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Will Limited Land, Water, and Energy Control Human Population Numbers in the Future?

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Abstract Nearly 60% of the world's human population is malnourished and the numbers are growing. Shortages of basic foods related to decreases in per capita cropland, water, and fossil energy resources contribute to spreading malnutrition and other diseases. The suggestion is that in the future only a smaller number of people will have access to adequate nourishment. In about 100 years, when it is reported that the planet will run out of fossil energy, we suggest that a world population of about two billion might be sustainable if it relies on renewable energy technologies and also reduces per capita use of the earth's natural resources.

Keywords Sustainable world population · Fossil fuels · Population growth · Agricultural land degradation

Introduction

Developed and developing nations need to provide a good quality life for their people while coping with rapid population growth, but "Population is the issue no one wants to touch" (Meadows 2000). The current world population is about 6.8 billion. Based on the present growth rate of 1.2% per year, the population is projected to double in approximately 58 years (Chiras 2006; PRB 2008). Because population growth cannot continue indefinitely, society can either voluntarily control its numbers or let natural forces such as disease, malnutrition, and other disasters limit human numbers (Bartlett 1997–98; Pimentel *et al.* 1999). Increasing human numbers especially in urban areas, and increasing pollution of food, water, air, and soil by pathogenic disease organisms and chemicals, are causing a rapid increase in the prevalence of disease and human mortality (Murray and Lopez 1996; Pimentel *et al.* 2007). Currently, more than 3.7 billion humans are malnourished worldwide—the largest number ever (WHO 2005a, b).

The planet's numerous environmental problems highlight the urgent need to evaluate available land, water, and energy resources and how they relate to the requirements of a rapidly growing human population (Pimentel and Pimentel 2008). In this article we assess the carrying capacity of the Earth's natural resources, and suggest that humans should voluntarily limit their population growth, rather than letting natural forces control their numbers (Bartlett 1997–98; Ferguson 1998; Pimentel *et al.* 1999). In addition, we suggest appropriate policies and technologies that would improve standards of living and quality of life worldwide.

Population Growth and Consumption of Resources

All of our basic resources, such as land, water, energy, and biota, are inherently limited because of human abundance. At the current growth rate of 1.2% the world's population will double to 13 billion in 58 years (PRB 2008).

The U.S. population doubled during the past 70 years from 151 million to more than 305 million, and based on current growth of approximately 1.1% per year (USCB 2002, 2009) is projected to double again to 600 million in the next 64 years. China's population is 1.3 billion, and despite government policy permitting only one child per

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couple, is still growing at an annual rate of 0.6% (PRB 2008). Note that the rate of population growth in the U.S. is nearly double that of the Chinese population.

In addition to limitations due to population size, high per capita consumption levels in the United States and other developed nations put further pressure on natural resources. Americans consume several times more goods and services because of relatively abundant per capita land, water, energy, and biological resources, as compared to the Chinese (PRB 2008). However, industrialized China emits more carbon dioxide than the U.S., largely due to its heavy use of coal (NEAA 2008). Achieving an average European standard of living ($35,000 per capita/yr.) or an average U.S. standard of living ($45,000 per capita/yr.) appears unrealistic for most countries because of serious shortages of basic natural resources (PRB 2008). This does not imply that both developed and developing countries cannot use their resources more efficiently than they are at present through the implementation of appropriate policies and technologies.

Thus far, Americans enjoy relative affluence because of fertile cropland, abundant water, and cheap fossil energy. If the U.S. population continues to expand as projected, however, resource shortages similar to those now being experienced by China and other developing nations will become more common (Table 1), and accelerated declines in living standards are likely.

Status of World Environmental Resources

The quantity and quality of cropland, water, energy, and biological resources determine the current and future status of the support services for human life. There are measurable shortages of fertile land, water, and fossil energy in many regions of the world, making it appropriate to ask, "Are we consuming too much?" (Arrow *et al.* 2004).

