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Limits to the potential of bio-fuels and bio-sequestration of carbon

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HIGHLIGHTS

- Global energy consumption is ~0.06% of solar; 43% of net primary production.
- 11 nations studied fall into 3 groups: consumption/solar = 1–10%; ~0.1%; 0.1–0.01%.
- % of energy captured in biomass is lower by ~3 orders of magnitude.
- Crops and natural ecosystems capture 0.1–0.3% and sugar 1% of solar energy.
- Significant bio-energy/carbon sequestration via biomass is unrealistic.

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ABSTRACT

This document examines bio-physical limits of bio-fuels and bio-sequestration of carbon by examining available solar radiation and observed efficiencies with which natural ecosystems and agricultural systems convert that energy to biomass. It compares these energy/carbon exchanges with national levels of energy use and carbon emissions for Australia, Brazil, China, Japan, Republic of Korea, New Zealand, Papua New Guinea, Singapore, Sweden, United Kingdom and United States.

Globally primary energy consumption (related carbon emissions) is currently equivalent to ~0.06% of the incident solar energy, and 43% of the energy (carbon) captured by photosynthesis.

The nations fall into three categories. Those with primary energy consumption that is: 1–10% (Japan, Korea and Singapore); ~0.1% (China, UK and the US) and; 0.1–0.01% (Australia, Brazil, Papua New Guinea, New Zealand and Sweden) of incident solar radiation. The percentage of energy captured in biomass follows this pattern, but generally lower by ~3 orders of magnitude.

The energy content of traded wheat, corn and rice represents conversion efficiencies of solar radiation of 0.08–0.17% and for sugar close to 1%, ignoring energy use in production and conversion of biomass to fuels.

The study implies that bio-fuels or bio-sequestration can only be a small part of an inclusive portfolio of actions towards a low carbon future and minimised net emissions of carbon to the atmosphere.

1. Introduction

In recent years concerns about the security of supply and cost of domestic and imported oil, and the desire to move towards a "carbon constrained" "low carbon" world to minimise further global climate change, have raised interest in bio-fuels[1] as an alternative fuel to conventional fuels (fossil), coal, gas and oil. This has occurred in many countries. These factors have themselves fostered the emergence of entrepreneurial development of bio-fuel companies and government interventions to support them.

Further, in some jurisdictions governments have clearly embedded strategies to encourage land-use practices to be part of a multi-pronged approach to reducing net greenhouse-gas emissions. For example, the Australian Government's policy on carbon farming[2] is a complimentary action to the introduction of a price on carbon and investments in energy efficiency and renewable energy sources.[3]

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[1] Bio-fuels are composed of biological materials that contain the energy from solar radiation, chemically trapped through the photosynthetic process as carbohydrate or oil. Until the mid-eighteenth century such fuels were primarily wood, then in fossilised form from coal and more recently oil and gas. The so-called fossil fuels have delivered the amenity that energy supplies to humans.

[2] http://www.cleanenergyfuture.gov.au/wp-content/uploads/2011/07/securing-a-clean-energy-future-summary.pdf.

[3] Indeed the emphasis on bio-sequestration of carbon into the landscape is even stronger in the Australian national Liberal Party's policy of direct action on the

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These two activities are strongly related as the photosynthetic process, in capturing carbon, captures a relatively fixed amount of energy, viz., between 16 and 18 GJ of solar energy is captured for every tonne of carbon, depending on the chemical nature of the final biomass.

Such developments have been supported by some agricultural communities and their elected representatives, understandably anxious to expand their options and capitalise on the wider community efforts to reduce greenhouse-gas emissions. Industry bodies are also expectedly, promoting the virtues and opportunities available through involvement in bio-fuel production or carbon sequestration. Academic assessments of the options have sent often conflicting messages about what might be achieved, from the very optimistic (e.g. Read, 2007) to the more cautious (e.g. Kheshgi et al., 2000; Marland and Obersteiner, 2008; Walker, 2009; Haberl et al., 2012; Smith et al., 2012) and pessimistic (Kiefer, 2013a, 2013b).

The satisfactory assessment of the potential and desirability of bio-fuels and bio-sequestration of carbon as part of a national policy portfolio requires a comprehensive analysis which cannot be attempted here. Rather we focus on the single question: "*from a biophysical perspective can the use of bio-fuels or bio-sequestration of carbon be a significant component in energy futures and greenhouse-gas emissions reduction*"? We will consider this question primarily in the context of Australia, but in doing so examine the scope for Brazil, China, Japan, the Republic of Korea, New Zealand, Papua New Guinea, Singapore, Sweden, the United Kingdom and the United States. These countries were selected to represent a range of national energy usages and geographic areas. The focus is specifically on whether the aspirations to use biomass as an energy source or method for offsetting emission from fossil fuel combustion are justified in terms of biophysical realities. We will also ask why there appears to be a hiatus between the investment and policy development in these areas and what might be described as underpinning physical science.

