Modelling the Costs of Climate Change and its Costs of Mitigation: A Scientific Approach

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Abstract

A thorough review is made of Climate Change Science, going into much greater detail than is typical of papers in Economics and specifically emphasising the hard thermodynamic limits of biological and physical processes. This theme is then continued in a historical review of theory relevant to Climate Change taken from Economics, Physics, Biology and Mathematics, clarified by extensive real-life historical time series plus calculations of fundamental thermodynamic limits – which results in a series of pointed, uncomfortable truths that our culture & society prefers to overlook.

Two types of "costs of climate change" models are then placed under the microscope: (i) The Stern Report (2007) and (ii) The Limits to Growth (2004) – both chosen as the two most widely known by the greater public. Both models are evaluated according to the scientific realities outlined in the previous two chapters, including going into some detail of the specifics of the models themselves through analysis of their source code implementations.

Finally, the author's subjective opinion is given as to the quality of the models given the results of the prior chapter. I conclude that the models are primitive, but not much better than the state-of-the-art currently employed by the Intergovernmental Panel on Climate Change. The hard reality is that we do not sufficiently understand the nature nor causes of climate change, only that it is happening – and thus building a realistic model is currently outside our capability. This is changing very quickly however – the paper has tried, where possible, to include the very latest research on climate change and to show by just how much the ground is currently moving.

Table of Figures and Graphs

Introduction

We stand at a fascinating point in human history: our behaviour, as a species, has begun to affect the entire planet and thus, from now on, what we do will not only affect our own destiny, but also that of the planet's. It has only been in the last few decades that we have developed models sophisticated enough to approximate these processes, and no matter what one's opinion is on the matter, everyone can agree that the accuracy of these models remains a lot to be desired.

This paper reviews two examples of the two main forms of Economic Climate Change modelling technique currently in widespread use. No claim is made that either is the best available in their particular field – in fact, they are simply the two best known by non-Economists – but both are fairly representative of their field's approach.

One assumption that this paper makes is that the single most important Economic effect of climate change will be its effects on agriculture and thus upon the food supply[i]. In recent weeks we have seen a surge of violent protest in over a dozen countries over a mere 50% increase in the cost of basic grains – indeed, this week's *The Economist* is dedicated to the issue (The Economist, 2008). This shows just how much of the world's population is extremely price sensitive to basic foodstuffs because of their grinding poverty – indeed, should this price inflation continue, rising grain prices will rapidly wipe out all the progress made in reducing world poverty during the last ten years (The Economist, 2008).

Most Economic models ignore the scientific realities underpinning the functioning of our biosphere and to emphasise that fact, a short overview of the science is made in "Chapter 1: Hard facts about Climate Change Science". These are the 'hard' cost boundaries which any Economic model must satisfy and this paper will zealously analyse how well the Economic models satisfy hard scientific realities.

In "Chapter 2: Uncomfortable Truths" we make clear some very uncomfortable truths regarding the true nature of our population and industrial growth. In particular we discuss the nature of Gross Domestic Product (GDP) and the nature of fundamental resource constraints.

Having done all the groundwork in the first two chapters, we finally turn to the two types of Economic Climate Change model in "Chapter 3: Two Kinds of Climate Change Model".

Chapter 1: Hard facts about Climate Change Science

It is rare to see in any paper about climate change (from an Economics perspective) an actual definition of climate change which almost certainly contributes to the often heated debates concerning it. It seems to me that few in Economics understand the details of how biology and physics actually work to keep the planet alive – however, this being outside the scope of this paper, I have relegated most of those details to the endnotes.

This paper simply takes climate change to mean "severe degradation of vital environmental support systems for planetary life" and specifically, by that, it means the following:

- The primary system maintaining life on planet Earth is photosynthesis[ii], that being the combination of carbon dioxide (CO_2) with water (H_2O) and red-blue low-entropy solar radiation (photons) into organic energy transport chemicals such as glucose ($C_6H_{12}O_6$), releasing oxygen (O_2) as waste. There are three kinds of photosynthesis[iii], of which C4 photosynthesis fixes 30% of planetary carbon dioxide using modest amounts of water despite being only 5% of planetary biomass (Osbourne & Beerling, 2006). Plants and animals then chemically react those organic energy transport chemicals with oxygen[iv] at some later point to provide growth or movement.
- The secondary system maintaining life on planet Earth is the Nitrogen-Phosphorous-Potassium (N-P-K) cycle without which all photosynthesising lifeforms cannot exist[v]. Of this, by far the most important to climate change is the Nitrogen cycle because 1.5% of a plant's dry weight is Nitrogen and it is extremely energy expensive to fix it from the atmosphere[vi]. However, it could be a far worse concern in the long term that we probably passed the Phosphorous Peak in 1989[vii].
- There is no doubt, **absolutely no doubt**, that photosynthesis is the single most important factor which makes our planet different from any other. Specifically, its atmosphere contains a large amount of the highly chemically reactive oxygen which cannot persist in any chemical system approaching equilibrium – thus, Earth's atmosphere is a system far from chemical equilibrium and has stayed that way for some 2bn years[viii].
- Anything which modifies this process at a planetary scale is cause for great concern, and anything which retards this process at a planetary scale is a severe threat to all life.

This process is a hard scientific fact, and yet its extremely obvious consequences are routinely ignored by far too many serious commentators. The first, and most obvious conclusion is the proportional limiting factors of photosynthesis:

1. Sunlight
2. Water
3. Nitrogen

Applying sufficient quantities of those three to any part of the planet usually produces a bounty of life in a very short time period. In most parts of the planet, the primary constraint on the quantity of life is severely limited by one of these (Taiz & Zeiger, 2006).

It is therefore really rather amazing that human beings have gone to the extent that they have to interfere with these three factors without considering the wider consequences. Part of the problem is understanding them at all – photosynthesis was not fully understood until 1966 with the discovery of the Hatch-Slack pathway (Hatch, 2002) – and even today no one is exactly sure which has precisely what effect, as every IPCC assessment report bravely admits.

In fact, it is extremely worthwhile to delve quite deeply into the specifics of climate change. We did not arrive at this point by accident – it resulted from a series of decisions usually made with the best of short-term intentions, but because we did not think our decisions through, we will shortly reap the long-term consequences. The fingerprints of the history of our choices are everywhere, they just need to be sown together and for that we need to summarise the most essential points such that we can unequivocally speak some uncomfortable truths in Chapter 2 below.

More importantly, knowing the details allows a far deeper analysis of how well the climate change models work, how accurate they are and how well they model the costs of climate change mitigation – only a proper knowledge of the science can illuminate that latter point.

1.1 Greenhouse Gases

According to the IPCC fourth assessment (IPCC, 2007), the following greenhouse gases are primarily responsible for warming the planet (in order of relative effect):

1. Carbon Dioxide (CO_2 379 ppm in 2005, has been 180-300 ppm during last 650,000 years[ix])
2. Methane (CH_4 1,774 ppb in 2005, has been 320-790 ppb during last 650,000 years)

3. Fluorine containing gases such as CFC, HCFC, HFC, PFC covered under the Montreal and Kyoto protocols.
4. Nitrous Oxide (N_2O 319 ppb, 270 ppb pre-industrial)
5. Ozone (O_3, too unstable to know pre-industrial levels)

Their relative contributions to warming are as follows:

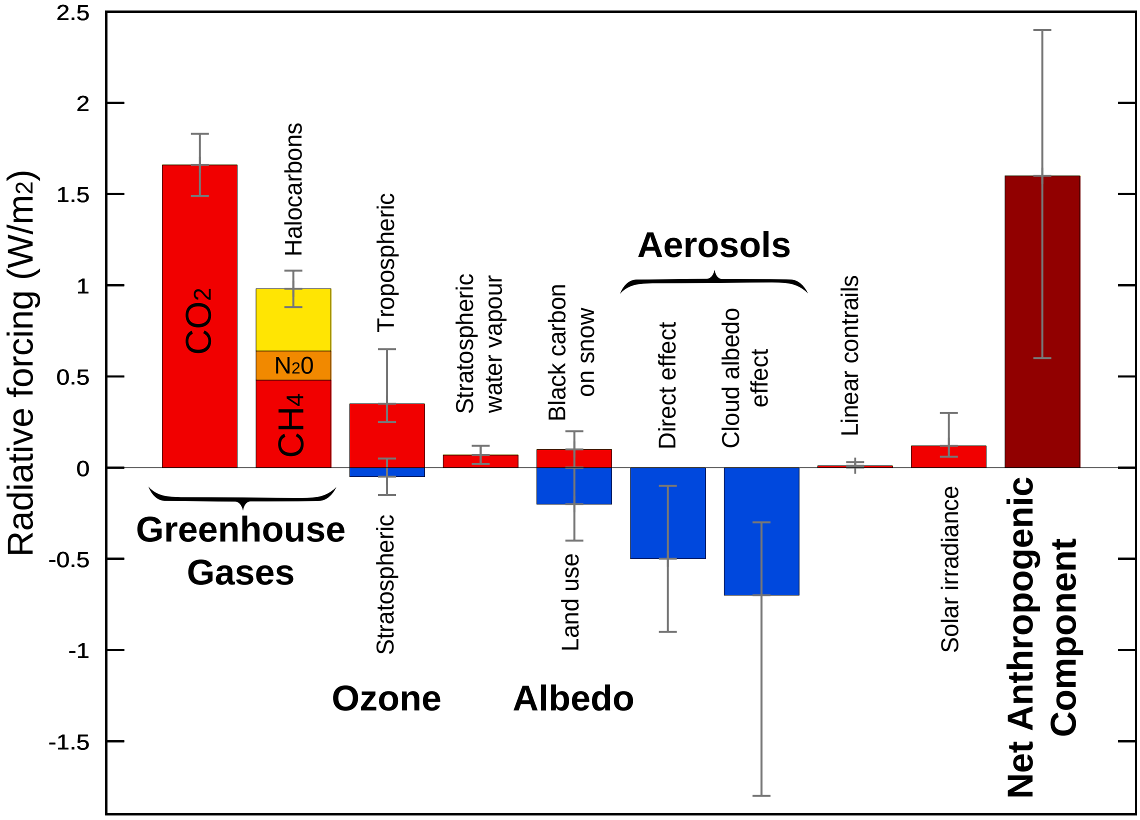

Figure 1: Components of Radiative Forcing (with error bars) according to the IPCC

One must remember that the IPCC is a conservative consensus opinion that necessarily must adopt a "wait and see" approach when the science is not yet certain. One can particularly see this in the error bars above for the effect of aerosols, to which we turn next.

1.2 Aerosol Pollution

Industrial processes and the burning of coal and biomass produce a great deal of aerosol pollution e.g.; soot and other small particulates. This has two main effects relevant to climate change: (i) the particulates directly interfere with vital life processes within plants & animals and (ii) they indirectly interfere with the fundamentals of atmospheric processes. The latter is the more directly relevant to climate change, so we shall discuss this first.

As a much simplified description, airborne particulate causes increased cloud albedo (reflectivity), thus reflecting more sunlight back into space, thus reducing the amount of sunlight reaching the ground and thus, both reducing global heating and at the same time the rate of photosynthesis. It has been estimated that there has been an average drop in sunlight reaching the ground of 4% globally with 10% across the continental USA between 1960 and 1990 (Liepert, 2002) with a slow improvement since then (Wild, et al., 2005). It is known that most water evaporation occurs due to direct solar radiation contact[x], so this has a direct effect on atmospheric water vapour content – additionally, the aerosols make clouds much finer and thus both thicker and less likely to rain. What this basically means is that the fresh water transport system has been substantially modified – however, the long standing paradox of decreasing pan & sea evaporation rates combined with increased rainfall has recently been resolved, showing that net rainfall has increased but the distance it is transported has dropped (Brutsaert & Parlange, 1998)[xi]. Water is dealt with more substantially below.

I should qualify this suggestion that aerosol pollution reduces global heating by bringing in some very new research just published last month in *Nature*. This very extensive review of multiple data sources has found that black carbon (soot), *in aggregate*, could contribute warming of as much as 55% of the increased CO_2 levels. It has been discovered that different wavelengths of solar radiation either pass through or are absorbed by a complex web of interacting pollutants such that greenhouse gas radiative forcing is reduced, but is more than made up for by black carbon absorbing a disproportionate amount of sunlight reflected by clouds. In other words, while the pollutants do reduce heating at the surface, they have been greatly increasing it in the upper atmosphere at the same time as substantially reducing photosynthesis through dimming. Around $2W/m^3$ is being transferred from the ground to the upper atmosphere – a huge amount in the context of the radiative forcing graph above (Ramanathan & Carmichael, 2008).

The chances are that even slightly increased shading has a disproportionately high effect on planetary photosynthesis as the C4 kind, punching far above its weight in carbon dioxide fixation, particularly likes strong, direct sunlight and reacts very negatively to any shading at all (Osbourne & Beerling, 2006). Unfortunately, despite extensive searching, I have not been able to find any study analysing the historical contribution of C4 photosynthesis to our climate – however, the results of the Osbourne & Beerling paper were simply not known until now.

It is important to not underestimate the effects of aerosol pollution on the human population. It has been estimated that rice yields (a C3 plant) in the Indian subcontinent alone between 1995 and 1998 would have been 11% higher were the thick, brown cloud hanging overhead not there (Auffhammer, Ramanathan, & Vincent, 2006) – and that figure explicitly does not include the effect of increased greenhouse gases on the rice, it solely accounts for albedo and rainfall effects. This I am sure is small comfort to those currently rioting there about food shortages (at the time of writing).