Table 1 Resources used and/or available per capita per year in the United States, China, and the world to supply the basic needs of humans (FAO 1998, 2006; Goklany 2001)

Resources	U.S.	China	World
Land			
Cropland (ha)	0.59	0.10	0.22
Pasture (ha)	0.79	0.30	0.52
Forest (ha)	1.01	0.15	0.61
Total	3.06	0.71	2.00
Water (liters $\times 10^6$)	1.7	0.45	0.60
Fossil fuel			
Oil equivalents (liters)	9,500	700	2,100

FAO (1998, 2006); Goklany (2001)

Land Resources

More than 99% of human food (calories) in the world is derived from the terrestrial environment. Although only 0.3% comes from the oceans and other aquatic ecosystems (FAO 2003), even these resources are being stressed near to breaking point.

As Botsford *et al.* (1997) note "the global marine catch is approaching its upper limit" and "management has failed to achieve a principal goal, sustainability." Worldwide, food and fiber crops are grown on 11% of the Earth's total land area of 13 billion hectares. Globally, the annual loss of land to urbanization and highways ranges from 10 to 35 million hectares (approximately 0.5%) (Döös 1994). Much of this land is prime cropland, including prime coastal and river valley land (Döös 2002; Ho and Lin 2004).

In 1960, when the world population numbered about 3 billion, approximately 0.5 ha of cropland was available per capita worldwide. This half a hectare is needed to provide a diverse, healthy, nutritious diet of plant and animal products—similar to the typical diet in the United States and Europe (Giampietro and Pimentel 1994). The average per capita world cropland is now only 0.22 ha, or about 40% the amount needed according to industrial nation standards (Table 1).

Grain production, the most efficient use of cropland because it provides more than 80% of world food, has not kept pace with population growth (Cassman *et al.* 2003). Grain consumption per capita has declined 12% from its peak in 1984 to 2006 (Kondratyev *et al.* 2003; Earth Policy Organization 2008). If the amount of grain land remains the same in 2050 as it was in 2000, grain land per capita will shrink from 0.10 to only 0.07 ha due to population growth (Larsen 2003). Already, in China the amount of available cropland is only 0.10 ha per capita, and rapidly declining due to continued population growth and extreme land degradation (Pimentel and Wen 2004). This shortage of productive cropland is one underlying cause of current worldwide food shortages and poverty (Leach 1995; Pimentel and Pimentel 2008).

Currently, Americans consume a total of nearly 916 kg/yr per capita of food products, (USDA 2007). While the Chinese consume less per capita, by all measurements, they have reached or exceeded the limits of their agricultural system (Pimentel and Wen 2004). Their reliance on large inputs of fossil-fuel based fertilizers—as well as other limited inputs—to compensate for shortages of arable land and severely eroded soils will present severe problems in the future (Wen and Pimentel 1992).

Since cropland has become relatively scarce worldwide, farmers will need to produce increasing amounts from what is currently available. This intensification exacerbates land degradation, including water and wind erosion, and the salinization and water-logging of irrigated soils (Kendall and Pimentel 1994; Crosson 1997), threatening most crop and pasture land worldwide (Fischer *et al.* 2005). Worldwide, more than 10 million hectares of productive arable land are heavily degraded and abandoned each year (Pimentel 2006).

The urgent need for more agricultural land accounts for 60% to 70% of deforestation now occurring worldwide (Myers 1990; Butler 2009), which, in turn, is the prime cause of soil degradation and loss of freshwater in South America and Asia and a major contributor to soil degradation on other continents (Oldeman *et al.* 1990). The vast majority of any future cropland expansion is expected to occur in Latin America and sub-Saharan Africa, leading to massive losses of the world's remaining tropical and temperate forests, savannahs, and grasslands (Kloverpris *et al.* 2008)

Current erosion rates of agricultural land by wind and water, the most serious causes of soil loss and degradation (Oldeman *et al.* 1990), are greater than ever (Pimentel 2006). On average, humans have increased soil erosion at least tenfold from what is geologically normal, with some areas eroding at a thousand times the normal rate (Montgomery 2007). Soil erosion on cropland ranges from about 13 tons per hectare per year (t/ha/yr) in the United States to 40 t/ha/yr in China (Pimentel and Wen 2004). Worldwide, soil erosion averages approximately 30 to 40 t/ha/yr, or about 30- to 40-times faster than the replacement rate (Pimentel 2006). Soil eroded by wind in Africa is detected in Florida and Brazil each year (Pimentel 2000).

