CLIMATE CHANGE AND FOOD PRODUCTION

by

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Reprinted from

ENERGY &
ENVIRONMENT

VOLUME 20 No. 7 2009

MULTI-SCIENCE PUBLISHING CO. LTD.
5 Wates Way, Brentwood, Essex CM15 9TB, United Kingdom

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ABSTRACT

The availability of atmospheric carbon dioxide is the *sine qua non* for all plant growth and thence for all marine and terrestrial life forms. The purpose of this paper is to show that proposed reductions in anthropogenic emissions of carbon dioxide (CO_2) to below the level of observed annual incremental biospheric absorption of those emissions would reduce the growth of the basic feedstock of all life forms. Agronomists have for long known and demonstrated in controlled experiments both in greenhouses and in field studies the dramatic impact of increases in its level on crop yields. These studies have all been local. The regression analysis here of historic data on global food production shows it may well be more dependent on *increases* in the availability of atmospheric carbon dioxide (henceforth written as [CO_2]) than on changes in fertilizer consumption and global mean temperature (GMT). This implies that if the drastic reductions in *total* anthropogenic emissions of CO_2 to be sought at Copenhagen (December 2009) are adopted and applied, they will, even if they aim at only a 60% reduction on the 2000 global level by 2050, bring emissions to below the incremental volume of their biospheric absorption. That could seriously imperil growth of global food production. We show how in its role as a fertilizer that raises global Net Primary Productivity (NPP), increases in [CO_2] have a natural *negative* feedback mechanism that offsets a large proportion of growing emissions: more [CO_2] causes more plant growth, but more plant growth takes up more CO_2 thus limiting the further rise. This contrasts with the unproven *positive* feedback assumed in *all* models deployed by the IPCC whereby, allegedly, rising [CO_2] will result in falling biospheric absorption and ever larger increases in [CO_2]. We show there is no sign in the observations since 1958 of "saturation" of the capacity of the planet to continue absorbing more than half of all anthropogenic emissions of CO_2, so there is no evidence for the IPCC's positive feedback. Biospheric absorption of increases in anthropogenic CO_2 emissions would only have to increase from the average 57% of all anthropogenic emissions from 1958 to 2008 to 60% to achieve the likely Copenhagen 60% emissions reduction target. The rapid growth of absorption of total anthropogenic emissions to over 6% p.a. between 1997 and 2006 relative to total emissions growth at 2.6% p.a. over that period (Le Quéré 2008) confirms this manner of attaining the Copenhagen target is easily attainable—and helps to explain the growth of food production at rates in excess of global population growth. It also limited the growth rate of aggregate [CO_2] between

1958 and 2008 to only 0.41% p.a. Our results show that with warming in the absence of growing carbon fertilization, agricultural production could be less by more than 10% by 2080 than at present (2007:Table 5.8). That means starvation for most of a global population likely then to be at least 50% larger than now.

Keywords: Carbon dioxide, climate change, food production, feedbacks, biospheres.

1. BIOSPHERIC ABSORPTION OF ANTHROPOGENIC EMISSIONS

A major gap in much of the work of the Intergovernmental Panel on Climate Change (IPCC)—and of leading economists working in the field of climate change like Stern (2007) and Garnaut (2008)—is their lack of emphasis on the evident continuing capacity of the planet's oceans and biosphere to absorb more than half of the increasing anthropogenic emissions of CO_2. This is associated with minimal assessment of the impact of rising emissions of CO_2 on net primary productivity (NPP) and thereby on growth of food production arising from enhanced photosynthesis in the world's biosphere, both oceanic and terrestrial. The result is a mistaken stress by the IPCC (Solomon *et al.* 2007), and subsequent papers like Solomon *et al.* (2009), Meinshausen *et al.* (2009), and Steffen *et al.* (2009), on the *gross* increase in anthropogenic emissions of CO_2 without taking into account the annual increments in photosynthetic uplifts of anthropogenic CO_2 emissions, as in this *non sequitur* with its omission of absorption rates: "the gap between current emission rates and those required to stabilize atmospheric CO_2 concentration at various levels (450, 650, and 1000 ppm) is growing rapidly" (Steffen *et al.* 2009: caption to their Fig.4).

The explanation for this imbalance lies in the parameterization of the CO_2 absorption effect in all models used by the IPCC and those later papers, most of which use the Michaelis-Menten (M-M) or similar functions derived for assessing the impact of elevated $[CO_2]$ on plant growth (Wigley 1993:421). The M-M function sets up a hyperbolic

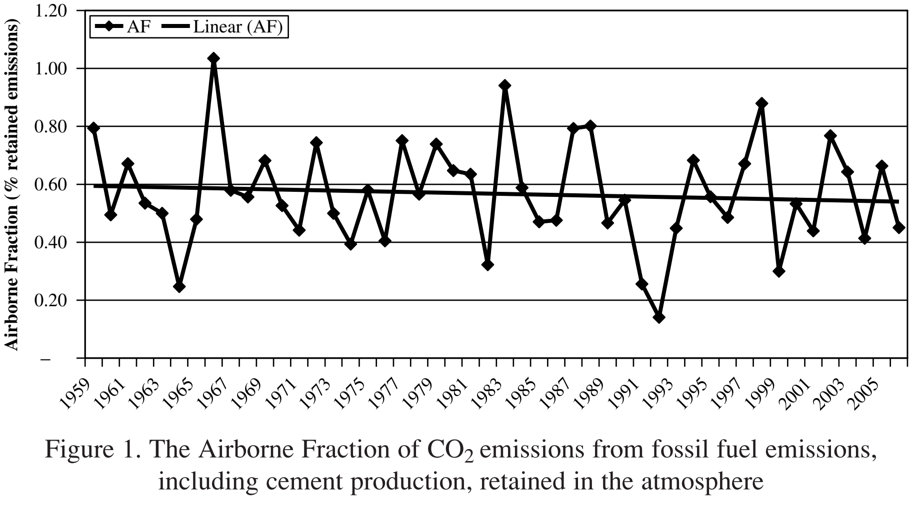

Figure 1. The Airborne Fraction of CO_2 emissions from fossil fuel emissions, including cement production, retained in the atmosphere