Furthermore, aerosol pollution has severe effects on the human (and animal) respiratory system (Johansson, Norman, & Gidhagen, 2007):

Environmental Risks	Global Estimate	Asian Estimate (S ,SE Asia + W Pacific)	Asia as a percent of Global
Unsafe Water	1,730,000	730,000	42%
Urban Outdoor Air	799,000	487,000	65%
Indoor Air	1,619,000	1,025,000	63%
Lead	234,000	88,000	37%

Figure 2: Excess Deaths from Selected Environmental Factors[xii]

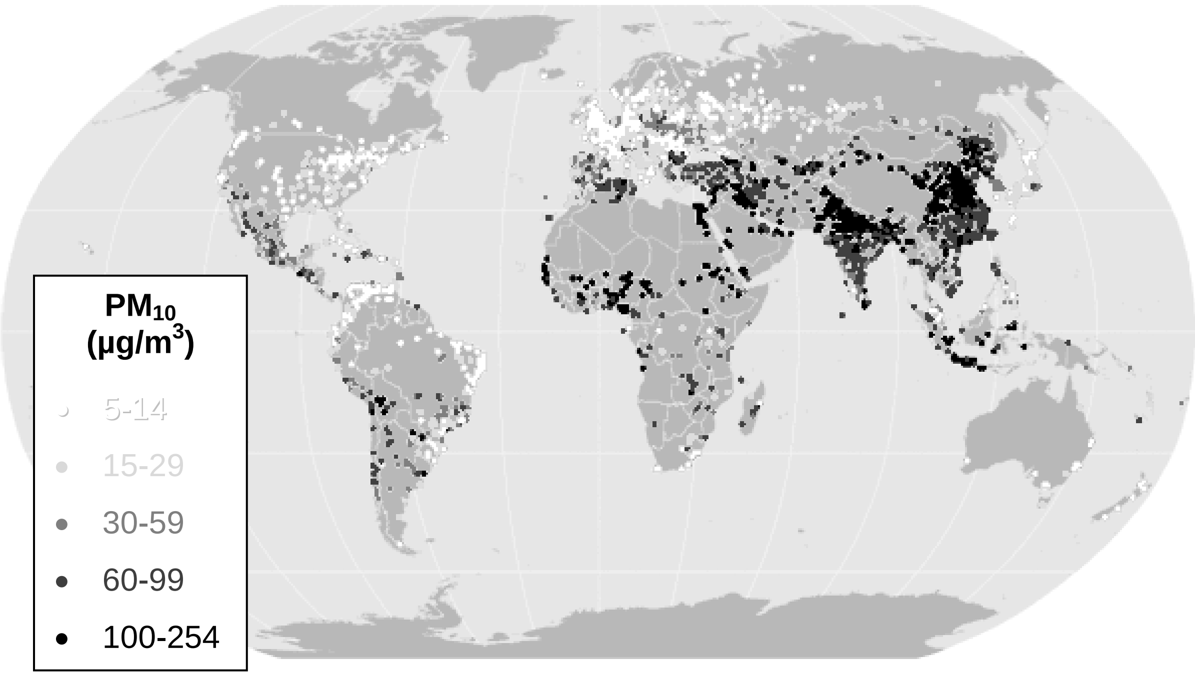

Figure 3: Estimated Particulate Matter <10 µm pollution in World Cities > 100,000 population

One can clearly see Asia's brown cloud. According to the World Health Organisation's World Health Report 2002 from which the above table was derived, some 40% (22.4m) of the then

56m people who died in the year 2000 were preventable (costing one third of global productive years[xiii]), so aerosol pollution **alone** caused 11.8% of the preventable deaths and 4.7% of total annual deaths in the year 2000 (World Health Organisation, 2002).

1.3 Water

Table 1: Inventory of water at the Earth's surface (Pidwirny, 2006)

Reservoir	Volume in km^3	% of Total	Average Residence Time
Oceans	1370,000,000	97.25	3,200 years
Ice Caps and Glaciers	29,000,000	2.05	20 – 100 years
Groundwater	9,500,000	0.68	shallow: 100 – 200 years
Lakes	125,000	0.01	50 – 100 years
Soil Moisture	65,000	0.005	1 – 2 months
Atmosphere	13,000	0.001	9 days
Streams and Rivers	1,700	0.0001	2 – 6 months
Biosphere	6000	0.00004	

Some 527,583km^3 of water is evaporated by the hydrologic cycle annually which equals a transport of some 40PW (a petawatt is 10^{15}W) of heat[xiv] - note that only 120PW reaches the biosphere, so a full **one third** of the sun’s energy powers the cleaning of fresh water[xv]. Only 9% (some 47,483km^3) makes it onto land (Pidwirny, 2006). The IPCC reports that atmospheric water vapour has increased by 4% since 1970 and precipitation onto land has risen by 2% this past century, however the incidence of very high and very low periods of rainfall has increased (IPCC, 2007).

Despite the tremendous amount of energy required for generating fresh water, it is probably the most consistently undervalued natural resource in developed countries due to heavy public subsidy (The World Bank, 2006) and favourable geographic location. However, for the population of any poor country or any country with a significant amount of land to the west of it[xvi] (such as most of the Middle and Far East, Russia and east Africa), water is more important than any other resource because crops and industrial processes need large amounts of fresh water. In fact, one can link fresh water and crop quantities as shown in Appendix B.

There are two main types of water flow important to agriculture: blue and green (Portmann, Siebert, & Döll, 2006). Blue water is runoff i.e.; the water which exceeds the land's absorption capacity and runs into streams, rivers etc. Green water is rainfall taken up by plants and reemitted through photorespiration. This latter kind is highly underemphasised by modern agriculture despite that it is the primary water supply in rainforests, and surprisingly that 80% of contemporary agricultural output is green water based (Rockström, 2003). Our emphasis on the former kind has led to rivers such as the Yellow River in China no longer reaching the sea.

Considering this, agricultural techniques are highly inefficient with an average of 38% efficiency in developing countries (Food and Agriculture Organization, 2003) with a state-of-the-art of 60% in Israel (Rosegrant, Cai, & Cline, 2002). Simple changes to practice such as use of no-till agriculture (already practised to some extent by 23% of US farms) or even throwing a clear plastic bag over crops can make a tremendous difference to water efficiency – Rockström discovered a potential $500km^3$/yr saving against a total $6800km^3$/yr (Rockström, 2003). Rather shockingly, Rockström also discovered that total human dependence on water is $65,000km^3$/yr which is 88% of total annual flow[xvii] – this means that there is not much slack left in the system.

1.4 Nitrogen Fixation

The details of how nitrogen is fixed from the atmosphere by Nature are in the endnotes[vi] – of more import to climate change is how humans have intervened in the process because it has probably caused more damage to fundamental natural systems than any other human action[xviii]. It has been long known that spreading animal manure upon cropland improves yields – though precisely why was only relatively recently discovered in the 19^{th} century. Animal urine and faeces contain urea ($(NH_2)_2CO$) which is synthesised as a transport for removing the toxically alkaline ammonia (NH_3) which is a waste by-product of metabolism[xix]. Urea is highly water soluble and contains more nitrogen than any other fertiliser (46.4%) – an advantage for the animal during excretion and also to the farmer for application to crops, but a major disadvantage for rivers, lakes and coastal seas where the only limiting factor for algal blooms is sufficient nitrogen.

Urea is broken down easily into ammonia and carbon dioxide, and so long as there is sufficient oxygen, aerobic bacteria will convert that ammonia by adding oxygen into a nitrite (e.g.; nitrous acid, HNO_2) and then a nitrate (e.g.; nitric acid, HNO_3). If there is insufficient oxygen however, anaerobic bacteria will convert nitrites or nitrates into nitrogen gas – this is why traditionally farmers ploughed their fields in order to aerate them. Imbalanced soil, where natural bacteria and fungi are not in a healthy balance, tends to produce excess intermediate Nitrogen-containing compounds because of a distorted conversion balance, and thus we get many of our most problematic Nitrogen-based aerosol pollutants as mentioned above.

For almost the entire of human history, the lack of nitrogen has been the most important limit to agricultural output when there is sufficient fresh water. Apart from highly expensive shipments of bat guano or saltpetre from Latin America, there simply was no high concentration source of nitrogen apart from manure.

All this changed with the invention of the Haber-Bosch ammonia synthesising process in 1911. This uses a hydrogen source (typically natural gas) and high temperatures and pressures to produce ammonia from atmospheric nitrogen. There are few things which happen in history that really utterly change the future of the human race, but this was one of them – as section 2.3 details, most of the human beings alive today could never have been without the invention of this process and its resultant effects on food production.

Unfortunately, we have used this process to fix very large amounts of nitrogen indeed – as reported in the January 2008 edition of *Nature*, we fix 160Tg per year while Nature fixes 110Tg on land and 140Tg in the oceans. This has had a catastrophic effect on Natural systems, especially all water-rich habitats where algal blooms deoxygenate the water, thus causing a mass die out of organisms and thus rendering many rivers and lakes uninhabitable as well as severely depleting coastal fish stocks. Further problems include a large increase in acid rain (which acidifies soil, causing leaching of vital minerals and nutrients), it catalyses the breakdown of the ozone layer and it acts as an aerosol pollutant with substantial human health costs (covered above). Much more detail on these effects, and the uncertainties and paradoxes apparent in the carbon-nitrogen cycles, are in that Nature article (Gruber & Galloway, 2008) or indeed any IPCC report.

Chapter 2: Uncomfortable Truths

As we have assumed that the single most important Economic effect of climate change will be its effects on agriculture and thus upon the food supply, before we can assess the climate change models, we need to understand fundamental resource limits, how effects of climate change are valued and how our food is grown.

2.1 Fundamental Resource Limits

I have worried before beginning this paper that I may be labelled by the end of it as a Malthusian catastrophist – and I certainly acknowledge that the majority of those who predicted doom & gloom over the last few centuries have been proven most wrong. Nevertheless, I wish to make clear that the division is not a simple binary one of "nay sayers" and "yay sayers" – rather the issue is somewhat more complicated, and knowing those details helps a lot. Before I begin, I should remind you of the three things which must be conserved according to the first and second laws of thermodynamics: (i) energy (ii) space (iii) time. This is important, because Physics allows you to substitute one or two for a *lesser amount* of the other, but there is no such thing as "getting something for free" which unfortunately many standard Economic models assume (e.g.; the Solow growth model[xx]).

Anything thus conserved is a "fundamental resource" i.e.; one which cannot be substituted. To date in our civilisation's history, we have proved remarkably adept at substituting one form of energy, space or time for another when we reached some limit – maybe we shall continue that trend, or maybe we won't (Chapter 3 discusses this in relation to the models). Climate Change is without doubt the most serious fundamental resource limit of all, because to put it frankly – we only have one planet, and it is most certainly not substitutable[xxi].

2.1.1 Food and Population

Thomas Malthus published his first edition of *An Essay on the Principle of Population* in 1798. Much simplified, he had observed that population growth was compound whereas food production growth was linear (this wasn't actually true – but see below), which could only result in boom/bust cycles where the bust meant mass famine among the poor, thus reducing the excess population. The graph is extremely obvious to any Economist, but I include it anyway:

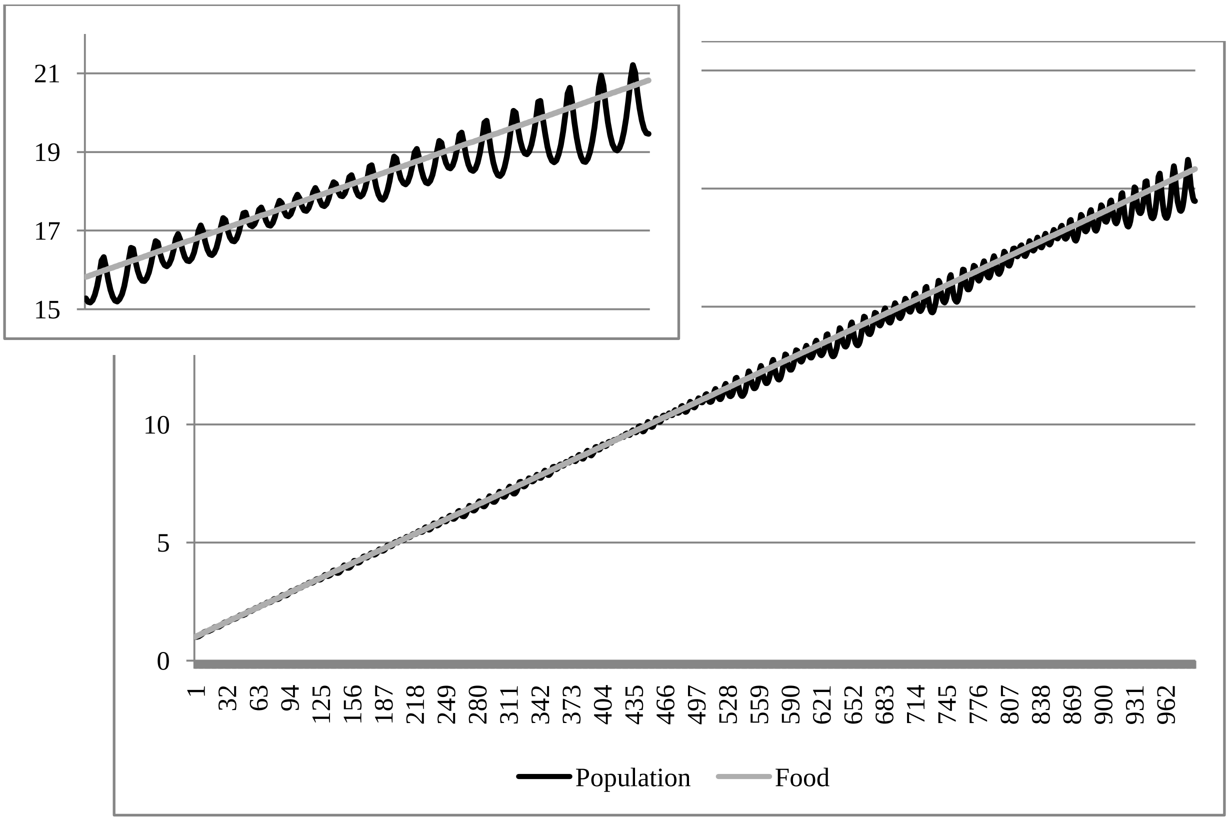

Figure 4: A Malthusian Food & Population Feedback model (with expansion of top right of graph)

The model starts with food and population at 1.0 but with food increasing linearly at 2% p/a and the population at a compound of 0.5% p/a. If however the population exceeds the food, a reduction of growth is made of the difference between the food and population. As you can see above, this results in a chaotic harmonic characterised by long periods of population growth punctuated at semi-unpredictable times by famine. Of course, real populations know when food is running out and can act in anticipation – however, the vicissitudes of weather make it far harder to predict in reality and thus this very simple model surprisingly captures something close to the truth (however do see below about sigmoid curves).

