maintained without interruption, weakening or loss of quality "forever," and

2. The environment on which this process feeds and to which it expels its waste is also sustained "forever."

by human activities.

[3]Since 1980, consumption of crude oil has decreased in France and Germany by ∼10%, while it increased in the U.S. by ∼16% (Mouawad, 2004). Therefore, a 25% cut in crude oil use can be achieved with off-the-shelf technology and a national energy policy. Such a policy simply does not exist in the U.S.

[4]Despite its inherent *very severe* weaknesses, see (Hayden, 2002) and (Patzek, 2004), Appendix C.

[5]Such as an ecosystem, or an organic crop rotation, see Parts II and III, and Appendices A-B in Patzek (2004).

Corollary 1 *A cyclic process, which is also "sustainable," must not release chemicals into the environment, i.e., its net mass production must be "close" to zero "forever."*

As demonstrated in, e.g., Patzek (2004), any *linear process* that depletes the finite stock of fossil fuels and minerals on the earth is irreversible and cannot be sustainable. If fossil fuels and earth minerals are consumed within a natural cyclic process (e.g., an annual or perennial crop cycle), this process ceases to be sustainable, even though it may be forced to go through tens or hundreds of cycles – thus *replacing* the crop many times – but at the cost of irreversible depletion of the fossil fuels and minerals.

With the expectation of a "truly great but brief, not a long and dull, career[6]" of humans on the earth, one may attempt to define the "forever" in **Definition 1** to mean, say, 160 years, i.e., the duration of our industrial civilization. With this operational definition of eternity, it will be much easier to find a "sustainable" agriculture (a sugarcane plantation) or forestry (an acacia and eucalypt tree plantation) operation *if* it exists at all. We remind you, however, that this paltry "eternity" is much much shorter than the ages of parts of the present Amazon forest, which might be close to 4000-12000 years (Pessenda et al., 2001), with at least 180-1500 years in steady state observed today in what is left of this forest (Francis and Knowlesb, 2001).

In this paper, we investigate some of the conditions under which the fossil fuel-aided biomass-for-energy cycles might be more beneficial than using the fossil fuels outright. To that effect, we write the mass, energy and free energy balances of industrial plantations in the tropics. There are many types of plantations. Some of the most common are simple/complex; small-scale/large-scale; and single-purpose/multi-purpose (Sawyer, 1993). We define the main class of plantations of interest in this paper as follows.

Definition 2 An **industrial plantation** is a large-scale, usually single-crop, forestry or agricultural enterprise, which delivers at regular time intervals biomass of consistent quality and quantity to remote chemical and/or power plants. (We do not focus here on the classical timber and wood pulp plantations.) □

In particular, in this paper we will describe large monocultures of acacias, eucalypts, and sugarcane. These monocultures deliver biomass in different forms to chemical plants and power stations, which convert it to automotive fuels and/or electrical energy.

[6](Georgescu-Roegen, 1971), page 304.

1.2 Background

Biomass production for *new* industrial uses,[7] such as automotive fuel, large-scale electrical power cogeneration, raw material for bulk chemicals, etc., is the ultimate marriage of convenience between the oldest and most powerful force that has shaped our civilization — agriculture (Cavalli-Sforza and Cavalli-Sforza, 1995; Manning, 2004) — and the modern chemical industry (Hamelinck, 2004). The latter is running out of cheap petrochemical feedstock, and the former strives to colonize the last few untouched corners of the earth. At the turn of the 21st century, out of this marriage, were born the unmistakably 19th century attempts to convert huge swaths of old agricultural land and freshly clear-cut or burned tropical forests into industrial plantations of trees, soybean[8], etc. The peculiarly U.S. contribution to this scheme is maize (corn) for ethanol. Even though the spirit is to convert the tropics (as well as the poor parts of the U.S. interior, Eastern Europe, and Russia) into gigantic sources of industrial raw (bio)materials[9] for the more developed countries or regions, the obfuscating language is decidedly 21st century, with terms like "green energy," "sustainable development," "renewable development,", "zero-emissions," "investment in the developing world," etc., used most often[10].

When produced industrially, i.e., in quantities of tens or hundreds of millions of tonnes, biomass should be viewed as another bulk fuel and raw chemical (just like crude oil, natural gas or coal), with its own global environmental hazards. The key difference, however, is that the old-age fossil fuels were created by the sun and the earth over hundreds of millions of years in the *past*, and

[7] Old industrial uses include timber for construction, panel products and furniture, and wood pulp for paper.

[8] Sugarcane is not usually planted in the cleared tropical forest.

[9] "...Green fuel is not just a humanitarian disaster; it is also an environmental disaster. Those who worry about the scale and intensity of today's agriculture should consider what farming will look like when it is run by the oil industry. Moreover, if we try to develop a market for rapeseed biodiesel in Europe, it will immediately develop into a market for palm oil and soya oil. Oilpalm can produce four times as much biodiesel per hectare as rape, and it is grown in places where labour is cheap. Planting it is already one of the world's major causes of tropical forest destruction. Soya has a lower oil yield than rape, but the oil is a by-product of the manufacture of animal feed. A new market for it will stimulate an industry that has already destroyed most of Brazil's cerrado (one of the world's most biodiverse environments) and much of its rainforest..." *Fuel for nought* by George Monbiot, *The Guardian*, November 23, 2004.

[10] "...It is shocking to see how narrow the focus of some environmentalists can be. At a meeting in Paris last month, a group of scientists and greens studying abrupt climate change decided that Tony Blair's two big ideas - tackling global warming and helping Africa - could both be met by turning Africa into a biofuel production zone. This strategy, according to its convenor, "provides a sustainable development path for the many African countries that can produce biofuels cheaply"..." *Fuel for nought* by George Monbiot, *The Guardian*, November 23, 2004.

pollute us today only when we use them[11]. In contrast, the new biomass and its accompanying chemical pollution are produced in 1/2–10 year crop rotations *today*, regardless of how we use it.

2 Ancient and Contemporary Fossil Fuels

We start by defining the different classes of fuels.

Definition 3 Fossil fuels: Coal, solid and semi-solid bitumen, heavy oil, oil, liquefied petroleum gas (LPG), and natural gas are *irreplaceable*[12] finite sources of energy in the form of fossilized and chemically transformed remains of buried plants and animals[13]. □

Definition 4 Industrial biofuels: Methanol, diesel, other Fischer-Tropsch fuels, and ethanol are *replaceable*[14], but generally unsustainable, sources of energy in the form of liquids obtained from industrially-grown biomass by gasification/catalytic conversion or fermentation/distillation in large chemical plants. □

Definition 5 Biomass fuels: Wood, twigs, leaves, grasses, crop leftovers, other vegetation, and dung are replaceable, but often not-quite-sustainable sources of energy in the form of plant and animal matter that are directly burned or converted into a low quality gas in small, low-tech anaerobic tank digesters or fixed-bed gasifiers. □

Definition 6 Plant "trash": Stems, roots, branches, leaves, straw, grass, underbrush, and wood chips/fragments *extracted* from parent ecosystems and converted into industrially desirable products (e.g., fuels), just like metal scrap is melted in a factory[15]. □

[11] We discount natural seeps of oil and gas (excluding man-made mines), and a distant possibility of decomposing methane hydrates under the thawing permafrost and warming oceanic water.

[12] On the time scale of human civilization; therefore, as sources of energy, all fossil fuels are *unsustainable* (Patzek, 2004).

[13] Not everyone agrees, and there is an ongoing scientific discussion of the biotic versus abiotic origins of petroleum, see Gold (1999).

[14] When a plant from one place is chemically disintegrated, its parts incinerated, and ash disposed into a toxic waste dump, it is not renewable, but is replaced later with another plant from another place. In addition, the term "renewable" has been abused so much that we want to avoid it.

[15] In the remainder of this paper we will demonstrate that plant leftovers are *not* equivalent to metal scrap. In view of Definition 1, "biotrash" is a concept incongruent with the current understanding of ecosystems. The origins of this concept can be traced back to the Renaissance and Enlightenment attitudes towards nature. For example, Galileo, Descartes, and Newton treated nature as a machine, which could be disassembled into parts with no penalty. Each of these parts could then be examined separately and understood completely.

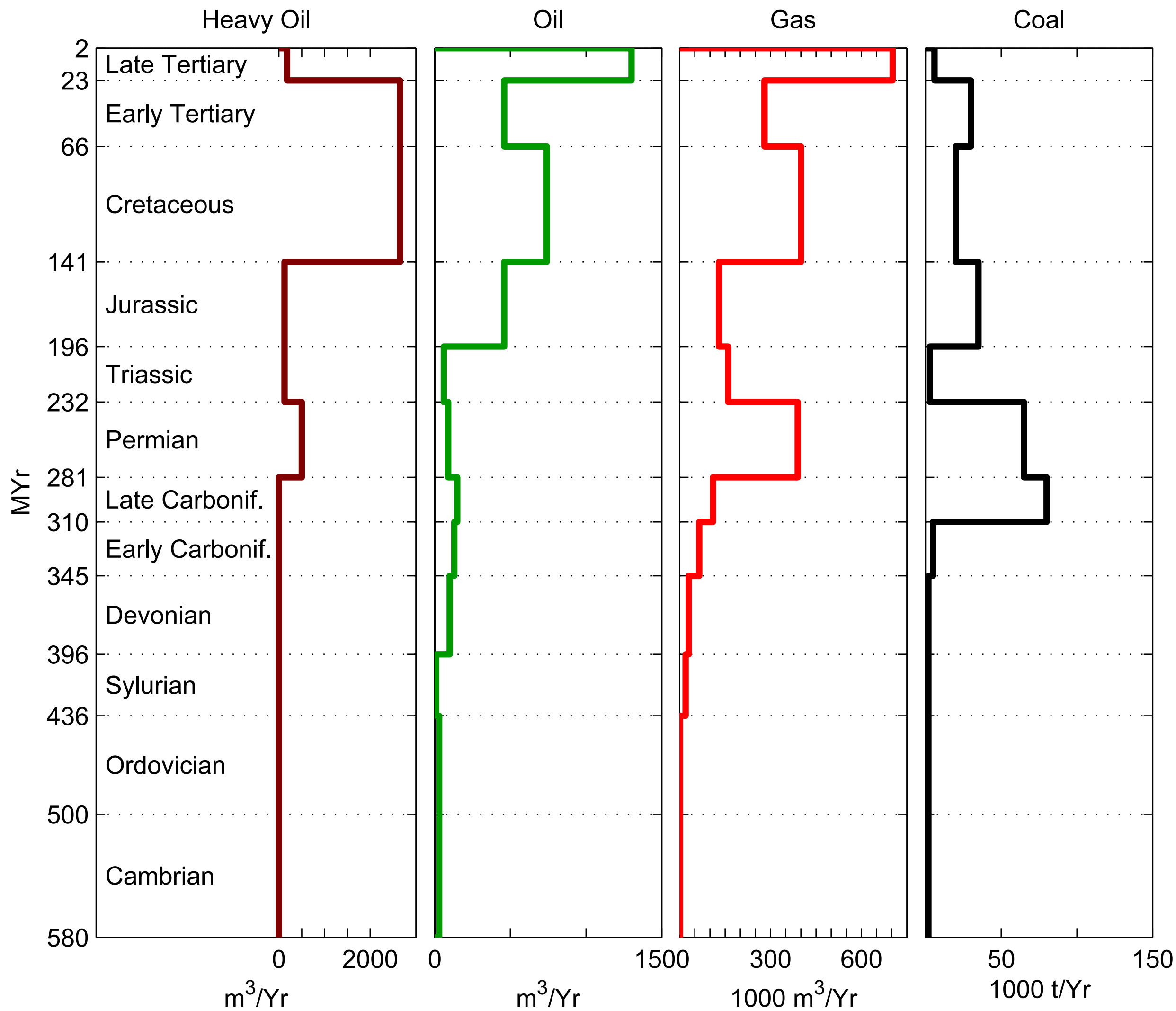

Figure 1: The average rates of accumulation of fossil fuels in the earth over geological time. The average rates of heavy oil deposition are from Demaison (1977). The average rates of oil and gas deposition are from Bois et al. (1982). The coal deposition rates are from Bestougeff (1980). Note the almost imperceptible global annual deposition rates of fossil fuels, and the unimaginably long duration of their deposition processes. These rates are a factor of 3–5 smaller than the best current estimates of fossil fuel endowments.

Industrial production of plant-derived fossil fuels (biofuels) is yet another human attempt to modify the carbon cycle on the earth[16]. The global carbon cycle is carried out by a myriad of processes that last from hours to hundreds of millions of years, and occur over surfaces from μm^2 to

[16] Not only the carbon cycle, but also the intertwined water, nitrogen, phosphorus, potassium, calcium, magnesium, iron, boron, manganese, zinc, selenium, copper, etc. cycles are modified.

thousands of km^2. Photosynthesis, respiration, air-sea exchange of CO_2, and humus accumulation in soils are all examples of short-term processes. The long-term carbon cycle, which occurs over millions of years, is responsible for the creation of fossil fuel deposits (Berner, 2003).

2.1 Ancient Generation of Fossil Fuels

Petroleum[17] consists of liquid (oil) and volatile (gas condensate and natural gas) organic compounds generated during the conversion of metastable macromolecular kerogen to thermodynamically favored lower molecular mass compounds (Seewald, 2003). The chemical reactions responsible for this transformation occur in response to the removal of kinetic barriers as temperature increases with progressive burial in sedimentary basins. Formation of an economic petroleum deposit requires, in addition to a suitable source rock containing sufficient organic matter, a sequence of geological events that leads to the expulsion, migration and trapping of the generated hydrocarbons.

Oil is generally thought to be geologically young, as it is thermodynamically unstable when subjected to elevated temperatures over long periods in open systems (Quigley and Mackenzie, 1988; Mango, 1991). Indeed, almost all petroleum production comes from rocks younger than 400 million years (Bois et al., 1982), and nearly 50% of the world's petroleum has been generated since the Oligocene (Klemme and Ulmishek, 1991). Since coal does not migrate from its burial location, its peak geological generation rate (Demaison, 1977) was some 50 times higher than those of petroleum.

Figure 1 shows that the estimated geological rates of deposition of heavy crude oil, petroleum, and coal were almost imperceptibly low. Note that these rates are inevitably approximate, and may differ from the true deposition rates by an order of magnitude. Nevertheless, it is the 400 million years of almost continuous deposition that resulted in today's fossil fuel accumulations in the earth. Integration of the deposition rates in Figure 1 gives the following estimates of the ultimate endowments of fossil fuels on the earth:

- Heavy oil – 3.5×10^{11} m^3 (2.2 trillion barrels (TB)),
- Conventional oil – 1.5×10^{11} m^3 (1 TB),
- Natural gas – 1.0×10^{14} standard (s) m^3 (3400 Tscf),
- Coal – 1.1×10^{13} metric tonnes.

[17]The term *petroleum*, as used here, includes conventional crude oil, gas condensate, and natural gas, but excludes heavy oil and bitumen.

By fitting the world's conventional oil & condensate production with a HUBBERT cycle (1949; 1956), one obtains 2 TB for the ultimate recovery. According to JEAN LAHERRERE (2004), this estimate may be extended to perhaps 3 TB *if* the uncertain and speculative future discoveries are factored in. If the average recovery factor for conventional oil is 0.4, its endowment can be generously estimated at $5 - 7.5$ trillion barrels ($8 - 12 \times 10^{11}$ m^3) for the world. From a similar analysis (Laherrere, 2004), the ultimate world gas production will be 10 000 Tscf (2.8×10^{14} sm^3), and may be extended to 12 500 Tscf (3.5×10^{14} sm^3) *if* unconventional gas and new discoveries are added. According to an informed speculation by DAVIS (2002), there are $8 - 9$ trillion barrels ($13 - 15 \times 10^{11}$ m^3) of heavy oil and bitumen in place worldwide, of which potentially 900 billion barrels of oil are commercially exploitable with today's technology. Canada alone has, by some estimates, 175 billion barrels of bitumen. The latter figure remains controversial; a more cautious BP estimate has been of the order of 17 billion barrels as recoverable[18].

Therefore, the respective endowment estimates obtained from Figure 1 are remarkably close (lower by a factor of $3-5$) to the current best estimates of the endowments of all known petroleum and heavy oil basins on the earth. Please note that we are not considering here the gigantic, probably $0.1-2\times10^{13}$ tonnes (maybe up to twice the coal endowment), world endowment of methane dispersed[19] in methane-gas hydrates (Kvenvolden, 1999), and kerogen in oil shales (1/3 of coal endowment in proved amount-in-place (Youngquist, 2003)). Environmental costs of tapping into the latter endowments may be prohibitive, especially with the rising CO_2 levels in the atmosphere as background.

2.2 Contemporary Consumption of Fossil Fuels

The current global consumption of conventional oil, condensate, and heavy oil is about 4.4×10^9 m^3 per year, see e.g., (Deresselhaus and Thomas, 2001). At an average $30 - 40\%$ net[20] extraction of their endowments, the *recoverable* heavy and conventional oil will be exhausted within $30 - 50$ years. The annual consumption of natural gas is about 2.4×10^{12} sm^3, and that of coal about

[18]BP's Statistical Review of World Energy, 2004. http://www.bp.com/subsection.do?categoryId=95&contentId-=2006480, accessed March 12, 2005.

[19]Unfortunately, it seems that the total hydrate volume estimates can be approximated by the following empirical equation: $10\,000\times10^{15}$ sm^3/2×cumulative number of hydrate papers published since 1971, cf. Figure 1(b) in (Milkov, 2004). This number exceeded 1000 by 2004.

[20]Thermal recovery of heavy oil requires burning of up to 50% of the recovered oil equivalent to generate the quantity of heat necessary to recover this oil.

4.5×10^9 tonnes.

Therefore, the current rate of crude oil consumption on the earth is about 300 000 times higher than the peak geological formation and deposition rates of heavy and conventional crudes in the Late Tertiary ($3 \times 2650 + 5 \times 1300$ m^3/yr[21]). Similarly, the current rate of natural gas consumption is about 1.4 million times higher than its peak geological deposition rate in the Late Tertiary (2 100 000 sm^3/year). Finally, the current rate of coal consumption is about 60 000 times higher than its peak deposition rate in the Late Carboniferous (80 000 tonnes/year).

We thus arrive at the important remark and, at the same time, the starting point of this paper.

Remark 1 (Rate effect.) Human attempts to replace, say, $10 - 15$ percent of the current annual consumption of liquid and gaseous fossil fuels (petroleum and heavy oil) with the plant-derived biofuels require the acceleration of natural processes of fuel formation and deposition by a factor of $30 - 140$ *thousands* — relative to the respective peak geological rates, which have lead to the presence of these fuels in the earth. In other words, we require that a natural carbon sequestration and transformation process that lasts 30 000 − 140 000 years be shortened to 1 year! (To put this statement into perspective, as of 300 000 years ago, the human brain evolved to its current size. As of 100 000 years ago, the early human hunters and gatherers were roaming parts of the Middle East and Asia. Agriculture, which has entirely defined our civilization, is less than 10 000 years old (Cavalli-Sforza and Cavalli-Sforza, 1995; Manning, 2004).) □

Corollary 2 *A four-order-of-magnitude acceleration of the natural rate of sequestration of solar energy as petroleum and heavy oil requires massive human intervention, usually in the form of ancient fossil fuels and earth minerals, which must be burned and/or chemically transformed* [22] *to help the industrial plants grow faster and be chemically transformed* [23] *into synthetic biofuels.* □

Corollary 3 *As demonstrated elsewhere (Patzek, 2004), this human intervention is irreversible and renders all industrial biofuel production processes unsustainable. On the other hand, there may*

[21] The overall deposition rates, have been obtained by rescaling the endowments derived from Figure 1 to the endowment values obtained from the estimates of ultimate recovery and educated speculation.

[22] Ammonia, the essential nitrogenous (proto)fertilizer, is synthesized from nitrogen (air) and hydrogen (natural gas) in the HABER-BOSCH process, without which the world's population could not have grown from 1.6 billion in 1900 to the 6 billion of today. Commercial synthesis is carried out at pressures $200 - 400$ bars and temperatures $400 - 650^0$C, over an iron catalyst.

[23] Diesel and other fuels are produced from gasified biomass using the FISCHER-TROPSCH process. Synthesis gas is generated at temperatures in excess of 900^0C, and processed at the pressure of about 60 bars and temperature of 250^0C, over a suitable catalyst that may contain cobalt, nickel or ruthenium, in addition to iron.

be temporary benefits from using biomass, rather than fossil fuels. □

Because of their very long deposition times, fossil fuel deposits achieve high energy density per unit area of land surface. For example, 1 hectare of a 100 m-thick oil reservoir, with 25% porosity, and 75% initial saturation of a 35^0 API oil with the density of 860 kg/m^3, contains roughly 7.2×10^6 GJ of free energy. If 1/3 of this oil is practically recoverable, then the energy density is 2.4×10^6 GJ/ha. An outstanding biomass plantation may sequester[24] 500 GJ/ha-yr, or ~0.6% per year of solar energy in the tropics[25]. Therefore, at best, an industrial biomass plantation would have to operate at the same high yield for 5000 years to sequester the *useful* solar energy deposited in one large oil field[26]. So, our example plantation would have to have been planted during the Bronze Age, and produced uninterrupted ever since. With harvests every 8 years, it would take 625 crop rotations with the same very high yield to replace the recoverable energy content of one large oil field – an obvious impossibility!

This formal introduction to the main subject of this paper – the inherent long-term impossibility of replacing fossil fuels with biofuels, and the unsustainability of biofuel production on an industrial scale – is somewhat dry and abstract. Therefore, we will follow it with several examples that, we hope, will shed more light on how industrial biofuels may fit into the global energy supply.

3 Biomass from Tropical Tree Plantations

The last Global Forest Resources Assessment 2000 (FRA 2000), conducted by the U.N. Food and Agriculture Organization (FAO), was the most comprehensive in its fifty year history (FAO, 2001). The world's tropical forests were still lost to other land uses at the net rate of 13.5 million ha/yr[27], while new forest plantation areas were established globally at the rate of 4.5 million ha/yr, with Asia and South America accounting for more new plantations than the other regions. Brazil, Indonesia, Sudan, Zambia, Mexico, the Democratic Republic of Congo, and Myanmar were rank-ordered as the countries which lost the most forest during the 1990s. Brazil's total forest area diminished by 22 million hectares over the decade, while Indonesia's forest area declined by 13 million hectares.

[24] Without accounting for delivery and handling losses, and a significant expense of fossil fuels.

[25] At 250 W/m^2 of average 24-hour, year-long insolation in the tropics, 78 840 GJ/ha-yr of solar energy are delivered to a horizontal surface.

[26] As we will demonstrate in Section 9, the net free-energy (shaft-work or electricity) yield from a very good biomass plantation will be *negative*.

[27] An area of the size of Greece.

For the 1990's as a whole, it was estimated that about 1.8 million ha/yr of new plantations were successfully established in the tropics. Of the estimated 187 million ha of plantations worldwide in the year 2000, Asia had by far the largest forest plantation areas. In terms of genera composition, *Pinus* (20%) and *Eucalyptus* (10%) remain dominant genera worldwide, although overall diversity of planted species increased. Industrial plantations accounted for 48%, non-industrial 26%, and unspecified for 26% of the global forest plantation estate[28].