relationship whereby rising [CO_2] has an initial beneficial impact, *cet. par.,* that tapers off rapidly and hits a ceiling whereby further rises in [CO_2] have zero impact on yield, *cet.par*. This effect was first formalized by Farquhar *et al.* (1980), but as later papers (e.g. Long 1991, Lloyd & Farquhar 1996, and Norby & Luo 2004) have shown, it is not generally applicable once the *cet.par.* assumption is dropped. The use of the Michaelis-Menten function in models like the MAGICC suite developed by Wigley and relied on by the IPCC (Randall & Wood 2007) produces seriously exaggerated projections of [CO_2] through to 2100 for any prescribed level of anthropogenic CO_2 emissions, because of its built-in positive feedback: more CO_2 emissions → declining further absorptions via photosynthesis to NPP → ever larger increases in temperature for any given increase in emissions → further declines in uplifts via NPP.[1] The outcome is the inflated projections of [CO_2] through to 2100 for each of the SRES emission projections. If instead of the Michaelis-Menten function, the MAGICC models simply used the observed relationship since 1958 of $a = 0.57e$ (where a is absorptions by the biospheres, and e is anthropogenic emissions), none of the IPCC's projections of [CO_2] to 2100 would be realized, as those are all dependent on the assumed positive feedbacks. This means that emission reductions do not have to be increased by up to 300 GtC over this century relative to the case where these assumed positive feedbacks do not apply (Solomon *et al.* 2007:791).

This inapplicable and unverified Michaelis-Menten parameter is what leads to the well-meaning but misguided policy prescriptions for reducing anthropogenic emissions by as much as 80–90% below the 1990 or 2000 levels by 2050, as a means of minimizing the global warming believed to result from growing [CO_2]. Such targets if attained would reduce the level of emissions to less than 2 GtC p.a., well below the observed level of their current absorption by the oceans and the global oceanic and terrestrial biospheres, at over 6 GtC in 2007–2008. Solomon *et al.* (2007) completely ignore the *negative* feedback from annual increases in [CO_2] which by raising the partial pressure of CO_2, boost oceanic and biospheric absorption of CO_2, and thereby increase productivity of the world's agriculture, forestry, and fisheries (e.g. Lloyd & Farquhar 1996, 2008, Norby & Luo, 2004).

The standard justification for downplaying the role of global biospheric absorption of CO_2 emissions is that "these natural CO_2 sinks are vulnerable to climate and land use change: they are highly likely to weaken in the future because of increasing ocean acidification, ocean circulation change, and water, temperature, and nutrient constraints on land CO_2 uptake" (Raupach *et al.,* 2009). Garnaut (2008) and Richardson *et al.* (2009) rely on a claimed increase in the airborne fraction (AF) of CO_2

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[1] For example, "there is unanimous agreement among the coupled-climate carbon cycle models driven by emission scenarios. . .that future climate change would reduce the efficiency of the Earth system. . . to absorb anthropogenic CO_2. . .For the A2 emission scenario, this positive feedback leads to additional [CO_2] varying between 20 and 200 ppm. . .by 2100. . .The higher the stabilisation scenario, the larger the climate change, the larger the impact on the carbon cycle, and hence the larger the required emission reduction; . . .the reduction in land carbon uptake. . .is driven by a combination of reduced NPP and increased soil respiration of CO_2 under a warmer climate" (Solomon *et. al..,* 2007:750, 790, for a contrary view see Wittwer 1992, 1998). As ever in the IPCC genre, model outputs are treated as evidence even though they cannot offer more than is implied by their parameters, in this case false application of Michaelis-Menten: e.g. in Randall *et al.* 2007:605: "For example, Friedlingstein *et al.* (2006) found that in all models examined, the sink decreases in the future as the climate warms", hardly surprising given the prescribed M-M parameter but not confirmed by our regression results (Table 3).

Table 1. Atmospheric Carbon: Stocks and Flows

	Opening GtC	Emissions Inflow	Land use Change	Total Emissions	Uptakes Uptakes	Closing GtC	Mauna Loa CO_2 ppmv	Airborne Proportion (%)
1959	668.5	2.5	1.3	3.8	1.8	670.4	315.6	51.7
1960	670.4	2.6	1.3	3.9	2.6	671.7	316.2	32.9
1961	671.7	2.6	1.4	4.0	2.3	673.4	317.0	43.5
1962	673.4	2.7	1.4	4.1	2.7	674.9	317.7	35.0
1963	674.9	2.8	1.4	4.3	2.9	676.3	318.4	33.2
1964	676.3	3.0	1.5	4.5	3.7	677.1	318.7	16.6
1665	677.1	3.1	1.5	4.6	3.1	678.6	319.4	32.5
1966	678.6	3.3	1.5	4.8	1.4	682.0	321.0	70.8
1967	682.0	3.4	1.5	4.9	3.0	684.0	322.0	40.0
1968	684.0	3.6	1.5	5.1	3.1	686.0	322.9	38.9
1969	686.0	3.8	1.6	5.4	2.8	688.5	324.1	48.4
1970	688.5	4.1	1.5	5.6	3.5	690.7	325.1	38.2
1971	690.7	4.2	1.4	5.7	3.8	692.6	326.0	33.1
1972	692.6	4.4	1.4	5.8	2.5	695.8	327.6	56.6
1973	695.8	4.6	1.4	6.1	3.7	698.1	328.6	38.3
1974	698.1	4.6	1.4	6.1	4.2	700.0	329.5	30.1
1975	700.0	4.6	1.4	6.0	3.4	702.7	330.8	44.3
1976	702.7	4.9	1.6	6.5	4.5	704.6	331.7	30.6
1977	704.6	5.0	1.6	6.6	2.9	708.4	333.5	56.9
1978	708.4	5.1	1.6	6.7	3.8	711.3	334.8	43.0
1979	711.3	5.4	1.6	7.0	3.0	715.3	336.7	56.8
1980	715.3	5.3	1.6	7.0	3.5	718.8	338.3	49.8
1981	718.8	5.2	1.7	6.9	3.6	722.0	339.9	47.7
1982	722.0	5.1	1.9	7.1	5.4	723.7	340.7	23.4
1983	723.7	5.1	2.0	7.1	2.3	728.5	342.9	67.8
1984	728.5	5.3	2.0	7.3	4.2	731.6	344.4	42.5
1985	731.6	5.5	2.1	7.5	5.0	734.2	345.6	34.1
1986	734.2	5.6	2.1	7.7	5.1	736.9	346.9	34.6
1987	736.9	5.8	2.1	7.9	3.3	741.5	349.0	57.9
1988	741.5	6.0	2.2	8.1	3.3	746.3	351.3	59.0
1989	746.3	6.1	2.2	8.3	5.4	749.1	352.6	34.5
1990	749.1	6.2	2.2	8.4	5.0	752.5	354.2	40.4
1991	752.5	6.3	2.4	8.7	7.1	754.1	355.0	18.6
1992	754.1	6.2	2.2	8.4	7.6	755.0	355.4	10.3
1993	755.0	6.2	2.2	8.4	5.6	757.8	356.7	33.0
1994	757.8	6.3	2.2	8.5	4.2	762.1	358.7	50.7
1995	762.1	6.5	2.2	8.7	5.0	765.7	360.4	41.7
1996	765.7	6.6	2.1	8.8	5.6	768.9	362.0	36.8
1997	768.9	6.8	2.1	9.0	4.4	773.5	364.1	51.3
1998	773.5	6.8	2.1	8.9	2.9	779.5	366.9	67.3
1999	779.5	6.8	2.1	8.9	6.8	781.5	367.9	23.0