Empirically, certainly for most of human history almost every society that has written down their history has written of regular famine – for example, there were 1,828 famines in China during the 2,019 years between 108 BC and 1911 AD (Mallory, 1926) and from my reading of the timings, they look quite similar to my model above – close, but not quite, to regular.

Famine held the world population growth rate to around 0.05% between 400-800AD, 0.1% between 800-1200AD, 0.08% between 1200-1600AD, 0.3% between 1600-1800AD and since then (US Census Bureau, 2008):

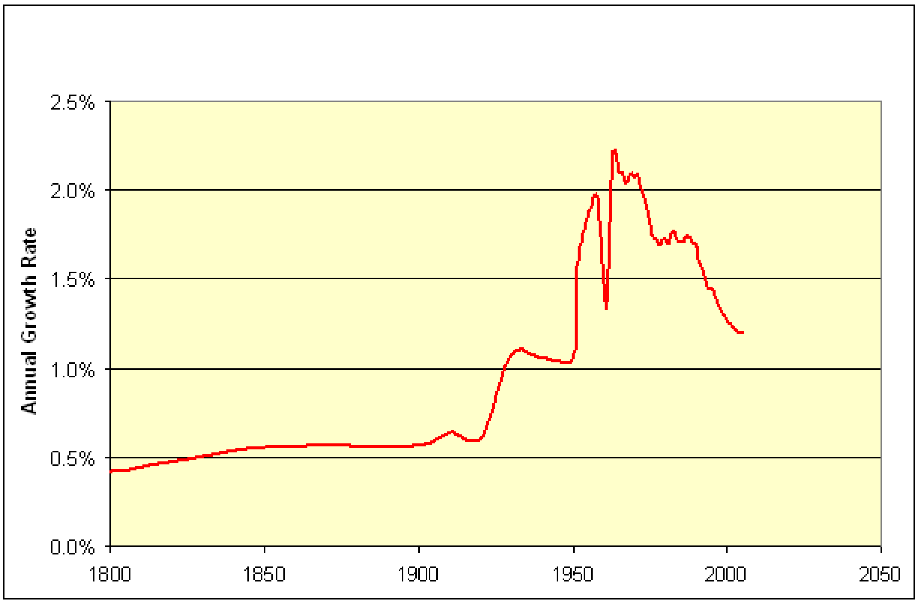

Figure 5: World Population Growth Rate 1800-2006

One can literally see the introduction of the second green revolution (described below in section 2.3) as it is brought firstly into western countries after the first World War, then developing countries after the second World War. Note how the growth curve approximates that of a normal (Gaussian) distribution – we'll come back to that.

In response to Malthus' 1798 essay, Pierre François Verhulst wrote a paper in 1838 which gave an improved population modelling equation called a logistic curve, the differential of which looks very similar to a normal curve (Verhulst, 1838):

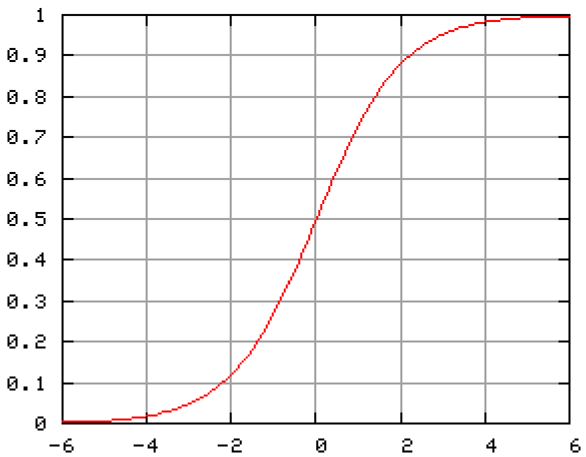

Figure 6: A logistic curve (also called a "S-curve")

This is what happens to an ideal population with perfect information knowledge (i.e.; zero environmental feedback delay) in a constrained environment. To explain, at the start the population grows unconstrained and thus it approximates exponential growth. Toward the middle, environmental constraints kick in and growth linearises, and towards the end growth goes into exponential decline.

This is why to Malthus, or indeed many of the commentators since, growth can appear to be exponential or linear depending on how detailed your data is and how far its time span stretches. In fact, the whole history of the Universe and evolution on planet Earth is probably a series of compounded S-curves[xxii] – so whenever there is a significant technological/ evolutionary advancement, a new S-curve begins, the system shifts exponentially from the old toward a new equilibrium, then linearly, then exponentially slows down as it reaches the new equilibrium. If you take the second derivative (i.e.; the derivative of the S-curve), you get a bell curve (approximating a normal distribution).

That second derivative in this context is actually very famous – most educated people have heard of something called "Hubbert's Peak". This term came from M. King Hubbert's 1956 paper which predicted "Peak Oil" when supplies would not run out, but their growth in output would stagnate and then fall (Hubbert, 1956):

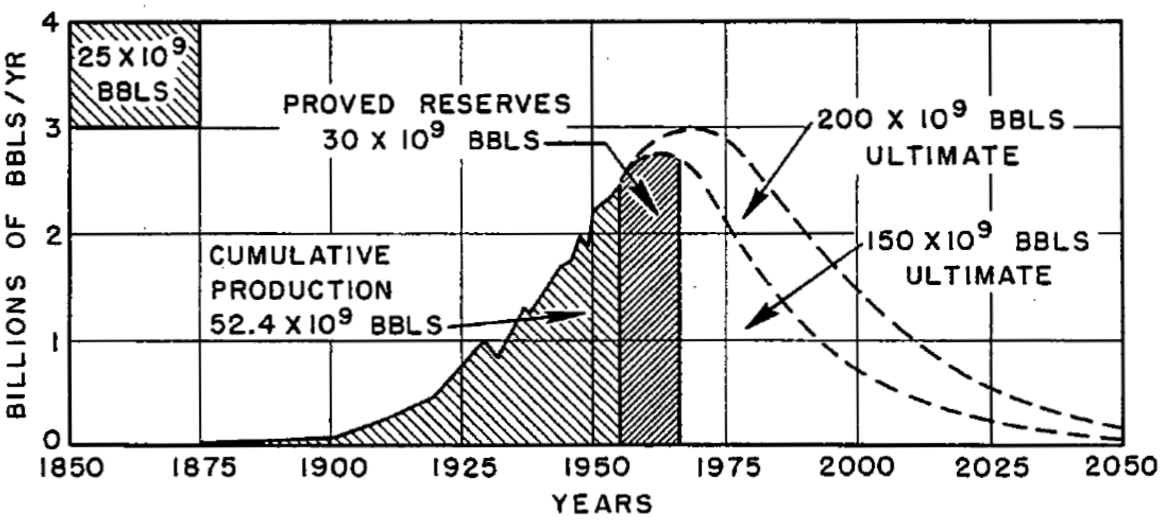

Figure 7: The original prediction of Peak Oil in US production from Hubbert's 1956 paper

Here's world phosphorous production as mentioned earlier:

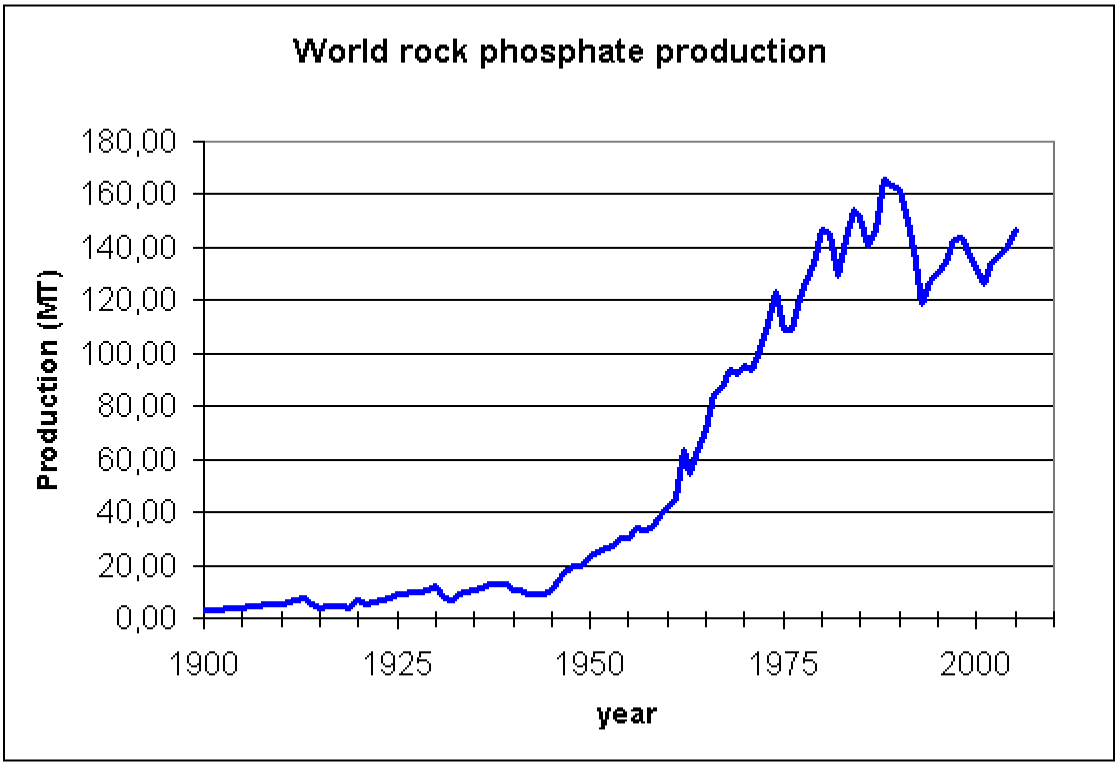

Figure 8: World Phosphorous Production (Déry, 2007)

One can see how the bell curve has already passed its peak.

So here's the first uncomfortable truth: Compound growth within constrained dimensions is **always** sigmoid – and even if there are substantial delays in feedback (which cause gluts & crashes, or boom & bust i.e.; oscillations), over the very long term it still results in a sigmoid curve. We even have fairly conclusive evidence from the fossil record suggesting that this so despite quite a few short term deviations due to mass extinctions (Fountaine, Benton, Dyke, & Nudds, 2005).

2.1.2 Energy and Industry

Somewhat paralleling but also advancing Malthus, the great Economist W.S. Jevons wrote *The Coal Question* in 1865 which was the first work that I am aware of to substantially treat the Economics of a fundamental resource. Taking coal as the "food" of industry, he projected that were Britain's use of coal to continue its then exponential growth, a simple inability to extract it quickly enough would constrain Britain's economy and thereafter, reduce it as the coal ran out – which was entirely likely given the then known coal reserves (Jevons, 1865). This argument by Jevons is exactly the same applied to Peak Oil today, and it was the brilliance of Jevons to have covered most of the problem all the way back in the 19th century – he even predicted how the oil shock of the 1970's would cause efficiency improvements in oil-using technology, thus causing an even greater increase in demand later on as the efficiency improvements opened up new forms of demand (the 'Jevons paradox').