FRA 2000 identified ten countries with the largest reported plantation development programs (by area): China with 24% of the global area; India with 18%; the Russian Federation and the U.S. each with 9%; Japan with 6%; Indonesia with 5%; Brazil and Thailand each with 3%; Ukraine with 2%; and the Islamic Republic of Iran with 1%. Together, these countries account for 80% of the global forest plantation area.

Within the same ten countries, an estimated 52 percent of forest plantations are grown for industrial purposes to supply raw material for industry; 26 percent for non-industrial uses; and the purpose was not specified in 22 percent. The countries with major industrial plantation areas (expressed as a percentage of national forest plantation area) included the U.S. (100%); China (83%); and India (37%). These three countries account for 73% of all industrial forest plantations globally.

3.1 Scope of the Problem

To satisfy a significant part of the ever-growing automotive fuel and electricity demand in the world, five billion oven-dried tonnes (5×10^{15}g) of biomass would be needed each year for decades to come. At 10 oven-dried tonnes (odt)/yr-ha of the average[29] replaceable dry mass yield from industrial plantations, this mass of bio-feedstock would require an annual harvest of 1/8 of the dedicated 500 million hectares of these plantations with the eight-year crop rotation – an area close to 1/2 of the total area of tropical forest on the earth in 2004. These estimates are not merely a product of our imagination. A *United Nations Bioenergy Primer* (Kartha and Larson, 2000) states: "In the most biomass-intensive scenario, [modernized] biomass energy contributes...by 2050...about

[28] What a plantation becomes with time is often different from its design goals (Sawyer, 1993).

[29] This is a high average yield, which must be sustained over many crop rotations. Natural tropical forests are nitrogen- (Perakis and Hedin, 2002) and phosphorus-limited (Mackensen et al., 2000). Boreal and temperate forests grow at average rates between 0.5 and 3 odt/ha-yr, and tropical forests grow twice as fast as temperate ones (Malhi et al., 1999). Sugarcane plantations may deliver 20-30 odt/ha-yr (Kheshgi et al., 2000).

one half of total energy demand in developing countries. ... The IPCC's[30] biomass intensive future energy supply scenario includes 385 million hectares of biomass energy plantations[31] globally in 2050 (equivalent to about one quarter of current planted agricultural area), with three quarters of this area established in developing countries."

To maintain a high average yield of biomass over many crop rotations (over, say, 100 years), industrial tree plantations require: (1) intense mechanical site preparation and weed control with pre- and post-emergent herbicides; (2) periodic fertilization with macronutrients (N, P, K, Ca, Mg and S), and micronutrients (Fe, Cu, B, Mn, Mo, Zn, Se, etc.); (3) continuous use of insecticides; and (4) improved matching of plant genotypes to the plantation sites. For example, in the Jari, Brazil, plantation (McNabb and Wadouski, 1999), the site preparation involved slashing and burning of the native forest in 1972; chainsaw fell or drag chain removal of plantation trees, rotary hoeing, intensive removal of "vegetative competition" by manual weeding and herbicides, and switching to different tree species several times every 6-10 years.

To increase chances of high biomass production, industrial plantation designers will inevitably tend to choose the biologically prolific sites in good climate, with seemingly[32] rich soil, good water supply, and easy access (i.e., the ever-receding boundaries of mature tropical forests), rather than the remote, poor quality habitats with damaged soil and little vegetation. Therefore, the new huge industrial plantations will negatively impact or destroy some of the most pristine ecosystems on the earth (this is a statement of fact, not a moral judgement). In effect, the low-entropy environment in the tropics will be *mined*, see (Patzek, 2004), just like everywhere else since times immemorial.

In summary, we are discussing here a possibility of the largest industrial forestry project in the history of mankind. This project would cause the severest ever competition for good-quality land, impact every ecosystem on the earth, and all humans.

3.2 Environmental Impacts of Industrial Biomass Production

Because large industrial plant monocultures for energy invade and modify important ecosystems, it is useful to list some of the impacts of this invasion. Soils of tropical forests are usually poor in nutrients. Nevertheless, undisturbed tropical forests seldom have symptoms of mineral deficiencies which are typical indicators of degradation (Zech and Dreschel, 1998). Tropical forests are sustain-

[30]Intergovernmental Panel on Climate Change.

[31]In addition to the old industrial plantations, see Footnote 7.

[32]Tropical forest plants recycle most of their nutrients above ground level and the forest soils are usually very poor (Odum, 1998).

able, steady-state ecosystems (Patzek, 2004), which recycle (almost) all mass "forever," most of it *above* the soil (Odum, 1998). In contrast to undisturbed tropical forests, man-made plantations with frequent crop rotations often show signs of degradation, such as mineral deficiency, yield decline, or susceptibility to attack by weeds and other pathogens. Soil-related imbalances are mainly caused by

1. The impacts of clearing natural forests, mechanical and chemical site preparation, and establishment of a plantation, and

2. The impoverishment of soil due to nutrient export by frequent harvesting and associated management activities (such as slash burning) (Zech and Dreschel, 1998; Mackensen et al., 2003) and erosion (Morris et al., 1983; Wiersum, 1984; Troeh et al., 1999).

Following mostly Kartha and Larson (2000), we will now briefly introduce the main components of soil fertility.

3.2.1 Soil Nutrient Content

The major soil macronutrients are nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulphur (S). Micronutrients (needed only in minute quantities) are iron (Fe), copper (Cu), chlorine (Cl), manganese (Mn), boron (B), zinc (Zn), molybdenum (Mo), and selenium (Se).

Dissolved nutrients are assimilated through the roots of plants, returned to the soil by decomposition of dead plant matter, and are mineralized (broken down again into soluble forms) by soil flora and fauna. In some cases, nitrogen is assimilated from the atmosphere by highly specialized microorganisms that live in the plant roots. There is a slow gain of nutrients through surface and rain water, and the weathering of minerals, and some loss due to soil leaching and erosion.

As we will demonstrate below, soil nutrient content is relatively quickly depleted by human management of industrial plantations. Therefore, synthetic fertilizers produced from fossil fuels and minerals are used, and these plantations are unsustainable in the long run (Patzek, 2004). On the other hand, one can imagine producing some of these fertilizers from parts of the harvested trees and slash.

3.2.2 Organic Content of Soil

Organic matter in weathered tropical soil is only 1-6% of the soil mass, but it is the soil's reservoir of nutrients: the raw material from which microorganisms release the soluble nutrients consumed by plants. In tropical soils at depths 0-1 m, organic matter content is 75-125 tonnes/ha (Mackensen and Fölster, 1999). Organic matter also stores inorganic nutrients which bind to the large organic molecules. Organic matter preserves soil fertility by preventing leaching and erosion, and improves soil *structure* (Tisdall, 1996) by increasing the porosity and permeability of the soil. Organic matter is produced when plants die and decay. Industrial plantations often rely on the frequent removal of whole plants or slash burning and volatilization. While *some* soil nutrients can be replenished by synthetic fertilizers, organic matter *cannot*. Therefore, industrial plantations usually mine soil organic matter, and are unsustainable.

3.2.3 Soil Structure

Soil is characterized by its density, porosity and permeability, lumped together as *structure*. Soil structure determines how easily plant roots can grow to access soil nutrients, and how easily water can flow through the soil to deliver these nutrients.

Soil structure is damaged by excessive removal of biomass (the main indicator of economic viability of an industrial plantation) (Veldkamp, 1994), tilling (Watts, 1997), and by compaction of the soil by machinery. As soil loses its ability to adsorb water, it is eroded and leached by water runoff.

As we will show below, maintaining good soil structure is often contradictory to increasing the short-term plantation yield and profit.

3.2.4 Soil Erosion

When deforestation (harvest) occurs during heavy rainfall season, topsoil washes away and leaves the plantation surface barren and sometimes scarred by gullies. More common, however, is chronic soil erosion enhanced by human management practices on industrial plantations. Even the almost imperceptible soil erosion rate of 1 mm/yr removes about 15 tonnes/ha-yr of top soil. Soil erosion in plantations can be several times higher, see **Figure 2**. Continuing high erosion rate of soil renders all agriculture unsustainable.

Figure 2: Slash burning (bottom) after windrowing (top). These photographs were taken by James H. Miller, USDA Forest Service, www.forestryimages.org (top), and John D. Hodges, Mississippi State University, www.forestryimages.org (bottom).

3.2.5 Soil Biodiversity

Bacteria, fungi, earthworms, insects, etc. are *all* essential components of a healthy soil. These species not only break down organic materials and provide nutrients to plants, but also improve soil structure. Some plants (e.g., acacias) rely on symbiosis with soil microflora to obtain some or most of their nitrogen.

Soil biodiversity suffers from frequent tillage and frequent application of broad-spectrum insecticides and herbicides. Herbicides are often used in industrial plantations to decrease "weed" competition for soil nutrients and water, and increase biomass yield in the short run.

Finally, healthy soil flora and fauna needs plentiful organic soil matter. The combined weight of earthworms and insects can be 3000 kg/ha, with ample organic matter.

3.2.6 Conclusion

We have briefly summarized some of the delicately balanced and interlinked contributors to the long-term health of soil, and contrasted their sustainability with the often contradictory requirements of human management of industrial plantations. The fundamental contradictions between the short-term high yield of biomass and profit, and the long-term survival of industrial plantations and ecosystems that surround them, will make these plantations unsustainable.

3.3 Impact of Fertilizer Treatment on Tree Growth

Figure 3 shows the impact of nitrogen fertilizer on average diameters at breast height of 5 year-old trees in a New Zealand plantation. With an intensive fertilizer treatment of 200 kg/N-ha-yr, dry-mass yield from the plantation increased up to 30% (Dyck and Bow, 1992). The response to the nitrogen treatment was most pronounced in the poorest soil (the stars). For the three more fertile soils, the respective tree-growth responses depended somewhat on harvest techniques.

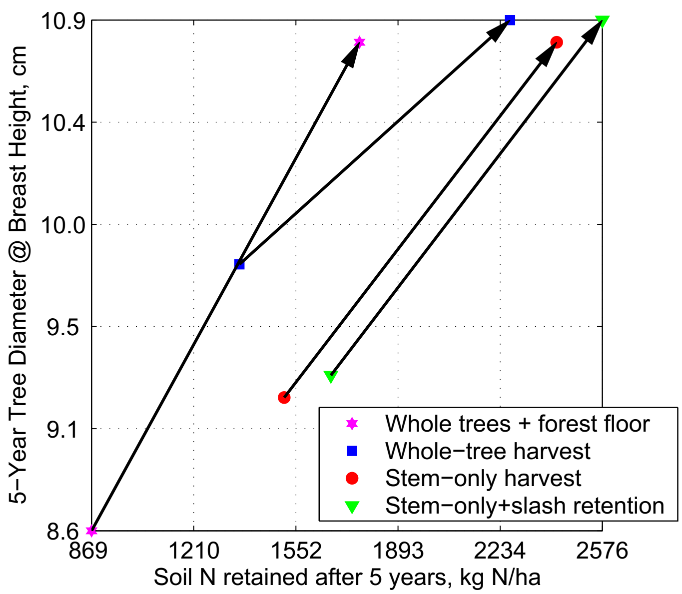

Figure 3: Impact of nitrogen fertilizer on tree growth. Shown are average tree diameters at breast height at the age of 5 years versus soil nitrogen retained after harvests of pine trees in eight stands of a New Zealand plantation. The beginning of each arrow is a final store of nitrogen in soil without treatment, and the end points at the incremental nitrogen store from a urea treatment of 200 kg N/ha-yr over 5 years. The various symbols denote four different plantation harvesting techniques. Source: Fig. 6 in Dyck and Bow (1992).

Figure 4: Application of fertilizers over an inaccessible tree plantation. This photograph was taken by Dave Powell, USDA Forest Service, www.forestryimages.org.

In contrast with tropical forests (Malhi et al., 1999), boreal forest trees are small in relation to their age and coniferous boreal forests have a very low net primary production of about 2.5 tonnes of carbon/ha-yr (∼5 tonnes/ha-yr of oven-dry wood), see (Jarvis and Linder, 2000) and the references therein. Since 1987, Jarvis and Linder (2000) have applied complete fertilizer through every growing season either daily in irrigation water or as a single solid dose at the start of the growing season. Jarvis and Linder found that growth on the heavily fertilized plots increased by 400%, regardless of all other parameters they varied.

Remark 2 Substantial reliance on synthetic fertilizers (and other field chemicals) will be required to maintain the high average biomass yield in industrial plantations over tens of crop rotation, see **Figure 4**. □

4 Characterization of Biomass Output of Tree Plantations

The role of industrial tree plantations in the tropics (and the tropical forests they increasingly replace) in the global carbon, nitrogen, phosphorus and other nutrient cycles, cannot be explained without the accurate estimates of the cumulative volumetric yield of freshly-cut biomass in m^3/ha-crop rotation, and of the average density of this biomass in kg of oven-dried wood per m^3 of fresh wood at the time of harvest.

The biomass of tropical production forests has been measured at a few sites scattered around the tropical world, but the area represented by these studies is infinitesimal (∼30 ha) (Brown and Lugo, 1982) compared with the total area of tropical forests[33]. Furthermore, there is strong evidence that the selection of these few sites was biased toward high biomass forests (Brown and Lugo, 1984).

The most thorough known to us studies of a terra-firme forest site in Eastern Amazonia were performed by Mackensen et al. (2000) and Klinge et al. (2004). These studies revealed that the mean living above-ground phytomass was 257 tonnes/ha, and the mean mass of litter was 14 tonnes/ha. The mass estimate by Mackensen et al. was *low* when compared with other published studies. More than 50% of carbon, 20% of total nitrogen, 10% of total phosphorus, and 66-99% of total potassium, calcium and magnesium were locked in the above-ground phytomass. Consequently, phytomass removal and destruction during forest conversion to a plantation will lead to major nutrient losses. The nutrient store estimate by Mackensen et al. was *medium-to-high* when compared with other published studies. Some of the nutrient losses can be replenished with synthetic fertilizers, but other cannot, leading to a slow degradation of plantation soil and biomass productivity.

The estimated (FAO, 2001) average absolute store of biomass in the world's forests is lower than the productivity of our example plantations in Indonesia, see **Figure 5** and **Section 9**. As far as bias goes, remember that Mackensen et al.'s (2000) study, also shown in Figure 5, resulted in lower mass (and presumably volume) estimates than most other studies of individual tropical forest plots, yet its reported total volume of biomass is 2.5 times the world average.

4.1 Volumetric and Mass Yield

On average, industrial plantations accumulate little biomass, in part because they lack the detrital biomass and shrubs of the mature natural forest floor, and in part because the plantation trees may be widely spaced to provide easy access (1,100 trees/ha). But, more importantly, plantations have small time-averaged biomass because they are felled and cleared near the time of maximum *mean annual increment* (MAI) of volume (Cannell, 1995).

Alternatively, industrial plantations for fuel and biomass feedstock may follow a different strat-

[33]The tropical forest area was ∼18 million km^2 in 1982, and it decreased by 22%, to 14 million km^2 in 1990-99, see http://earthtrends.wri.org.

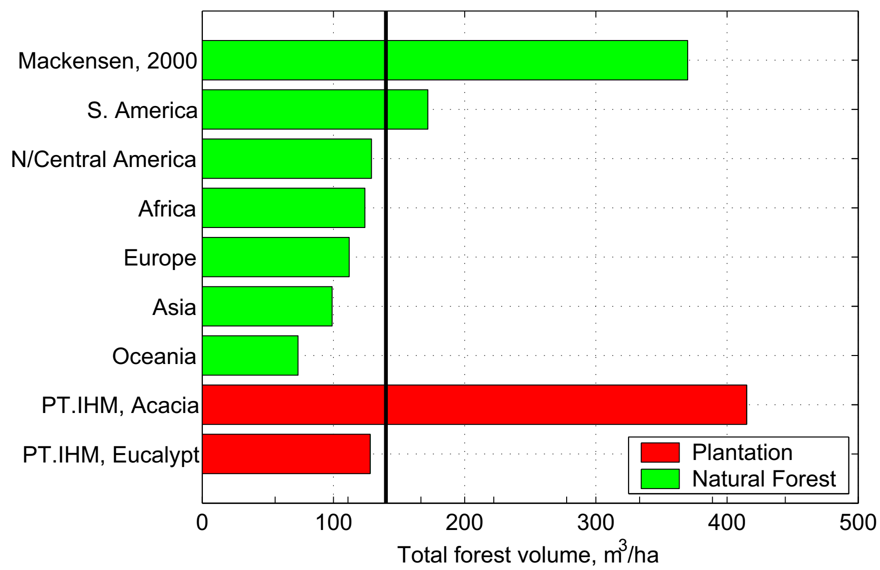

Figure 5: Total volume (over bark) and above ground of woody mass estimated by FAO (2000) for 166 countries, representing 99% of the world's forest area. Note that the mean world forest volume of 126 m^3/ha (the vertical line) is dominated by South America. The definitive study by Mackensen et al. (2000) of a prolific terra-firme forest site in East Amazon is also shown. The mean volumetric stemwood (over bark) yields of 8-year old acacia and eucalypt stands in the example PT.IHM plantation in Indonesia are shown in red.

egy of the closest possible tree spacing, say 40,000 trees/ha, and very short, e.g., annual rotation. The biomass accumulation in such plantations is also low compared with mature natural forest.

Trees consist of several parts: stem (trunk), bark, branches, leaves, and roots. These parts have different usefulness as industrial sources of biomass. For example, branches with leaves, and roots are protofractal (Mandelbrot, 1977); therefore, they fill large areas in their respective bulk volumes. Conversion of the dispersed, low bulk density branches and leaves to the compacted wood pellets requires cumbersome collection, crushing, and other energy-intensive processing, which may make their industrial use too inconvenient and expensive. On the other hand, tree bark, roots, branches, and leaves (or sugarcane green tops, leaves, roots, and bagasse[34]) play crucial roles in nutrient recycling, buildup of soil carbon and controlling soil erosion. Therefore their ecological

[34]Once the sweet juice is squeezed from sugar cane, the crushed outer stalk material, or bagasse, remains. Along with cereal straw and bamboo, bagasse is among the world's most widely used and available non-wood fibers. Sugarcane is the most widely grown crop in the world; in 2004, its annual production of 1318 million tonnes was nearly double that of corn grain, 705 million tonnes. The dry mass of sugarcane stems was 400 million tonnes, and that of corn grain was 600 million tonnes. Source: FAO: faostat.fao.org accessed March 29, 2005.

value dwarfs whatever *price* they may bring[35]. We will discuss this crucial point later in the paper.

Table 1: Fractional masses of above-the-ground tree parts

Part mass	*E. globulus*[a] %	*E. camaldulensis*[b] %	*A. mangium*[b] %
Stem	55.2	61	58
Bark	8.8	13	12
Branches	16	8	19
Leaves	20	18	11
Total	100	100	100

[a] A one-year old stand of eucalypts harvested for energy, http://www.eeci.net/archive/biobase/B10237.html

[b] Calculated from (Nurvahyudi and Tarigan, 2003) for a seven year old stand

Trees are almost self-similar (Verwljst, 1991; Hiratsuka et al., 2003), and their proportions are roughly the same regardless of the age. As a rule of thumb, therefore, a tree stem is slightly more than half of tree mass above the ground, see **Table 1**.

Remark 3 From Table 1 it follows that the net mass of stemwood harvested from an industrial tree plantation may be just above 1/2 of the total mass yield of that plantation. □

4.2 Wood Density

Wood density is the most important determinant of wood quality and a critical factor in short-rotation forestry. It is defined in three different ways:

1. The true wood density at a given temperature and moisture content

$$\varrho = \frac{\text{Mass of wood at some content of moisture}}{\text{Volume of the same wood}} \tag{1}$$

2. The oven-dry density of "green" wood

$$\varrho' = \frac{\text{Mass of oven-dried wood}}{\text{Volume of fresh "green" wood}} \tag{2}$$

[35]These plant leftovers are the proverbial "biowaste" that – some researchers claim – can be taken away and processed at no environmental cost.

after heating the wood in an oven at 103^0C until constant mass is achieved.

3. The air-dry "ambient" wood density

$$\varrho'' = \frac{\text{Mass of air-dry wood with 12\% of moisture by weight}}{\text{Volume of this wood}} \tag{3}$$

4. It turns out (Reyes et al., 1992) that

$$\varrho' = 13.4 + 0.800\varrho'' \qquad (r^2 = 0.988) \quad \text{kg/m}^3 \tag{4}$$

so these two wood densities can be used almost interchangeably.

The wood *material* density of 1530 kg/m^3 is almost constant for all lignified cellulosic cell wall material which is completely nonporous (Dinwoodie, 1981). Wood in a tree is 60-80% porous, and its pores are filled with air and water. Therefore, true wood density can vary by a *factor of three*, depending on the type of tree, its age, season, and water deficit conditions. For example, daily radial growth of six-year-old *Eucalyptus nitens* trees was monitored for two years by WIMMER et al. (2002), under different irrigation regimes. In general, lower wood density occurred early in the growing season, and higher wood density later. The irrigated trees showed a relatively smooth seasonal pattern without visible association with soil water deficits. The density variation over the two years was about 500 kg/m^3. Maximum density of around 900 kg/m^3 was reached at the end of the growing season. The irrigated-droughted trees showed a large wood density variation between 400 kg/m^3 and 1150 kg/m^3. The droughted trees showed somewhat less variability, and their density ranged from 270 kg/m^3 in mid-spring of the first season to 850 kg/m^3 at the end of the second season. Some literature values of air-dry densities of the various *Eucalyptus* and *Acacia* tree species are shown in **Table 2**.

Remark 4 While estimates of gross volumetric yield from a plantation are commonly published, their translations to net mass of oven-dried wood exported from this plantation are not. In energy applications, the average net mass yield of dry wood in kg/ha-yr is more important than the volumetric yield of wet "green" wood in m^3/ha. □

4.3 Wood Heating Value

Gross (high) heating value (HHV) of wood shows little variation among species (mean ± SD = 19.73 ± 0.98 MJ/kg for hardwood species) (Harker et al., 1982). However, the gross heating value

Table 2: Air-dry density of industrial wood, see Eq. (3)

Botanical name/ Common name	Density kg/m^3
Eucalyptus diversicolor Karri (W. Australia)	829[a]
Eucalyptus hemilampra Mahogany (New South Wales)	1058[a]
Eucalyptus marginata West Australian mahogany	787[a]
Eucalyptus citriodora	640[b]
Eucalyptus deglupta	340[b]
Eucalyptus deglupta	377-452[c]
Acacia mangium	520[d]

[a] Physical Properties of Common Woods, www.csudh.edu/oliver/chemdata/woods.htm

[b] (Reyes et al., 1992)

[c] Plantation-grown in Hawaii, http://www.hawaii.gov/hfciforest/non-native/mindanao.html

[d] CIRAD Forestry Dept., www.cirad.fr/activites/bois/en/syst/asia/acaciamangium.pdf

of wood is not converted completely to useful heat because hydrogen (about 6% of wood mass) is also combusted. If a fire is open to the atmosphere, the heat generated by the combustion of hydrogen is lost as latent heat of vaporization of the produced water. This loss is equivalent to about 1.4 MJ/kg (Harker et al., 1982). Heat is also lost in vaporizing moisture contained in the wood. Thus the moisture content of wood is the most significant factor affecting the production of usable heat when wood is burnt, see **Table 3**.