(continued)

Table 1. (Continued)

	Opening GTC	Emissions Inflow	Land use Change	Total Emissions	Uptakes Uptakes	Closing GtC	Mauna Loa CO_2 ppmv	Airborne Proportion (%)
2000	781.5	7.0	2.1	9.1	5.3	785.2	369.6	41.0
2001	785.2	7.1	***1.5***	8.6	5.5	788.4	371.1	36.2
2002	788.4	7.2	***1.5***	8.7	3.2	793.9	373.7	63.5
2003	793.9	7.5	***1.5***	9.0	4.2	798.7	376.0	53.6
2004	798.7	7.9	***1.5***	9.4	6.1	802.0	377.5	34.8
2005	802.0	***8.2***	***1.5***	9.7	4.3	807.4	380.1	56.0
2006	807.4	***8.4***	***1.5***	9.9	6.1	811.2	381.9	38.3
Average								42.1

Source: CDIAC

NB Figures for emissions in italics are from Canadell et al. 2007; for land use change to 1999, Gitz & Ciais 2004

emissions, implying that emissions have grown faster than the land and oceanic sinks (Canadell *et al.*, 2007:18868). In reality, there is no basis for this widely held belief, as the data on fossil fuel CO_2 emissions and absorptions between 1959 and 2006 show the respective growth rates are 2.32% p.a. and 2.98% p.a., while the annual increments to $[CO_2]$ as measured at Mauna Loa accordingly grew more slowly than the emissions, at 2.07% p.a., contrary to the claims in Canadell *et al.* 2007 (log linear growth rate calculations from data base in CDIAC 2008, see Table 1 here). Within that period there were occasions when emissions grew faster than absorptions, and *vice versa*, so it is always possible to pick a period to produce a desired finding, as in Canadell *et al.* (2007), but clearly over the whole period of nearly 50 years there is no evidence that emission growth has been faster than the rate of absorption. To the contrary, Fig. 2 and Fig. 4 above both show how absorptions have more than kept pace with fossil fuel emissions (including those from cement production).

We show how any adverse effect of rising temperature on primary productivity since the current warmer period began in the later 1970s has been more than offset by the beneficial effects of rising emissions of CO_2. Cline (2007) and Crimp *et al.* (2008) amongst many others have demonstrated these effects. Reducing emissions of CO_2 below the rate of absorption by the global biosphere, as proposed at the IPCC's Bali conference (2007), and as may be endorsed at Copenhagen in December 2009, will have very damaging consequences for primary productivity of agriculture, fisheries, and tree crops and forestry. World food production will fall - and prices will rise (Cline 2007:72).

The British government's *Stern Review* (Stern, 2007: xvi) states, "ultimately stabilization [of the atmospheric concentration of carbon dioxide and other 'equivalent' greenhouse gases (CO_2-e) at between 450 and 550 parts per million (ppm)] requires that annual emissions be brought down to more than 80% below current levels". In 2000-2006 an annual average of 5 GtC (55%) of total carbon dioxide emissions (including those from deforestation etc.) of 9.1 GtC p.a. (billion

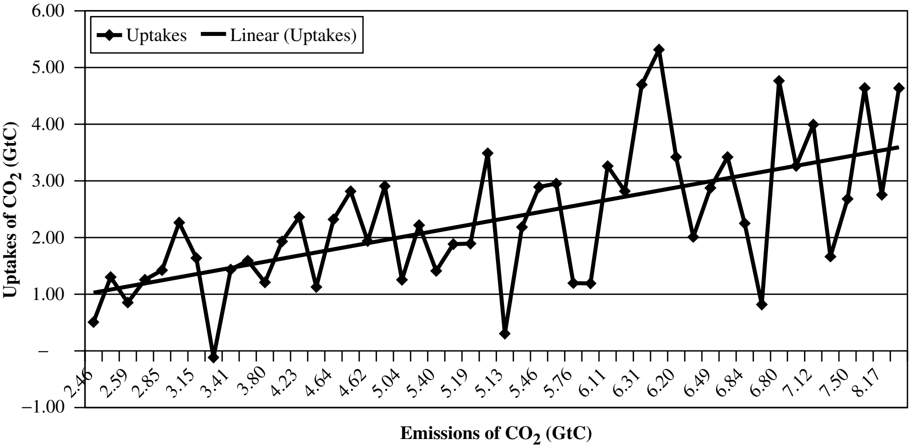

Figure 2. Carbon Dioxide Emissions and Uptakes 1960–2007

Source: CDIAC

tonnes of carbon) were taken up by the biosphere, for a net increase in the atmospheric concentration of CO_2 of 4.1 GtC p.a. (equating in volume terms to the average increase in atmospheric CO_2 as measured at Mauna Loa of 1.79 parts per million p.a., Canadell *et al.,* 2007:Table 1). If instead emissions had been only 1.8 GtC in 2000–2006, as proposed by Stern, clearly the net oceanic and biospheric uptake could not have been 5 GtC. Neither the *Stern Revie*w nor its Australian counterpart, the *Garnaut Report*, with their calls for reductions in emissions of up to 90%, offered any guidance on the impact to be expected of such a drastic decline in the availability of low-level incremental atmospheric carbon dioxide to oceanic and terrestrial life forms.[2]