As we all know, the coal reserves never ran out[xxiii] because oil came along to replace it. Many modern criticisers of Malthus and his contemporary form of Paul Ehrlich (who wrote *The Population Bomb* in 1968), have argued that technology makes our civilisation different from previous ones. Julian Simon, in a very famous paper entitled 'More People, Greater Wealth, More Resources, Healthier Environment' (Simon J. L., 1994), makes a good and strong argument that free market capitalism has always found substitutes for fundamental resources, so when the wood supply reached capacity it found coal, when the coal supply reached capacity it found oil and when the oil supply reached capacity after OPEC price rises in the 1970's it found nuclear. However, in my opinion, there is a major fly in his logic:

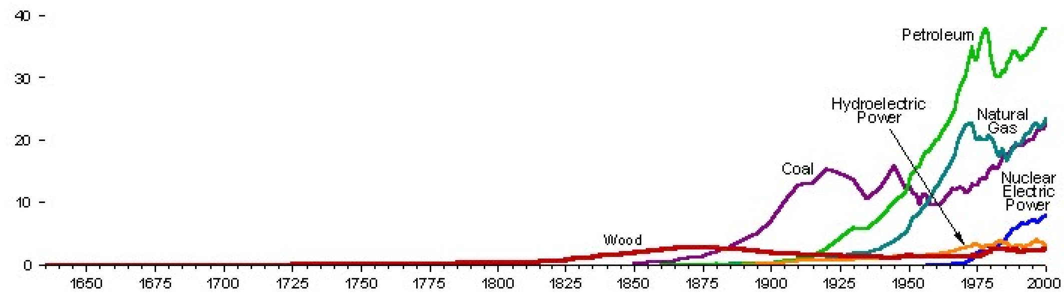

Figure 9: US Energy Breakdown in quadrillion BTU 1635-2000 (US Energy Information Administration)

A substitute is only a substitute if it replaces the original – as is very clear from this graph, wood, nor coal, nor any other energy source *has ever actually declined* – they have plateaued for a while, but have always returned to their ascent such that the *total* energy consumption continues its meteoric rise. Let us have a look at food production per capita:

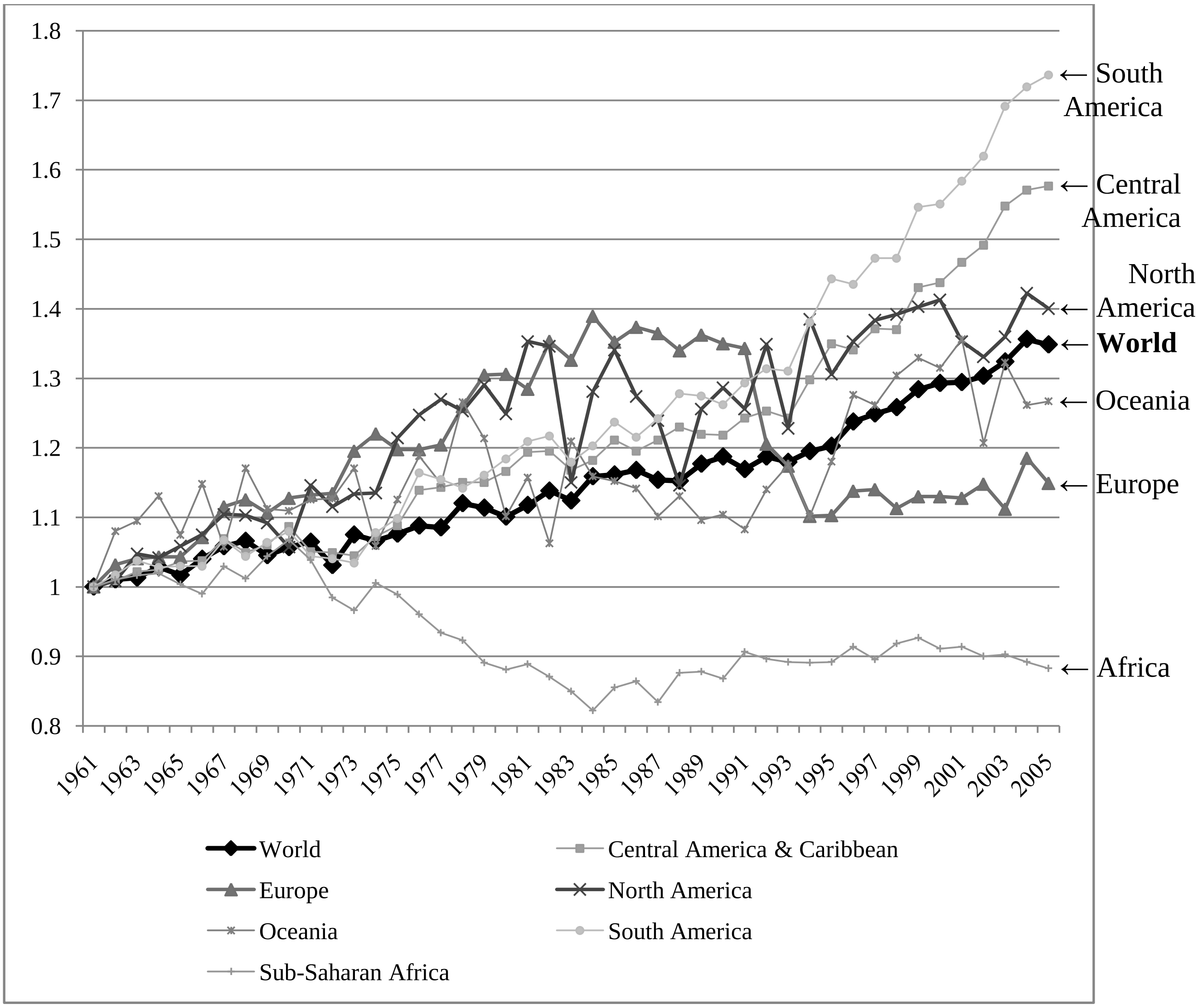

Figure 10: Food Production per Capita for selected areas (normalised to 1.0 = 1960)

As one can see, world per capita food production has never dropped below 1960 levels ever nor does it show much sign of doing so any time in the near future with it standing at 1.35 times the 1960's level in 2005. Even every subregion of the world has exceeded population growth except for Africa – as every Economist knows, the famines of the last fifty years have been caused by *allocation* problems, not supply problems. How this was achieved by substituting fossil energy to gain more food (the second green revolution) is covered in section 2.3 below.

Julian Simon wrote a very famous neo-liberal Economics book entitled *The Ultimate Resource* in which he advocates a major difference between "engineering" and "economic" modelling of resources (Simon J. L., 1981). This very same difference is precisely what separates our two climate change models and is discussed in much greater detail in Chapter 3

– but for now, I find Simon's argument to be logically flawed and here's the next uncomfortable truth:

From the empirical evidence, all of the "substitutions" in **fundamental** resources such as food and industrial energy have actually been *augmentations* of that resource – the original resource carried on being used at near-maximum levels simultaneously. This is NOT the same as say the substitution of lignum vitae (a very hard, naturally lubricating wood originally used for shaft bearings) with sealed white metal bearings – these are close substitutes, and one completely replaced the other due to lignum vitae resources becoming over-exploited.

The uncomfortable truth is that fundamental resource limits have never actually been fixed by capitalism OR technology – they've simply been made to hide. And unless we find some new energy resource (most pundits currently think it will be wind or nuclear – which it won't because nuclear can only easily generate electricity, not hydrocarbons[xxiv]) to augment the current ones, we have a very big problem. Note that Jevons did discuss the use of oil as a substitute for coal, and he dismissed it thus: "It is evident, in short, that the sudden demand for the manufacture of petroleum, added to the steady and rising demand of the gas works, will use up the peculiar and finest beds of oil and gas-making coals in a very brief period" (Jevons, 1865). He was wrong in the short term, but may well be quite right in the long term.

It could be that we are aware of a new resource, but simply have underestimated its potential as Jevons did. Whatever it might be, it will have to be carbon-neutral at the very least, and while this author can think of many possible alternatives, they all come with caveats as bad as or worse than nuclear power[xxv].

2.2 Value and Gross Domestic Product

It is highly important to cover GDP before discussing the climate change models for the simple reason that the models tend to state consequences of action or non-action in terms of effect on GDP. This can be highly misleading, because as we shall shortly see, GDP doesn't mean what most people think it means.

Most people think GDP means "a measure of the economy" and in this they are absolutely correct. Unfortunately, they tend to think of that in *positive* terms, so for them when a politician or economist says "the economy is doing well" they take that to mean that people somewhat similar to themselves are experiencing an improving life (which usually means a rising income).

GDP's actual definition is the money market value of all final goods and services transactions in an economy in a year and it is invariably termed in whichever currency is the most important in the world (currently that's the US dollar). One can crudely adjust GDP for local cost differences via Purchasing Power Parity (PPP), but nevertheless one is still converting all kinds of human economic activity into a money value based on current market prices.

This has very obvious problems. The first is that *any* kind of monetary human economic activity adds to GDP, so if crime jumps tenfold then GDP rises through the extra costs of imprisoning people, buying replacement goods for those stolen etc. Similarly, if climate change costs become onerous, GDP will *rise* to reflect the added human activity even if everyone's life becomes much less pleasant to live.

The second problem with GDP is that it only values certain kinds of economic activity but not others. Traditionally, this meant that women's contribution to the home was not counted as no final goods or services transaction happened but this problem has diminished in the west as more women have started to work – though not yet of course in developing nations. It doesn't count barter or non-monetary exchange so charity, community & volunteer work is left out. This results in a very significant proportion of human economic activity in developing countries being totally excluded.

The third problem with GDP is that of the things it does value, it does so at *current* market prices according to *current* perceptions of value. This creates an automatic bias towards the status quo i.e.; Westerners, because it is our purchasing power which decides the relative value of things for the rest of the world and it is also us who sets accounting rules or world trade rules, and historically we have tended to bias them in favour of ourselves.

One can adjust for the first two problems, so this is US GDP per capita adjusted for wealth gap effects, housework, volunteering, education, resource depletion, pollution, environmental damage, leisure time, military, capital item depreciation and debt:

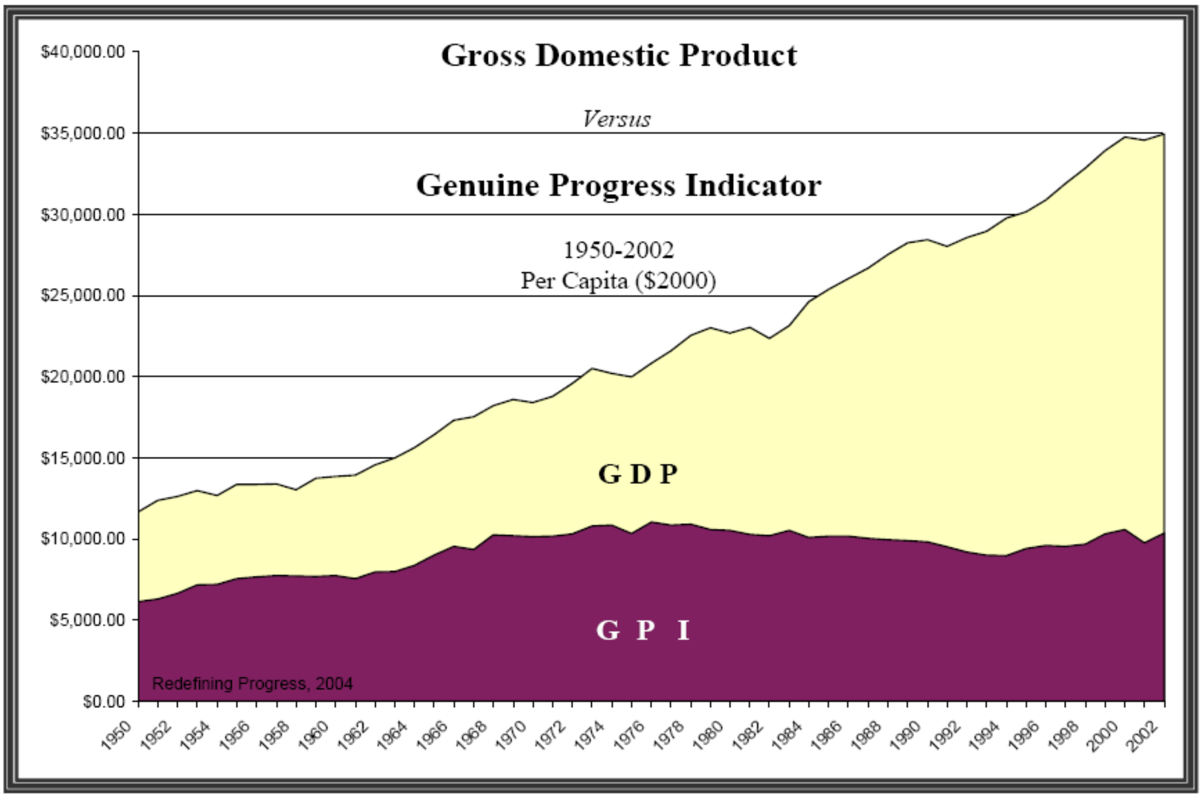

Figure 11: 'Genuine Progress Indicator' for the US 1950-2002 (Redefining Progress, 2008)

One huge effect of all three of these problems is that GDP effectively values a human life in terms of net contribution to a Western style mostly male monetary economy. Thus, one person generated in 2007 an average of (PPP adjusted) US$45,845 in the US economy whereas it was only US$309 in the Democratic Republic of the Congo (International Monetary Fund, 2008) – realistically speaking, such an actual differential of human activity seems unlikely[xxvi].