Table 3: The relative heating value of wood as a function of moisture content

Moisture (%)[a]	0	10	25	50	75	100	150	250	400
Heating value (%)[b]	100	90	78	63	52	44	33	20	10

[a]Moisture content is the weight of moisture as a percentage of wood oven-dry weight for a fixed weight of green wood

[b]Heating value is the amount of usable heat produced by wood at a given moisture content compared with that produced by oven dry wood

4.4 Moisture Content of Harvested Wood

Given sufficient time, it is relatively easy to decrease the moisture content of harvested wood to about 25% by weight by sun-drying (Jirjis, 1995). If a lower moisture content is required, and time is of essence, steam-drying must be employed, and additional fossil fuels consumed. In humid tropical climate, dead wood is quickly rotted (loses mass and calorific value) by the fast growing bacteria and fungi, and may self-ignite when stored in piles. Finally, it may be impossible to sun-dry large quantities of wood that converge on a central processing facility from the surrounding industrial plantations.

Remark 5 As it may be impossible or inconvenient to naturally dry industrial wood, the initial moisture content in harvested wood matters. □

4.4.1 Acacia Species

YAMAMOTO et al. (2003) evaluated the distribution of moisture across stemwood at breast height in *Acacia mangium*, *A. auriculiformis*, and hybrid *Acacia* grown in 3 Asian countries. Moisture contents of the stems of *Acacia mangium* and hybrid *Acacia* were extremely high not only in sapwood but also in heartwood in most cases. Highest moisture content found in the inner heartwood was about 250% in both species. Stem wood of *A. auriculiformis* generally showed a slightly lower moisture content than those of the other two species. The large amount of water in stem wood, especially in the heartwood of these *Acacia* species hampers drying. Fast-growing trees such as these *Acacia* species absorb soil water at a very high rate and could have a negative effect on the soil properties.

Remark 6 Among some 32 tropical tree species sampled in Malaysia, *Acacia mangium* shows the highest stomatal conductance and net photosynthetic rate in the sun leaf, reflecting the highest water requirement for rapid growth (Matsumoto et al., 2000). Excess absorption of soil water damages soil structure. □

4.4.2 Eucalypts

Compared with *Acacia* species, eucalypts have a lower water content of about 34–103% (San Luis and Olaño, 1985). On the other hand, in dry climate, annual evapotranspiration from eucalypts can exceed the annual rainfall by a factor of four, owing to groundwater extraction by their roots

(Greenwood et al., 1985). Historically, eucalypts have been used to dry-up marshlands and deliberately lower the water table when saline water is close to the surface (Calder, 1992). Therefore, eucalypts are also known to be voracious water consumers.

5 Tropical Plantations of Acacias and Eucalypts

In this paper, we will consider two tropical industrial tree plantations in Indonesia. The first one will consist of *Acacia* trees, and the second one of *Eucalyptus* trees.

Remark 7 The Indonesian plantations are the best-described *examples* of generic tropical plantations. The nutrient losses calculated here will be similar, but *not* identical to those published by (Mackensen and Fölster, 1999; Mackensen and Fölster, 2000; Mackensen et al., 2000; Mackensen et al., 2003). For example, our erosion rates will be higher. □

5.1 Acacia Plantations

Acacia species such as *A. mangium Willd*, *A. auriculiformis Benth.* and hybrid *Acacia* are major fast-growing plantation species not only for pulp and timber production but also for greening purposes throughout tropical Asia regions, see YAMAMOTO et al. (2003) and the references therein. Their importance as plantation trees can be attributed to rapid growth, rather good wood quality, and tolerance to a range of soil types and pH values. *A. mangium* occurs naturally in Queensland, Australia, Papua New Guinea, the islands of Sula, Ceram, Aru, and Irian Jaya, Indonesia, while *A. auriculiformis* occurs naturally in the Northern Territory and Queensland, Australia, Papua New Guinea, and Irian Jaya. Industrial-scale plantation establishment of *A. mangium* in Sumatra and other parts of Indonesia began in the early 1980s. A typical industrial plantation of another *Acacia* species is shown in **Figure 6**. Emphasis has recently been placed on hybrids between *A. mangium* and *A. auriculiformis* for plantation, due to their superior characteristics in terms of growth rate and wood properties required for pulp and paper production. At present, these three *Acacia* species are planted in many areas of tropical Asia. Worldwide, there are 8.3 million hectares of Acacia plantations, 95% in Asia (IUCN, 2001).

5.2 Eucalyptus Plantations

By the end of the twentieth century, eucalypts have become the most widely planted hardwood species in the world, see TURNBULL (1999) and the references therein. Reliable global estimates of

Figure 6: A five year old plantation of *Acacia nilotica* ready for harvest. The photograph is by Dr. Doug Maguire, Oregon State University, www.forestryimages.org.

areas of planted eucalypts are difficult to obtain, but published reports suggest that in 2001 there were at least 17.8 million ha (IUCN, 2001). Over 90 percent of these forests have been established since 1955, and about 50 percent in the 1980's. An assessment of plantation areas in the tropics indicates over 16.8 million ha of eucalypts at the end of 1990. There are large plantation areas in tropical America (4.8 million ha) and in tropical Asia (11 million ha). The American statistic is dominated by Brazil, where there are an estimated 3 million ha of eucalypt plantations; some 2.3 million ha of these plantations survive from an area of 2.9 million ha approved for plantations with government incentives between 1967 and 1984. Increased plantation areas are projected in several countries. Plantings will continue in Brazil, but not at the very high rates of the recent past because there will be more effort to increase the productivity and quality of existing areas. Both China and India have active reforestation programs and, although there has been some resistance to eucalypt plantations in the latter, the great demand for wood will undoubtedly ensure that planting continues.

6 Example Plantation

The site we will use as an example is located in the industrial plantation concession PT.IHM, NW of Balikpapan in East-Kalimantan, Indonesia, see (Mackensen et al., 2003) and the references therein.

Figure 7: A fast growing industrial plantation of *Eucalyptus deglupta* in Papua New Guinea. The photograph is by John W. Turnbull, Chief Scientist; Centre for International Forestry Research, Bogor, Indonesia.

This region has a moist tropical climate with a mean annual precipitation of 2000 - 2500 mm, and mean annual temperature of 26^0C. The geology is characterized by Tertiary sand, silt, and clay sediments. The topography is undulating with short steep (50 to 200 m) slopes and narrow valleys and crests.

Ali- and Acrisols are found in 80% of the concession area. They are characterized by low pH (4.5 – 4.8), high aluminum saturation (56 – 91%), an effective cation exchange capacity (ECEC) of 18 – 26 cmolc/kg clay in the top meter, and a clay content of between 20 to 42%. Another 10 to 15% of the soils are sandy and nutrient-poor Ferral- and Arenosols with a similar acidity, a low ECEC of 9 - 10 cmolc/kg clay and a clay content of between 10 and 20%. The nutrient stores (0 - 100 cm) decrease in the sequence Alisols, Acrisols, Ferralsols/Arenosols in the following range: N 11 000 – 6000 kg/ha; P 1691 – 721 kg/ha; K 757 – 236 kg/ha; Ca 1455 – 566 kg/ha; Mg 618 – 247 kg/ha.

The PT.IHM concession started in 1993 to establish 10 000 - 15 000 ha/yr of industrial tree plantation for wood pulp. While in the beginning *Eucalyptus deglupta* was the dominant species, *Acacia mangium* is now planted on 80% of the area. Investment calculation of PT.IHM was based on a mean annual increment (MAI) of 25 m^3/ha for both species during a rotation length of 8 years. Because of delays in plantation management, the acacia and eucalypt harvests reported by

Mackensen et al. were from the first crop rotations[36].

6.1 Mass Output of an Acacia Stand

The reported harvest volumes of *Acacia mangium* stem wood over bark[37] were 320-510 m^3 for eight-year old trees[38]. Only tree stems and stem bark were exported from the plantation yielding on average 415 m^3/ha of fresh wood. The average density of air-dry acacia wood was, say, 520 kg/m^3, see Table 2, or, using Eq. (4), 430 kg of oven-dried wood/m^3 of green wood. Finally, the average oven-dry wood mass exported from the plantation is estimated by us to be 178 tonnes/ha-crop or 22 odt/ha-yr[39]. This wood had the gross (high) heating value of 440 GJ/ha-yr. Note that we have not accounted yet for biomass losses in harvesting, as well as moving and handling, which are estimated at 5% and 15%, respectively (Turnhollow and Perlack, 1991). With these average losses, our plantation productivity decreases to 142 odt/ha-crop or 17.8 odt/ha-yr. The first type of loss actually benefits the plantation soil, and the second one can be minimized through an efficient central wood pellet factory located close to the plantations.

Remark 8 The maximum average energy output of the industrial *A. mangium* stand in the PT.IHM concession (approximately the wood's chemical exergy (Patzek, 2004)) is 350 GJ/ha-yr. If this wood were converted into an automotive fuel, its exergy (free energy relative to the environment conditions (Szargut et al., 1988; Patzek, 2004)) would be partially consumed because of the various inefficiencies of the conversion process[40]. Then the fuel would be burned in a 15%-efficient car. If this wood were directly burned in an efficient electrical power station (with 35% efficiency), some **123** GJ/ha-yr of electrical shaft work would be generated. Therefore, the *A. mangium* plantation considered here may deliver 3 times more electricity per hectare and year than average ethanol from corn in the U.S., burned in a 60%-efficient fuel cell, see Patzek (2004), that does not exist, see Appendix A. □

[36] Dr. Jens Mackensen, private communication, Sept. 2004.

[37] The harvest volume is based on stem (down to a minimum of 10 cm in diameter - following standard plantation practice) plus stem bark. Dr. J. Mackensen, private communication, Sept. 2004.

[38] The actual ages of the plantation trees were 8-12 years (Mackensen et al., 2003).

[39] The actual measured mass of tree stems and tree bark of some 100 tree species of different ages on Plots A2 and A3 of the PT.IHM plantation was 148 and 163 odt/ha, respectively, see Table 6 in (Mackensen et al., 2000). So our estimate of the acacia mass yield may be a bit optimistic.

[40] Energy efficiency of the Fischer-Tropsch process is about 55%, e.g., (Hamelinck, 2004).

We stress again that the mass yield of the PT.IHM *A. mangium* stand is based on the average growth rate of the *first* tree rotation over eight years. The subsequent rotations are likely to gain less volume. So our calculations of the stand sustainability are *inevitably optimistic* as they assume the same high mass yield over several tree rotations.

6.2 Nutrient Balance of an Acacia Stand

6.2.1 Management-Independent Nutrient Fluxes

In their earlier paper, Mackensen and Fölster (Mackensen et al., 2001) assumed that nutrient fluxes in an undisturbed forest balance out in the long term. These fluxes are constant nutrient inputs via bulk precipitation, weathering of soil parent material, sedimentation, fixation of nitrogen by *Rhizobium* bacteria (in acacia stands), and decay of plant matter. The constant output fluxes are nutrient leaching outside of the tree root zones, natural soil erosion, and denitrification (gaseous losses of nitrogen as NO, N_2, N_2O).

The intensity of the constant "background" nutrient fluxes is increased through different plantation management styles. Mackensen et al. (2003) have shown that the management-dependent fluxes clearly dominate nutrient budgets and destroy the natural long-term balances.

6.2.2 Nutrient Loss through Harvest

The masses of nutrients exported with stemwood and stembark of the 8-year old *A. mangium* trees in our example plantation are listed in **Table 4**. We have consistently picked the high-end estimates in (Mackensen et al., 2003) because they are valid for the nominal volumetric yield of 300 m^3/ha of wood, while the actual mean yield is 415 m^3/ha. The slash (tree branches and leaves, bark, and undergrowth) left on the plantation *recycles* additional nutrients and organic carbon to the soil. Based on the data in Tables 1 and 4, the main nutrient inputs are calculated in **Table 5**.

Table 4: Nutrient loss in wood exported from an *Acacia mangium* stand of 1100 trees/ha and the nominal yield of 300 m^3 of stemwood and stembark. Source: Mackensen et al. (2003)

Quantity	N	P	K	Ca	Mg
Nutrient kg/ha	296	3.9	107	234	14.4

The maximum nutrient *recycling* from tree slash are estimated in **Table 5**.

Table 5: Estimated maximum nutrient *recycling* from tree branches and leaves in an *Acacia mangium* stand in Table 4. Source: Mackensen et al. (2003)

Quantity	N	P	K	Ca	Mg
kg/ha	126.9	1.7	45.9	100.3	6.2

6.2.3 Estimated Nutrient Loss through Soil Erosion

Erosion rate in undisturbed forest varies between 0.03 and 6.2 tonne/ha-yr with the median of 0.3 tonne/ha-yr (Wiersum, 1984). In industrial plantations, where the organic layer above the soil is nonexistent and undergrowth was cleared during stand establishment and harvest, the median erosion rate is 53 tonnes/ha-yr (and its range is 1-183 tonnes/ha-yr) (Wiersum, 1984). Even worse erosion, from 150 to 600 tonnes/ha, results from windrowing (Figure 2), a "trash"-disposal technique commonly used on plantations (Morris et al., 1983).

Remark 9 Disturbing natural forest soil may accelerate its rate of erosion 10–1000 times, see also (Troeh and Thompson, 1993; Troeh et al., 1999), especially on steep hill slopes. □

Lacking data for the first crop rotation on the hill-slope plantation in this example, Mackensen et al. have chosen the minimum erosion rate of 50 tonnes/ha per crop rotation of 8 years or 3.8 mm topsoil/ha-crop (6.25 t/ha-yr), which – in the long run – may be an oversimplification that is 8 times smaller than the median annual erosion rate in plantations[41]. The erosion losses of soil nutrients estimated by Mackensen et al.(2000; 2003) from several international data sets are listed in **Table 6**.

Table 6: Estimated nutrient loss through soil erosion in an *Acacia mangium* stand in Table 4. Source: Mackensen et al. (2003)

Quantity	N	P	K	Ca	Mg
Nutrient kg/ha	77	7.4	4	20	5

[41] Other compensating factors are mentioned in Mackensen et al. (2003). In addition, the studied tree stands were the first rotations, and the soil condition was as good as it would ever be.

6.2.4 Estimated Nutrient Loss through Slash Burning

Burning residual phytomass (slash) results in nutrient loss through volatilization and ash transport by the wind. The data on phosphorus content of undergrowth are uncertain. A strong correlation between the mean living above-ground phytomass (LAGP) and phosphorus storage in LAGP in an Amazon forest indicates the important role P may play in phytomass accumulation on zonal tropical soils (Mackensen et al., 2000). The estimate of nutrient loss in the *Acacia mangium* stand corresponding to Table 4 is shown in **Table 7**.

Table 7: Estimated nutrient loss through slash burning in an *Acacia mangium* stand in Table 4. Calculated from MACKENSEN et al. (2003)

Quantity	Total Slash	N	P	K	Ca	Mg
kg/ha	39800[a]	369	3[b]	131	71	22

[a] Total slash is made of the *Acacia* branches and leaves, and the undergrowth

[b] Number assumed in Table 5 in (Mackensen et al., 2003)

6.2.5 Estimated Nutrient Loss through Soil Leaching

Leaching of nutrients from a disturbed topsoil is not fully understood and, in addition, water fluxes in the soil are generally unknown. Nevertheless, based on the published literature data, and their own calculations MACKENSEN et al. have arrived at the estimates shown in **Table 8**.

Table 8: Estimated average nutrient loss by soil leaching in an *Acacia mangium* stand in Table 4. Source: MACKENSEN et al. (2003)

Quantity	N	P	K	Ca	Mg
Average kg/ha	94	0.1[a]	100	9.1	11.2
Range kg/ha	18-189	no data	60-197	3.7-27.4	6.1-30.2

[a] Lack of data on phosphorus content of undergrowth

The data on the rate of leaching of phosphorus are uncertain. Phosphorus leaching should be negligible in the old acidic soils on the plantation as P is converted to Al and Fe phosphates. Leaching estimates are based[42] on a few case studies on similar soils in Brazil and Malaysia.

[42] Dr. JENS MACKENSEN, private communication, Sept. 2004.

6.2.6 Nutrient Losses and Irreversible Soil Depletion

The summation of the nutrient losses in Tables 4 – 8 is displayed in **Table 9**. The bottom two rows of the latter table list the nutrient losses calculated for the median soil erosion rate in plantations of 4 mm topsoil/yr.

Table 9: Total nutrient losses in an *Acacia mangium* stand in Table 4. Calculated from Mackensen et al. (2003)

Quantity	N	P	K	Ca	Mg
kg/ha	836.0	14.4	342.0	334.1	52.6
kg/ha-yr	104.5	1.8	42.8	41.8	6.6
kg/ha[a]	1412.0	69.8	371.9	483.7	90.0
kg/ha-yr[a]	176.5	8.7	46.5	60.5	11.3

[a] Assuming the median erosion rate of of 53 tonne/ha-yr, or 4 mm topsoil/yr

The total nutrient losses in Table 9 (first row) compare well with the high losses calculated earlier by Mackensen and Fölster (2000). For a nominal volume of 200 m^3/ha, these losses in kg/ha were 617 (N), 7 (P), 383 (K), 333 (Ca), and 62 (Mg).

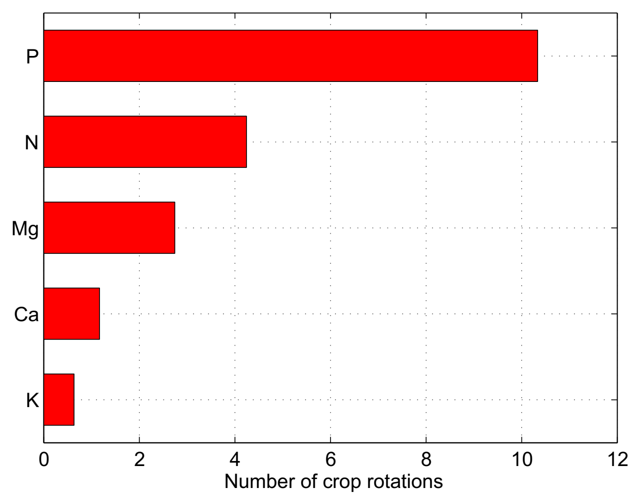

Figure 8: Minimum time of soil nutrient depletion by our average *Acacia mangium* stand. This plot was obtained by dividing the minimum estimates of soil nutrients in Section 6, by the maximum rate of depletion in Table 9. Note that the rate of depletion of phosphorus is highly uncertain due to lack of data. Also note that acacia is a nitrogen-fixing plant and availability of N, therefore, does not restrict the number of rotations.

The minimum time of the irreversible depletion of essential nutrients stored in 100 cm of topsoil in the Acacia stand is shown in **Figure 8**. The poorer soils in the plantation may be depleted and destroyed within 1-10 crop rotations (tree harvests). Therefore, synthetic fertilizers must be supplied continuously, and slash left to decompose to limit the rate of destruction of the plantation soil and nutrient depletion. In summary, there is really no forest "waste" to be hauled off from an industrial plantation free of environmental charges.

6.3 Mass Output of an Eucalyptus Stand

In the PT.IHM plantation, the reported (Mackensen et al., 2003) harvest volumes in eight-year old[43] stands of *Eucalyptus deglupta* trees were 44-190 m^3 of stem wood over bark (the average mean annual increment of tree volume (MAI) was 16 m^3/ha-yr), sharply lower than those of *A. mangium*. The MAI reported by MACKENSEN et al. (2003) was close to those in a comparable plantation in Brazil (McNabb and Wadouski, 1999), see **Figure 9**. Only tree stems and stem bark were exported from the plantation. The average volumetric yield was $16 \times 8 = 128$ m^3/ha of fresh tree stems with bark. The average density of the air-dry eucalyptus wood was, say, 415 kg/m^3, see Table 2, or, using Eq. (4), 345 kg of oven-dried wood/m^3 of green wood. So the average dry wood mass exported from the plantation was 44 odt/ha-crop or 5.5 odt/ha-yr. This wood had the gross (high) heating value of 109 GJ/ha-yr. With 20% overall biomass losses from the plantation to the pellet factory, the net delivered mass yield decreases to 35 odt/ha-crop or 4.4 odt/ha-yr.

Remark 10 The maximum energy output of the industrial *E. deglupta* stand in the PT.IHM concession (approximately the wood's chemical exergy) is 87 GJ/ha-yr. If this wood were directly burned in an efficient electrical power station (with 35% efficiency), some **30.4** GJ/ha-yr of electrical shaft work would be generated. Therefore the *E. deglupta* plantation considered here may deliver 24% less electrical shaft work per hectare and year than the combination of average corn-ethanol yield in the U.S. and a non-existent 60% efficient fuel cell. □

6.4 Nutrient Balance of an Eucalypt Plantation

6.4.1 Nutrient Losses through Plantation Management

The nutrients lost from our example plantation of 8-year old *E. deglupta* trees are listed in **Table 10**. The summation of the nutrient losses in Table 10 is displayed in **Table 11**. The bottom

[43] The actual ages of the plantation trees were 8-12 years (Mackensen et al., 2003).

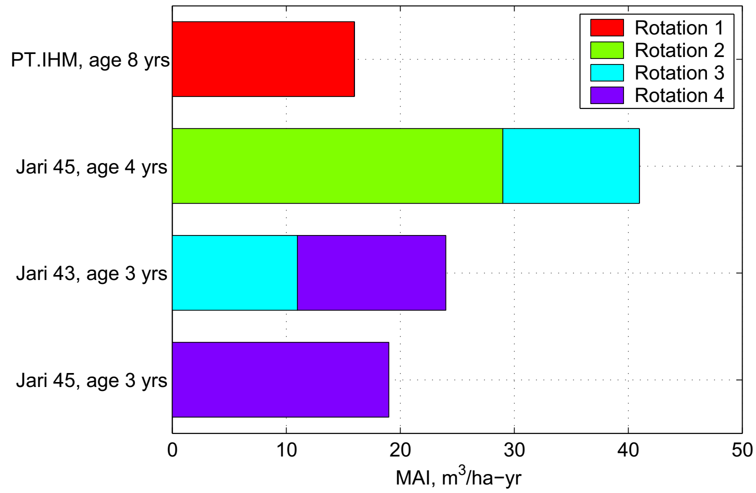

Figure 9: The mean annual increments (MAI) of eucalypts of *different ages* in two plantations, after a different number of rotations. The Jari River plantation is in the Amazon region of Brazil, (McNabb and Wadouski, 1999), and the PT.IHM plantation is in Indonesia (Mackensen et al., 2003). Note that the MAI's generally decrease with the number of crop rotations, regardless of fertilization and weed/pest control schemes. The Eucalypt species are *E. deglupta*, *grandis* and *urophylla* in Jari, and *E. deglupta* in PT.IHM.