In Section II we outline the results of various studies that have analyzed the impact of rising [CO_2] on crop yields, and then present our own econometric analysis of the impact of [CO_2] fertilization on world food crop production. We discuss the likely impact of the emissions reduction targets proposed by the IPCC and its leading member governments on world food supplies. Section III concludes.

2. CARBON DIOXIDE AND WORLD FOOD PRODUCTION

The *Stern Review* has this to say on the impact of rising [CO_2] on global temperature and world food production:

> In tropical regions, even small amounts of warming will lead to declines in yield. In higher latitudes, crop yields may increase initially for moderate increases in temperature but then fall. Higher temperatures will lead to substantial declines in cereal production around the world, particularly if the carbon fertilization effect is smaller than previously thought, as some recent studies suggest (Stern 2007:79–80).

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[2] See Freeman Dyson (2007) on the importance of low-level CO_2 for plant growth.

The "recent studies" cited by Stern (Parry *et al.* 2004, Warren *et al.* 2006, Long *et al.* 2005) offer no evidence of any decline in cereal production during the period of recent global warming.[3] Parry *et al.* (2004) state "most plants growing in atmospheric CO_2 higher than ambient exhibit increased rates of photosynthesis" (2004:55). Moreover, *pace* Stern's claim, this paper displays the yield increases associated with elevated CO_2 (2004: Fig1). The paper by Warren *et al.* (2006) also admits "CO_2 fertilization is the strongest driver of uncertainty in the results" (2006:5), which hardly supports Stern's claim that it shows "the carbon fertilization effect is smaller than previously thought", not least because the paper produced no data of its own showing any decline in the CO_2 fertilization effect.[4] Similarly the findings of Long *et al.* (2005, 2006a) are quite different from Stern's assertions. What they actually showed was that while FACE (free-air concentration enrichment) experiments to determine the effect of elevated atmospheric CO_2 on photosynthesis and yield of various crops showed reduced yields as compared with those from greenhouse or other semi-enclosed chamber experiments, the yield increases at 550 ppm CO_2 remained strong, at 12–14% for the C_3 crops, rice, wheat and soybeans. These yield increases were recorded despite the significantly higher temperatures (more than 1^o C) in the FACE plots than outside them (Long *et al.* 2005, Table 1 and Fig.1). Stern's claims are also not supported by the findings of Long *et al.* (2006a) that rising temperature does not fully offset rising yields in C_3 crops resulting from the reduction in Rubisco-based respiration produced by elevated CO_2 (see also Long *et al.* 2006b:326).

None of these papers considers the impact of the widely proposed *reduction* in emissions by 80% from the 2000 level by 2050, and the resulting declining atmospheric concentration of CO_2 on global agricultural, forestry, and fishery yields, but they do simulate zero fertilization effects in order to derive worst-case outcomes of rising atmospheric CO_2. Thus Parry *et al.* show the "additional risk of hunger without CO_2 effects" (2004:Fig.14). Ironically Warren's Figure 3.1 contradicts Stern's account of this paper by showing "that world wheat yields decline by 22% for a temperature rise of 3–4° C above 1990 in the absence of CO_2 fertilization" (2006:28, see also comments below on similar findings of Cline 2007). Ironically, these authors' zero fertilization scenarios confirm that with Stern-type emission reduction policies

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[3] Parry *et al.* (2004) admit their "combined model and scenario experiments demonstrate that the world, for the most part, appears to be able to continue to feed itself under the [IPCC's Special Report on Emissions Scenarios] SRES scenarios during the rest of the century" – without noting that this finding is by no means assured if emissions are brought below those in the SRES scenarios (2004). The models used by Warren *et al.* (2006) show that the terrestrial biosphere will continue to be a sink, if only until 2050 (2006:8), but that is because all those models use the Michaelis-Menten function (or its variants) that prescribe fixed or falling CO_2 absorptions as $[CO_2]$ rises. While none of these authors consider what the impact on NPP of Stern's proposed reduction of gross CO_2 emissions by 80% from the 1990 level might be, they do state that their more optimistic results depend on the presence of CO_2 fertilization.

[4] The study by Warren *et al.* (2006) was funded by the British government's DEFRA and was not peer-reviewed. Some bias is evident from its assumption that no carbon released by deforestation is offset even minimally by carbon uptakes from crops such as oil palm, when it is known they absorb more CO_2 per hectare p.a. than primary rain forest (Lamade and Bouillet, 2006: Table 1).

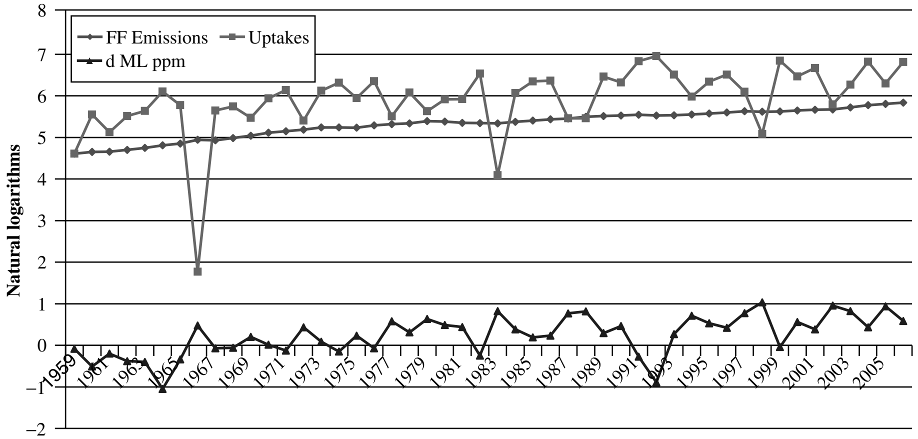

Figure 3A. Fossil Fuel Emissions, Absorptions, Increments at Mauna Loa Natural Logs, 1959–2006.