We start in Section 2 with an assessment of the annual solar radiation incident on each nation comparing that in Section 3 with the respective national primary energy consumption rates. Section 4 briefly discusses the efficiencies of the photosynthetic process and in Section 5 estimates are made of the net primary production of each nation again comparing these with the respective energy consumption rates. Section 6 explores the efficiency of key crop species in capturing solar energy and carbon. Section 7 discusses the implications of these analyses, and briefly discusses why it might be that policy development and commitments to bio-fuels and bio-sequestration has progressed so far despite the implications of these calculations and in light of other considerations.

2. Setting bounds on available solar energy

The annually averaged incident solar radiation flux was estimated for each of the several selected nations (Table 1). The 1° by 1° gridded Global Solar Radiation climatology (July 1983–June 2005) of NASA (http://eosweb.larc.nasa.gov/sse/; last viewed on January 15, 2013) was used. For each nation the grid cells for which the corner reference latitude/longitude fell within the geographic limits of country were identified. The average annual flux density (kWh m^{-2} day^{-1}) for each cell was converted to an annual flux (J yr^{-1}) after estimating the areal extent of each grid box (α_i). The combined flux for all cells falling on the country was obtained by summing the value for the individual cells (I_i). The estimate was then corrected by the ratio of the geographical area represented by all of the relevant one-degree cells (α_s) to the actual area of the nation (α_g),

$$S_i = (\Sigma\Sigma\alpha_i I_i)\alpha_g/\alpha_s \quad (1)$$

In the case of Singapore, no cell reference points fell within the national borders, so that the two most adjacent cells were used in the same way as above.

An estimate of the intercepted solar radiation by the global land surface was made in the same way, but by sampling only every 5° of latitude and longitude, and correcting for the global land area (less the area of Antarctica and Greenland). The annual incident energy for each nation and globally is compared in Table 1.

In general the variation within and between countries reflects the expected decrease of insolation at higher latitudes modified to various degrees by local cloudiness. For example the wide range of annual average incident solar radiation for each latitude band (1°) in Australia reflects the latitudinal extent of the country and the existence of significant regions of low cloudiness. Table 1 also shows the average solar radiation flux density weighted by the area of each respective country.

Table 1
The estimated incident solar radiation falling annually on a number of selected nations and the world land surface (excluding Greenland and Antarctica) based on a 1° by 1° radiation climatology from NASA. The area-weighted national average and range of latitudinal average insolation for each country (and the world) is also shown.

Country	Area[a] Mkm^2	Estimated incident solar radiation			
		Total J yr^{-1}	Weighted national average (MJ m^{-2} day^{-1})	Range of latitudinal average (MJ m^{-2} day^{-1})	
				Low	High
Australia	7.692	5.72×10^{22}	20.4	12.7	23.9
Brazil	8.515	5.84×10^{22}	18.8	15.6	19.1
China	9.597	5.38×10^{22}	15.4	12.3	16.7
Japan	0.377	1.79×10^{21}	13.0	11.9	13.7
R Korea	0.100	5.21×10^{20}	14.3	14.3	14.3
New Guinea	0.453	2.97×10^{21}	17.6	17.1	18.4
New Zealand	0.268	1.34×10^{21}	13.6	11.5	16.0
Singapore	0.001	4.40×10^{18}	17.0	16.3	17.7
Sweden	0.450	1.49×10^{21}	9.1	7.9	10.3
UK	0.243	8.39×10^{20}	9.5	8.6	9.8
US	9.827	4.80×10^{22}	14.4	8.7	17.3
World (5° resolution)	132.8	8.09×10^{23}	16.7	6.8	21.1

[a] National geographic area: http://en.wikipedia.org/wiki/List_of_countries_and_dependencies_by_area.

3. Comparison of levels of solar radiation interception with primary energy consumption

A comparison was made of the annual incident solar radiation and the respective energy consumption rates for each country (Table 2). The primary energy consumption data were taken for the year 2009, and of course, these numbers would vary from year to year, related to the level of economic performance and the general growth in affluence and energy demand. But the comparison serves its purpose, showing clearly the relativity of current energy demand and the incident solar energy for each country. The countries fall roughly into three groups:

Group 1: Includes Japan, Korea and Singapore where the ratio of energy consumption to incident solar radiation is of order

(*footnote continued*)
environment and climate change where the claim is that this is "the single largest opportunity for CO_2 emissions reduction in Australia".