Table 10: Nutrient recycling and losses in an *Eucalyptus deglupta* stand of 1100 trees/ha and the yield of 128 m^3 of stemwood and stembark. Calculated from Mackensen et al. (2003)

Quantity, kg/ha	N	P	K	Ca	Mg
Slash Recycling, kg/ha	18.9	1.0	54.0	22.3	5.1
Crop	44.0	2.3	126.0	52.0	12.0
Erosion	77.0	7.4	4.0	20.0	5.0
Slash/Burn	195.0	9.3	79.0	61.0	19.0
Leaching	49.9	0.0[a]	60.0	7.8	10.3

[a] Lack of data

two rows of the latter table list the nutrient losses calculated for the median soil erosion rate in plantations of 4 mm topsoil/yr. Note the eucalypts secrete a toxin that prevents many other plants from growing; a meager understory may contribute to soil erosion in the long run.

The total nutrient losses in Table 11 (first row) compare well with the high losses calculated in (Mackensen and Fölster, 2000). For a nominal volume of 200 m^3/ha, these losses in kg/ha were

Table 11: Total nutrient losses in an *Eucalyptus deglupta* stand in Table 4. Calculated from Mackensen et al. (2003)

Quantity	N	P	K	Ca	Mg
kg/ha	365.9	19.0	269.0	140.8	46.3
kg/ha-yr	45.7	2.4	33.6	17.6	5.8
kg/ha[a]	941.9	74.4	298.9	290.4	83.7
kg/ha-yr[a]	117.7	9.3	37.4	36.3	10.5

[a] Assuming the median erosion rate of of 53 tonne/ha-yr, or 4 mm topsoil/yr

358 (N), 6.7 (P), 383 (K), 261 (Ca), and 74 (Mg). The only significant difference is in phosphorus, which we feel might be lost in slash burning and leaching in larger quantities.

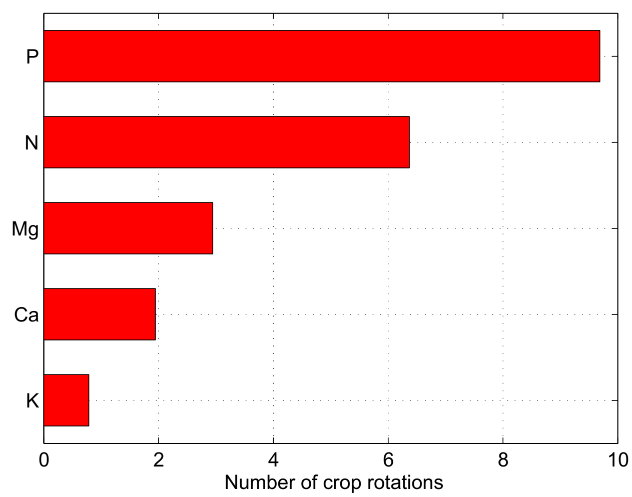

Figure 10: Minimum time of soil nutrient depletion by our average *E. deglupta* stand. This plot was obtained by dividing the minimum estimates of soil nutrients in Section 6 by the maximum rate of depletion in Table 11.

The minimum time of the irreversible depletion of essential nutrients stored in the 100 cm of topsoil in the Eucalyptus stand is shown in **Figure 10**. The poorer soils in the plantation may be destroyed within 1-10 tree harvests. Note that the estimates of tree productivity in the Jari plantation, Figure 9, do not go beyond the fourth crop rotation. Various fertilizers have been applied on that plantation. In the PT.IHM plantation, 100 kg/ha of an NPK fertilizer was applied, much below the management-related nutrient losses, which would require 5500 kg/ha of this fertilizer, see Table 4 in (Mackensen and Fölster, 2000).

7 Fertilizer Efficiency

When N, P, and K are applied as synthetic fertilizers, their uptake efficiencies by plant roots vary significantly, see (Mackensen et al., 2000) and the referenced therein. The telegraphic summary of Section 4 in Mackensen et al. (2000) is as follows. Efficiency of uptake of nitrogenous fertilizers, averages 37-46%, see **Figure 11**. Efficiency of uptake of phosphorus fertilizers is extremely low (Mackensen et al., 2000) and averages 3-8%. Although leaching losses of P are low, the major restriction for P uptake is the formation of Al- and Fe-phosphates which immobilize P. About 75% of applied triple superphosphate was immobilized on the PT.IHM plantation. If this fertilizer were applied at lower rate, the immobilization might reach 90%.

Remark 11 Here we assume that in the long run calcinated lime will be used to deacidify soil and decrease immobilization of P. The average efficiencies of fertilizer uptake are about 0.5 (N), 0.1 (P), 0.7 (K), 0.7 (Ca), and 0.7 (Mg), respectively. □

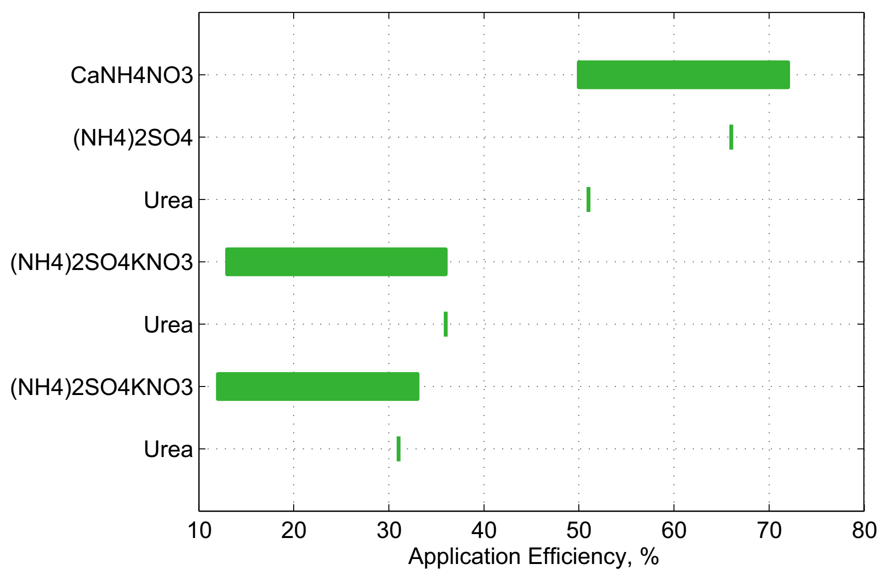

Figure 11: Efficiencies of nitrogenous fertilizer applications from Table 2 in Mackensen and Fölster (2000). Note the unusually high efficiency of some $CaNH_4NO_3$ applications. The average uptake efficiency of N from all the experiments is about 50%. The different efficiencies for urea are from three experiments in different soils, etc.

8 Fossil Energy Requirements of Industrial Biomass Production

Wood pellets, see **Figure 13**, are the most valuable product of an industrial wood-for-energy plantation. They are easy to transport over long distances, relatively safe and easy to store, and easy to process in an overseas chemical plant.

Large industrial tree plantations are highly mechanized, and require fossil energy to fell trees, strip branches from tree stems, transport the bark-covered stems from the plantation slopes to a wood pellet-making facility, produce wood pellets, and transport these pellets to a local port by truck and train, or barge, and overseas by ship. Fossil energy is also required to mechanically prepare the plantation sites for each new tree rotation, deliver fertilizers, herbicides and insecticides to the trees, or remove weeds.

Part of the fossil energy requirement may be satisfied by burning the local "biowaste" (slash, undergrowth) to produce heat and electricity, thereby stripping the vital nutrients from the soil, and exacerbating erosion problems. This is the Faustian dilemma[44] of industrial forestry: What is "saved" in "biowaste" must be put back as fertilizers and other measures to fight the ever-growing rate of soil depletion and erosion. The remaining energy requirement is due to automotive fuel use in forest machinery and transportation vehicles.

8.1 Wood Pellet Production

The conversion of wet and perishable stemwood/stembark, see **Figure 12**, to dry, compact and portable wood pellets, see **Figure 13**, is the single biggest energy outlay of an industrial biomass-for-energy plantation. An inefficient facility using the wood "waste" is out of question. Consider the following example:

Example 1 A wood pellet production facility in New Zealand (Nielsen and Estcourt, 2003) produces 8000 tonnes of pellets per year by using 36 GWh of steam generated from 20 000 tonnes/yr of "low-quality wood waste" (with the heating value of 6.4 MJ/kg) as heat and electricity. Therefore, the specific energy requirement to produce wood pellets is

$$\frac{36\ \text{GWh} \times 3600\ \text{s/h}}{8000\ \text{tonnes of pellets}} = 16\ \text{MJ/kg} \tag{5}$$

Thus, the transformation of raw wood into pellets requires $16/20 = 80\%$ of the calorific content of oven-dry hardwood[45]! If wood pellets are produced in small quantities as a byproduct of other

[44] "So geht und schafft sie mir zur Seite" (Go and get them out of there) FAUST tells MEPHISTO in line 11275.

[45] Or 90% of the calorific content of 10%-wet hardwood, see Section 4.3

Figure 12: Typical *Acacia* harvest wood is difficult to transport and process in an overseas chemical plant. Note the wide annual growth rings. This photograph is from www.hear.org/starr/hiplants/-images/.

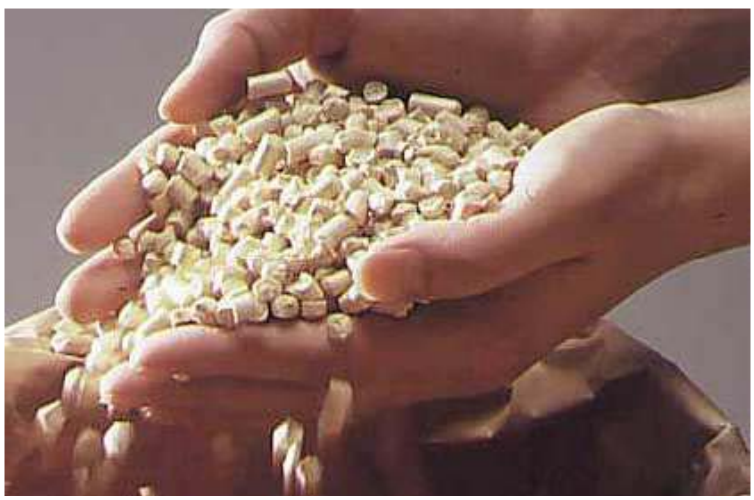

Figure 13: Typical wood pellets may be 6-7 mm in diameter, 8-10% moisture by weight, and have density of about 600 kg/m^3 of the moist wood material (Theka and Obernbergera, 2004). This photograph is from www.woodpellets.org.

industrial processes (paper pulp and timber production), this inefficiency may be tolerated because there exists genuine "waste" wood. If the large-scale production of wood pellets is the only goal, then the whole concept breaks immediately down, because 4 kg of the wood must be burned to produce 1 kg of pellets. □

Table 12: Total energy requirement of a modern wood pellet factory. Source: Theka and Obernbergera (2004)

Quantity	Scenario 1	2	3	4	5	6
Pellets, tonne/yr	23652	16894	23652	23652	70956	23652
Wood chipping, kWh/t pellets	84.32	84.32	84.32	84.32	84.32	84.32
Electricity, kWh/t pellets	151.87	134.58	171.42	158.67	128.02	153.57
Water evaporated, t/yr	26017	18584	26017	26017	78052	26017
Heat, kWh/t pellets	1100.00	1100.00	1210.00	951.50	1100.00	1100.00
Total MJ/kg pellets[a]	6.39	6.21	6.99	5.92	6.14	6.41
Total MJ/kg pellets[b]	8.21	7.90	8.96	7.80	7.78	8.24

[a] Assuming 35% efficiency of electric power plant
[b] Assuming 20% efficiency of electric power plant

A thorough economic analysis of eleven alternative designs of a state-of-the-art pelleting factory has been performed by Theka and Obernbergera (2004). Because wood leaving the tropical plantations is wet, we will consider here only their Scenarios 1-6, which require drying of raw material with 55% of moisture by weight[46]. The energy costs of chipping tree stems were not included in the analysis by Theka and Obernbergera (2004), while the energy costs of griding the chips were partially included.

Our estimate of energy required to chip the raw wood is based on the work by Spinelli and Hartsough (2001), who estimated that, given the chipper power in kW, and a wood piece mass in metric tonnes, the time to chip this wood is

$$t_{\text{chip}} = 60 \times \left(0.02 + \frac{13.1}{\text{Piece mass} \times \text{Power}} + \frac{566}{\text{Power}}\right) \quad \text{s} \tag{6}$$

Here we have assumed that the wood chippers are stationary electrical machines, 250 kW in power, and the wood pieces are 300 kg on average.

As the wood pelleting facilities of interest here will operate in remote locations in the tropics, no heat recovery as district heat is included. Also, the assumed 35% efficiency of an electric power plant may be difficult to achieve in remote conditions; therefore, a 20% efficient electric power plant is also considered, see **Table 12**. The results for the more efficient power plant are shown in **Figure 14**. The average of all scenarios involving 55%-wet raw wood is 6.4 MJ of primary energy

[46]Therefore, we assume that at times significant sun-drying of the very wet fresh wood is available.

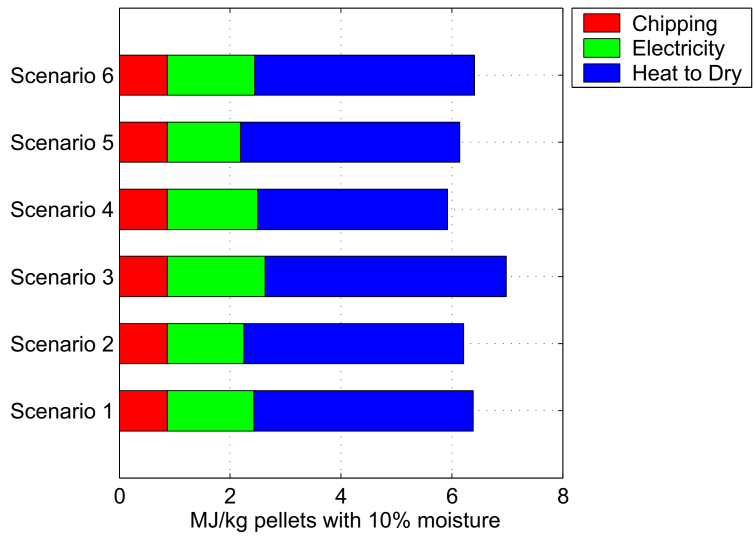

Figure 14: Energy required to produce wood pellets with 10% moisture from saw dust with 55% moisture. The energy efficiency of the electric power plant is 35%

per kilogram of 10%-wet pellets. For the lower power plant efficiency, the resulting average primary energy requirement is 8.1 MJ/kg of pellets.

Remark 12 A highly-efficient conversion of 55%-wet raw wood to 10%-wet wood pellets requires on average 33 – 41% of the gross calorific value of oven-dried wood. This conversion will be carried out in a central, state-of-the-art facility, capable of producing 20 000 – 60 000 tonnes of pellets per year. If "wood waste" from tree plantations were used to power this facility (the most probable scenario), additional fertilizer use and other soil conservation measures would have to ensue.

Parenthetically, the energy cost of converting raw wet wood into portable pellets is comparable to the energy dissipated on fermenting aqueous glucose to a beer with 8% ethanol by weight. However, the wood pellets are a high quality fuel or feedstock, while the 8% beer needs a lot more heat to separate the remaining 92% of water from the ethanol. □

8.2 Herbicide, Insecticide, and Fungicide Use

Following McKenzie et al. (1998), we will assume that herbicides are applied at a rate of 8.5 kg/ha of the eucalypt plantation. We will assume the same application rate for the acacia plantation. Therefore, the specific herbicide application rate is ∼1 kg/ha-yr. We will also assume that insecticides and fungicides are applied at the same rate of 1 kg/ha-crop.

8.3 Fossil Fuel Use

Fossil fuels are used in the establishment of a plantation, in harvesting it, reestablishing each next crop rotation, and in wood hauling. The use rates are highly plantation-specific. Following Turnhollow and Perlack (1991), we will assume that about 16 GJ/ha, or 2 GJ/ha-yr in equivalent diesel fuel is used on average to maintain a plantation. At 43.3 MJ/kg of average diesel fuel (Patzek, 2004), this energy requirement translates into 370 kg/ha or ~50 kg/ha-yr of equivalent diesel fuel.

9 Restoration Work

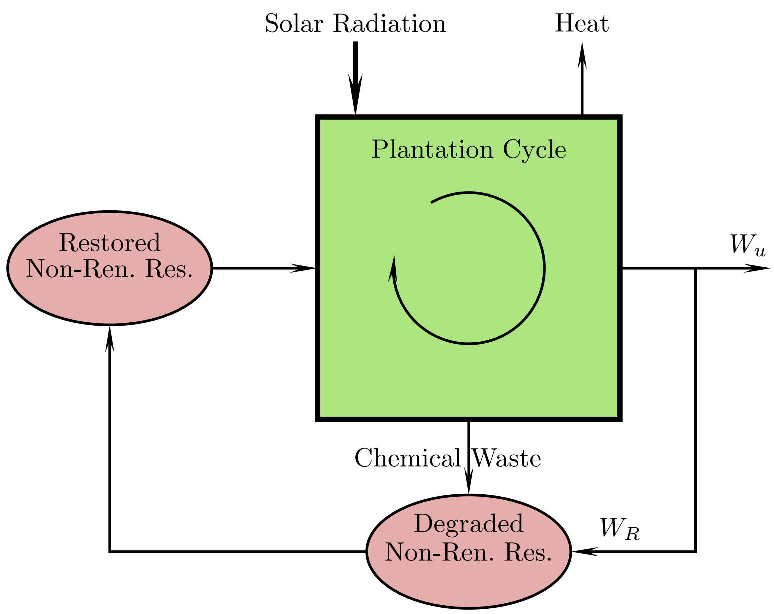

Figure 15: A part, W_R, of the useful work, W_u, from the industrial biomass cycle is diverted to "undo" mining of the environment by this cycle. If $W_u > W_R$, there is net benefit from the plantation, otherwise its use should be abandoned (Patzek, 2004).

In contrast to the sun-driven tropical forest at steady state, the industrial biomass cycle relies on fossil energy, minerals, and chemicals. Therefore, a part W_R of the useful work W_u from the cycle, must be diverted to restore the non-renewable resources depleted by this cycle, see **Figure 15**. As long as the useful work exceeds the restoration work, $W_u > W_R$, the industrial biomass plantation may be beneficial, otherwise it is indefensible; for details, see (Patzek, 2004).

The minimum restoration work is equal to the sum of the cumulative exergy consumption (CExC) by all the processes that convert natural resources into inputs of the industrial biomass cycle. The specific CExC for each such input is listed in (Patzek, 2004), Table 23. The CExCs per kg of elemental P, K, and Ca were converted from those listed in Table 23 per kg of P_2O_5, KCl, and CaO.

We will now calculate the maximum useful (shaft) work obtainable by converting the acacia and eucalypt tree biomass into pure electricity, the FISCHER-TROPSCH diesel fuel and electricity, and ethanol. The diesel fuel and ethanol will then power a very efficient car (close to three times more efficient than an average car in the U.S.).

9.1 Electricity from Wood-Burning Power Station

The simplest option is to burn the wood pellets outright in an efficient power station using a steam turbine. A possibility of wood gasification and a gas/steam turbine combined cycle should also be considered. We assume that the overall exergy efficiency of the power station is 0.35, including pellet pulverization, ash disposal, boiler protection from wood alkali, and removal of SO_x and NO_x from flue gas. The overall efficiency of transmission power lines and transformers is assumed to be 0.90. Both assumptions are rather optimistic.

Remark 13 Per 1 kg of 10%-wet wood pellets, an efficient power plant produces the maximum useful work of **5.59** MJ/kg as electricity. □

9.2 The Fischer-Tropsch Diesel from Wood

The FISCHER-TROPSCH (FT) synthesis produces hydrocarbons of different lengths from a gas mixture of H_2 and CO. The large hydrocarbons can be hydrocracked to form mainly diesel of excellent quality. The fraction of short hydrocarbons is used in a combined cycle with the remainder of the syngas. Overall lower heating value (LHV) energy efficiencies are 33 - 40% for atmospheric gasification systems and 42 - 50% for pressurized gasification systems (Tijmensen et al., 2002).

The overall exergy efficiency[47] of the FT process using feedstock of poplar wood containing 50 wt% moisture, is 51.2% (Ptasinski et al., 2004). This efficiency is further subdivided as 38.5% for the liquids and 12.7% for the tail gases. The exergetic content of the tail gases can be utilized for the production of electricity. Including a gas turbine/steam turbine combined cycle (with electrical

[47] Defined as exergy content of the FT products divided by the exergy content of all input materials, heat and work.

efficiency of 50%) would bring the electrical efficiency to 6.5%.

Since our feedstock consists of 10%-wet wood pellets from the dedicated overseas acacia or eucalypt plantations, the energy of the 400^0C process steam that would have been used to dry a 50%-wet feedstock is instead converted to electricity with 30% efficiency. Therefore, 1 kg of 10% wet wood pellets with the exergy of $19.73 \times 0.9 = 17.76$ MJ/kg (see Table 3), delivers $0.385 \times 17.76 = 6.84$ MJ as the FT diesel fuel, $0.065 \times 17.76 = 1.15$ MJ of electricity from syngas, and

$$1.1 \text{ kWh as drying steam/kg pellets} \times 3.6 \text{ MJ/kWh} \times 0.3\text{MJ}_e/\text{MJ} = 1.19 \text{ MJ}_e/\text{kg} \tag{7}$$

as electricity from the process steam.

If the FT diesel fuel is then burned to power a 35%-efficient car, the shaft work is $6.84 \times 0.35 = 2.39$ MJ/kg pellets.

Remark 14 Per 1 kg of 10%-wet wood pellets, the combined-cycle and FT synthesis process produces the maximum shaft work of 2.39 MJ/kg and 2.34 MJ/kg as electricity. The grand total is **4.73** MJ/kg pellets. □

9.3 Ethanol from Wood

In terms of useful shaft work, wood conversion to ethanol is by far the poorest of the three alternatives presented here, and we shall provide only an approximate conversion efficiency. Ethanol is obtained from enzymatically converting wood[48] cellulose (∼45% by weight) into glucose, wood hemicellulose (∼30% by weight) to xylose, and fermenting both sugars to 8-10% industrial beer. This beer is then distilled to 96% ethanol using ∼19 MJ/kg ethanol in fossil fuels, and the remaining water is excluded in molecular sieves (Patzek, 2004). The respective conversion efficiencies, assumed after Badger (2002), are listed in **Table 13**.

Therefore, from 1 kg of 10%-wet pellets, one may obtain $0.9 \times (0.131 + 0.069) = 0.18$ kg of 100% ethanol at the fossil energy expense of 3.4 MJ to distill the beer plus more energy and chemicals to process the wood. For simplicity, we will assume that the remaining 0.23 kg of lignin in the wood pellets will deliver the necessary 3.5 MJ of heat. The chemical exergy of the produced ethanol is (Patzek, 2004) $29.65 \times 0.18 = 5.33$ MJ/kg pellets. If this ethanol is then burned to power a 35%-efficient car, 1.87 MJ/kg pellets is obtained as shaft work.