Source: CDIAC 2008

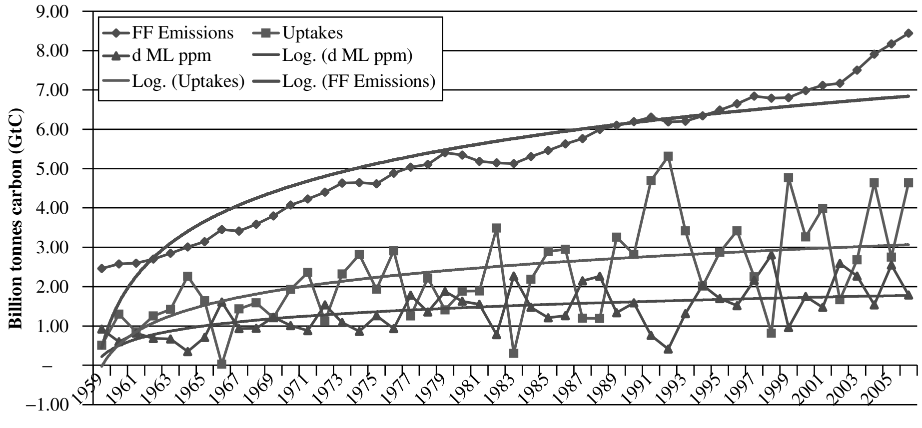

Figure 3B. Fossil Fuel Emissions, Absorptions, Increments at Mauna Loa Billion tonnes carbon (GtC) 1959–2006.

Source: CDIAC

there would be a potentially catastrophic impact on world food production, because of the reduction in CO_2 fertilization that these policies would produce.

The multivariate regression models estimated here go beyond FACE and chamber experiments to determine the relative contribution of key variables to recorded annual world food production since 1980, Yt. This is assumed to be a function *cet.par.* of global mean temperature Tt, the concentration of CO_2 in the atmosphere Ct, and world consumption of fertilizers Ft,

$$Yt = f\,(Tt,\ Ct,\ Ft) \tag{1}$$

The data for world food crop production from 1980 to 2003 is an index (1979–1981 = 100) taken from FAO Yearbooks (1993, 2005) (see Table 1). Global mean temperature for the same period is the GISS series (from CDIAC 2007). The atmospheric concentration of CO_2 (at Mauna Loa) is also drawn from CDIAC (2007). World consumption of fertilizer is sourced from IFADAT (2007). This first regression uses indices for all variables with 1980 = 100.

The regression results derived from the data in Table 2 show very high values for the adjusted R^2, at 0.99 and for F at 799.97, and a large and strongly significant coefficient (5.76) on [CO_2], with the t statistic at 36.06, and the P-value at 0.012.[5]

Table 2 World Food Production, Fertilizer Consumption, Mean Temperature, and Atmospheric Carbon Dioxide

Food prod	Temp	°C	Mauna Loa ppm	Fertilizers
1980	100.00	14.23	338.34	100.00
1981	102.44	14.18	339.18	98.85
1982	105.79	14.33	340.67	98.70
1983	105.68	14.46	342.94	105.93
1984	111.19	14.45	344.41	112.41
1985	113.90	14.39	345.62	110.82
1986	115.78	14.56	345.67	114.35
1987	116.21	14.46	349.03	119.47
1988	118.23	14.39	351.29	124.24
1989	122.88	14.26	352.63	122.52
1990	125.62	14.48	354.22	117.89
1991	125.16	14.44	354.98	115.15
1992	127.23	14.15	355.39	107.48
1993	128.31	14.19	356.7	103.18
1994	131.87	14.32	358.74	104.47
1995	134.65	14.46	360.44	111.13
1996	140.68	14.39	361.96	114.53
1997	143.77	14.41	364.12	116.95
1998	146.86	14.76	366.93	117.56
1999	151.96	14.46	367.89	119.84
2000	155.06	14.42	369.64	117.07
2001	156.76	14.57	371.11	118.81
2002	159.54	14.69	373.7	122.39
2003	162.79	14.67	375.97	127.51

Note: The index of food production has 1980=100; the index for fertilizer consumption has 1980–81=100 but is shown as 1980 here.
Sources: CDIAC, IFADAT (for fertilizer consumption), FAO (Annual Yearbooks, 1993, 2004).

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[5] Taking the shorter period from 1983 to 2003, the R^2 falls slightly, to .98. All three parameters have positive coefficients, but only that on CO_2 is significant.

Perhaps surprisingly, the coefficient on fertilizers is marginally negative (–0.047) but not significant ($t = –0.67$), while that on temperature is larger (0.365) and positive, but also not statistically significant (because $t = 0.767$ so < 2, the critical minimum value). The large negative value for the intercept (–507.9965) represents the negative food production index if there were zero values for fertilizer use, global temperature, and [CO_2].

The first regression equation is:

$$\underset{(42.55)}{Yt = -507.99} + \underset{(0.475)}{0.365Tt} + \underset{(0.159)}{5.756Ct} - \underset{(0.069)}{0.047Ft} \tag{2}$$

Figures in parentheses are the standard errors. The coefficient on C, atmospheric CO_2, is significant at the .95 level.

As is normal with time series analysis, the possibility of auto-correlation of the data series has to be considered, especially when as here the raw data for all three independent variables show a rising trend (see Fig.4). The Durbin-Watson tests (the latter statistic is just over the critical level of 2) shows this is not the case for these variables.