All these issues majorly affect what is really meant by a statement such as "failing to curb carbon emissions to 1990 levels will reduce GDP by 5%". I think a very clear example of this is Germany’s GDP per capita during the second world war:

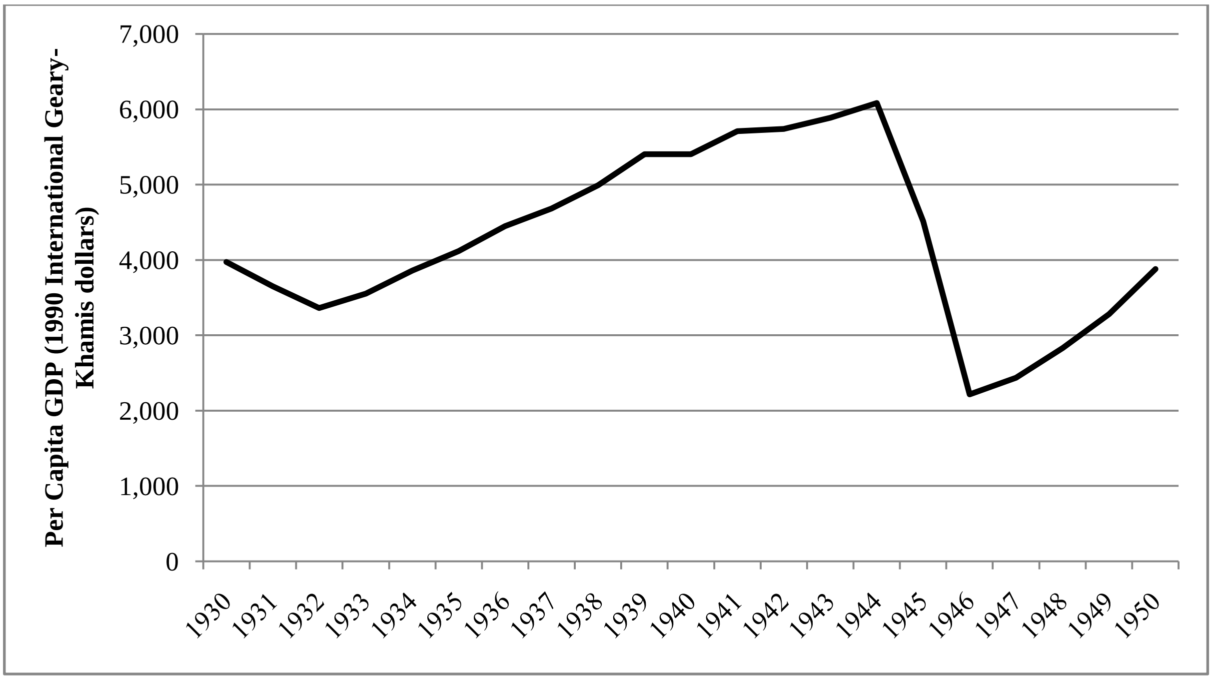

Figure 12: German GDP per capita 1930-1950 (Groningen Growth and Development Centre)

Despite that bombs were raining down upon them and the population was falling, final goods and services transactions per capita rose at a very healthy rate during the war – not least because as the less protected parts of the population (i.e.; the poorer ones) were killed off, a per capita index is bound to improve.

This is the problem with using a measure such as GDP to gauge costs to society. The third uncomfortable truth is that talking about effects on GDP without some sort of negative production adjustment probably doesn't tell us much that is useful except to what affects rich Western men.

2.3 The Green Revolutions

Most people alive today in the West (even the older ones) cannot remember what farms and fields used to look like – they think that what they see today in the countryside has always been. This is an urban myth – thanks to the second green revolution, fields today look quite unlike fields a century ago and thanks to the first green revolution, a Roman citizen would find much unusual in even the fields of a century ago.

The first green revolution was the powerhouse of the original medieval expansion of Islam – much improved agricultural techniques, later adopted by Western Europe, allowed the Muslim population to grow much faster than its neighbours[xxvii] which in turn gave it the workforce and soldiers to invade its neighbours. In fact, most of what differs even in today's agriculture from the Roman system was invented during the Islamic Golden Age: ideas such as cash cropping, scientific selective breeding of plant strains and livestock, modern concepts of flood irrigation and specialisation of crops to location and indeed a form of property rights all were strong features of the first green revolution – and all are still considered to be at the heart of our own agriculture. As the simplest example, the Romans cropped once every two years, allowing the land to rest – like us, the Muslims had four full harvests in the same time span, using "artificial" (in the sense of it not being animal dung) fertilisers to maintain the soil (Watson, 1974).

I should add at this point that I find Thomas Homer-Dixon's argument in his 2007 book *Upside of Down* persuasive. This books details an extensive thermodynamic analysis of the Roman Empire undertaken by the author which concludes that the real cause of decline was exhaustion of soils through over-exploitation – not political problems as is commonly held, though these certainly did not help (Homer-Dixon, 2007). Even with much improved scientific knowledge of soil operation, I would speculate that the decline of the Islamic Age had exactly the same cause – the time spans are about the same for micro-nutrients to become depleted as is currently happening in rice fields even with advanced strains of rice (International Rice Research Institute, 2008).

The second green revolution originates in the period between the world wars. The Haber-Bosch method had made available hitherto unavailable amounts of nitrogen, but a big problem was that traditional strains of grain (invented by the Muslims) did not react well to large inputs of nitrogen because they grew too tall and big, and thus became top-heavy and prone to falling over which resulted in substantial crop loss. Scientists thus introduced by selective breeding dwarf genes from inbred varieties to shorten the crop and to remove the amount of energy invested in leaf or stem building (U.S. Department of Agriculture and Agricultural Research Service, 2006). As noted in Chapter 1, photosynthesis has a fairly fixed efficiency and thus in order to maximise yield for humans, **investment of the plant in its other parts must be sacrificed** (this is a requirement of the first law of thermodynamics, that energy will be conserved).

By the 1960's, these special high-yielding strains of "Burr-Leaming" maize (1921), "Gaines" wheat (1962) and IR8 rice (1966) had increased yields by 60% (U.S. Department of Agriculture and Agricultural Research Service, 2006), 67% (U.S. Department of Agriculture and Agricultural Research Service, 2006) and 500% (Datta, Tauro, & Balaoing, 1968) respectively. But this came with five major costs:

1. Abnormally high levels of nitrogen (e.g.; IR8 requires a trebling of nitrogen input, Datta, Tauro, & Balaoing, 1968) – for without this, most high-yielding strains underperformed their Muslim predecessors because their stems would be too weak and leaves too small to grow well.
2. Repeated application of pesticides because these new strains were much less pest resistant – and additionally, as there are only a few high yielding crop strains, this leads to monoculture which greatly increases disease propagation rates.
3. Increased weed control, as due to being much shorter, weeds tend to crowd out the grain plants.
4. Much increased water requirements, as drought resistance was greatly impaired by the lower fibrous content of stalks and leaves – this had been used be the plant to retain moisture. Appendix B shows how these new strains require 60-100% more water per metric tonne produced.
5. Much reduced nutritional content, partially because the soil can only provide so many micro-nutrients per hectare, but also because the plant must expend energy on nutrition which had been bred out in favour of calorific content.

In other words, one does not get something for free – the iron laws of thermodynamics mean that all you can do is **shift the allocation of energy investment**. And to get these high calorific yields, *much* higher quantities of other inputs are required.

So long as these crops remained mostly in the West, the problem was contained. Unfortunately, in response to imminent famine in India in the 1960’s, the US supplied high-yielding crop strains which did indeed allow the population of India to surge – as noted in the population growth graph depicted in Figure 5. This example was rapidly copied by almost all developing countries with the notable exception of most of Africa.

Now here comes the uncomfortable truth. Selective breeding has definite declining marginal returns and even if we fully understood genetic engineering, there is **nothing** that we can do about the fundamental efficiency limits of photosynthesis. I have calculated that there is a fundamental thermodynamic maximum of 40kW/hectare for C3 and 65.8kW/hectare for C4[xxviii] photosynthesis that no technological advancement can break. Empirical testing has found lab-perfect maximums of 23.5kW/hectare and 41kW/hectare (due to some energy being required for roots, stems and leaves – water transport is already accounted for) and maximums in outdoor conditions of 7kW/hectare and 12kW/hectare[xxix] (e.g.; the leaves don't cover all of the ground etc).

A simple calculation shows that IR8 rice (a C3 plant) already yields 4.7kW/hectare under ideal conditions in India[xxx]. This is already better than half perfect, and given that IR8 yields today have decreased by more than 20% when planted in identical conditions to 1970 (International Rice Research Institute, 2008), it would suggest that one is already pushing hard at natural limits. Given that 200 kilograms of nitrogen is already added per hectare in modern rice farming (International Rice Research Institute, 2008), that nitrogen's price is intimately linked to that of natural gas, that there isn't much arable land not already in use[xxxi], and furthermore that we have little more fresh water to go around, there appears to be extremely little room for manoevour.

This is my point – the last two green revolutions worked because there was one limiting factor, and surpluses in other factors were substituted in for that factor. We may be within thermodynamic and material limits of photosynthesis – maybe we can double current yields by disseminating state-of-the-art techniques more widely into developing countries, but the BIG question is "so what?"

Because all that means is that **at most** we could double our population once again and then we really have completely run out of road and *famine is guaranteed on a scale numerically hitherto unknown in human history*. The uncomfortable truth is that while high yielding crops were shared with developing nations for the best of intentions[xxxii], it only saved tens of millions of lives in the short term. Humans, being humans, procreate, so for every person saved by the second green revolution in the 1960's, we caused the addition of around three more. In other words, *we delayed the problem* AND *we made the eventual death toll much worse*. It is well known that the rate of population increase is shrinking, but we are still projected to add another 50% to world population (US Census Bureau, 2008) and as shown in Figure 10, crop yields have plateaued in the US and Europe since the 1980's – which suggests that for all the hyperbole of the supposed coming third green revolution as according to Monsanto, US crop yields have not significantly improved despite widespread planting of genetically engineered crops.

No one is sure what will happen when inflation in the price of artificial fertiliser makes food too expensive to buy. Even the very best techniques in organic farming won't increase current yields, so this means that available food calories are going to at best plateau while the population continues to increase – right back to that Malthusian conclusion. We can gain some insight into the future through the current food price rise which is due to increased wealth allowing more people to eat meat. Meat multiplies its effective grain consumption by between five and ten times (Miller, 1971) so while grain per capita continues to rise, effective grain per capita is shrinking and hence there is an effective supply shortage. I have tried to find reliable data for the amount of grain going into biofuels production so I could generate a graph offsetting world grain production by its diversion into meat and biofuels, but the best I could find was a single paper written in 2007 before the current food crisis which did indeed predict it (Runge & Senauer, 2007) – and sadly it was very short on numbers.

Here's the fourth uncomfortable truth: we should have NEVER given food technology to populations who could not stabilise their numbers before that technology's S-curve usefulness runs out. Unless we can guarantee that adopting that technology simply does not postpone the problem until later, and makes it numerically much worse in the process, such kinds of short-term thinking potentially consign many millions more to needless suffering.

I personally don't think saying "we didn't know" is good enough. We had, and still have, a moral duty to think about the consequences of our actions just a little bit further ahead than a few years from now. Indeed, had we done precisely this, possibly we could have avoided climate change itself when the first warnings were issued to society back in the 1970's.

Chapter 3: Two Kinds of Climate Change Model

We have spent the last two chapters covering the basic science intimately underpinning climate change & agricultural production and then issues with how we measure, understand and value our world. It is now time to investigate how contemporary models perform when modelling the costs of climate change and the costs of its mitigation. Note that none of these models actually models climate change itself – there are models which do, but they are outside the scope of this paper.

As Julian Simon correctly said (Simon J. L., 1981), there are two main kinds of economic model: "economic" and "engineering". I can't explain it better than him, so here's the direct quote:

> *"What Is the Best Way to Forecast Scarcity and Costs?*
>
> *There are two quite different general methods for forecasting costs of any kind: the economist's method and the technologist's (or engineer's) method. The engineering method is commonly used in discussions of raw materials, but I shall argue that the conclusions about costs reached with it are usually quite wrong because it is not the appropriate method.*
>
> *With the technical engineering method, you forecast the status of a natural resource as follows: (1) estimate the presently known physical quantity of the resource, such as copper in the earth that's accessible to mining; (2) extrapolate the future rate of use from the current use rate; and (3) subtract the successive estimates of use in (2) from the physical "inventory" in (1). (Chapter 2 discusses technical forecasts in greater detail.)*
>
> *In contrast, the economist's approach extrapolates trends of past costs into the future. My version of the economist's method is as follows: (1) ask whether there is any convincing reason to think that the period for which you are forecasting will be different from the past, going back as far as the data will allow; (2) if there is no good reason to reject the past trend as representative of the future as well, ask whether there is a reasonable explanation for the observed trend; (3) if there is no reason to believe that the future will be different than the past, and if you have a solid explanation for the trend--or even if you lack a solid theory, but the data are overwhelming--project the trend into the future."*

In a nutshell, an economic model projects past *human* perceptions of value into the future whereas an engineering model projects past physical processes into the future. In other words, the former is a kind of *cognitive* model whereas the latter is a kind of *physical* model. The former implicitly assumes a trend of technological progress allowing continuing "business as usual" via ever improving substitution whereas the latter implicitly assumes fundamental (non-substitutable) limits. As we covered during the previous two chapters, neither is right nor wrong – indeed as section 2.3 showed, we already can double agricultural yields in perfect outdoor conditions and half the absolute maximum of 40-60kW/hectare (i.e.; 20-30kW/hectare, some three times higher again) could become possible someday.

The Stern report is a tried & true economic model (which we will call "type A") of climate change whereas the Limits to Growth almost exclusively models physical transformations of things like water, soil, fossil fuels etc (which we will call "type B"). Having clarified this, time for our own analysis:

3.1 Model Type A – The Stern Report

The Stern report, published in 2006, commendably tries to estimate the effects of various kinds of climate change on the economy. In what I describe next I have mostly focused on its treatment of agricultural effects though of course there will be considerable costs incurred by more extreme weather patterns and such.

Stern mostly bases his conclusions on feeding the IPCC third assessment data into an economic model called PAGE2002. This stochastic model gives out results in terms of statistical probabilities and thus Stern found it preferential because he could state probabilities of outcome. PAGE2002 is particularly notable for its inclusion of an Arrow-style "learning function"[xxxiii] which has a log-log relationship between technology usage and cost which can cause the "technology lock-out" of environmentally benign technologies, but can also reduce the cost of abatement by 50% (Alberth & Hope, 2006) (i.e.; in simple words, PAGE2002 takes account of the Jevons paradox described earlier).

PAGE2002 is quite a simple model despite it incorporating endogenous technical change. It considers only three climate change gases plus aerosol cooling in eight world geographical zones, plus only three fixed (i.e.; fixed cost and effectiveness) abatement technologies (Hope, 2006). It has been labelled by Richard Tol as the most pessimistic of the economic climate change models because it does not allow for climate change to benefit the economy due to it fixing a floor on the benefits and cost reduction of abatement technologies (Tol, 2006).