[48]Generally, wood is 40 – 50 % cellulose, 20–35% hemicellulose, 15 – 35% lignin, < 1 % ash, and 1 – 2% miscellaneous compounds.

Table 13: Yields of ethanol from cellulose and hemicellulose. Source: Badger (2002)

Step	Cellulose	Hemicellulose
Dry wood	1 kg	1 kg
Mass fraction	×0.45	×0.30
Enzymatic conversion efficiency	×0.76	×0.90
Ethanol stoichiometric yield	×0.51	×0.51
Fermentation efficiency	×0.75	×0.50
EtOH Yield, kg	0.131	0.069

Remark 15 Per 1 kg of 10%-wet wood pellets, the combined conversion of wood's cellulose and hemicellulose to ethanol produces the maximum shaft work of **1.87** MJ/kg, provided that all process energy is delivered from the unused components of these pellets. In reality, this shaft work will be lower. □

Table 14: Restoration work for the example *A. mangium* stand.

Quantity	Flux/Specific use	Specific CExC	Exergy/CExC
10%-wet pellets	19360 kg/ha-yr	17.76 MJ/kg	347.25 GJ/ha-yr
N	176.5 kg/ha-yr	99.60 MJ/kgN	17.58 GJ/ha-yr
P	8.7 kg/ha-yr	38.50 MJ/kgP	0.34 GJ/ha-yr
K	46.5 kg/ha-yr	24.58 MJ/kgK	1.14 GJ/ha-yr
Ca	60.5 kg/ha-yr	14.06 MJ/kgCa	0.85 GJ/ha-yr
Mg	11.3 kg/ha-yr	24.58 MJ/kgMg	0.28 GJ/ha-yr
Herb/insecticides	2.00 kg/ha-yr	300.1 MJ/kg	0.60 GJ/ha-yr
Equiv. diesel	50.0 kg/ha-yr	53.20 MJ/kg	2.23 GJ/ha-yr
Electricity[a]	0.23 kWh/kg pellets	11.83 MJ/kWh	53.60 GJ/ha-yr
Heat to dry wood	1.09 kWh/kg pellets	3.6 MJ/kWh	76.22 GJ/ha-yr

[a] Assuming 35% efficiency of electric power plant

Now we will calculate the restoration work. The minimum restoration work is equal to the CExC in the production of fertilizers, insecticides, herbicides, electricity to grind wood and produce pellets, heat to dry raw wood, and fuels to run the plantation and transport the wood and pellets. The quantity of fertilizers considered here is equal to the quantity of nutrients lost from the soil, given the median soil erosion rate for plantations. In reality, this quantity should be **30-90% higher**, because of the low uptake efficiencies of the respective fertilizers, see Section 7.

Remark 16 Here we assume that 30-90% of N, P, K, Ca, and Mg in the plantation soil are "forever" resupplied through nitrogen fixing by acacias and other plants, mineral weathering and thriving soil flora/fauna. This may not be true (Zabowski, 1990), especially when herbicides and insecticides are used, whole plants are harvested (Dyck and Bow, 1992), and erosion increases (Wiersum, 1984; Morris et al., 1983). □

9.4 Acacia Plantation

The exergy output as 10%-wet wood pellets (first row), and the cumulative exergy consumption (CExC) for each major input to the example *A. mangium* stand, are listed in **Table 14**. The distribution of CExC is plotted in **Figure 16**. The total restoration work is W_u = **153** GJ/ha-yr. Note that the CExC required to generate the heat and electricity used to dry raw acacia stemwood from 55% to 10% of water content and chip it is the largest cost, followed by nitrogen fertilizer. The prolific *A. mangium* stand delivers

Option 1: **109** GJ/ha-yr of electricity (**-43** GJ/ha-yr relative to W_u), or

Option 2: **92** GJ/ha-yr of FT diesel fuel/car work plus electricity (**-61** GJ/ha-yr relative to W_u), or

Option 3: **36** GJ/ha-yr of ethanol/car work (**-117** GJ/ha-yr relative to W_u), see **Figure 17**.

For convenience, the major exergy flows in the example acacia stand are summarized in **Table 15**.

Remark 17 Regardless of the useful output option, there is no exergy benefit from the example *Acacia mangium* stand. At best, this stand is *unsustainable* by 43/153 = 28%; at worst it is unsustainable by 76%. Cutting down on the CExC in wood drying by a factor of two will make Option 1 "sustainable" by 22 GJ/ha-yr and Option 2 will break even. Option 3, conversion of wood to ethanol, can never be sustainable. Heavy reliance on sun-drying of stemwood will be required, but may be unfeasible for large pellet making facilities. □

9.5 Eucalyptus Plantation

The exergy output as 10%-wet wood pellets (first row), and the cumulative exergy consumption (CExC) for each major input to the example *E. deglupta* plantation, are listed in **Table 16**. The

Table 15: Summary of exergy flows in the example *A. mangium* stand

Stem+bark exergy	434.06	GJ/ha-yr
Slash exergy[a]	98.65	GJ/ha-yr
Pellet exergy	347.25	GJ/ha-yr
Exergy consumed in pellet production	129.82	GJ/ha-yr
Exergy consumed in biomass production	23.02	GJ/ha-yr
Useful work as electricity	109.38	GJ/ha-yr
Useful work as FT-fuel[b] & electricity	91.57	GJ/ha-yr
Useful work as ethanol[b]	36.16	GJ/ha-yr

[a] The slash stays on the plantation

[b] In conjunction with a 35%-efficient internal combustion engine

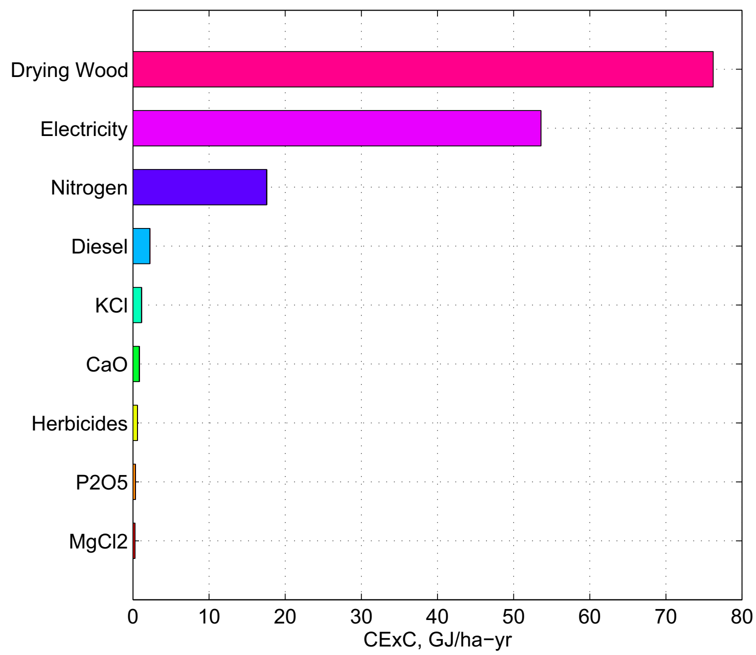

Figure 16: CExC in the *A. mangium* wood pellet production.

distribution of CExC is plotted in **Figure 18**. The total restoration work is $W_u = \mathbf{49.1}$ GJ/ha-yr. Note that the CExC in generating the heat and electricity necessary to dry raw eucalypt stemwood from 55% to 10% of water content and chip it is the largest expenditure, followed by nitrogen fertilizer. The not-so-prolific *E. deglupta* stand delivers

Option 1: 27.3 GJ/ha-yr of electricity (**-21.7** GJ/ha-yr relative to W_u), or

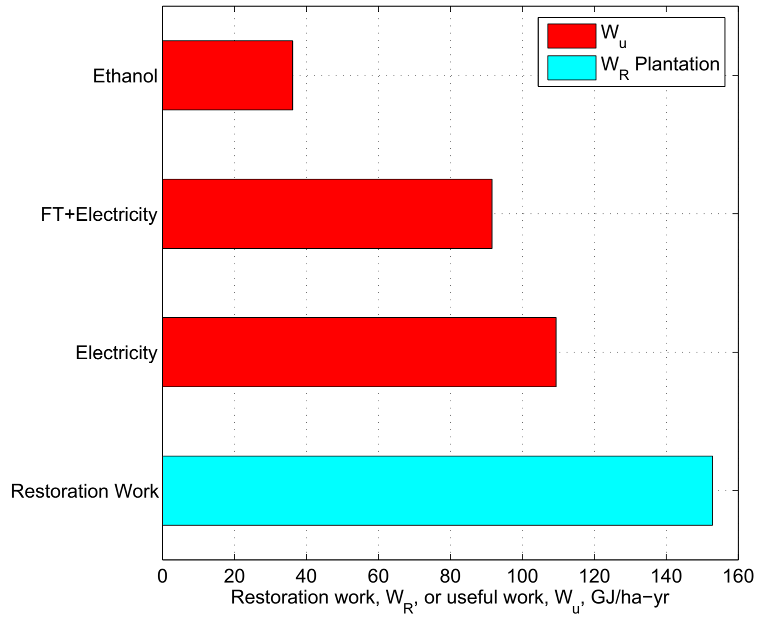

Figure 17: Maximum useful work and restoration work for the example *A. mangium* stand.

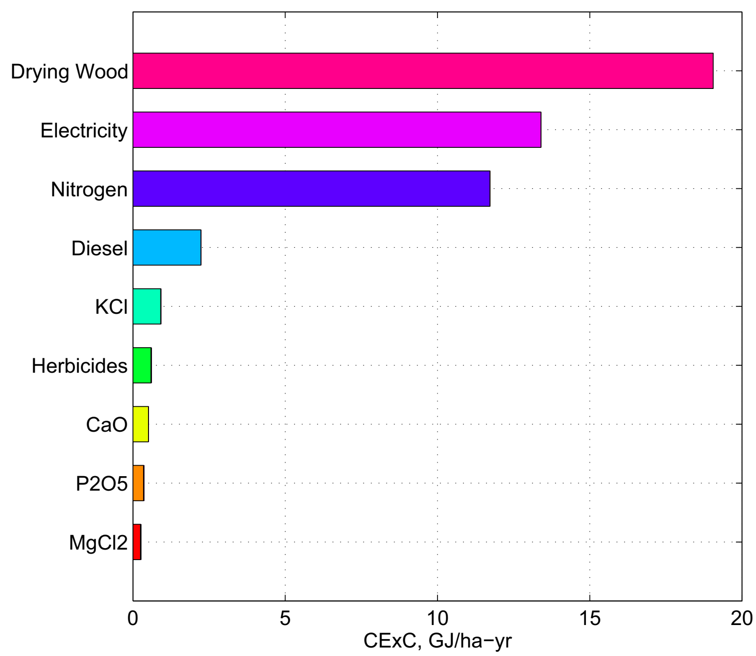

Figure 18: CExC in the *E. deglupta* wood pellet production.

Option 2: 22.9 GJ/ha-yr of FT diesel fuel/car work plus electricity (**-26.2** GJ/ha-yr relative to W_u), or

Option 3: 9.0 GJ/ha-yr of ethanol/car work (**-40.0** GJ/ha-yr relative to W_u), see **Figure 19**.

Table 16: Restoration work for the example *E. deglupta* stand.

Quantity	Flux/Specific use	Specific CExC	Exergy/CExC
10%-wet pellets	4840 kg/ha-yr	17.76 MJ/kg	86.81 GJ/ha-yr
N	117.7 kg/ha-yr	99.60 MJ/kgN	11.73 GJ/ha-yr
P	9.3 kg/ha-yr	38.50 MJ/kgP	0.36 GJ/ha-yr
K	37.4 kg/ha-yr	24.58 MJ/kgK	0.92 GJ/ha-yr
Ca	36.3 kg/ha-yr	14.06 MJ/kgCa	0.51 GJ/ha-yr
Mg	10.5 kg/ha-yr	24.58 MJ/kgMg	0.26 GJ/ha-yr
Herb/insecticides	2.00 kg/ha-yr	300.1 MJ/kg	0.60 GJ/ha-yr
Equiv. diesel	50.0 kg/ha-yr	53.20 MJ/kg	2.23 GJ/ha-yr
Electricity[a]	0.23 kWh/kg pellets	11.83 MJ/kWh	13.40 GJ/ha-yr
Heat to dry wood	1.09 kWh/kg pellets	3.6 MJ/kWh	19.05 GJ/ha-yr

[a] Assuming 35% efficiency of electric power plant

Remark 18 Regardless of the useful output option, there is no exergy benefit from the example *Eucalyptus deglupta* stand. At best, this stand is *unsustainable* by $21.7/49.1 = 44\%$; at worst it is unsustainable by 81%. Cutting down on the CExC in wood drying and chipping by a factor of two will make *not* make this stand "sustainable" because of its relatively poor productivity. □

For convenience, the major exergy flows in the example eucalypt stand are summarized in **Table 17**.

Table 17: Summary of exergy flows in the example *E. deglupta* stand

Stem+bark exergy	108.52	GJ/ha-yr
Slash exergy[a]	61.41	GJ/ha-yr
Pellet exergy	86.81	GJ/ha-yr
Exergy consumed in pellet production	32.45	GJ/ha-yr
Exergy consumed in biomass production	16.60	GJ/ha-yr
Useful work as electricity	27.35	GJ/ha-yr
Useful work as FT-fuel[b] & electricity	22.89	GJ/ha-yr
Useful work as ethanol[b]	9.04	GJ/ha-yr

[a] The slash stays on the plantation

[b] In conjunction with a 35%-efficient internal combustion engine

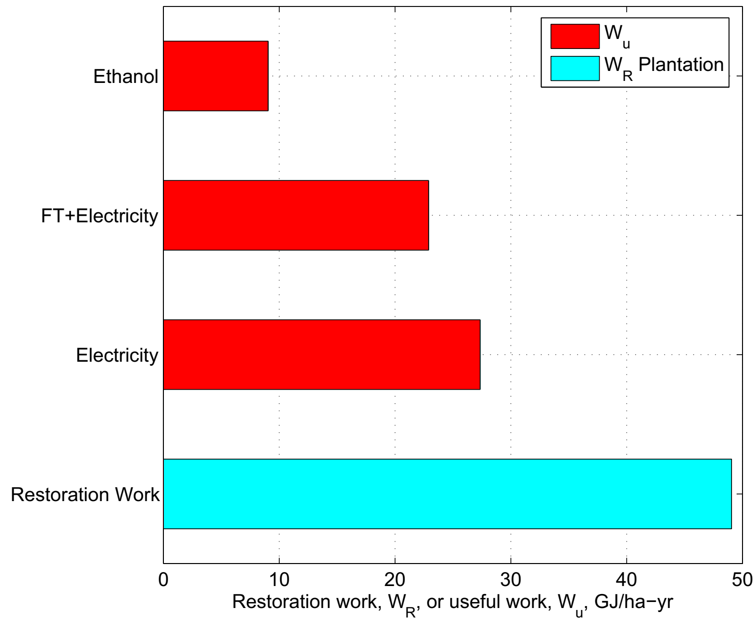

Figure 19: Maximum useful work and restoration work for the example *E. deglupta* stand.

10 Sugarcane Plantations for Ethanol

As Brazil is the largest producer of sugarcane and cane-based ethanol in the world, we will attempt to perform the free-energy balance of an average sugarcane plantation/ethanol plant in that country. In contrast to the detailed plant mass and nutrient balances in the PT.IHM plantation in Indonesia, sugarcane plantations in Brazil are not nearly as well described (FAO, 2004). Almost all of the FAO statistics on the consumption of nutrients by sugarcane are based on educated guesses and algebraic adjustments to match the regional estimates[49].

10.1 Sugarcane Plant

Sugarcane, like corn, belongs to the grass family, *Graminae*, characterized by segmented stems, blade-like leaves, and reproduction by seed, see **Figure 20**. Sugarcane is a tropical C_4 plant that cannot survive freezing temperatures. It thrives in abundant sunlight and warm temperatures (25-30^{0}C), and with plentiful water (75-150 cm/yr) (Srivastava, 2004).

[49]See Chapter 6 in (FAO, 2004).

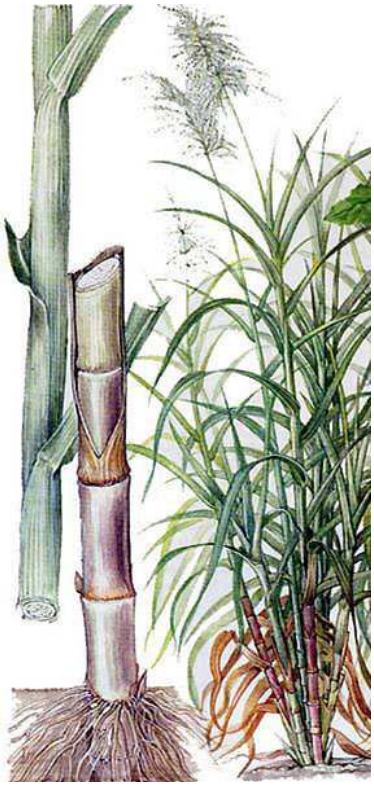

Figure 20: Sugarcane plant *Saccharum officinarum*. The cut, juice-rich stem is the foreground. From the brown stems grow green tops (right). Some dying brown leaves are also shown.

10.1.1 Mass Balance

Table 18 lists average mass composition of delivered commercial sugarcane in Zimbabwe using conversion factors from Hall et al. (1993). The sugarcane growth period is 12 months. The total above ground standing biomass does not include detached leaves. Associated with 1000 kg of fresh cane are: 140 kg of bagasse, 160 kg of Brix[50], 92 kg of attached tops + leaves (mostly water); not included are the 188 kg detached, i.e., dead leaves. The remaining 608 kg is water; hence the 30/70 % split of fresh cane between dry mass and moisture. The harvested part of sugarcane are stems (or stalks), commonly reported in harvest statistics, e.g., by FAO[51]. It is not clear if the attached tops and leaves are included in these statistics, or not. We assume that the attached tops and leaves are *not* included.

Macedo et al. (2001) have investigated the amount of "trash" (tops, dry and green leaves)

[50]Brix is the total soluble solids, i.e., sucrose, glucose, fructose, and water soluble impurities. Brix is measured in the cane juice with refractometry.

[51]Food and Agriculture Organization of the United Nations, http://www.fao.org/

per tonne of cane stalk for three of the most extensively planted varieties in Brazil (SP79-1011, SP80-1842, and RB72454), and calculated their average mass to be 140 kg (dry-basis). Only 45 kg of this trash stays attached to the cane stems. It is difficult to compare Macedo et al.'s estimate with the $189 + 90 = 279$ kg of dry and green leaves estimated by Woods (2000).

Table 18: Mass composition of commercial sugarcane plant[a]

Total above-ground standing biomass, t/ha (%)	
Total fresh mass	150 (100)
Dry mass	45 (30)
Moisture	105 (70)
Main stem biomass, t/ha	
Fresh mass	115[b]
Dry mass	35
Biomass components at harvest, % total above ground dry mass	
Stems	77
Leaves	23
Fermentable sugar content, % stem dry mass	
Sucrose %	44
Glucose %	3
Fructose %	2
Gum, Starch %	2
Total %	51
Total stem sugar, t/ha	13.2[c]
Fiber Content, % stem dry mass	
Hemicellulose[d] %	17
Cellulose %	24
Lignin %	8
Total[e] %	49

[a] Based on Table 4.2, p. 86 of the Ph.D. Thesis by Jeremy Woods (2000), and on *Composition of Sugarcane, Information Sheet*, December 2000, http://www.sasa.org.za/sasex/ISHEETS/General%2011.3.pdf

[b] The mean cane stem yield in Brazil was 71.4 t/ha in 2002, see Table 19

[c] Woods reports $35 \times 0.49 = 17$ t/ha of total sugars. He apparently assumed the same sugar content in leaves and tops as in stems. The sugar in stems only must be multiplied by 0.77 yielding 13.2 t/ha

[d] Calculated from *The use of fibrous residues in South Asia* by M.C.N. Jayasuriya, http://www.unu.edu/unupress/unupbooks/-80362e/80362E06.htm

[e] May contain extraneous materials: soil, trash, etc.

Remark 19 In this paper, we will assume that associated with with 1 metric tonne of harvested sugarcane stems are, on the *dry mass basis*, 140 kg bagasse, 160 kg of fermentable sugars and starch, and 45 kg of "trash" (attached tops and leaves). This sugarcane stem makeup is similar to that reported in Table 1 in Kheshgi et al. (2000), and agrees with the attached "trash" mass reported in (Macedo et al., 2001). □

10.1.2 Average Cane Stem Yield

Brazil is the largest sugarcane producer in the world, followed by India. In 2002, Brazil harvested 372 million tonnes of sugarcane[52] and India 297 million tonnes (FAOSTAT data, 2004).

The sugarcane crop areas and yields in different parts of Brazil are listed in **Table 19**. On average, 71.4 tonnes/ha-yr of sugarcane stems were harvested in Brazil in 2002 on 5.2 million hectares. This country-wide average accounts for the monotonically decreasing sugar yields from the first cane ratoon to the subsequent ones. The FAO estimate based on the 2002 field data is somewhat higher than the older estimate of 65 t/ha-yr used by Kheshgi et al. (2000).

Table 19: Sugarcane crop areas and yields in Brazil by region[a] (2002)

Region ⟶	N	NE	Center W	SE	S	Overall
Sugarcane Area/1000 ha	15	1148	499	3146	407	5215
Harvested Yield kg/ha	62099	53936	75310	76640	73557	71377

[a] (FAO, 2004), Chapter 3, Table 7

By using the average plant composition, together with the average cane stem yield, 10.0 odt/ha-yr of bagasse, 3.2 odt/ha-yr of attached "trash," and 11.4 odt/ha-yr of fermentable sugars and starch were produced in Brazil in 2002.

10.1.3 Average Ethanol Yield

Gómez and Borzani (1988) showed that the average ethanol yield is linear with the total fermentable sugar content:

$$m_{\text{EtOH}} \approx 0.385 m_{\text{sugars}} \qquad R = 0.9994 \tag{8}$$

[52]In comparison, 257 million tonnes of corn grain were harvested in the U.S. But, Brazilian sugarcane delivered only 57 million tonnes of sugar, while the U.S. corn delivered 144 million tonnes of starch, i.e., 2.5 times more ethanol raw material.

where m is mass, and R is the linear correlation coefficient. The slope 0.385, corresponds to 75% of the theoretical slope 0.511 (Patzek, 2004). Therefore, on average, 4.4 tonne EtOH/ha-yr, or 5525 L EtOH/ha-yr, were produced in Brazil in 2002. Our estimate is higher than the 5170 L EtOH/ha-yr used by Kheshgi et al. (2000).

10.1.4 Average Free Energy from Sugarcane

The chemical exergy (approximately high heating value) of ethanol (see Section 9.3) is 29.65 MJ/kgEtOH $\times$ 5525 kgEtOH/ha-yr = 130.4 GJ/ha-yr. The high heating values of other sugarcane stem parts are listed in **Table 20**.