Erosion adversely affects crop productivity by reducing the water-holding capacity of the soil, water availability, nutrient levels and organic matter in the soil, and soil depth (Sanchez 2002). Croplands on steeper slopes are especially at risk for accelerated erosion. Over the next century, 33% of the steepest of U.S. cropland is projected to fall out of production due to erosion (Montgomery 2007). Estimates project that agricultural land degradation alone can be expected to depress world food production between 15% and 30% by the year 2020 (Crosson 1997; Pimentel 2000). The global economic cost of soil erosion is estimated to be about $400 billion per year (Lal 1997), emphasizing the need to implement known soil conservation techniques, including biomass mulches, no-till, ridge-till, terracing, cover crops, grass strips, crop rotations, or combinations of all of these. All these techniques essentially require keeping the land protected from wind and rainfall energy with some form of vegetative cover.

The current high erosion rates throughout the world are of great concern because of the slow rate of topsoil renewal; it takes approximately 500 years for 2.5 cm (1 in.) of topsoil to form under agricultural conditions (Troeh *et al.* 2004a). The U.S. is losing soil at ten times the rate of sustainable replacement, and the rate is higher in the rest of the world (NAS 2003).The effects of climate change are expected to lead to increased intensity of storm events worldwide (SWCS 2003), with predictions of 20% to almost 300% increases in erosion rates in some areas as a result of high-intensity rainfall (Nearing *et al.* 2004; Montgomery 2007).

The fertility of nutrient-poor soil can be improved by large inputs of fossil-based fertilizers. The global doubling of grain yields from 1961 to 2000 can be partially attributed to the 700% increase in fertilizer use during the same period (Matson *et al.* 1997; Tilman *et al.* 2001). This practice, however, increases dependency on limited fossil fuels necessary to produce these fertilizers.

If the U.S. population were reduced from the current 305 million to 200 million, per capita cropland would increase to about 0.7 ha (USDA 2007). Using more crop rotations, cover crops, grass strips, mulches and other types of soil conservation technologies will require additional cropland. Still the U.S. should have ample cropland available for domestic food production, plus some for export.

Water Resources

The present and future availability of adequate supplies of freshwater for human and agricultural needs is already critical in many regions, like the Middle East (Postel 1997). Rapid population growth and increased total water consumption are rapidly depleting available water. Between 1950 and 1995, per capita availability of freshwater worldwide declined by about 70% (Gleick 2008–2009).

All vegetation requires and transpires massive amounts of water during the growing season. Agriculture uses more water than any other activity on the planet. Currently, 70% of water removed from all sources worldwide is used solely for irrigation (Pimentel and Wilson 2004). Of this, about two-thirds are consumed by plant life (non-recoverable) (Postel 1997). For example, a corn crop that produces about 9,000 kg/ha of grain uses about 7 million liters/ha of water during the growing season (Pimentel and Pimentel 2008). To supply this much water, approximately 1,000 mm of rainfall per hectare—or 10 million liters of water—is required. The estimated "minimum amount of water required per capita for food is about 400,000 l per year worldwide and in the United States, the average amount of water consumed annually in food production is 1.7 million liters per capita per year" (Sustainable World Water 2002). Most of the 1.7 million liters is for irrigated food production.

Water resources and population densities are unevenly distributed worldwide. Even though the *total* amount of water made available by the hydrologic cycle is enough to provide the world's current population with adequate fresh water—according to the *minimum* requirements cited above—most of this total water is concentrated in specific regions, leaving other areas water-deficient. Water demands already far exceed supplies in nearly 80 nations of the world (Gleick 1993). In China, more than 300 cities suffer from inadequate water supplies, and the problem is intensifying as the population increases (Berk and Rothenberg 2003). In arid regions, such as the Middle East and parts of North Africa, where yearly rainfall is low and irrigation is expensive, the future of agricultural production is grim and becoming more so as populations continue to grow. Political conflicts over water in some areas have even strained international relations between critically water-starved nations (Gleick 1993).