The basic premise of Stern is that continuing economic growth (which he assumes will continue at the average rate of the last fifty years or so) means growth in greenhouse gas emissions which could cause a rise in world atmospheric temperature. Should things continue as at present, it suggests a 77% to 99% chance of a temperature increase of 2C should effective CO_2 levels exceed 550ppm and a 50% chance of exceeding a 5C increase by the end of the century (Stern, 2007). That's rather important considering that the planet is already normally 4C warmer than average as we are currently at a warm glaciation point:

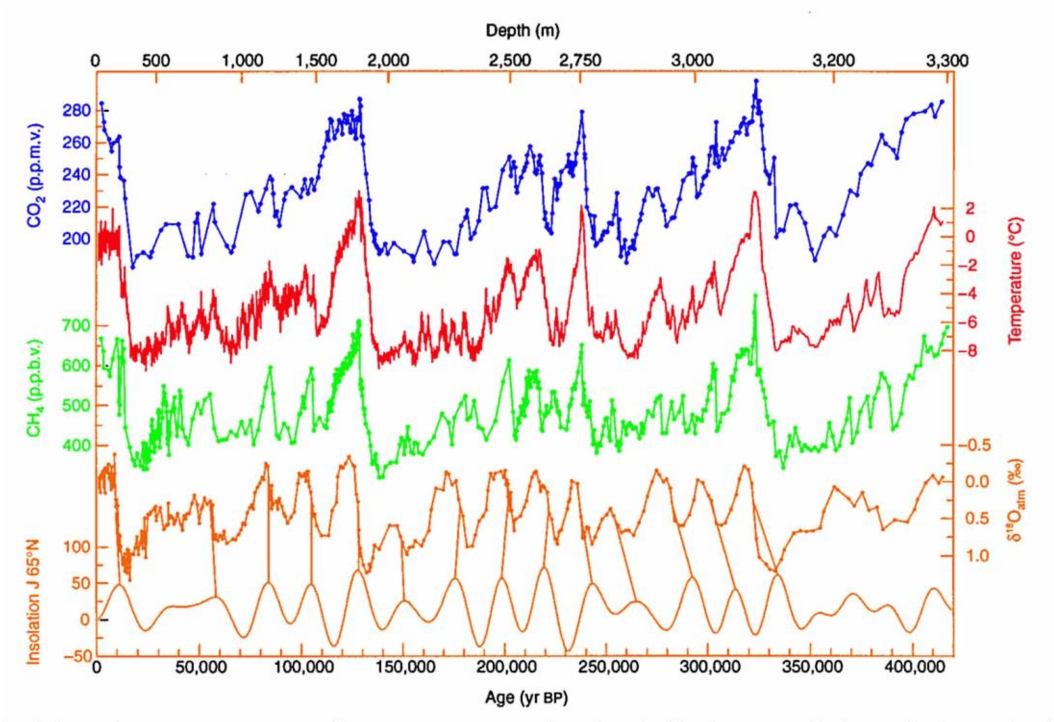

Figure 13: Atmospheric history according to Vostok ice core 0-430,000 years (Petit, et al., 1999)

As Vostok shows, we are at precisely the worst possible point to be pumping even more greenhouse gases into the atmosphere and we are all very aware of how many species become extinct with even a 2C temperature change (think ice ages, and these happened thousands of times more slowly giving life a chance to adapt).

Stern covers four main economic effects from warming:

1. Melting glaciers will increase flood risk – important as much of the world's population lives near the coast.
2. Declining crop yields in equatorial zones due to increased temperature and thus water requirements.
3. Movement of equatorial diseases such as malaria north into highly populated Western countries.

4. Massive loss of marine ecosystems with particular impact on fishing which is the only source of protein for most of the world's poor.

From just these direct effects and the associated 2-3C warming, Stern estimates a permanent loss of at least 5% in per capita consumption (Stern, 2007).

In addition, according to Stern such a rise in temperature may have secondary effects such as killing off the world's rainforests, changing the flows of ocean currents transporting heat from the equator to the rest of the planet and the release of even more methane through the melting of permafrost (which would cause a runaway warming effect). These "non-market" effects could cause a total loss of 20% in per capita consumption (Stern, 2007).

Stern now turns to the costs of mitigation. He aims for no more carbon to be produced than the earth can sink which he has at 80% of current emissions, thus the annual costs of stabilisation at around 500-550ppm would be around 1% of GDP by 2050 with a range of -2% (a gain) to +5%.

Neo-Classical Economic theory says that consumption is directly linked to welfare and Stern does not even question this assumption despite that welfare increases (as determined by health, education and happiness) are known to barely respond to consumption past around US$15,000 (PPP) a year (Wilkinson, 2007), which most people in developed nations exceed.

3.1.1 Critical Response

I would generally say that most of the reaction to Stern's report has been positive – indeed, Her Majesty's Treasury has a list of supportive quotes from eminent and often Nobel prize winning Economists on the Stern Review website[xxxiv]. However, I have noticed that this reaction mostly consisted of general statements about it being time to act, it being "timely" and that government and business now had no recourse to an economics-based refusal to change.

The negative commentary has mostly focused on how Stern estimated costs with the two sides of the debate saying that he placed too much or too little weight on the costs of doing nothing and taking action now. Partha Dasgupta along with many Economists had particular criticism of Stern's choice of "pure rate of time preference" and rate of risk aversion which he calculated would imply a savings rate of 97.5% while the observed rate is around 15% (Dasgupta, 2007). Many pointed out that the IPCC estimates that a temperature rise of 2-3C will take one hundred, not fifty years and that the scientific consensus on its effects during the next fifty years are much more moderate than Stern's (BBC News, 2007).

William Nordhaus, a conservative Economist, actually has strong praise for the Stern report saying that it corrects most of the main problems he has with contemporary climate change economic analysis (Nordhaus, 2007). He particularly likes how it bites the bullet in advocating a substantial increase in the price of carbon which he calls a "simple yet inconvenient economic insight" which is in his opinion "virtually absent from most political discussions of climate change policy".

He then goes on to spend much of the rest of his paper criticising Stern's "extreme" choice of a social discount rate of "essentially zero" which "combined with other assumptions, this magnifies enormously impacts in the distant future and rationalizes deep cuts in emissions, and indeed in all consumption, today. If we were to substitute more conventional discount rates used in other global-warming analyses, by governments, by consumers, or by businesses, the Review's dramatic results would disappear" (Nordhaus, 2007).

This is based on the same problem that Dasgupta has – Stern's idea of weighing future generations as effectively equal to current ones runs strongly contrary to traditional Economic thinking because it eliminates the incorporation of the historical trend of ever improving technology. If technology were to continue at historical rates of the last few hundred years, humans in fifty years time would be far more able to employ technological means not available as cheaply at present to mitigate climate change – and thus, *the rational choice* is to shelve currently high costs onto them through a simple cost-benefit choice.

Now that's quite an assumption to make, **especially** given how welfare no longer correlates with consumption past $15,000, and we'll come back to it in the concluding remarks. Note that Stern has since said in interview that he felt it was his duty to be more cautious than scientific consensus, thus his use of pessimistic modelling and pessimistic variables – in particular, he points out that the fourth IPCC assessment was more pessimistic than the third and that he expected that trend to continue (BBC News, 2007).

3.2 Model Type B – Limits to Growth

The Limits to Growth, first published in 1972, has become a *cause célèbre* among a certain class of commentators and I don't think anyone could claim that it hasn't stayed in the public mind since its original publication – even if not accurately so. Its original authors have published updates, the first in 1993, the second in 2004 and they have updated their computer model with improved data as it has become available. This paper exclusively examines the 2004 model which is a very substantial improvement over the preceding books – it now uses scientific consensus research (thanks to the IPCC) in almost all its quantitative variables and the few exceptions such as forest clearance have since had solid empirical evidence provided in the fourth IPCC assessment[xxxv]. In particular, one should note that the 2004 edition has addressed practically every criticism of the 1973 book *Models of Doom: A Critique of the Limits to Growth* with five main ideological exceptions (Cole & Pavitt, 1973):

1. Limits to Growth holds that most phenomena treated by their computer model World3 are exponential because the entire model assumes that everything attempts to reach maximum growth as quickly as possible (which is also quite an assumption to make as we'll deal with in the concluding remarks). They still have not changed this viewpoint despite that population growth has definitely become linear in the last twenty years – however, due to the environmental constraints built into the model, most of the scenarios output S-curves and for most of those, population growth linearises from around 1980 till between 2015 and 2025.
2. Limits to Growth is not anti-technology nor is it anti-growth. In fact, it is exactly the opposite: it advocates *increased* rates of technology growth and it **strongly** advocates a decoupling of economic growth from growth in the rate of use of *non-renewable* resources. It argues specifically that the free market will not achieve either without incentives – either negatively, through taxation on non-renewables or positively through focused government-led or private initiatives. One specific reason why they argue this is because the price of raw materials (they specifically treat copper) has declined despite that ore quality has declined massively – Jevon's Paradox once again.
3. Its title is actually a misnomer – it is not concerned about actual limits to growth at all, rather it tries to convey that overshoot (due to feedback delays as shown in the Malthusian model described in section 2.1.1) is the biggest challenge facing the planet. As chapter 1 in the 2004 edition (entitled 'Overshoot') says, the authors have not been very clear about this in previous editions, but in this edition they repeatedly state that under any scenario there will be plenty of all fundamental resources left in 2100 i.e.; there will be **no** shortages (in the absolute sense) of anything! The big problem is one of rate of supply i.e.; the Hubbert Peak will have long passed for all fundamental resources.

4. No attempt is made to predict the future at any stage because as the authors say, one cannot predict the future not least due to non-linear amplifications of tiny initial differences in start conditions. The authors repeat this on several occasions throughout the book and indeed removed the year labels off the time axis in the 1972 edition to emphasise the point. The year axes are back in the 2004 edition, but multiple scenarios are presented each with quite different conclusions.
5. While their World3 model does incorporate a form of the Solow growth model, no other attempt is made to include any form of economic modelling which includes substitution effects or innovation effects or even allocation effects such as how a market might innovate in response to relative price changes caused by climate change. Why? The authors state that it because they are not interested in how limits to growth appear to people, they are only concerned with the physical processes themselves. This echoes into point 1 above i.e.; they assume that there is and will continue to be a market failure.

As I already have a Software Engineering degree, I was able to read the source code for World3 directly and thus what I am about to say is based on my study of the model. The World3 model is considerably more complex than the PAGE2002 model in my opinion. There are many, complicated feedback loops which introduce substantial non-linearities into the model and these appear to have been hand-tuned to fit history rather than empirically derived. Substitution is permitted at the physical process level, so for example agricultural yields can be increased so long as there is a continual application of non-renewables. Unlike PAGE2002, World3 is not a stochastic model and does not generate probabilities of outcome given the same initial starting conditions – in this sense, it is an "old style" dynamic model which recent study has found to be wanting (Alberth & Hope, 2006).

Because of the lack of a pricing mechanism, there is also no distinction made between different types of fossil fuel nor types of agricultural output. In fact, all non-renewable resources are lumped together and treated as one resource as is all agricultural output. A Solow growth model is applied to industry, non-renewables, renewables and agriculture separately. Dollar amounts are used internally, but their value is quite meaningless except to compare say year 2000 in the model with year 2050 within the same iteration. Pollution is dealt with as something which accumulates through application of non-renewables and as it grows, it retards productivity with an additional "toxicity" measure for agricultural land.

Also, because of the lack of a pricing mechanism, Limits to Growth makes no attempt whatsoever to cost how much mitigation might be other than by increasing the amount of reinvestment made from earnings and modifying the technological effects. Scenarios 3 to 6 add various technological improvements while scenarios 7 and 8 have forced restraint made on population and consumption. Scenario 9 combines both, and is the only one which has a completely happy outcome. Scenario 6 with its heavy investment in improved technology produces a reasonable success but with very heavy investment costs borne by succeeding generations.

3.2.1 Critical Response

The critical response to the 1972 Limits to Growth was overwhelming and most of it was negative. This was partially due to it being perceived at the time that its predictions of doom had not come true despite that it had made no predictions – only scenarios. It probably didn't help that the graphs were missing their year labels – had they been included, they would have shown doom beginning from 2015, not the 1980's as most assumed at the time.

However we are concerned with the 2004 edition. This has received almost no negative feedback at all from my considerable research on the matter – in fact, there is a considerable lack of any commentary at all other than on internet blogs which has been mostly faint praise. The only serious criticism has been that the IPCC models are much more up to date with the state-of-the-art modelling techniques. This isn't disputed by the authors of the book – indeed, they commend the IPCC for it.

3.3 Analysis of both models in the context of Hard Science

I have boiled the hard science of chapters 1 and 2 into nine main questions:

3.3.1 How do they handle the three main greenhouse gases?

PAGE2002 directly models carbon dioxide, methane and a third virtual gas to represent all the others. These directly feed into agricultural production in eight separately modelled geographic regions.

World3 does not model greenhouse gases at all, it simply treats them as "pollution" which retards agricultural output.

3.3.2 How do they handle aerosol pollution? Is its differing effects upon C3 & C4 photosynthesis distinguished?

PAGE2002 directly models aerosol pollution as something which retards agricultural output but also reduces the rate of warming (an assumption which may now be suspect). World3 has only one pollution count which industrial production increases. Neither make any distinction between crop types.

3.3.3 How do they handle fresh water? As Appendix B shows, fresh water = food.

PAGE2002 completely ignores water. World3 counts water as a renewable resource and it models all renewables as one.