Table 20: Sugarcane trash and bagasse heating values[a]

Sample	Moisture (%wt)	HHV[b] MJ/kg dry	HHV MJ/kg wet[c]
Dry leaves	11.3	17.4	15.5
Green leaves	66.7	17.4	9.7
Tops	82.5	16.3	9.1
Bagasse	50.0	18.0	11.3

[a] (Macedo et al., 2001), Table 4
[b] High Heating Value
[c] Calculated with use of Table 3

Assuming that the proportion of dry to green leaves is 1:1, and the leaves constitute 20% of tops mass, the specific chemical exergy of sugarcane "trash" is $0.5 \times 0.2 \times 17.4 + 0.8 \times 16.3 = 14.8$ MJ/kg dry. For a summary of the average Brazilian sugarcane plantation outputs, see **Table 21**.

Remark 20 In 2002, on average, one hectare of sugarcane plantation in Brazil delivered **130.4** GJ/ha-yr as 100% ethanol, **179.9** GJ/ha-yr as dry bagasse, and **47.5** GJ/ha-yr as dry "trash." Another 5.7 odt/ha-yr of detached "trash" could be collected and delivered to mill (Macedo et al., 2001). The chemical exergy of the latter trash is **84.4** GJ/ha-yr. □

10.2 Average Free Energy Cost of Sugarcane Ethanol

To calculate the *net useful work* from solar energy sequestered by sugarcane-ethanol, we need first to subtract from the free energy outputs in Table 21 the free energy spent on producing the ethanol. Following Brazilian practice, we will use bagasse associated with the cane to produce

Table 21: Summary of average Brazilian sugarcane plantation outputs

Average cane stem yield	71400	kg/ha-yr
Total sugars	11424	dry kg/ha-yr
Bagasse	9996	dry kg/ha-yr
Attached "trash"	3213	dry kg/ha-yr
Mill trash	5712	dry kg/ha-yr
Bagasse water	9996	kg/ha-yr
Attached "trash" water	9046	kg/ha-yr
Alcohol yield	4398	kg/ha-yr
Alcohol yield	5525	L/ha-yr
Alcohol yield[a]	77.4	L/t cane
Sugar Exergy	187.4	GJ/ha-yr
Alcohol Exergy	130.4	GJ/ha-yr
Dry Bagasse Exergy	179.9	GJ/ha-yr
Dry Attached Trash Exergy	47.5	GJ/ha-yr
Dry Mill Trash Exergy[b]	84.4	GJ/ha-yr

[a] Yields of 85 L EtOH per tonne of cane (almost 10% higher) have been reported for mills in SE Brazil with advanced continuous fermentation technology (Macedo et al., 2001). Because of higher efficiency (∼90% vs. 75%-84% in the batch mode), ease of operation, and substantial savings in water consumption, continuous fermentation is preferred. In (Patzek, 2004), an 84% fermentation efficiency was used.

[b] This additional "trash" is usually left on the plantation. Otherwise, it requires extra collection and baling operations that cost about 90 MJ/odt of the trash, see Table 7 in (Macedo et al., 2001), and depletes significant amounts of soil nutrients, Figure 22.

steam and electricity necessary to crush sugarcane, squeeze the juice, ferment it, and distill the resulting dilute alcohol brew to anhydrous alcohol. We will also use the bagasse and the attached "trash" to remove excess water from fresh bagasse and wet attached tops and leaves, i.e., to dry them from a 50% and 74% (by weight) water content, respectively, to a 10% water content. The calculated (conservatively low) cumulative exergy consumption in steam drying is then 4.4 MJ/kg dried matter. As it happens, there is enough chemical exergy in the bagasse and dry attached "trash" to perform both tasks.

Brazil's 330 sugar/ethanol mills present a wide variation of sizes, technology and age, but average free energy consumption in them is not too far from that listed in **Table 22**. The various exergy costs in this table have been calculated from the data in Table 1 in Macedo et al. (2001). In Brazil, all electrical power, mechanical energy, and process steam are generated during the crushing

Table 22: Summary of exergy consumption in average sugar/ethanol mill in Brazil[a]

Boiler pressure/temperature	22/300	bar/^{0}C
Electricity generation efficiency	25	%
Exergy in mill consumed as electricity	15.4	GJ/ha-yr
Exergy in mill consumed as mechanical power	20.6	GJ/ha-yr
Exergy in mill consumed as heat[b]	94.2	GJ/ha-yr
Exergy to dry bagasse and trash[b]	83.8	GJ/ha-yr
Total exergy consumed to produce ethanol[c]	130.2	GJ/ha-yr
Specific exergy consumed to produce ethanol	23.6	MJ/L
Extra electricity from trash & bagasse	3.3	GJ/ha-yr

[a] Based on average Brazilian data in Table 1 of (Macedo et al., 2001)

[b] Assuming a high 90% overall efficiency of the steam generation system

[c] Equal to the cumulative exergy consumption in producing this ethanol, see Table 21

season. The main fuel is bagasse and attached "trash," but fuel oil is also used. The increase in the size of the mills that took place in Brazil in the 1990's has exhausted the existing boiler capacity. Therefore, little or no extra electricity is generated, in agreement with the assumption that all the bagasse and almost all attached "trash" are burned to produce the ethanol in Table 21.

10.3 Summary

In the end, an average Brazilian sugarcane plantation for energy sequesters **130.4** GJ/ha-yr (0.41 W/m^2) as the net chemical exergy of its anhydrous ethanol product and **3.3** GJ/ha-yr as electricity (0.0001 W/m^2). This output is almost 2 times higher than the 70.8 GJ/ha-yr in ethanol produced from an average corn field in the U.S. (Patzek, 2004). The main reason is that corn in the U.S. grows less than 6 months/year and sugarcane in Brazil grows 12 months/year before each harvest. If these 130.4 GJ/ha-yr in sugarcane ethanol are used to power a 35% internal combustion engine (an efficient Toyota Prius car), one obtains **45.6** GJ/ha-yr (0.14 W/m^2) of shaft work. If a 60% efficient fuel cell could be used[53], one would obtain **78.2** GJ/ha-yr (0.25 W/m^2) of shaft work. Note that the cumulative exergy consumption in ethanol production (not counting the Biological Oxygen Demand (BOD) removal from distillery wastewater) is *equal* to the ethanol's chemical exergy.

Per kilogram of output biofuel (anhydrous ethanol), the average sugarcane plantation produces 10.37 MJ as useful work from a 35%-efficient internal combustion. This efficiency should be com-

[53] But it cannot, see Appendix A.

pared with the 5.59 MJ/kg of wood pellets as electricity from the example Acacia plantation in Indonesia. Therefore, sugarcane ethanol is 85% more efficient as a source of shaft work than the acacia wood pellets[54].

Remark 21 We assume that **5.3** odt/ha-yr of the non-attached sugarcane "trash" is left on the plantation to help rebuild soil organic carbon (SOC). This "trash" should be mulched and decomposed, not burned. □

Now we will calculate the environmental free-energy expenditure on sequestering solar energy as sugarcane ethanol in Brazil.

11 Nutrient Balances in Sugarcane Plantations

The most common agricultural soils in Brazil are Xanthic, Rhodic & Haplic Ferrasols (Latossolos), 39% of agricultural land area, Rhodic & Haplic Acrisols and some Lixisols (Argissolos), 20% of the area, and Lepto, Fluvi, Rego & Arenosols (Neossolos), 15% of the area (FAO, 2004), see Chapter 2, and Tables 2 and 3. The SE region of Brazil, most important to sugarcane production, has predominantly deep soils of usually low natural fertility. The NE region, second in importance, has soils of medium to high natural fertility, but most are shallow due to a low degree of weathering. The Center West region has soils that are deep and well-drained, and also have low natural fertility. The least productive North region has deep, highly weathered, acidic, and low natural fertility soils. In all cases, the low natural soil fertility may easily be corrected by liming and fertilization[55]. Mineral and synthetic fertilizers are extensively applied in the modern, large sugarcane plantations in Brazil (FAO, 2004).

11.1 Nutrient Removal by Sugarcane

Figure 21 shows that nutrient fluxes in a sugarcane plantation depend on the management of bagasse, attached and collected "trash," molasses, filter cake, process water, etc. (Ando et al., 2001). One management strategy would be to remove from the field only the stems of sugarcane. Most of the other plant parts including tops, leaves, stubbles, and roots remain as residues. Thus, most of the nutrients contained in these residues are returned to the field. In the process of sugar

[54]One could instead sun-dry raw acacia wood and burn it directly to generate electricity next to the plantation, with a yield comparable to that of sugarcane ethanol. The environmental impact of this choice could be quite serious.

[55]Preserving soil structure and limiting soli erosion are not as easy.

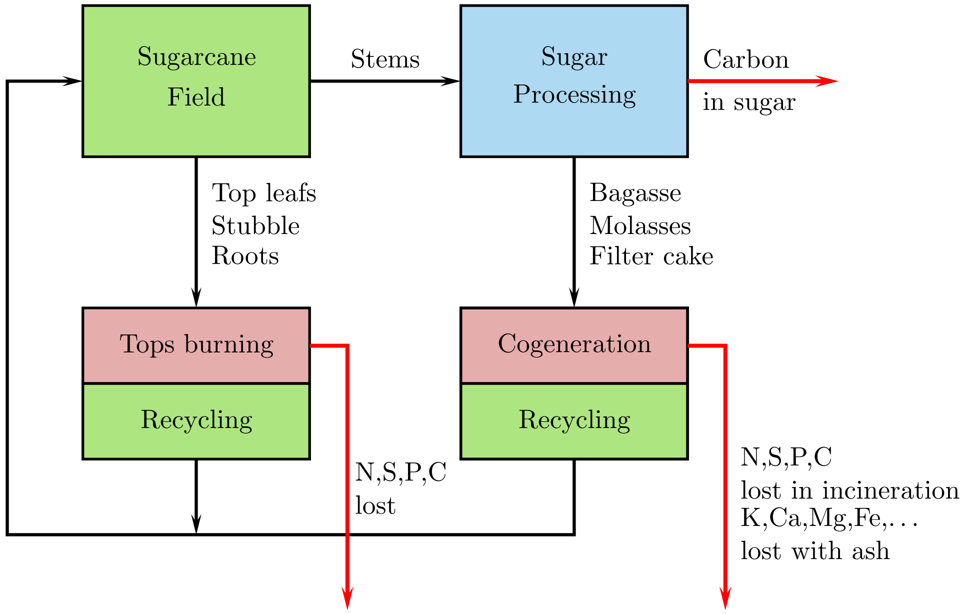

Figure 21: Production of sugar from sugarcane. In the field and the sugar/ethanol mill, decisions can be made whether to recycle plant parts or burn them and remove vital nutrients. Biomass production from sugarcane relies on processing of whole plants, thus removing the maximum possible amounts of nutrients.

refining and ethanol production in mills, bagasse, filter cake and molasses are discharged as by-products. The main element of the sugar, bagasse and molasses taken out of this organic matter cycle is carbon; on the other hand, filter cake contains large amounts of nutrients. In order to increase recycling of the nutrients, the leaves of sugarcane should not be burned during harvesting, and filter cake should be returned to the plantations[56].

For centuries, sugarcane has been grown on plantations as a continuously-harvested monoculture crop, but its sustainability has not yet been evaluated systematically. Recent work by Brazilian researchers, leads to an estimate of the mean sugarcane productivity decreasing by 50% over 360 years (Sparovek and Schnug, 2001). Interestingly, over the first 50 years, this productivity remains almost constant. Thereafter, it declines very fast along a logistic curve. Sugarcane is a C_4 plant and can fix carbon effectively; it tends to leave a great deal of plant residues in the field. N removed from the nutrient cycle is compensated for by N derived from N_2 fixation (Urquiaga et al., 1992; Boddey, 1995; Ando et al., 2001; Urquiaga et al., 2001). Sugarcane in Northeast Thailand has

[56]This type of recycling is not practiced in industrial sugarcane plantations, which rely heavily on the fossil energy from bagasse and cane "trash."

shown vigorous growth even in very infertile sandy soil, and the fact that it has been planted for over 300 years in infertile soil on the Nansei Islands in Japan without any decreases in production and soil fertility suggest that sugarcane production maintains a sustainable nutrient cycle (Ando et al., 2001). Brazil's sugarcane plantations have a similar long history, see (FAO, 2004), Chapter 3.

Remark 22 As with corn (Patzek, 2004), and acacia and eucalypt trees (Section 5 and the following), we arrive at the following Faustian bargain: either to remove and burn more cane "trash" to help with mechanized plantation management and industrial power generation, but lose vital nutrients and soil organic carbon, or recycle organic matter as much as possible and use other fossil fuels[57]. The current intensive industrial practices of sugarcane cultivation started in Brazil about 15-20 years ago, and their long-term effects on the sustainability of today's high yields are unknown. □

Table 23: Sugarcane "trash[a]" and bagasse ash analysis

Ash mineral analysis[b]	Units	Dry leaves	Green leaves	Tops	Bagasse[c]
N[d]	g/kg	4.5	3.6	8.7	17
P_2O_5	g/kg	0.4	2	2.5	0.5
K_2O	g/kg	1.2	12.8	29.7	1.9
CaO	g/kg	4.7	3.5	2.3	1.0
MgO	g/kg	2	2.1	2.3	0.8
Fe_2O_3	g/kg	1.1	0.5	0.3	3.1
Al_2O_3	g/kg	4.2	1.7	0.6	4.4
CuO	mg/kg	< 0.06	< 0.06	< 0.06	0.1
ZnO	mg/kg	10	17	34	37
MnO_2	mg/kg	160	100	140	72
Na_2O	mg/kg	94	98	94	78

[a] In (Macedo et al., 2001), Table 4

[b] Dry basis

[c] Authors' estimates from a variety of sources, including the Technical University of Vienna, Chem. Eng. Department, http://-solstice.crest.org/discussion/gasification/current/msg00170.html, and (Turn et al., 2002). Significant differences exist among the different sources, most likely because of different soil mineral contents and availabilities

[d] The ultimate elemental analysis of sugarcane, Hawaiian data from Tables 1-A and 1-B (clean bagasse) in (Turn et al., 2002)

[57] In short, Mother Nature knows no "trash."

11.1.1 Cane Harvest Losses

The specific harvest losses of major macro- and micro-nutrients are estimated in **Table 23**. The calculations are based mostly on Brazilian (Macedo et al., 2001) and Hawaiian (Turn et al., 2002) data. These cane harvest losses are then multiplied by the fluxes of dry cane parts from Table 21, and the results are listed in **Table 24**, and plotted in **Figure 22**.

Table 24: Estimated[a] sugarcane harvest losses in kg/ha-yr

Nutrient	Bagasse	"Trash"	Total	Recycled[b]
N	170	25	195	44
P_2O_5	5	7	12	13
K_2O	19	81	100	144
CaO	10	9	18	15
MgO	8	7	15	13
Fe_2O_3	31	1	33	2
Al_2O_3	44	3	47	6
CuO	0.001	0.000	0.001	0.000
ZnO	0.373	0.096	0.469	0.171
MnO_2	0.718	0.443	1.161	0.788
Na_2O	0.775	0.303	1.079	0.539

[a] Based on data in Table 23

[b] Nutrients recycled from the detached "trash" left to decompose in the field. This trash is also crucial in rebuilding SOC

11.1.2 Erosion Losses and SOC Depletion

A Geographical-Information-System (GIS) aided study of soil erosion in SE Brazil was conducted by Sparovek and Schnug (2001). The sugarcane crop area showed the highest mean erosion rate[58] of 31 tonnes/ha-yr. The authors estimated the mean time to 50% decline in sugarcane yield to be 360 years, with a 25%-decline predicted to occur in over 100 years.

In NE Brazil, Resck (1998) reported a SOC loss of 69% within 5 yr of cultivation by a heavy disk harrow in quartz sand (< 15% clay content) and 49% in a Latosol (30% clay content). Plowing decreases aggregate stability, disrupts macro-aggregates and exposes SOC to microbial processes

[58] 90% of erosion rates estimated from 11 238 points were between -100 t/ha-yr (deposition) and +101 t/ha-yr, with the mean of 15 t/ha-yr.

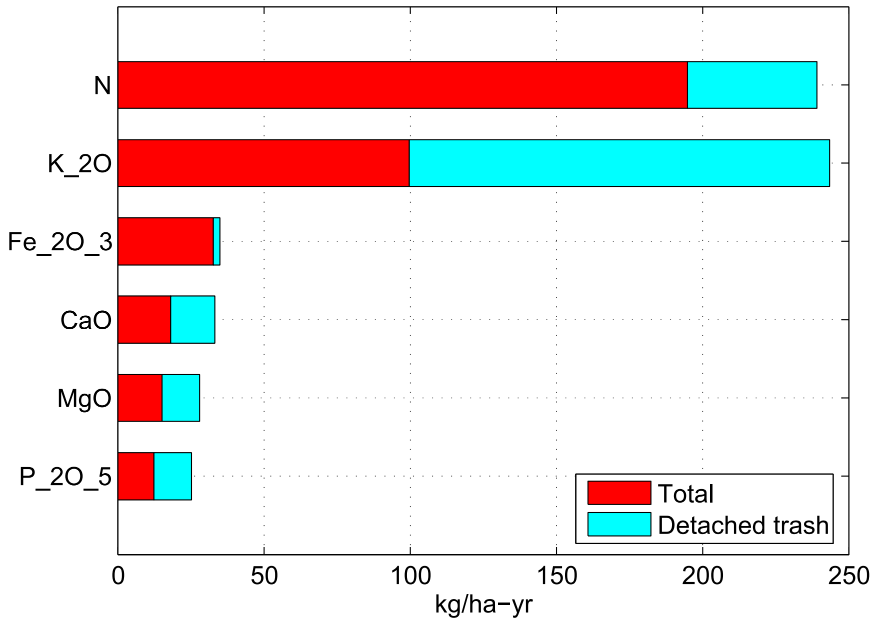

Figure 22: Harvest nutrient losses for estimated for Brazilian sugarcane. Note that these losses are significantly higher that those estimated for the *A. mangium* stand in Table 9. Sugarcane grass simply grows much faster than acacia trees and is harvested annually, not every 6-10 years.

(Tisdall and Oades, 1982).

The current no-tillage treatment of soil in sugarcane plantations greatly reduces losses of SOC and helps to preserve the soil structure and lessen the erosion rate. The *incremental* carbon sequestration rate for no tillage in South Brazil was estimated at $\sim$1 t/ha-yr (Sá et al., 2001). There is a *close relationship* between the SOC content and amount of crop residues[59].

Remark 23 Since erosion-related nutrient losses are not being replaced in sugarcane plantation soils in Brazil, we can only speculate that the nutrients removed by the erosion will contribute to the long-term decline of cane productivity, which will become appreciable within 100 years. □

For the purpose of estimating the sustainability of ethanol production from sugarcane we will estimate the mean nutrient losses due to erosion from Table 6, scaled to reflect the mean erosion rate of 31 t/ha-yr, see row 1 of **Table 25**.

[59]Therefore, the detached sugarcane plant residues, termed "trash" by some biofuel aficionados, must not be removed from the plantations, nor be burned over there.

11.1.3 Nutrient Losses from Residue Burning

If the detached sugarcane "trash" is burned on the plantations, the majority of the nutrients listed in the last column of Table 24 will be removed, and need to be accounted in the fertilizer application requirements. Some nutrient losses will double. As far as we know, slash burning is still common in Brazil.

11.1.4 Nutrient Losses Through Leaching

We will estimate nutrient losses by leaching from the average values in Table 8. The results are listed in row 2 of **Table 25**.

Table 25: All nutrient losses in sugarcane plantations in Brazil

Loss kg/ha-yr	N	P_2O_5	K_2O	CaO	MgO
Est. Erosion	47.7	10.5	3.0	17.4	5.1
Est. Leaching	11.8	0.1	15.1	1.6	2.3
Harvest	194.8	12.4	99.8	18.1	15.2
Total	254.3	23.0	117.8	37.0	22.7
Total+Slash	298.6	35.8	261.5	52.2	35.6

11.2 Nutrient Replacement with Fertilizers

The latest UNFAO estimates (FAO, 2004) of fertilizer application rates in Brazil are listed in **Table 26**. We note that small farms are responsible for 14% of Brazil's sugarcane. These farms grossly underfertilize their fields, see (FAO, 2004), Chapters 3 and 7. To reconcile the real-life fertilizer application rates with the demands of nutrient replacement we will make the following assumptions:

1. From our optimistic assumption that all detached sugarcane "trash" is decomposed, we will omit it in our estimated fertilizer application rates.

2. Following the UNFAO assumptions (FAO, 2004) about efficiency of the various fertilizers, we will assume that average efficiency of N fertilizers is 60%, that of phosphates is 30% (likely too optimistic in view of our discussion in Section 7), and the efficiency of lime, potassium and magnesium fertilizers is 70%, see (FAO, 2004), Chapter 7.

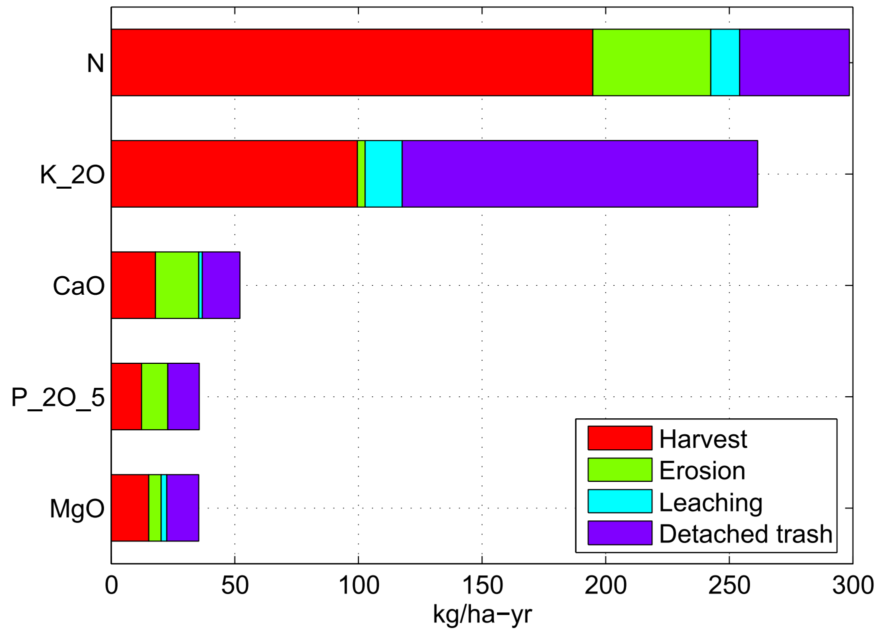

Figure 23: Total harvest losses for estimated for Brazilian sugarcane. Note the importance of nutrient recycling from the decomposed detached "trash."

3. Sugar cane has been grown in Brazil for many decades with low or zero applications of nitrogen fertilizers. There are many areas in the country where sugarcane has been grown for decades, even centuries, and neither cane yields, nor soil N reserves, appear to fall with time, despite this apparent deficit in N supply. These results have led to research concerning the contribution of biological nitrogen fixation to the maintenance of cane productivity (Urquiaga et al., 1992; Boddey, 1995; Urquiaga et al., 2001).