Because of their slow recharge rates, usually between 0.1% and 0.3% per year (Wheal 1991; Covich 1993), groundwater resources must be carefully managed to prevent depletion. Yet, groundwater resources are also mismanaged and overtapped. In the state of Tamil Nadu, India, groundwater levels declined 25–30 m during the 1970s as a result of excessive pumping for irrigation (UNFPA 1991; Pimentel 2002). In Beijing, the groundwater level is falling at a rate of about 1 m/yr; while in Tianjin, China, it drops 4.4 m/yr (Postel 1997). In the United States, aquifer overdraft averages 25% higher than replacement rates. In an extreme case such as the Ogallala aquifer under Kansas, Nebraska, and Texas, the annual depletion rate is 100% to 140% above replacement (Ehrlich and Ehrlich 1997). In parts of Arizona, water in some aquifers is being withdrawn 10-times faster than the recharge rate (Gleick *et al.* 2002).

Desalinization of ocean water is not a viable source for freshwater needed by agriculture, because the process is energy intensive and, hence, economically impractical. A desalinization system in East Africa, for example, reports 70% less energy than other systems, yet still requires 2.3 kwH (nearly 2,000 kcal) per cubic meter (1,000 l) of water (Gilau *et al.* 2007). The amount of desalinized water required by 1 ha of corn would cost $14,000, while all other inputs, like fertilizers, cost only $500 (Pimentel *et al.* 2004). This figure does not even include the additional cost of moving large amounts of water from the ocean to inland agricultural fields.

Another major threat to maintaining ample fresh water resources is pollution. Considerable water pollution has been documented in the United States (USCB 2008), but this problem is of greatest concern in countries where water regulations are less rigorously enforced or do not exist. Developing countries discharge approximately 90% to 95% of their untreated urban sewage directly into surface waters (WHO 1993; Pollution Problem 2009). Downstream, the polluted water is used for drinking, bathing, cooking, and washing (WHO 1992).

Overall, approximately 95% of the water in developing countries is polluted (WHO 1992). There are, however, also serious problems in the United States. The Environmental Protection Agency (EPA 1994) reports that 40% of U.S. lakes are unfit for swimming due to runoff pollutants and septic discharge.

Pesticides, fertilizers, and soil sediments as well as some 100,000 different chemicals applied to crops (Nash 1993) pollute water resources when they accompany eroded soil into a body of water. In addition, industries all over the world often dump untreated toxic chemicals into rivers and lakes (WRI 1993; WHO 1993). Although some new technologies and environmental management practices are improving pollution control and the use of resources, there are economic and biophysical limits to their use and implementation (Gleick 1993).

Food Production

Reducing the calorie intake from about 3,747 kcal per day to about 2,300 kcal would improve the health of the U.S. population. Moreover, a primarily plant-based Mediterranean diet of minimally processed foods and seasonal and locally produced foods is highly recommended (Willett *et al.* 1995).

What has been thought of as waste (manure) from livestock will be a valuable source of nutrients for crop production and an energy source in the form of biogas (Ro *et al.* 2007; Cantrell *et al.* 2008). All livestock should be moved back on farms to make use of the manure and produce biogas.

The primary plant foods in the future will probably be rice, wheat, corn, potatoes, soybeans, cabbage, and a few other plant foods. All of these crops can be produced without any liquid fuel except for the 60 l of ethanol per hectare to run small tractors (Pimentel *et al.* 2008a). For a population of 200 million, estimated as sustainable for the U.S. in the absence of fossil fuels, the area of cropland needed would be 100 million ha, based on 0.5 ha/capita. This reflects the present use of cropland in the U.S., and is estimated to be applicable to a fossil fuel-free future because lower crop yields could be offset by a decrease in the consumption of meat.

The ethanol required to operate the tractors would therefore amount to 60 billion liters. Although with current conventional corn technology the energy balance in producing ethanol is negative, if an organic corn production technology were employed similar to that in Table 2, then the energy balance would become positive (output exceeds input). Growing corn this way is likely to yield a useful 2,000 l of ethanol per ha, so the area of corn needed to produce the ethanol would be 30 million ha. The total of 130 million ha is less than the total area of cropland in the USA, but only ethanol needed for producing crops has been accounted for, and liquid fuels will be needed for other reasons.