3.3.4 How do they handle rising costs of fertiliser due to rising costs of energy and thus falling of food production per capita?

PAGE2002 completely ignores fertiliser or energy costs. Its only concept of falling food production per capita is through the greenhouse effects.

World3 simply treats fertiliser as a non-renewable, thus ignoring manure. Most World3 scenarios have food per capita dropping severely.

3.3.5 How do they handle fundamental resources? Is energy, space and time conserved?

PAGE2002 allows for two types of substitution effect: (i) one of its three fixed mitigation technologies and (ii) a log-log learning curve applied to each. It assumes a rising cost of fossil fuels over time but not that our total dependence on them will change.

World3 does allow certain substitutions of larger amounts of non-renewables to gain more renewables.

Both conserve energy, time and space as nothing is gained for free. Most Economic models do not.

3.3.6 How do they handle overshoot? Do they accept logistic behaviour? How about the Hubbert curve?

PAGE2002 being stochastic doesn’t exactly incorporate the notion of overshoot except as a probability that some limit will be exceeded – what happens thereafter is unknown (which is fair enough). It does accept logistic behaviour through its log-log response functions and a sort of Hubbert curve does emerge in its statistical outputs.

World3 was designed specifically to demonstrate all kinds of overshoot as the authors gleefully cover over several pages. It therefore has logistic behaviour and Hubbert curves throughout.

3.3.7 Do they integrate the Jevons Paradox? How are the effects on welfare calculated?

PAGE2002 specifically incorporates the Jevons Paradox but assumes that human welfare is directly linked to consumption (and thus GDP). As covered before, unadjusted GDP is pretty useless for most of the world's population.

World3 also specifically incorporates the Jevons Paradox by assuming that non-renewables grow cheaper through time due to technological improvements and that that investment in improvement can be spurred by shortages – but this simply brings on collapse quicker. World3 models welfare by a direct implementation of the UN's Human Welfare Index which is the average of life expectancy, education and consumption.

3.3.8 Does it take account of synergies?

This is something that I haven't covered yet in this paper, yet it seems highly important for calculating the cost of mitigation. Synergies are when you can reorganise a system's inputs in such a way as for them to gain off one another for "free" simply through better arrangement. A simple example is tying a power plant's waste heat into a local town's heating system – the town is heated for "free". Another example is that by investing more money when building a factory into slightly wider pipes, pumping costs can be halved or quartered throughout the life of the factory and thus saving many more times the initial investment. There are many more examples: *Natural Capitalism* (Hawkin, Lovins, & Lovins, 1999) is packed full of them taken from real-world industrial examples. Making a 2x improvement at sources plus a series of 2x improvements along the supply chain can generate a 40x efficiency improvement by the production of the finished good.

PAGE2002 does incorporate synergies after a fashion through their learning curve, but it's not a great fit. World3 also incorporates them after a fashion through their scenarios diverting much production into technological advances, but once again it's not a great fit.

All in all, neither model is particularly good in modelling the costs of mitigation. Neither is detailed enough in their physical model.

3.3.9 Does it take account of ecosystem (and thus agricultural) collapse due to rapid warming?

PAGE2002 has a statistical probability of total collapse which increases in likelihood as the temperature rises. World3 has no concept of rising temperature, just increasing “pollution” past whose tipping point collapse occurs.

I find neither approach particularly helpful given that any warming in such a short time period at all, even 1C, is too unpredictable and therefore risky to contemplate.

Conclusion

I am going to be extremely blunt in this conclusion – I have reviewed many of the models beyond PAGE2002 and World3 including the IPCC ones and as shown at the end of Chapter 3, I find them quite primitive. In fact, I find them *worryingly* primitive considering where the hard science is pointing. As a trained computer engineer, I know there is no shortage of talent capable of generating far better quality models – sadly, they are tied up generating quant models for the finance industry in the City because that's where the money is (in fact, some friends of mine from there just retired after becoming burned out by the sixty hour weeks).

However before considering the technical nature of the models, we have a severe problem with the assumptions we are using before we design those models. As this paper has shown, there are substantial implicit assumptions in how we term worth in our Economics, and many of these are quite shocking.

For example, we know that welfare isn't correlated with consumption after US$15,000 (it becomes tied to *relative* consumption over your perceived peer group instead – Wilkinson, 2007). So why on Earth would Limits to Growth take as granted that consumption at present levels in developed countries should be stabilised across all citizens in the World? Or even worse, Stern takes as granted that consumption should continue to exponentially increase at historical rates which through compounding yields ridiculous levels within fifty years? Make no doubt of it – a huge majority of the human population's effective carbon emissions are generated by both the richest AND the poorest segments of the world population[xxxvi], so too much AND too little consumption by too many people is the main driver of climate change[xxxvii]. Yet, the scientific advisor typically assumes that no politician will ever seriously accept trying to reduce people's consumption for their own good – despite that examples such as tobacco and car use stand contrary.

Another example is a simple moral one: the rich consistently tend to value poor people as of less worth than rich ones, and Western people as of more worth than those in developing nations. In Economics, we value people according to earning or consumption ability. In all cases, we only think a few decades ahead at most and pray to the great god of technological progress that some new fix will come in time to prevent catastrophe occurring as a consequence of our actions – when this has been a historical oddity only occurring very recently indeed. We see this most evident in Economic criticism of Stern's report because he didn't use a discount rate – which is even more morally repugnant considering that we then use this presumed magic of technological progress as a justification for a "do nothing" attitude on the basis that future generations will be better equipped for it. I wonder, do any of these people ever consider that our predecessors living thirty years ago made the **exact same** cost-benefit analysis and thus shelved this problem onto us? If after the last thirty years of wondrous technological progress we are **still** not ready to act, then how can we genuinely expect people in the next thirty years time to be any different?

No, this is patheticness of the worst kind. This is weakness of will, the worst of the NIMBY[xxxviii] syndrome, passing along the buck as we selfishly and self-destructively try to consume as much as possible now before we get caught out. We are like children, left alone in a sweetshop and despite feeling the nausea coming on, are desperate to consume more before we get caught and spanked for our misdemeanours.

More of the same is not going to stop climate change – it was more of the same which got us into this position to begin with. Limits to Growth is no better with its bleak assumptions of human nature – we aren't stupid, and we *can* limit our own growth if we so choose. Millions of chronically obese people make the decision every year to reduce their eating for their own good – we are sentient animals, capable of seeing the end of the train line coming and slowing down. By assuming the worst *of* us, we model the worst *in* us and *of course* we are then doomed.

No, it is only through transformation into a new & better form of ourselves which will save us. The West must lead the way – we got the World into this state (indeed, some 77% of excess greenhouse gases currently in the atmosphere were generated by the West), and we have a moral duty & obligation to clean up after ourselves. Such a transformation would need to tackle the fundamental functioning of our education, health, sanitation, agricultural, financial, business, political, religious and psychological systems. The change need not be profound – as we know from non-linear dynamics, small changes spread widely can utterly transform a system, and for most of us daily life would be nearly identical to at present.

One thing is for sure – we have an unfortunate weakness with subjects outside our own discipline. Economics should have hard science realities built into its core, yet I have seen precious little reality intrude into Neo-Classical Economics – indeed, most of the progress seems to be being performed by Physicists in Econophysics which was never mentioned even once during my course here at St. Andrews. Indeed, a more pluralist Economics teaching would do wonders for our quality of graduate.

This is not to say that those in other academic disciplines are much better. I personally was stunned during the research for this paper about how much is definitely known, yet how little of that is modelled. I fully appreciate how overly complex models quickly become a mess of feedback loops, yet how many of these computer models reside as open source software on a publicly accessible website such as sourceforge? If the IPCC is serious about getting some more complex & representative models together (e.g.; like the models used for weather forecasting), why doesn't it get experienced computer programmers to sort out the complexities for it? Why not put these models into an easily downloadable program which people can tinker with on their own home computers? This has been done with protein folding via the Stanford@Home project and indeed searching for extra-terrestrial intelligence so it's not without precedent. I worry that some of these researchers have too much to lose from letting outsiders muck around with their work, and preventing climate change will not be helped by partisan academic pride.

Lastly, in my opinion the modelling of the costs of mitigating climate change lies in a lamentable state and I see very little chance for any substantial improvement any time soon. If we still aren't precisely sure what is heating up the planet and how, costing a mitigation strategy seems rather far off. I personally find it interesting that anyone is bothering at all given current knowledge, but sadly our value system ascribes little value unless it is in money terms – witness the furore after all when Robert Costanza ascribed a US$33tn value to the top seventeen ecosystem services ten years ago (Costanza, et al., 1997). One thing which both Stern and Limits to Growth **did** achieve was getting people's attention (even if Stern's 20% of GDP with a 2C rise was laughably low once considering the known agricultural effects of such a quick & large rise). It was for that reason I chose those two climate change models in particular, and I am very glad to now know so much more about their details.

I hope you enjoyed reading these details as well, and thank you for reading them.

Niall Douglas

Monday 28th April 2008

Appendix A: Top twenty six causes of Worldwide loss of DALYs

One fifth of world loss of DALYs is due to lack of good food (World Health Organisation, 2002):

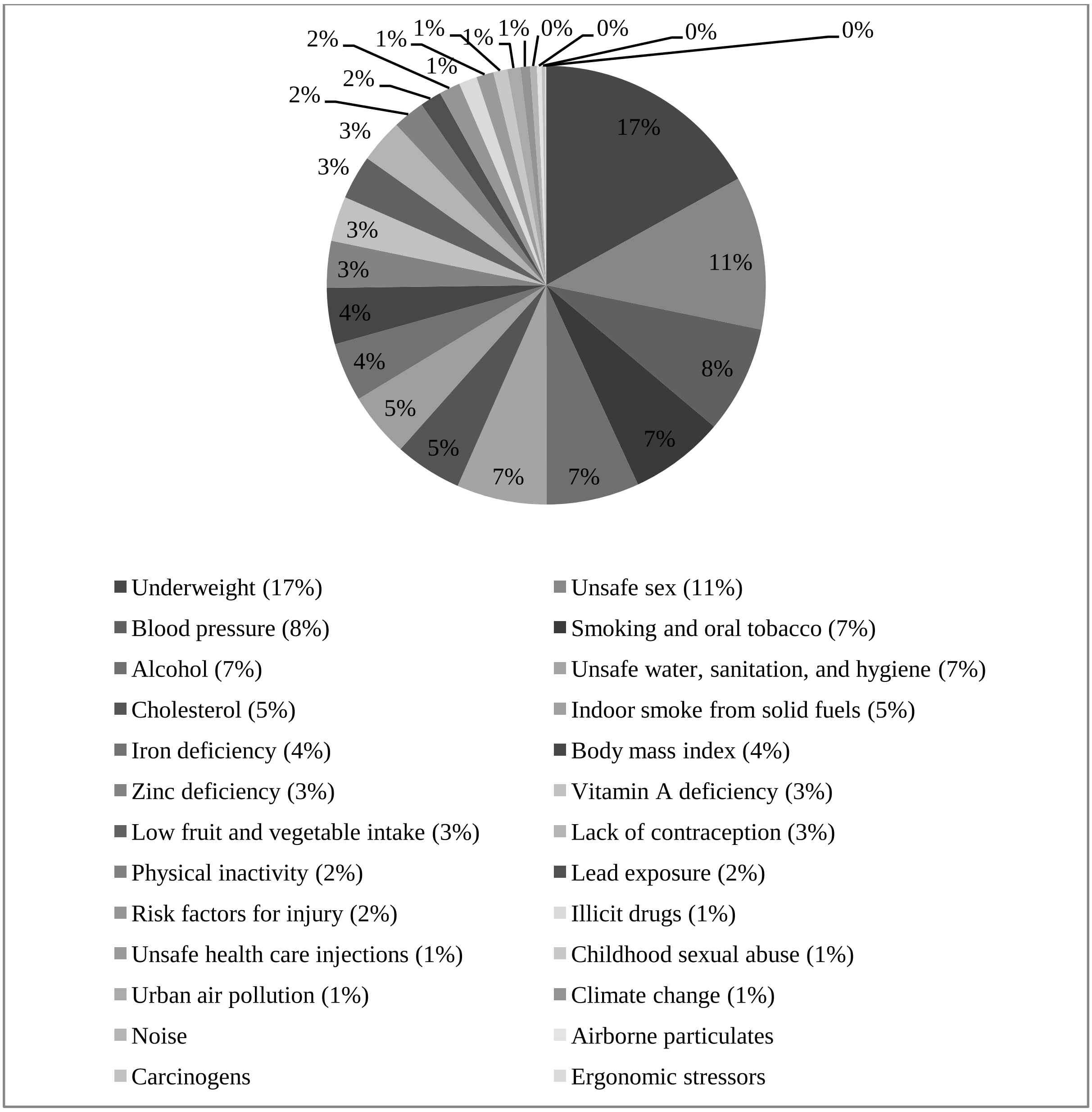

Figure 14: World Loss of Disability Adjusted Life Years (total = 1.46bn) in year 2000

Appendix B: Correlation of Fresh Water and Crop Quantities for Selected Crops

Source: Rockström (2003)

Note how selective breeding has increased the maximum water requirement for many of these crops and thus the average water required per tonne of food. The lower end of the range reflects more traditional breeds. Note also how oil production (e.g.; for biofuels) is particularly water intensive.