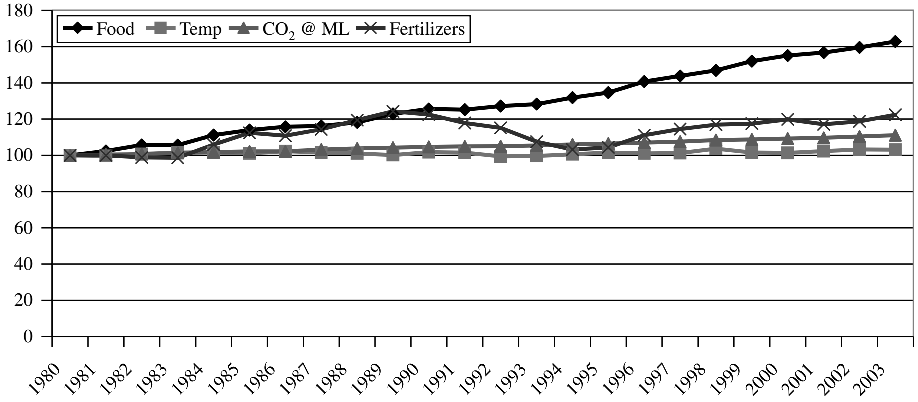

Figure 4. Indices (1980 = 100) of world food production, global mean temperature, atmospheric carbon dioxide, and fertilizer consumption

For comparison, here are the results from regressing global temperature Tt on the atmospheric concentration of CO_2 at Mauna Loa Ct between 1980 and 2005:

$$\underset{(5.256)}{Tt = 79.41} + \underset{(0.0497)}{0.209Ct} \tag{3}$$

The adjusted R^2 is 0.3998, F is 17.65, and the t-statistic for CO_2 is significant at 4.2, with the *P-value* at 0.0003. Figures in parentheses are standard errors. If the Mauna Loa series is auto-correlated, then that has clearly not done much to raise the explanatory power of (3), which implies that $[CO_2]$ explains less than half of the change in temperature from 1980 to 2005. Such a result may explain why this statistic is not reported by the IPCC with its 95% confidence that global warming is “predominantly” due to the anthropogenic influence on $[CO_2]$ (Solomon *et al.* 2007). However if we take the log of $[CO_2]$ at Mauna Loa and regress global temperature on that, then we raise the adjusted R^2 to 0.788, and have:

$$\begin{array}{l} Tt = -\,18.95\ +\ 3.28\log(\mathrm{Ct}) \\ \qquad\quad (1.447)\ (0.247) \end{array} \tag{4}$$

With $F = 174.92$, the t-statistic for $[CO_2]$ is significant at 13.22. Clearly the relationship between $[CO_2]$ and global mean temperature between 1959 and 2007 is more semi-logarithmic than linear, given the higher R^2 in (4) than in (3). This has important implications for the result of our regression of world food production, $[CO_2]$, and temperature in (2) above, since the declining log linear growth rate of the latter relative to the former largely helps to explains the evident much more powerful impact of rising $[CO_2]$ than of rising global temperature on world food production. The absence of such sensitivity analysis in the work of Cline (2007) amongst others is cause for concern.

We show in Table 3 the results of further regressions for a longer data series (1962–2002), showing the impacts on just global cereal yields of the terrestrial absorption of CO_2 (as inferred from the CDIAC data (2009) on total anthropogenic CO_2 emissions relative to increases in $[CO_2]$, increases in total fertilizer (NPK) usage (FAO 2009), and the global mean surface temperature data (GMT, GISS 2009). As above, only the CO_2 absorption has a positive and significant coefficient *($t > 2$),* and while that on GMT is negative, it is insignificant *($t < 2$).*

A major reason for the evidently powerful role of rising $[CO_2]$ in explaining growing world food production is that it tends to reduce the rate of photorespiration which accounts for a loss of as much as 30% of the carbohydrate formed in C_3 photosynthesis (Long *et al.* 2006b: 321), especially in the hotter and drier climates where in the past C_3 plants such as wheat and rice have been less successful, *cet. par.*, than C_4 crops like

Table 3. Carbon dioxide, temperature, and cereal yields

Dependent variable World Cereal Production 1962–2002	*Independent Variables*			*Basic Statistics*		
Annual change in Yield, kg/ha	Terrestrial CO_2 Absorption	Changes in Fertilizer Usage	GMT 1962–2002	Adj R2	F	Durbin-Watson
Beta Coefficients (standardized)	0.388	0.173	–0.116			
t-statistics	2.635	1.184	–0.784	0.145	3.255	2.688

Sources: NOAA; www.globalcarbonproject.org; FAO, ProdStat.

maize and sorghum. Elevated CO_2 increases photosynthetic efficiency and thus yield by reducing the oxygenation reaction of Rubisco (*op.cit*., 322).[6]

The conclusion that CO_2 is a more potent fertilizer than commercial nitrogenous and phosphate fertilizers, might be considered inconvenient, especially for producers of the latter. The data on total fertilizer consumption (Table 2) show it grew by only 27.5% between 1981 and 2004, implying the world's farmers were using less fertilizer than might be expected when food production grew by 62.7% over that period. Conversely, [CO_2] grew by only 11%, so its very large coefficient confirms the "FACE" field experiments showing just how powerful a growth agent it appears to be.

The food regression (equation 2) also suggests that rising global mean temperature can have a positive effect on agricultural production, even if its coefficient is small and statistically insignificant. Nevertheless it casts some doubt on claims by Parry *et al*. (2004) and the *Stern Review* (2007: Box 3.4) that rising temperatures will have a negative global impact on agricultural yields. But it is of course true that primary food production is not dependent only on [CO_2], temperature, and fertilizer usage. Rainfall is also important, especially in explaining annual variability in yields, but "global average rainfall" has no meaning in terms of being a predictor of crop yields in specific locations.