Table 2 Energy inputs and costs of corn production per hectare (8,000 kg corn) in the United States and potential for reduced energy inputs compared with 8,228 kcal X 1000 total energy inputs for conventional United States corn tillage. Pimentel *et al.* (2008a,b); Pimentel and Patzek (2008)

Inputs	Quantity	kcal × 1000
Labor	15 h	608
Machinery	10 kg	185
Ethanol	60 L	684
Nitrogen	Legumes	1,000
Phosphorus	45 kg	187
Potassium	40 kg	130
Lime	600 kg	169
Seeds	21 kg	520
Irrigation	0	0
Herbicides	0	0
Insecticides	0	0
Electricity	13.2 kWh	34
Transport	75 kg	25
Total		3,542

It may be noted that although processing the 8,000 kg/ha of corn shown in Table 3 into 2,000 l of ethanol would require an estimated 9 million kcal of non-liquid energy, this is mostly heat energy that could come from wood or an electrical energy source.

The 30 million ha needed for ethanol production adds 30% to the 100 million ha of cropland needed to grow crops for consumption. Using draft animals would require much the same actual area. Two teams (four horses) would be needed to manage 20 ha in a practical manner, and this would require 7 ha of land to provide the corn, hay and pasture needed for the horses (Morrison 1946; Ferguson 2008). Thus 100 million hectares would require 35 million hectares of land for horses. This is a larger area but only 3% would be cropland (Morrison 1946), i.e., about 1 million ha of cropland; so horse power could be a better choice.

Table 3 Potential renewable energy for the United States

Energy technology	Current quads	Projected (2100) quads[c]
Biomass	3.3[a]	7
Hydroelectric	2.9[a]	5
Geothermal	0.3[a]	3
Solar thermal	0.06[b]	10
Photovoltaics	0.06[b]	10
Wind power	0.3[a]	8
Biogas	0.001[b]	0.5
TOTAL	6.8	43.5

[a] EIA (2008)

[b] USCB (2008)

[c] Calculated from Pimentel (2008)

Of the 400 million draft animals used in world agriculture, 19 million are located in sub-Saharan Africa, primarily oxen (Muvirimi and Ellis-Jones 1999). Although there is a tradition of using oxen and horses, donkeys and cows will increasingly be used for draft power (Muvirimi and Ellis-Jones 1999).

Nitrogen nutrients should be produced using nitrogen-fixing legume crops, such as vetch. The U.S. uses 13 million tons of commercial nitrogen per year (USDA 2007). Currently biological nitrogen fixation in the U.S. yields approximately 14 million tons of nitrogen per year (Pimentel 1998). Even with a major reduction in livestock population, possibly 300 million tons of nitrogen could be produced on farms. Note that since 1950 most livestock manure is not produced on farms (NAS 1989). One ton of cow manure has 6 kg of nitrogen, and can only be transported slightly more than 8 km before the nitrogen energy benefits in the manure equal those of inorganic fertilizer (Wiens *et al.* 2008), which is why livestock that are grass-fed must be managed on the farm.

Nitrogen fertilizer can be produced employing electrolysis but requires 8,800 kcal/kg of electrical energy (IFFCO 2008). This electrical energy translates into 26,400 kcal. The energy required for nitrogen production using electrical energy is reportedly much higher than producing nitrogen fertilizer using natural gas, which requires 16,000 kcal per kilogram of nitrogen (Patzek, T., Personal Communication, 2009).

Energy Resources

Over time, people have relied on various sources of power ranging from human, animal, wind, tidal, and water energy, to wood, coal, gas, oil, and nuclear sources for fuel and power. Fossil fuel energy permits a nation's economy to feed an increasing number of humans, as well as to improve the general quality of life in many ways, including the protection from numerous diseases.

About 473 quads (1 quad=10^{15} BTU or $1{,}055\times10^{18}$ Joules) from all energy sources are used worldwide per year (International Energy Annual 2007). Increasing energy expenditure is caused by rapid population growth, urbanization, and high resource consumption rates (Table 1). Increased energy use also contributes to environmental degradation (Pimentel and Pimentel 2008). Energy use has been growing even faster than world population. From 1970 to 1995, energy use was increasing at a rate of 2.5% (doubling every 28 years) whereas worldwide population grew at only 1.7% (doubling every 42 years) (PRB 1996; International Energy Annual 1995–2007). Current energy use is projected to increase at a rate of 2.2% (doubling every 32 years) compared with a population growth rate of 1.2% (doubling every 58 years) (PRB 2008; International Energy Annual 2007).