Table 2: m^3 of Water per metric tonne of Food

Photosynthesis Type	Crop	Climate	Water Requirements Range		Average
C_3	Wheat	Temperate	780	1640	1480
C_3	Barley	Temperate	540	1580	1000
C_3	Rye	Temperate	540	2640	1270
C_3	Oats	Temperate	540	2640	1370
C_3	Rapeseed	Temperate	1530	2030	1780
C_3	Temperate Cereals	Temperate	660	2300	1250
C_3	Green Beans	Temperate	500	670	580
C_3	Green Peas	Temperate	1430	2000	1720
C_3	Potatoes	Temperate	200	400	250
C_3	Rice	Tropical	900	1400	1150
C_4	Maize	Tropical	940	1460	1150
C_4	Millet	Tropical	590	4370	1630
C_4	Sorghum	Tropical	1100	1800	
C_4	Tropical Cereals	Tropical	500	2480	1400
C_4	Sugar Cane	Tropical	100	200	150
C_4	Cotton	Tropical	2080	2230	2160
C_4	Sunflower Seed	Tropical	1530	3500	2370
	Dry Beans	Tropical	1730	2500	2120
	Soya Beans	Tropical	1250	1960	1610
	Bananas	Tropical	230	320	280
	Oranges	Tropical	200	500	350

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Notes

[i] One could assume instead that the single most important Economic effect will be to the biosphere. That seems obvious of course, but it's a vastly bigger question than merely treating agricultural effects. James Lovelock has advocated in his books that we risk the death of the entire planet (Lovelock, 2007) but I can't see how he's being serious given the planet's current position in the ice age cycle (i.e.; we are on a medium term trend of cooling having just come out of an ice age only 20,000 years ago). See Figure 13.

[ii] To be specific, much simplified this is $6CO_2 + 12H_2O + 56$ photons $\rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O$.

[iii] Everything in this endnote comes from (Taiz & Zeiger, 2006) and (Osbourne & Beerling, 2006). There are three main types of photosynthesis, C3, C4 and CAM. C3 was evolved during a time lacking atmospheric oxygen using the enzyme RuBisCO to fix the carbon dioxide using only 10 photons – unfortunately, it also fixes oxygen which in the modern environment makes it a very energy inefficient process (as half of the photosynthesis simply gets converted to heat through oxidation, a process called photorespiration). C4 uses 14 photons to fix carbon dioxide by drawing it alone into separate structures, thus saving 4 photons as C3 costs 18 photons in our oxygen rich atmosphere. CAM, a "slowed down" form of C4, interestingly fixes a store of carbon dioxide at night for use during daylight – this is to prevent water loss in arid regions.

Note that there is a tremendous difference between the water usage and heat response of C3, C4 and CAM. C3 loses at least 97% of its water due to the heating from photorespiration and this worsens rapidly with increasing heat or lack of carbon dioxide. C4 has little response to heat, and does well with very low carbon dioxide levels and moderate water. CAM needs almost no water at all, but at the cost of a very slow growth rate determined by how much carbon dioxide can be stored during a night.

Note for reference that around 95% of biomass is C3 and 5% is C4 with C4 only becoming more than a negligible proportion of biomass in just the last 6m years. Despite this, 30% of global carbon dioxide fixation is by C4 plants such as maize, sugarcane, bamboo and most grasses (trees and any larger plants are C3). C4 photosynthesis needs direct sunlight with shading of no less than 25% which mostly eliminates them within forests. See Appendix B.

[iv] To be specific, much simplified this is $C_6H_{12}O_6 + 6O_2 + 6H_2O \rightarrow 6CO_2 + 12H_2O + 16$ photons. Note that 40 photons are irreversibly lost to heat thus making this reaction a maximum of 28.6% efficient.

[v] For reference (Taiz & Zeiger, 2006), the essential minerals for plants are (weighted by percentage in dried plant matter): Carbon/Hydrogen/Oxygen: 95%; Nitrogen 1.5%; Potassium: 1%; Calcium: 0.5%; Phosphorous: 0.2%; Magnesium: 0.2%; Sulphur: 0.1%; Iron, Copper, Zinc, Manganese, and Molybdenum: trace. One gets from this the relative importance of mineral inputs for plants.

[vi] This is due to the triple bond in Nitrogen gas, making breaking it up for use very energy intensive. Only a specialised form of bacteria called *diazotrophs* are capable of this – unfortunately, they do not work well in the presence of oxygen which makes their effectiveness in soil and seawater poor (like C3 photosynthesis, they evolved prior to atmospheric oxygen). Only a very select set of plants symbiotically form colonies of diazotrophs, one of which is legumes. For legumes, it costs around 11-13% of total plant respiration to fix nitrogen sufficient for their own growth, only thereafter does the fixed nitrogen become available for other plants (Ryle, Powell, & Gordon, 1979).

[vii] This corresponds to Peak Oil, so it's not that it's run out but rather demand is outstripping supply and there is a resulting large price increase. I get this from a single paper in French no less, and I am relying on Google's translation of it into English, but he appears to have made a systematic analysis of Phosphorous production and I can find no fault with his methodology nor his data (Déry, 2007). I would add though that the ocean floor is full of phosphorous and thus a somewhat more expensive substitute can indeed be found.

[viii] Some would argue now for the Gaia hypothesis (that the entire biosphere is an organism), but this is also outside the scope of this paper.

[ix] We know this from ice core samples e.g.; the Vostok ice core sample. See Figure 13.

[x] Solar radiation literally knocks water molecules off the surface of the water into vapour. This has a much greater effect than simple heat of even 30C because the wavelength of 6000K solar radiation happens to correspond closely with the precisely the energy required to vaporise water molecules. Simple heating at 30C only accounts for a few percent of total evaporation as 300K radiation (background heat) doesn't resonate well with water.

[xi] Yes this directly contradicts my earlier statement that the aerosols make clouds thicker and less likely to rain – therefore one would assume that they would carry moisture further. This is one of the many paradoxical behaviours in climate science – but just because there are minor unexplained phenomena does not mean climate change is not happening.

[xii] This and the following graph was taken from 'The Global Burden of Disease Due to Urban Air Pollution: Estimates and Uncertainties' by Aaron Cohen at http://www.irr-neram.ca/CQ5Vancouver/Cohen.ppt.

[xiii] This means Disability Adjusted Life Years (DALYs) which is a statistical measure of "sufficient healthiness to work".

[xiv] I calculated this as follows: the latest heat of evaporation of water is 2.27MJ/kg and its specific heat capacity is 1.84kJ/kg/K – this means water vapour carries roughly 2.4MJ/kg of energy. Given that there are 31,556,926 seconds in a year, this comes to 40.124PW.

[xv] I calculated this as follows: the Solar Constant, the amount of energy from the sun reaching the visible Earth, is roughly 1366 W/m^2 with a ±0.1% by solar variation. As the Earth's cross section is around 1.274 x 10^{14} m^2, this means 1.74 x 10^{17} W reaches the planet. The reflectivity (albedo) of the planet is around 30%, so that much is immediately reflected out unchanged leaving 70% actually entering the biosphere, which equals 1.2 x 10^{17} W. I felt it important to include these figures because we as a species deeply underestimate how energy expensive it is to generate fresh water – we take it for granted, and we shouldn't.

[xvi] Why? Because the prevailing wind on planet Earth comes from the West, so the further one is from the sea on the West, generally speaking the less rain one gets.

[xvii] Yes, this is about twice the amount deposited on land by rain. However we are currently enjoying a bonanza of free water due to glaciers melting, plus I don't know if Rockström is including aquifer derived water.

[xviii] My own opinion – but I'd doubt many of the experts would disagree.

[xix] For reference, only mammals, amphibians and some fish excrete urea. Birds and Reptiles excrete uric acid – almost certainly a vestige of being the evolutionary descendents of dinosaurs.

[xx] I don't mean to say that the Solow model just assumes automatic technological growth – it does contain an investment ratio and it then assumes that that somehow causes the technological growth. The big question I kept asking back in first year is *why* that assumption should hold true? From where does technological growth come from – indeed, what *is* technological growth? I have some answers to this of my own design but they are highly outside the scope of this paper.

[xxi] Indeed some have argued that we should go to space precisely because we will "use up" this planet and need some new ones to exhaust. I find this mentality pretty pathetic.

[xxii] I refer you to http://ourworld.compuserve.com/homepages/tmodis/TedWEB.htm as a very interesting application of S-curves to our known history since 8bn years ago. Like most who read it, it's very hard to find fault with his logic yet it couldn't possibly be correct surely?

[xxiii] Actually, it's just possible that they did indeed run out. See http://www.theoildrum.com/node/2697 for a review of Britain's coal reserves and a comparison of their historical estimation to reality.

[xxiv] The reason why nuclear or wind power cannot replace coal or oil is very simple: much of our industry depends upon cheap hydrocarbons, and nuclear or wind power can only easily provide electricity. As an example, the Haber-Bosch nitrogen fixation process previously described requires a supply of hydrogen – the

only way nuclear can supply this is to hydrolise water which is extremely energy expensive and it also releases a very toxic waste compound which is oxygen. Oxygen is highly carcinogenic and already kills most people who live to old age; moreover increasing its atmospheric concentration would be an extremely bad idea indeed (think of how well fire burns in a higher oxygen atmosphere) and besides, should we really be using up water to fix nitrogen when human and animal waste already contains plenty?

[xxv] For instance, we may learn how to tap the planet's electromagnetic field as some of the much vaunted "free energy" devices do. However, what happens if such devices become widely deployed? Remember that a very great deal of harmful solar radiation is kept off the planet by our electromagnetic field and woe betide anyone who messes with that. I would apply a similar rationale to geo-thermal - it's fine as a *store* for energy captured from the sun, but I wouldn't go tapping it too extensively.

[xxvi] I am aware that to bypass this problem, GDP per capita is sometimes looked upon as amount "value added". This is think actually says what it means: value added *to* rich Westerners.

[xxvii] It's rare that I would recommend a Wikipedia page, but this one is beautifully written: http://en.wikipedia.org/wiki/Muslim_Agricultural_Revolution - and its author is one of the largest & most trusted contributors to Wikipedia. Note that I have NOT sourced anything from that Wikipedia page – everything comes from (Watson, 1974).

[xxviii] Spreading the solar constant out over the entire Earth surface (to adjust for night time), and after adjusting for albedo at 30%, I get 2.35MW/hectare of solar radiation at the equator. Most of the planet's biomass grows in temporate regions which get about half that at 1.175MW/hectare (Britain gets 1MW/hectare).

Half the sun's light is photosynthetically active radiation (the blue and red components of light, which is why most plants are green). 20% is lost to reflection and absorption, photosynthesis itself is a theoretical maximum of 28% plus another half must go on water respiration in C4 plants, so we take 50% x 80% x 28% x 50% = 5.6% conversion to carbohydrates in C4 plants, which equals 65.8kW/hectare. C3 plants tend to transport much more water than C4, so you can multiply by 60% again yielding 40kW/hectare for C3 plants. This is the **maximum** possible amount of photosynthesis and no new technology can break this.

[xxix] Lab grown C3 and C4 plants in perfect conditions have produced 2% and 3.5% efficiency (which equals 23.5kW/hectare and 41kW/hectare) but outdoor grown plants will never exceed a fraction of that. http://www.arenergysystems.com/ reports that C3 plants can expect a maximum outdoor efficiency of 0.6% and C4 plants 1% (American Alternative Energy Systems, 2008) which gives a realistic maximum of 7kW/hectare and 12kW/hectare.

[xxx] I calculated this as follows: IR8 can generate 10 tonnes/hectare under optimal conditions (Datta, Tauro, & Balaoing, 1968). Rice has an energy content of 14.8MJ/kg so that's 148,000MJ/hectare. As there are 31,556,926 seconds in a year, this comes to 4.7kW/hectare for IR8.

[xxxi] There is a substantial amount of land abandoned after the end of Communism in Russia and other former Soviet states (something which some commentators bang on about incessantly as the reason there is no coming food shortage). It is however coming back into use, and it is just less than the currently estimated amount of over-utilised land that will become lost to agriculture in the next decade. I think this balances the two out for the next ten years.

[xxxii] Some strongly hold the viewpoint that these high yielding crops were given to developing nations as a way of ensnaring them into further dependence on the chemical industries of the Western nations. Given the then cold war climate, I can see that this kind of thinking may have played a part – however, surely such a dependence was temporary at best as the developing nations could source the same chemicals elsewhere – even by then they were becoming commodities. Something else may well apply to Monsanto-type seeds though – some of these are deliberately made sterile to force third world farmers to repurchase seeds every year, meanwhile the engineered strains neuter the normal strains in a neighbour's field and thus a heavy negative externality is created.

[xxxiii] This is Kenneth Arrow's formulation of the Jevon's Paradox i.e.; costs drop through "learning by doing" (Arrow, 1962).

[xxxiv] http://www.hm-treasury.gov.uk/media/1/2/20061028_Quotes-7.pdf

[xxxv] This is my own assessment – in the 2004 book, the authors say that they did not have exact figures for how much carbon was being emitted through tropical forest clearance & burning, and so had to make an estimate (p77). From my own reading, the fourth IPCC assessment seems to have medium (5 out of 10) agreement which suggests a more recent improvement in data quality.

[xxxvi] The richest, as we know, consume a lot of stuff which generates a lot of greenhouse gases. However the very poorest have little choice but to eat into agricultural capital (e.g.; forests) in order to stay alive at a subsistence level by clearing biomass for agricultural land or firewood for cooking. Indeed, around half of black carbon is generated by the very poor in inefficient burners (Ramanathan & Carmichael, 2008), so when combined with its greenhouse gas output, one can see that the poor contribute around 40% of climate warming just as the rich do. In other words, the poor and the rich are about equal in their contributions and the majority of the population (around 60%), neither rich nor poor, contribute relatively little at only 20%.

[xxxvii] In other words, it's **the severity of the wealth gap** which is the primary driver of climate change.

[xxxviii] Not In My Back Yard