A report commissioned by the Garnaut Review (2008:128–132) found that under "no-mitigation" until 2100 (i.e. "business as usual"), rising [CO_2] would raise Australia's wheat yields by up to 20% by 2030, averaging 15% across ten of the main wheat areas, despite assumed rising temperatures of up to 4^o C and reduced rainfall of up to 30% (Crimp *et al*. 2008:6). With stabilization of CO_2-e at 550 ppm by 2100, cumulative yield increases would be less, averaging only 4.83% by 2100 (Garnaut 2008:132). A similar report on Australia's livestock industry also commissioned by the Garnaut Review found that "in the case of increasing CO_2 to 750 ppm, there was an

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[6] Note the negative feedbacks (e.g. reduced dark and photo-respiration, reduced water requirements) from increasing [CO_2] in the following passage: "Most green plants, including trees, algae, and most major food crops, use the C3 pathway, so named because the first products of photosynthesis (called photosynthate) have three carbon atoms per molecule. C3 plants respond most dramatically to higher levels of CO_2. At current atmospheric levels of CO_2, up to half of the photosynthate in C3 plants is typically lost and returned to the air by a process called photo-respiration, which occurs simultaneously with photosynthesis in sunlight. Elevated levels of atmospheric CO_2 virtually eliminate photo-respiration in C3 plants, making photosynthesis much more efficient. High CO_2 levels also sharply reduce dark respiration (the partial destruction of the products of photosynthesis during night-time) among C3 plants. Corn, sugarcane, sorghum, millet, and some tropical grasses use the C4 pathway, so named because the first products of photosynthesis have four carbon atoms per molecule. C4 plants also experience a boost in photosynthetic efficiency in response to higher CO_2 levels, but because there is little photo-respiration in C4 plants, the improvement is smaller than in C3 plants. Instead, the largest benefit C4 plants receive from higher CO_2 levels comes from reduced water loss. Loss of water through leaf pores declines by about 33 % in C4 plants with a doubling of the CO_2 concentration from its current atmospheric level. Since corn and other C4 plants are frequently grown under drought conditions of high temperatures and limited soil moisture, this superior efficiency in water use may improve yields when rainfall is even lower than normal" (Wittwer, 1992).

11% increase in pasture growth, which increased to a 16% increase in terms of LCC (livestock carrying capacity) and a similar change [in the value in current A$ of total livestock production] of 15%" (McKeon *et al.* 2008:17). This increase in LCC was omitted from the *Garnaut Review* itself—yet it is clearly another important *negative* feedback.

The case is different with another potentially important omitted variable, the improved crop varieties that created the "Green Revolution". The most comprehensive analysis is probably that by Evenson and Gollin (2003a) summarizing their book (2003b). Table 1 of the former shows the results of their analysis, indicating that while improved varieties had significant impacts on yields across the world, in all cases the yield increases attributable to "other inputs" was larger, by an order of magnitude, at least double in many cases. These authors define "other inputs" as the residual not accounted for by modern varieties, and they did not consider [CO_2] explicitly. It seems likely that rises in [CO_2] were a major contributor not only perhaps to the "other inputs" but also to some of the yield increase attributable to modern varieties, since that could *not* happen without photosynthesis based on [CO_2]. Thus while it is likely that improved varieties contribute to the large correlation between yield and [CO_2] reported above, the latter is in effect a proxy for the role of the improved varieties. Correspondingly, the improved varieties also help to explain the on-going rapid growth of the biosphere's uptakes of [CO_2] that is evident in our Fig.2.

What will be more than inconvenient for the present and future inhabitants of this earth is if the present net additions to [CO_2], amounting to over 4 GtC a year on average from 2000–2006 (Canadell *et al.* 2007: Table 1), were to be reduced to perhaps less than two GtC, as would result from attainment of the 83% reduction (from the 2005 level) target proposed by the administration of President Obama and similarly legislated (October 2008) by the United Kingdom. For if universally adopted and implemented, then the absorption of CO_2 fossil fuel emissions by the biosphere, at the 2000–2006 rate of 66% of those emissions, at over 5 GtC p.a., which overwhelmingly account for the increase in food production described here, will perforce drop to less than 2 GtC p.a. That implies at least a *pro rata* – possibly worse —reduction in primary food production that not even improved crop varieties will be able to offset.

The aggregative data used in our regression showing the powerful fertilizing capability of growing levels of [CO_2] are confirmed by innumerable micro studies of the yield enhancement resulting from enriching real greenhouses by injecting them with CO_2. There are also very many studies of "free-air CO_2 enrichment" (FACE) field experiments that have confirmed the large fertilizing effect of elevated [CO_2] levels even in open fields. The experiments release jets of CO_2-enriched air or pure CO_2 gas into the fields: "exposure to elevated CO_2 resulted in a 31% increase in the light-saturated leaf photosynthetic rate and a 28% increase in the diurnal photosynthetic rate of carbon assimilation when averaged across all FACE experiments and species". Trees showed the greatest response, followed by fertilized C3 crops (e.g. wheat). Thus trees showed a 28% increase in above-ground dry matter production, but crop yields increased by “only” about 15 to 17%—and many wheat farmers would be quite content with that (Ainsworth and Long, 2005:354–5, 358).[7]

Cline’s results support the discussion above of the likely adverse effects of declining carbon emissions and atmospheric concentration on world food production. For his models show that “developing country regions suffer losses of about 20% without carbon fertilization”, with only 6% losses in the industrial countries (2007: Table 5.10). Cline’s “without carbon fertilization” cases (with prescribed warming) are a special case, given his “central estimate of the carbon fertilization effect by the 2080s [that] is set in this study at a 15% increase in yield” (2007:25). It is difficult to avoid the conclusion from Cline’s analysis that if CO_2 emissions were drastically reduced the world would experience massive losses in food production from what would otherwise be expected.[8]

3. DISCUSSION AND CONCLUDING COMMENTS

We noted in Section 1 that if anthropogenic emissions of CO_2 had already been less than 2 GtC in 2007, as implied by the 80% reductions from 2000 levels proposed for a future carbon stabilized world by both the Stern *Review* 2007 and *Garnaut Report* 2008, the net absorption of those CO_2 emissions by the oceans and biosphere could not have reached the actual level of about 6 GtC in 2008. At the least, Stern and Garnaut should have offered some guidance on the impact to be expected of such a drastic decline in the availability of additional CO_2 to the oceans and biosphere.