Although about 50% of all the solar energy captured by photosynthesis worldwide is used by humans, it is still inadequate to meet all of humanity's need for food (Pimentel and Pimentel 2008). To make up for this shortfall, about 473 quads of fossil energy (oil, gas, and coal) are utilized worldwide each year (International Energy Annual 2007). Of this, 109 quads are utilized in the United States (USCB 2008). The U.S. population consumes 70% more fossil energy than all the solar energy captured by harvested U.S. crops, forest products, and other vegetation each year (Pimentel *et al.* 2008b). Industry, transportation, home heating, and food production account for most of the fossil energy consumed in the United States (USCB 2008). Per capita use of fossil energy in the United States is 9,500 l of oil equivalents per year, more than 13 times the per capita use in China (Table 1). In China, most fossil energy is used by industry, but approximately 25% is used for agriculture and the food system (Pimentel and Wen 2004).

Developed nations annually consume about 70% of the fossil energy worldwide, while the developing nations, which have about 75% of the world population, use only 30% (International Energy Annual 2007). The United States, with only 4.5% of the world's population, accounts for almost 25% of the world's carbon emissions from fossil fuels (West 2008; PRB 2009).

Several developing nations that have high rates of population growth are increasing fossil fuel use to augment their agricultural production. In China, there has been a 100-fold increase in fossil energy use in agriculture for fertilizers, pesticides, and irrigation since 1955 (Pimentel and Wen 2004).

Fertilizer production on the whole, though, has declined per capita by more than 22% since 1991, especially in the developing countries, due to fossil fuel shortages and high prices (IFIA 2008).

World oil production has peaked and the world's supply of oil is projected to last approximately 40 years, if use continues at current rates (Energy Information Agency 2008). The earth's natural gas supply is projected to peak at 2020 and coal is projected to peak at 2025 (Energy Information Agency 2008). In the U.S., natural gas supplies are already in short supply and it is projected that the U.S. will deplete its natural gas resources in about 40 years (W. Youngquist, Personal Communication, petroleum geologist, Eugene, Oregon, 2008).

Both the production rate and proven reserves of oil and natural gas have continued to decline. In the United States, oil and natural gas production will be substantially less in 20 years than it is today. Neither is now sufficient for domestic needs, and supplies are imported in increasing amounts yearly (USCB 2008). Analyses suggest that at present (2008) the United States has consumed about 90% of its recoverable oil so that we are currently consuming the last 10% of domestic reserves. The United States is now importing about 60% of its oil (USCB 2008).

At present, electricity represents about 34% of total U.S. energy consumption (USCB 2008). Nuclear power production of electricity contributes about 20% and has some advantages over fossil fuels because it requires less land than coal-fired plants and does not contribute to acid rain and global warming.

All chemical and nuclear energy consumed ultimately winds up as heat in the environment. The Second Law of Thermodynamics limits the efficiency of heat engines to about 35%. This means that approximately two-thirds of the potential energy in fuel, whether chemical or nuclear, is converted into heat, while the remaining one-third is delivered as useful work (and, eventually, also converted into heat).

More efficient end-use of electricity can reduce its costs while at the same time reducing environmental impacts. Commercial, residential, industrial, and transportation sectors all have the potential to reduce energy consumption by approximately 33% while saving money (American Physical Society 2008; NASA/C3P 2008). Some of the necessary changes to reduce consumption would entail more efficiently designed buildings, appliances, and industrial systems (American Physical Society 2008; NASA/C3P 2008).

Using available renewable energy technologies, such as biomass and wind power, an estimated 29 quads of energy can be supplied in the U.S. with the full implementation of eight different renewable energy technologies (Table 3) (Pimentel *et al.* 2002). Worldwide we estimate that the need for 200 quads of renewable energy could be produced from 20% to 26% of the land area (Yao Xlang-Jun, personal communication, Cornell University, 1998; Exploring the Future 2001; Zweibel *et al.* 2007). Daily *et al.* (1994), Desvaux (2009), and Mann (2009) all suggest an optimum population for the earth of about 2 billion people. We suggest that a self-sustaining renewable energy system producing 200 quads of energy per year for about this number would provide each person with 5,000 l of oil equivalents per year (half of America's current consumption per year but an increase for most people of the world). However, the appropriation of over 20% of the land area for renewable energy production will further limit the resilience of the vital ecosystem that humanity depends upon for its life support system.