4. We will agree with the assertion of avid biofuel advocates (Dobereiner et al., 1999), Table 1, that contributions up to 190 kgN/ha-yr can be obtained from the biological reduction of atmospheric nitrogen. Thus, we will subtract 190 kg N from the estimate in Table 25, and rescale the remainder by dividing it by 0.6.

5. We will add to the lime application twice the nitrogen fertilization rate, and rescale the result by dividing it by 0.7.

6. After UNFAO (FAO, 2004), Chapter 4, Table 9, we will assume that ammonium nitrate and urea (1:1) are the two major nitrogen fertilizers in Brazil. Ammonium nitrate is sold together with the single superphosphate, which is the main phosphate fertilizer in Brazil.

Table 26: Fertilizer use in sugarcane farming in Brazil[a]

Region	N	P_2O_5	K_2O	Total
North	14	28	63	105
Northeast	31	30	79	140
Center West	57	60	130	247
Southeast	61	57	118	236
South	76	45	113	234
Total	55	51	110	216

[a] (FAO, 2004)

The overall fertilizer application rates required to render sugarcane production in Brazil "sustainable" are listed in **Table 27** and shown if **Figure 24**.

Table 27: Estimated fertilizer application rates required for the "sustainable" Brazilian sugarcane production

Application Rate	N	P_2O_5	K_2O	CaO	MgO
kg/ha-yr	100	80	170	240	30

11.3 Mill Wastewater Cleanup

All three categories of waste, i.e. liquid, air and solid, are generated by sugar/ethanol mills. According to a thorough study commissioned by the Pakistani Chambers of Commerce & Industry and The Netherlands Government (FPPCI, 2001), most aggressive liquid effluent ("stillage") originates from the distillery unit, in which BOD_5 and COD concentrations are in the range of 40 000 mg/L and 100 000 mg/L, respectively.

Vinasse, a residual substance left after sugarcane alcohol distillation, represents a major environmental problem for the ethanol industry (Polack et al., 1981; Cortez and Brossard Pérez, 1997). No one has found a convenient and economical disposal solution for this black-reddish[60], viscous, high BOD_5, and acid material which is produced in quantities up to 15 times larger than those of

[60]Vinasse presents a light brown color, total solids content from 20 000-40 000 mg/L, when it is obtained from straight sugarcane juice and a black-reddish color, and total solids ranging from 50 000-100 000 mg/L when it is obtained from sugarcane molasses.

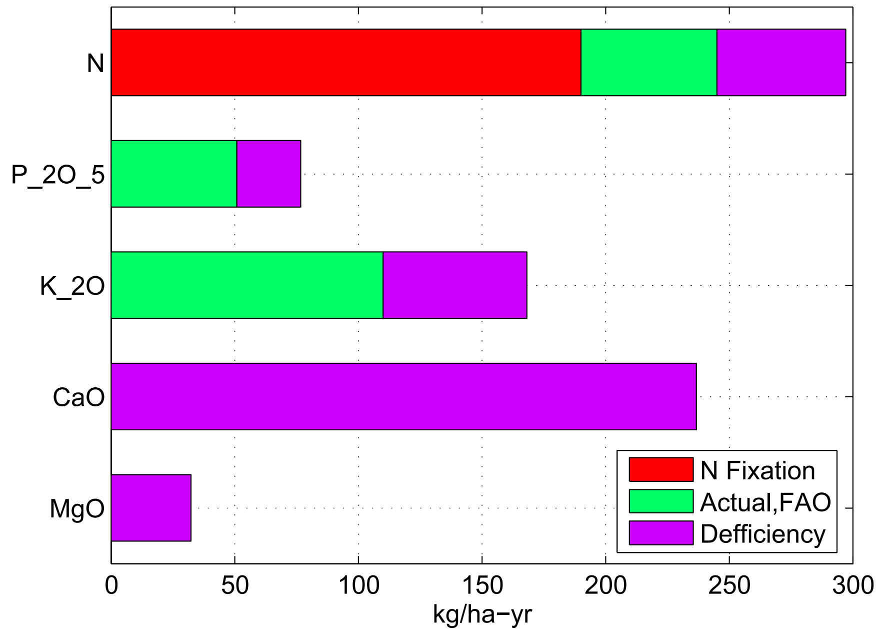

Figure 24: Estimated fertilizer application rates required for the "sustainable" Brazilian sugarcane production.

the alcohol itself.

Since here we are interested only in ethanol-producing mills, we calculate the amount of BOD as

$$\text{BOD} = 0.02 \text{ kg BOD/L } \text{H}_2\text{O} \times 5572 \text{ L EtOH/ha-yr} \times 14 \text{ L } \text{H}_2\text{O/L EtOH} = 1547 \text{ kg BOD/ha-yr} \tag{9}$$

We have used a minimum[61] BOD concentration of 20 000 mg/L, and a *low* multiplier of 14 to convert from the ethanol to wastewater volume. A factor of 12 is generated in alcohol distillation, and an additional factor of at least 2 is needed in the cane mill. Distilleries are one of the highest consumers of raw water with consumption in the range of 25-175 L/L of alcohol (Uppal, 2004). The raw water requirement includes both process and non-process applications. Water consumption in process application (e.g., yeast propagation, molasses preparation, steam generation, etc.) is in the range of 14.5-21.4 L/L of alcohol production. Water consumption in non-process applications

[61]COD values are always higher than BOD_5. Control of the discharge of the COD is an important concern for sugar/ethanol mills. Some organic materials are resistant to biological degradation and are not consumed by organisms because of their toxic nature. For example, if bagasse contaminates the water system, the cellulose found in it degrades extremely slowly. Other type of non-biodegradable material that may accompany sugar cane is the organic pesticide (FPPCI, 2001).

(e.g. cooling water, steam generation, for making potable liquor etc.) is much higher, between 102.65 and 240 L/L of alcohol production (Ansari, 2004). Most units depend on natural sources of water supply such as ground water and surface water (rivers, canals, etc.) for their raw water requirement.

To remove BOD_5 from distillery wastewater typically requires 0.7 kWh/kg BOD for a novel aerobic/anearobic treatment process of brewery effluent (Driessen et al., 1997), to 2.3-4.13 kWh/kg BOD in conventional denitrification/treatment processes (Henze, 1997; Bois et al., 1982). Here we will assume conservatively that only 1 kWh is used on average to remove 1 kg BOD from the distillery wastewater. Then, the cumulative exergy consumption[62] in the removal of BOD_5 in a sugar/ethanol mill effluent is 18.6 GJ/ha-yr.

Remark 24 In terms of the cumulative exergy consumption, removal of wastewater contamination in a sugar-ethanol distillery is very expensive, **18.6** GJ/ha-yr. Our estimate may be conservative, as the real BOD concentrations may be 2 times higher, and the wastewater volumes 10 times larger. Also, when alcohol is produced from molasses, the BOD concentrations are 5-7 times higher (FPPCI, 2001; Uppal, 2004). In addition, distilleries need large settling ponds that contaminate ground and surface water. The cost of removing the latter contamination is unaccounted for. □

12 Restoration Work

The cumulative exergy consumption in sugarcane and ethanol production in Brazil is listed in **Table 28**. The cumulative exergy consumption in ethanol distillation is deducted from the chemical exergy of bagasse and attached "trash" burned in the distillery, see Section 10.2. Cleanup of the distillery wastewater BOD must be done with grid electricity and small "trash" leftovers.

Figure 25 shows the individual components of the CExC in order of importance. The CExC in ethanol distillation (130 GJ/ha-yr) dwarfs all other free energy expenditures, and is not shown. The second largest expense is the BOD cleanup (probably underestimated by us, see Section 11.3). Diesel fuel use on the plantation, and in transporting cane stems to the distillery and fertilizers, etc. to the fields, are the third and fourth largest expenses. Nitrogen fertilizer is only the fifth largest expense.

The total restoration work (minus the CExC in distillation) and the useful shaft work from the various ethanol applications are shown in **Figure 26**.

[62]Assuming the combined efficiency of electricity generation in the grid and sugar/ethanol mill to be 0.3.

Table 28: CExC in production of Brazilian sugarcane/ethanol

Quantity	Flux/Specific use	Specific CExC	Exergy/CExC
N[a]	107 kg/ha-yr	87.55 MJ/kgN	9.39 GJ/ha-yr
P	77 kg/ha-yr	16.80 MJ/kgP	1.29 GJ/ha-yr
K	168 kg/ha-yr	12.89 MJ/kgK	2.17 GJ/ha-yr
Ca	237 kg/ha-yr	10.05 MJ/kgCa	2.38 GJ/ha-yr
Mg	32 kg/ha-yr	12.89 MJ/kgMg	0.42 GJ/ha-yr
Herb/insecticides[b]	3.40 kg/ha-yr	300.1 MJ/kg	1.02 GJ/ha-yr
Equiv. diesel[c]	300 kg/ha-yr	53.20 MJ/kg	13.41 GJ/ha-yr
Transportation[d]	83353 kg/ha-yr	0.12 MJ/kg	10.23 GJ/ha-yr
Machinery	72 kg/ha-yr	45.90 MJ/kg	3.30 GJ/ha-yr
Seed[e]	115 kg/ha-yr	16.72 MJ/kg	1.92 GJ/ha-yr
BOD_5	1547 kg/ha-yr	12.00 MJ/kg	18.57 GJ/ha-yr
Distillation[f]	5525 L EtOH/yr-ha	23.57 MJ/LEtOH	130.23 GJ/ha-yr

[a] 50% ammonium nitrite and 50% urea, see (Patzek, 2004) and Table 5.2 in (Szargut et al., 1988)

[b] (Constantin et al., 2003; Macedo et al., 2003)

[c] Calculated from Brixius, W.W. and F.M. Zoe, 2004, *Tires and Tractors in Agriculture*, http://filebox.vt.edu/users/rgrisso/-Grisso/Dist_Lecture/REFERENCE.

[d] Over 80 t/ha-yr transported in Class 8b trucks with an average round-trip distance of 160 km (Wang et al., 1997)

[e] 460 kg of seed divided into 4 ratoons

[f] CExC in generation of electricity, mechanical work and steam

Remark 25 If ethanol is the main product of a sugarcane-for-energy plantation, only the non-existent 60%-efficient fuel cell option might be called "sustainable," yielding an extra **14** GJ/ha-yr (0.04 W/m^2). The 20%- and 35%-efficient internal combustion engines lose **-38** and **-18** GJ/ha-yr, respectively. □

13 Discussion

The industrial tree and sugarcane plantations considered in this paper are sun-driven, man-made "machines," whose ultimate output is *shaft work*. These vast and enormously complex machines should be compared against two other, much simpler devices that also convert solar energy into shaft work: solar cells and wind turbines. Solar cells (whenever their panel areas measured in km^2 become commercially available) convert solar energy *directly* into electricity, the most valuable flow

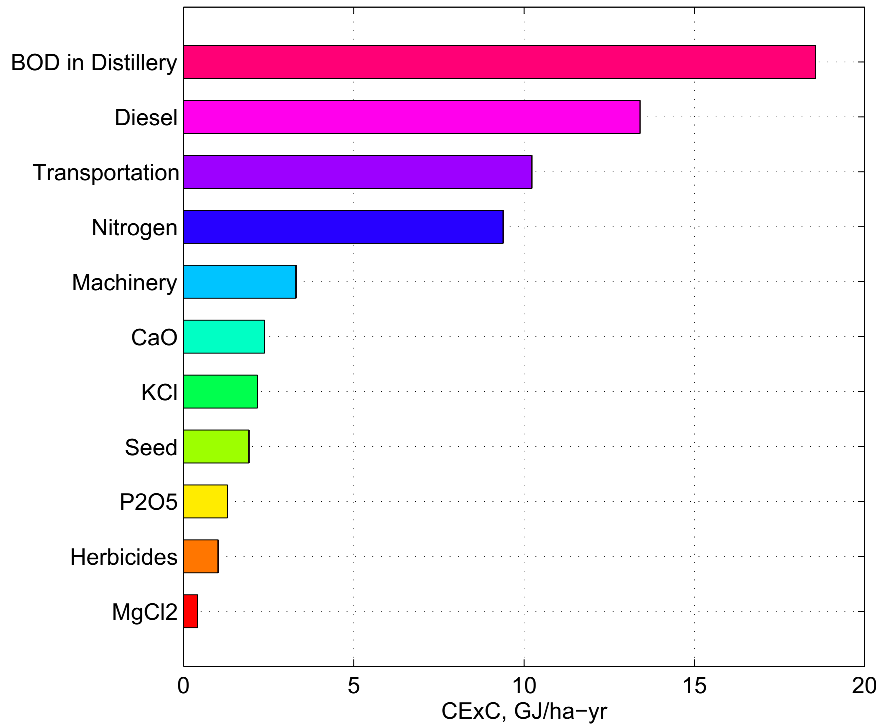

Figure 25: Estimated cumulative exergy consumption (CExC) in Brazilian sugarcane ethanol production excluding ethanol distillation. The CExC in ethanol distillation, equal to the ethanol's chemical exergy, was subtracted elsewhere from the chemical exergy of bagasse and attached "trash."

of free energy, that can be further converted into shaft work with small losses. Wind turbines produce electricity from the kinetic energy of the sun-driven wind, and will not be considered here. Therefore,

Remark 26 All biofuel-producing systems should be judged on their ability to generate shaft work, not merely a biofuel. These systems consume massive amounts of free energy — environmental low entropy — to produce their shaft work. But, as a rule, only the fundamentally incomplete energy balances, see (Patzek, 2004), are performed to evaluate merits of the industrial biofuel-producing systems. □

Therein lie the reasons for confusion surrounding the various published estimates of biofuel system efficiencies. For example, in (Dobereiner et al., 1999) it is claimed that

> . . . Brazil is the only country in the world where biofuel programmes are energetically viable. The overall energy balance of ethanol production on Brazil is 2.5. If bagasse is

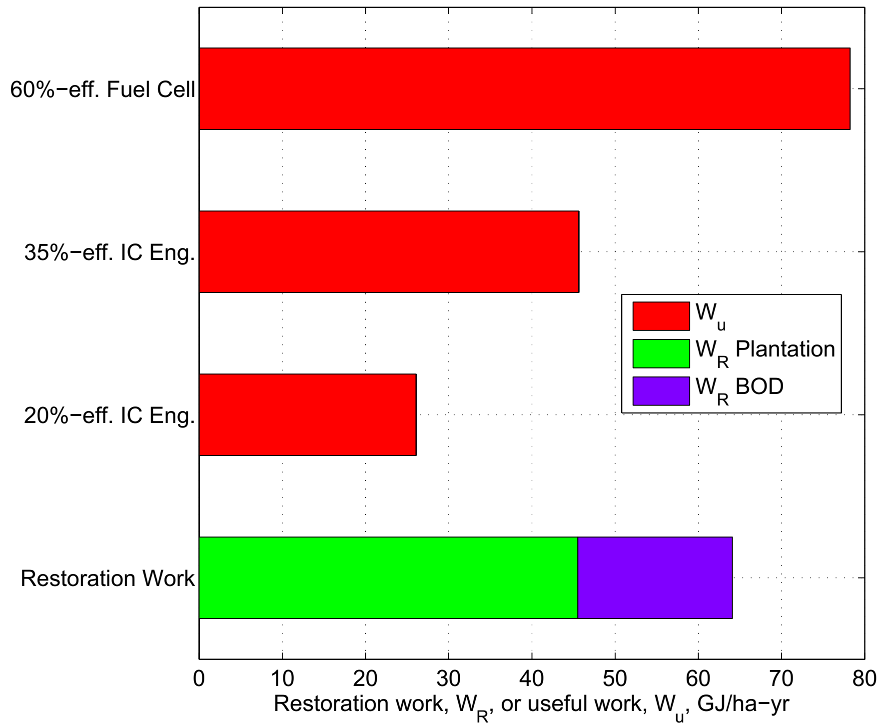

Figure 26: Maximum useful work and restoration work for an average sugarcane plantation in Brazil. Note that only the 60%-efficient fuel cell option, had it existed, might be called "sustainable."

> used to produce all factory power, the energy balance increases to 4.5 and if in addition all N fertilizers are eliminated, it increases to 5.8. . . (page 200)

The simple fact is that a mere (evidently incomplete) energy balance is insufficient to make such claims (Patzek, 2004).

Figures 27 – 30, summarize the results of this paper. We start from the ancient solar energy stored in a good quality oil reservoir described in Section 2. We assume that this reservoir is produced at a constant average rate over 20 years. If all oil-in-place could be produced, 1 m^2 of the reservoir would deliver almost 1300 W of heating power. If only 1/3 of the oil in place is recoverable, this heating power decreases to about 430 W. But we are *not* interested here in heat generation; instead we want to obtain useful work of a rotating shaft, such as an electric motor, or a car engine. This being the case, we choose to use a 35%-efficient internal combustion engine: a good power station, or a Toyota Prius. The amount of useful driving power generated from 1 m^2 of the example reservoir is then roughly 150 W. The only problem with our oil reservoir is that after 20 years there is *no* oil left to drive the internal combustion engine; this resource is finite and irreplaceable.

If, like the Norwegian government, we insisted on recovering 50% of the oil-in-place, the shaft power from the oil reservoir would increase to 250 W, which happens to be the time-averaged solar power across a horizontal surface in the tropics. One m^2 of horizontal solar cells may generate 10% of the average solar power, i.e., 25 W of electricity[63].

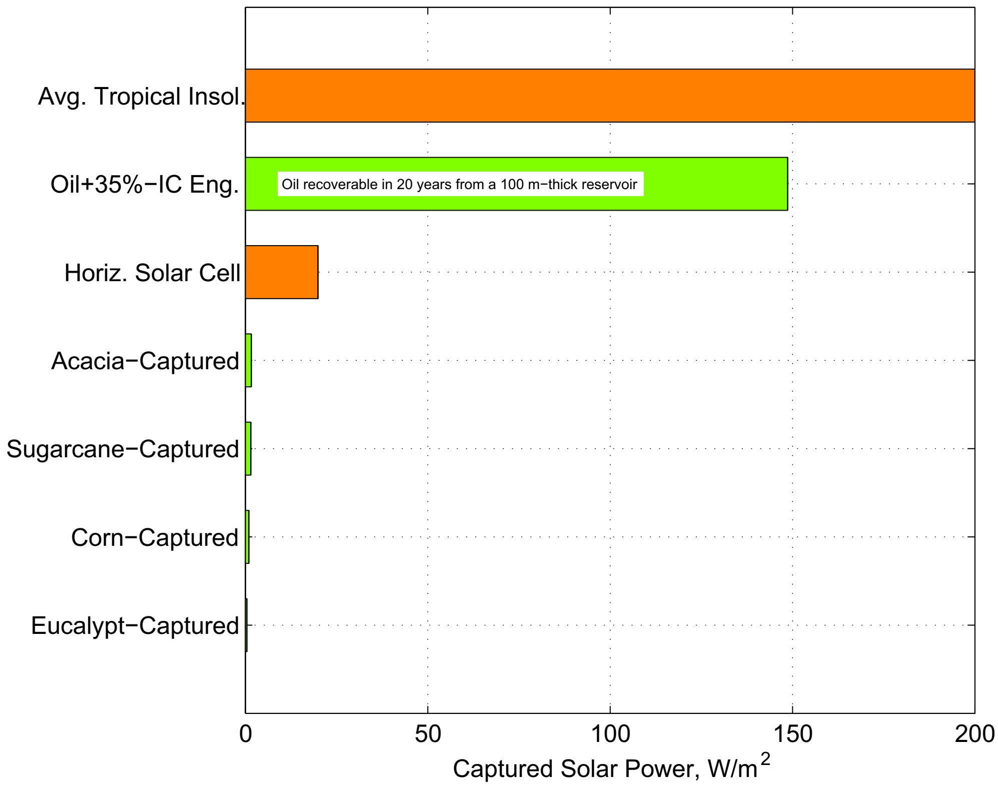

Figure 27: From the top: The time-averaged solar power across 1 m^2 of the horizontal surface in the tropics; solar power extracted from 1 m^2 of a good oil reservoir by producing it over 20 years and generating shaft work through a 35%-efficient internal combustion engine; solar power captured by a horizontal solar cell panel; *all* solar power captured by 1 m^2 of *A. mangium*, Brazilian sugarcane, U.S. corn, and *E. deglupta*. Note that the specific amounts of solar power captured by these plants are almost invisible at this scale.

Our exceptionally prolific stand of *Acacia mangium* trees, Figure 28, captures 1.39 W/m^2 as stemwood+bark, and 0.31 W/m^2 as slash, which is usually destroyed by burning. Twenty percent of the stemwood mass is lost in harvest, handling and processing. Again, we do not want to just burn the wood, but we convert its free energy to electricity and/or automotive fuels. For the three

[63]Of course free energy is also used to produce solar cells. The life-cycle analysis of solar cells will be performed later.

scenarios discussed in this paper, the amount of solar energy captured as electricity is 0.35 W/m^2; as the FT-diesel fuel + a 35%-efficient car (a Toyota Prius) + electricity, 0.29 W/m^2; and as ethanol, 0.11 W/m^2. The negative free energy cost of pellet manufacturing is 0.41 W/m^2 (as much as sugarcane-ethanol manufacturing), and the plantation maintenance consumes about 0.1 W/m^2 (a bit less than the 0.14 W/m^2 to run a sugarcane plantation). The net solar power captured by this planation is negative, unless the free-energy cost of pellet manufacturing is cut in half.

Table 29: Solar power captured, consumed, and output by by acacia and eucalypt trees

Quantity	Acacia	Eucalypt	Units
Stem capture	1.39	0.34	W/m^2
Slash[a] capture	0.31	0.19	W/m^2
Pellet capture	1.10	0.28	W/m^2
W_R in pellet production	0.41	0.10	W/m^2
W_R in acacia plantation	0.07	0.05	W/m^2
Electricity capture	0.35	0.09	W_e/m^2
FT+electricity capture	0.29	0.07	W/m^2
Ethanol capture	0.11	0.03	W/m^2

[a] This slash is no "trash" and should be left on the plantation to decompose

The not-so-prolific stand of Eucalyptus deglupta in Figure 29, more representative of average plantations, captures 0.34 W/m^2 as stemwood+bark, 0.19 W/m^2 as slash. When this energy is converted to electricity, only 0.09 W/m^2 is captured. The FT-diesel fuel/car/electricity option captures 0.07 W/m^2. Finally, the ethanol/car option captures 0.03 W/m^2. The negative free energy of pellet production is 0.10 W/m^2, and the eucalypt plantation maintenance consumes 0.05 W/m^2. It seems that the net solar power captured by the eucalypt planation is always negative, no matter what we do about wood pellets. For convenience, the acacia and eucalypt capture efficiencies are listed in **Table 29**.