Section 2 outlined our regressions showing that growth of $[CO_2]$ is strongly associated with the increase in world food production from 1962 and 1980 to 2003. Being based on historic outcomes they provide exceptionally strong support for the “laboratory” results from localized greenhouse and “FACE” field trials, confirming the unequivocal fertilizing effect of elevated $[CO_2]$ on crop yields. We noted that there is a potential problem of auto-correlation of the data on the growth of the concentration of atmospheric CO_2 due to its continuous growth (albeit at the slow rate of less than 0.5% p.a.). This is a problem with all time series that show steady growth including the CPI, GDP, world population, and many others. The regressions reported here all pass the Durbin-Watson test statistic for absence of auto-correlation. Moreover our regressions show such drastic reductions may well have the capacity to produce major

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[7] These are much the same authors of a later article (Long *et al.* 2006) cited by Stern (2007:82) for showing that high yield gains (“18–25%”) only accrue in greenhouses or field chambers, and that “in near-field conditions” there would be “[only] an 8–15% increase in yield for a doubling of carbon dioxide for responsive species (wheat, rice, soybean), and no significant response for non-responsive (maize, sorghum)”. The paper’s reported FACE yields for rice, wheat and soybeans of 12–14 % (2006:1918) belie Stern’s claims, and he chose not to mention either that the former plants are far more important than the latter, at a ratio of 3:1 by value (Cline 2007) or that many studies (e.g. Wittwer 1992, 1998) do show some response of the latter to enhanced CO_2.The studies he favours do not discuss the impact on yields of *reducing* CO_2 emissions by 80 per cent.

[8] “The rising level of atmospheric carbon dioxide is a universally free subsidy, rising with time, on which all can reckon when it comes to crop productivity”, Wittwer (1998:291).

declines in global food crop yields, with concomitant rises in grain and other food prices given on-going population growth, as is the corollary of Cline's analysis (2007).

This finding is similar to Freeman Dyson's (2007):

The fundamental reason why carbon dioxide in the atmosphere is critically important to biology is that there is so little of it. A field of corn growing in full sunlight in the middle of the day uses up all the carbon dioxide within a meter of the ground in about five minutes. If the air were not constantly stirred by convection currents and winds, the corn would stop growing…

Most biogeochemical and physical systems incorporate feedbacks and naturally stable systems almost always have negative feedbacks. Here we have explained and documented the negative feedback source, namely that more CO_2 causes more plant growth but more plant growth takes up more CO_2 thus limiting the further rise. Anthropogenic emissions of CO_2 currently amount to around 10 GtC p.a., which is about 10% of the annual total flux from the planet and the atmosphere, or 2.5% of the total CO_2 fluxes or turnover between the atmosphere and the planet of over 150 GtC (Houghton 2004: Fig.3.1). Most of that turnover comprises plant growth on the one hand and plant and animal respiration on the other. New incremental plant growth (both marine and terrestrial) would only have to increase from the present level of around 6 GtC p.a. to 8.5 GtC to absorb all current anthropogenic CO_2 emissions from combustion of fossil fuels.

The main conclusions of this paper are:

1. If the Stern (2007), Garnaut (2008) and Hansen 2008 recommendations for anthropogenic emission reduction targets are adopted at Copenhagen (December 2009) and globally implemented, they will reduce emissions below the growing level of photosynthetic uptakes, and are then likely to lead to the large reductions in agricultural, forestry, and fishery productivity indicated both by our regression results above and by Cline (2007). This will certainly cause more immediate hardship to more people than the as yet non-evident "dangerous" climate change asserted in the advocacy of the IPCC (Solomon *et al.* 2007).
2. It follows that emission reduction targets should take into account terrestrial and oceanic uptakes of CO_2, which have for 50 years absorbed more than half of global CO_2 emissions. That means such targets should *never* reduce emissions to below either the *current* or the *ongoing* level of global absorption of CO_2.
3. Given that the average level of annual net new global biospheric absorption of anthropogenic emissions has been 57% since 1958, which means that net emissions have been only 43% on average, that in turn means the likely Copenhagen target of a 60% reduction by 2050 in total emissions from the 2000 level is already being over-fulfilled. The dangerous fallacy in the Copenhagen targeting is the false belief that reducing total emissions by 60% from the 2000 level will have no impact on the annual new biospheric absorption, which embodies incremental global NPP, i.e. yields and output of all food crops, livestock, forestry, and fisheries (Lloyd and Farquhar 1996, 2008).
4. The IPCC's reliance on models (notably Wigley's MAGICC) based on the Michaelis-Menten function forces its projections of the atmospheric concentration of CO_2 (i.e. $[CO_2]$) to produce a continuous increase to nearly

500 ppm by 2050, and 780 ppm or 1000 ppm by 2100 if not before (Solomon *et al*. 2007:Fig.10.20). Our observationally based parameter yields much more plausible levels that might just reach 450 ppm by 2050 and 562 ppm by 2100 (projecting from end-2008 at the observed growth rate of 0.41% p.a. from 1958 to 2008). The behaviour of the CO_2 emissions absorption function will be of the form *(1-e-ax),* an inverse exponential asymptote, rather than the logarithmic (growth slows down) as used by the Bern models, and the hyperbolic (growth ceases) of the MAGICC models; neither of the latter is supported by observations of the growth of absorption of the total global CO_2 sink since 1958.[9]

5. The crucial implication of this paper's findings for the negotiators who will assemble at Copenhagen in December 2009 is that they should grasp the moral imperative of NOT trying to get the world to abandon cheap fossil fuel energy in favour of uneconomic renewable and other sources, and instead devoting resources to raising natural absorption of CO_2, for example by helping African and SE Asian countries to raise their cereal yields to North American and European norms. That will not only be cheaper than seeking such will o' the wisps as Carbon Capture and Storage (CCS), it will have tangible financial benefits, unlike CCS and the like.

ACKNOWLEDGMENTS.

The author is indebted to comments by Don Aitkin, Bill Bowen, Ron Duncan, Ray Evans, Michael Hammer, John Millett, Barry Ninham, John Nuttall, Colin Pardoe, David Pilbrough, Freeman Dyson, Tom Quirk, Ted Swart, Geoffrey Smart, and David Tribe. Two peer reviewers also made helpful comments. All remaining errors are the author's.

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[9] Michael Hammer, personal communication, 19 June 2009.

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