The prolific average sugarcane plantation in Brazil in Figure 30, captures 0.59 W/m^2 as stem sugar, 0.57 W/m^2 as bagasse, and 0.42 W/m^2 as "trash," both attached and detached. Because of the unique ability of satisfying the huge CExC in cane crushing, fermentation, and ethanol distillation (0.41 W/m^2), as well as fresh bagasse + "trash" drying (0.27 W/m^2), with the chemical exergy of bagasse and the attached "trash," sugarcane is the only industrial energy plant that may be called "sustainable." The sugarcane ethanol has the positive $W_u - W_R$ balance when used

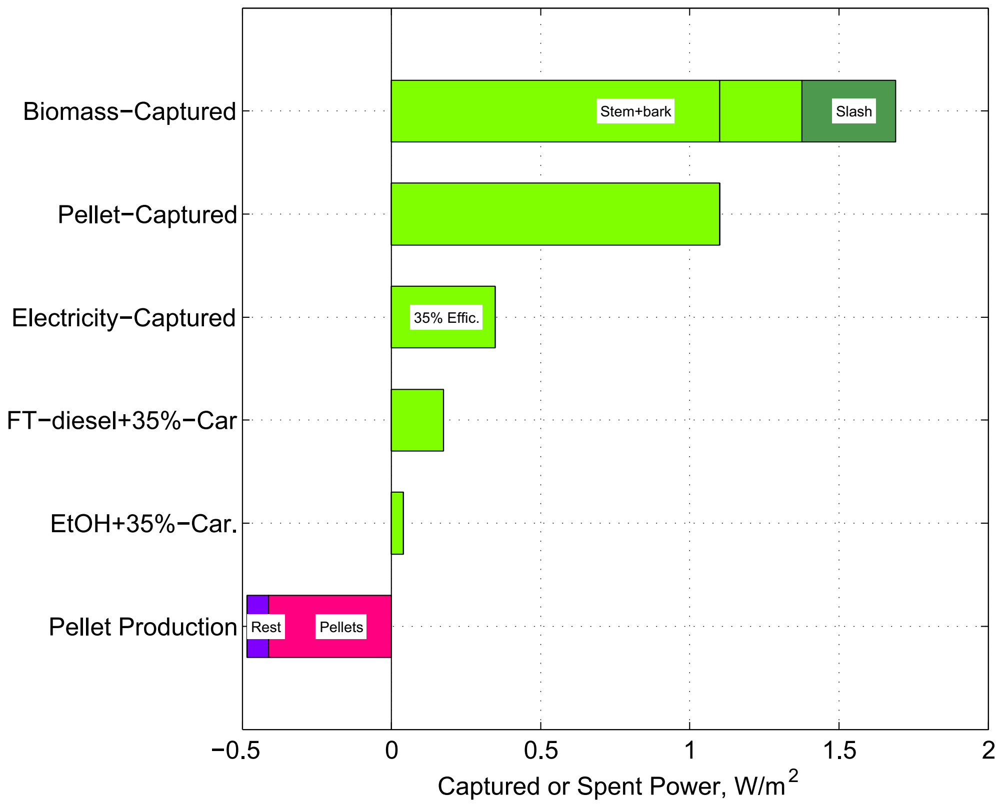

Figure 28: From the top: Solar power captured by 1 m^2 of the example *Acacia mangium* stand in Indonesia; as electricity generated from wood pellets in a 35%-efficient power plant; as FT-diesel fuel in a 35%-efficient car and electricity; and as ethanol from the pellets powering a 35% efficient car. The negative free energy costs of producing the acacia wood pellets and maintaining the plantation (Rest) are larger than our three options of generating useful shaft work from the captured solar energy.

with 60%-efficient fuel cells, a technology that still is in its infancy, and whose real efficiency of generating shaft work is 38%, see **Appendix A**. The remainder of the "trash" must be left in the soil to decompose and improve the soil's structure. The free energy used to produce cane (0.14 W/m^2) and clean the distillery wastewater BOD (0.06 W/m^2) exceeds the benefits from a 35-% and 20%-efficient internal combustion engines (0.14 and 0.08 W/m^2, respectively). For convenience all these numbers are listed in **Table 30**.

So the most important lesson from this paper is as follows.

Remark 27 The solar power captured by industrial tree and sugarcane plantations is *minuscule* when compared with an oil reservoir (for a limited time only) and with solar cells (for practically

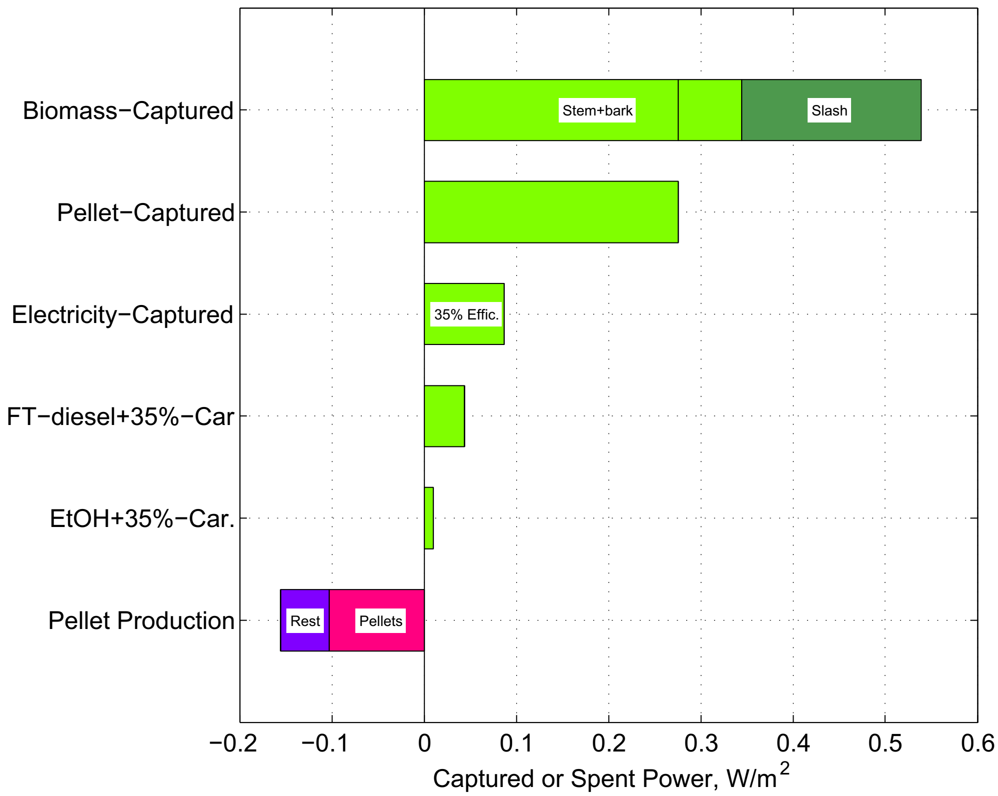

Figure 29: From the top: Solar power captured by 1 m^2 of the example *Eucalyptus deglupta* stand in Indonesia; as electricity generated from wood pellets; as FT-diesel fuel in a 35%-efficient car and electricity; and as ethanol from the pellets powering a 35%-efficient car. The negative free energy costs of producing the eucalypt wood pellets and maintaining the plantation (Rest) are larger than our three options of generating useful shaft work from the captured solar energy.

infinite time). To make things worse, what little solar energy is captured by the plants goes in tandem with a disproportionate environmental damage and a negative free energy balance. We conclude that government and industrial funding for "renewable energy[64]" sources will be spent much more wisely on the development of large-throughput, efficient technologies of manufacturing solar cells (possibly poly-crystalline silicon-based cells). □

[64]We want to be very clear: solar cells, wind turbines, and biomass-for-energy plantations can *never* replace even a small fraction of the highly reliable, 24-hours-a-day, 365-days-a-year, nuclear, fossil, and hydroelectric power stations. Claims to the contrary are popular, but irresponsible. To the extent that we live in a hydrocarbon-limited world, generate too much CO_2, and major hydropower opportunities have been exhausted worldwide, new nuclear power stations must be considered. For example, environmentalists are fighting a 13-stage dam on the Nu River, the *last* untamed large river in Asia, which flows through a remote, pristine region in western China (*Chinese Project Pits Environmentalists Against Development Plans*, Jim Yardley, The New York Times, Jan. 3, 2005).

Table 30: Solar power captured, consumed, and output by sugarcane

Stem sugar capture	0.59	W/m^2
Dry bagasse capture	0.57	W/m^2
Dry attached "trash" capture	0.15	W/m^2
Dry mill "trash" capture	0.27	W/m^2
Ethanol capture	0.41	W/m^2
Extra electricity capture	7.7e-005	W_e/m^2
CExC in cane production	0.14	W/m^2
CExC in ethanol production	0.41	W/m^2
CExC in bagasse and trash drying	0.30	W/m^2
CExC in BOD removal	0.06	W/m^2
20%-efficient IC engine output	0.08	W/m^2
35%-efficient IC engine output	0.14	W/m^2
60%-efficient fuel cell output[b]	0.25	W/m^2

[a] The detached "trash" > 1/2 of the total must be left in the soil to decompose

[b] In Appendix A we show that the 60%-efficient fuel cells do not exist, and their real efficiency is just above that of a 35%-efficient internal combustion engine, or a hybrid-diesel car

14 Summary & Conclusions

Gigantic tree plantations could be designed to replace, say, 10% of the fossil energy used globally every year for 40-80 years. About 500 million hectares (a little more that 1/2 of the United States area) of new plantations would be needed. These plantations would be implemented in the tropics in good climate with plentiful water supply, apparently good soil, and easy access, i.e., along the ever-receding edges of natural tropical forests and along major rivers. Talk about developing industrial tree plantations for profit in degraded and sterile environments does not seem practical or convincing. Therefore, the new biomass-for-energy plantations will impact disproportionately many of the most important ecosystems on land and in shallow sea water. Will the global damage of tropical forest and clean water sources be beneficial in terms of saving other earth resources? The answer based on the work presented in this paper is a decisive *no*. In order to be profitable, a biomass-for-energy plantation must achieve a consistently high yield of dry wood mass. Trees that grow fast (e.g., *Acacia mangium*) use more water and nutrients than the slower-growing species. Consequently, these fast-growing trees damage soil and their wood is excessively wet after harvest.

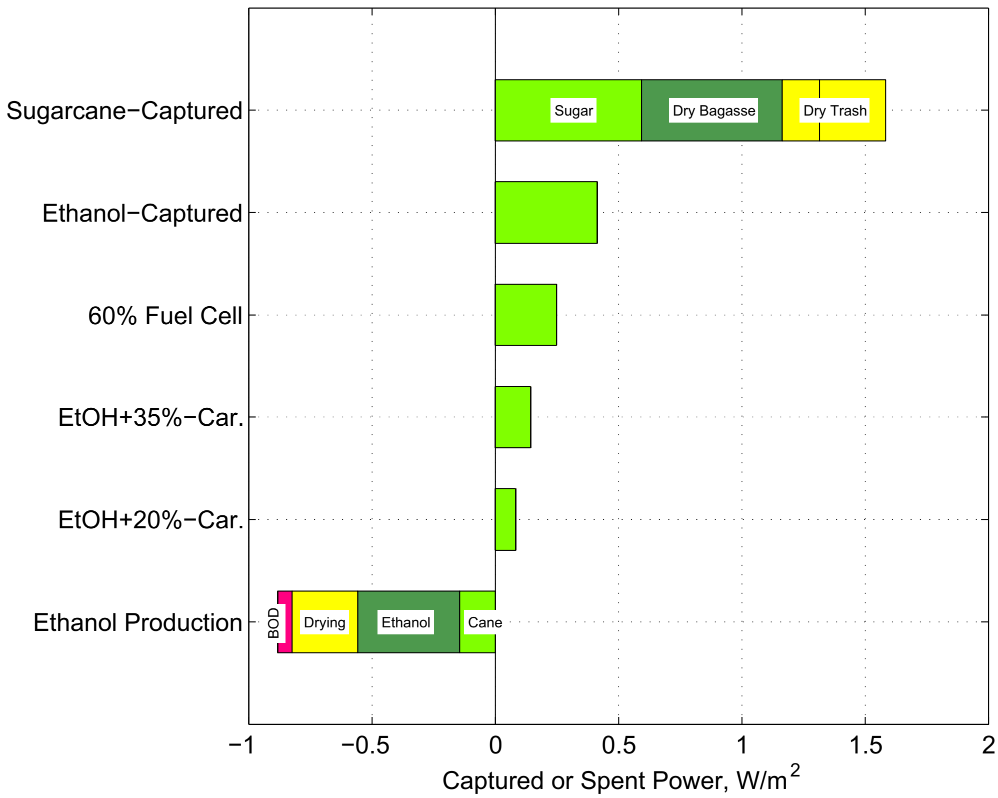

Figure 30: From the top: Solar power captured by 1 m^2 of the average sugarcane plantation in Brazil: as the chemical exergies of sugar, bagasse, and "trash"; as the chemical exergy of ethanol; as electricity from a non-existent (Appendix A) 60%-efficient fuel cell; as shaft work from a 35%-; and 25%-efficient internal combustion engine. The negative free energy costs of producing the sugarcane (Cane) and cleaning up the distillery wastewater (BOD) are larger than both internal combustion engine options, but smaller than the fuel cell option. The negative costs of ethanol distillation (Ethanol), and bagasse + "trash" drying (Drying), are paid with the chemical exergies of bagasse and attached "trash" (the left part of the rightmost bar segment at the top).

We find that sustainable generation of electricity and/or Fischer-Tropsch (FT) diesel fuel from wood pellets produced in remote tropical plantations is impossible, unless sun-drying of raw wood and improved soil management are widely implemented. In our opinion, the scale and rate of wood processing necessary to replace a substantial fraction of automotive fuel and electricity demand on the earth makes the widespread sun-drying of wood impractical or impossible.

The gigantic tropical sugarcane plantations on mostly agricultural land suffer from the similar weaknesses. Their shaft work output from burning cane-ethanol in the efficient internal combustion engines is insufficient to cover the cumulative free energy consumption in producing this ethanol. The only option that gives a marginal benefit is the conversion of the sugarcane ethanol to hydrogen used in 60%-efficient fuel cells to produce electricity (Deluga et al., 2004), but such cells do not exist, see **Appendix A**.

In general

1. Biomass-for-energy plantations are environmentally costly and inefficient engineered systems, and their long-term high yields are uncertain and questionable.

2. Locally-produced electricity from biomass seems to be the best option that could make a prolific acacia and sugarcane plantation "sustainable," if their immediate environments were not degraded by the toxic ash and air emissions.

3. The Fischer-Tropsch automotive fuel from biomass is not as good an option, and the plantations producing it are not sustainable.

4. Ethanol from tree biomass seems to be an especially poor choice.

5. The anhydrous ethanol automotive fuel from sugarcane stems is a better option, yet it is unsustainable too, even when burned in efficient hybrid cars.

6. Plant residues, called "trash" by those who do not understand their vital importance to the long-term survival of plantation soils, should be kept on the plantations and allowed to decompose.

7. Plant "trash" *cannot* be a significant source of biofuels, and it is *not* independent of parent ecosystems.

In particular, for the tree plantations, we reiterate the following:

1. The most desirable product of dedicated industrial tree-for-energy plantations may be wood pellets produced in very efficient central facilities close to the plantations. Production of these pellets requires 33-41% of the high heating value of the wood.

2. Excellent site characterization by Mackensen et al. (1999; 2000; 2003), enabled us to use two average stands of acacias and eucalypts in a freshly established, prolific plantation in Indonesia as the examples of generic industrial tree plantations in the tropics.

3. Our example acacia and eucalypt stands were the first tree rotations, and received small fertilizer treatments of ∼100 kg NPK/ha. The plantation trees were mostly depleting the initial store of nutrients in the plantation soil, i.e., the environmental low entropy (Georgescu-Roegen, 1971; Patzek, 2004).

4. We have calculated the minimum restoration work of nonrenewable natural resources depleted by the example tree stands, and compared it with the maximum useful work obtained from the plantation wood pellets as (a) electricity generated in an efficient power station, (b) the FT diesel fuel burned in a 35%-efficient car plus cogeneration electricity, and (c) wood-ethanol burned in a similarly efficient car.

5. If this useful work is larger than the minimum restoration work, the example stands are "sustainable" under our assumptions, otherwise they are not.

6. To calculate the long-term restoration work, we have assumed fertilizer treatments equal to the amounts of soil nutrients (N, P, K, Ca, and Mg) depleted during a single tree rotation and site preparation that follows each harvest.

7. We have assumed that fertilizer application efficiency is 100%, i.e., 30-90% of the various nutrients are provided by natural (management-independent) fluxes.

8. We have neglected the cumulative exergy consumption in sea transport of wood pellets and their storage costs.

9. Under the conservative assumptions in this paper, it is possible to show that even an exceptionally prolific stand of *Acacia mangium* (22 odt/ha-yr), see Figure 5, is not "sustainable" with respect to Options (a) and (b) above, unless the cumulative exergy consumption in wood drying and chipping is cut in half. In view of Item 1 above this cannot be done, unless sun-drying of raw wood is employed, which in turn may be impossible when wood is processed at a very high rate.

10. Conversion of acacia wood pellets to ethanol that powers the same efficient car, Option (c), is never sustainable.

11. The example stand of *Eucalyptus deglupta* is not "sustainable" with respect to Options (a)-(c), with or without sun-drying of wood, because its net productivity is only ∼5 odt/ha-yr, close to the average productivity of tropical forests, see Figure 5.

12. After several tree rotations, the progressively damaged soil may not support the consistently high biomass yields from the two tree stands.

13. In the long run, therefore, increased fertilizer, herbicide, and insecticide treatments are inevitable, and their inherent high exergy costs and negative environmental impacts will increase the degree of unsustainability of these two stands.

14. Plantation management and average biomass yield are highly site-specific, and it is difficult to make sweeping generalizations from an analysis of the two example tree stands.

For the sugarcane plantations we conclude that

1. An average sugarcane plantation in Brazil is as efficient in sequestering solar energy as the prolific acacia plantation (all acacia slash must be left on the plantation to decompose, but only some sugarcane slash is left), and its maintenance costs a little more free energy than that of the acacias.

2. Ethanol production from sugarcane is driven by burning the cane leftovers, bagasse and parts of attached cane tops, and converting their heat of combustion to steam, electricity and shaft work. Sugarcane stem crushing, juice extraction and fermentation, and ethanol distillation consume almost exactly the same free energy as wood pellets from the acacia stems and bark.

3. We have calculated the free energy consumed to clean the sugarcane distillery wastewater; it is non-negligible, and requires extra fossil fuel and grid electricity.

4. Despite efficient sequestration of solar energy, the prolific sugarcane-for-ethanol plantation in Brazil is not sustainable according to our strict criteria, unless its ethanol powers 60%-efficient fuel cells. The problem is that such cells do not exist, see **Appendix A**.

5. The sugarcane slash and attached tops sequester a significant amount of solar energy, and deplete significant amounts of nutrients from the soil. The attached tops and leaves are burned in the distillery. The detached leaves and slash should be left to decompose and improve structure of the plantation soil.

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A Efficiency of a Fuel Cell System

In their Science paper, Deluga et al. (2004) claim the following:

> ...Further, combustion used for transportation has ∼20% efficiency as compared with up to 60% efficiency for a fuel cell...The efficiency of these processes for a fuel cell suggests that it may be possible to capture >50% of the energy from photosynthesis as electricity in an economical chemical process that can be operated at large or small scales. (p. 996).

Following Deluga et al., Patzek (2004) used 60% as an estimate of the overall efficiency of a hydrogen fuel-cell car. Even this optimistic estimate could not make the industrial corn-ethanol cycle sustainable to within a factor of two. Not so with sugarcane ethanol. It might be called somewhat sustainable if the path from the ethanol to electric shaft work were 60% efficient.

First, we assume that the cane ethanol-water mixture used to generate hydrogen is analytically pure C_2H_5OH and H_2O. Thus, there are no other contaminants to poison[65] the delicate catalyst that will convert this EtOH-H_2O mixture to hydrogen, carbon dioxide and carbon monoxide (Deluga et al., 2004). The catalyst is made of a rare-earth metal, rhodium[66], and a Lanthanoid, cerium[67]. The catalytic reaction is claimed to have 100% selectivity and >95% conversion efficiency. We assume the conversion efficiency $\eta_1 = 0.96$.

After Bossel (Bossel, 2003), we summarize efficiency of a Proton Exchange Membrane (PEM) fuel cell as follows. In fuel cells, gaseous hydrogen is combined with oxygen to water. This process is the reversal of the electrolysis of liquid water and should provide an open circuit voltage of 1.23 V (Volts) per cell. Because of polarization losses at the electrode interfaces the maximum voltage observed for PEM fuel cells is between 0.95 and 1.0 V. Under operating conditions the voltage is further reduced by ohmic resistance within the cell. A common fuel cell design voltage is 0.7 V. The mean cell voltage of 0.75 V may be representative for standard driving cycles. Consequently, the average energy released by reaction of a single hydrogen molecule is equivalent to the product of the charge current of two electrons and the actual voltage of only 0.75 V instead of the 1.48 V

[65] The commercial ethanol fuel is *very* dirty by chemical catalysis standards, but we will ignore this unpleasantness.

[66] Rhodium is a precious metal whose price is about US$30 000/kg, 3×more expensive than gold, http://-www.kitco.com/charts/rhodium.html.

[67] The nanoparticles of cerium dioxide are called *ceria*, and cost $250/kg, http://www.advancedmaterials.us/58N-0801.htm

corresponding to the hydrogen high heating value[68]. Therefore, in automotive applications, PEM fuel cells may reach mean voltage efficiencies of

$$\eta_2 = \frac{0.75 \text{ V}}{1.48 \text{ V}} = 0.50 \tag{10}$$

However, there are more losses to be considered. The fuel cell systems consume part of the generated electricity. Typically, automotive PEM fuel cells consume 10% or more of the rated stack power output to provide power to pumps, blowers, heaters, controllers, etc. At low power demand the fuel cell efficiency is improved, while the relative parasitic losses increase. The small-load advantages are lost by increasing parasitic losses. Let us assume optimistically that for all driving conditions the net power output of an automotive PEM fuel cell system is about $\eta_3 = 0.9$ of the power output of the fuel cell stack.

Depending on the chosen drive train technology, the DC power is converted to frequency-modulated AC or to voltage-adjusted DC, before motors can provide motion for the wheels. Energy is always lost in the electric system between fuel cell and wheels. The overall electrical efficiency of the electric drive train can hardly be better than $\eta_4 = 0.9$.

By multiplying the efficiency estimates, one obtains for the maximum possible tank-to-wheel efficiency of a hydrogen fuel cell vehicle

$$\eta = \eta_1\eta_2\eta_3\eta_4 = 0.96 \times 0.50 \times 0.90 \times 0.90 = 0.38, \tag{11}$$

or 38%. This optimistic estimate agrees exactly with another analysis (31-39%) (Fleischer and Ørtel, 2003), and is significantly less than the 60% used by the promoters of a hydrogen economy and hydrogen fuel cell vehicles.

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[68] According to Faraday's Law, the standard enthalpy of combustion of hydrogen, $\Delta H_f^0 = -285.9$ kJ/mol, can also be expressed as an electrochemical potential ("standard potential") $U^0 = -\Delta H_f^0 / n_e F = 1.48$ V with $n_e = 2$ being the number of electrons participating in the conversion and $F = 96485$ Coulomb/mol the Faraday constant.

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