U.S. house size could be reduced from the current average of 2,500 sq.ft. to about 1,000 sq.ft., as it was about 60 years ago and is currently in the British Isles (USCB 2008). Heat would come from wood fuel in the northeast and north-central states. About 2 ha of forest would be needed per home, which would provide about 6 tons of wood fuel per year, adequate for a 1,000 sq.ft. well insulated home. In low rainfall regions where there is little wood fuel available, wind power or photo-voltaics will be used for heat. Here, the problem of intermediacy of energy supply can be offset by storing the heat in large hot-water or sand tanks.

Biological Resources

In addition to land, water resources, crops and livestock species, humans depend on the presence and functioning of approximately 15 million other species existing in agro-ecosystems and nature (McNeely 1999). More than 60% of the world's food supply comes from rice, wheat, and corn species (Brown 2008) and as many as 20,000 other plant species are used by humans for food (Vietmeyer 1995). Humans have no technologies that can substitute for the food—and some medicines—that some plant species in wild biota provide. Plants, animals, and microbes also carry out many essential activities for humans, including pollination of crops and wild plants, recycling manure and other organic wastes, degrading chemical pollutants, and purifying water and soil (Pimentel *et al.* 1997). Humans, again, have no synthetic substitutes for such ecosystem services (Daily and Ehrlich 1996).

Pest insects, pathogens, and weeds destroy crops and thereby reduce food and fiber supply. Despite the yearly use of 3.0 million tons of pesticides and other controls worldwide, about 40% of all potential crop production is lost to pests (Oreke and Dehne 2004). Specifically, in the United States, about 0.5 million tons of pesticides are applied each year, yet pests still destroy about 37% of all potential crop production. Estimates suggest that pesticide use could be reduced by 50% or more, without any reduction in pest control and/or any change in cosmetic standards of crops, through the implementation of sound ecological pest controls, such as crop rotations and biocontrols (Pimentel 1997).

Approximately one third of the United States' and world's food supply relies either directly or indirectly on effective insect pollination (Science Daily 2008). Honeybees and other wild bees play an essential role in pollinating U.S. crops. They also are vital for pollinating natural plants.

Worldwide, environmental pressure from the human population is the prime destructive force and the primary cause of reduced biodiversity (Pimentel *et al.* 2006). Humans currently occupy 95% of the terrestrial environment with either managed agricultural and forest ecosystems or human settlements (Western 1989). The major focus of world biological conservation has been on protecting national parks that cover only 3.2% of the world's terrestrial area (Reid and Miller 1989). However, most species diversity occurs in managed terrestrial environments, so increased efforts should be devoted to improving the sustainability of agricultural and forest ecosystems (Pimentel *et al.* 1992).

Resources and Human Diseases

As world population increases and resources are limited, human health suffers. Populations living in polluted regions are prone to infectious diseases, including tuberculosis, diarrhea, and parasitic worms. WHO (2008) reports that the world's annual death rate is 58 million. Diseases, including malnutrition, cause 18 million deaths per year. Poverty in developing countries reduces the availability of foods and increases malnutrition. WHO (2005a, b) reports nearly 60% of the world population is malnourished.

About 90% of the diseases occurring in developing countries result from a lack of clean water (WHO 1992). Worldwide, about 4 billion cases of disease are contracted from water and approximately 50 million deaths result from all diseases from water, food, air, and soil each year (WHO 2004). About 6,000 people die each day from a lack of access to clean water (Rijsberman 2004). Shistosomiasis and malaria, common diseases throughout the tropics, are examples of parasitic diseases associated with aquatic systems (Hotez and Pritchard 1995).

Intestinal parasites introduced through contaminated food, water, and soil, impact health by reducing intake of nutrients in various ways (Shetty and Shetty 1993). Hookworms, for instance, which thrive in contaminated moist soils in the tropics, can remove up to 30 ml of blood from a person in a single day, leaving them weak and susceptible to other diseases, including HIV/AIDS, which affects up to 37% of the population of some countries (Hotez and Pritchard 1995; Stillwaggon 2006). From 5% to 20% of an infected person's daily food intake is used to offset other illnesses and physical stress caused by disease, thereby diminishing his/her nutritional status (Pimentel and Pimentel 2008).

Transition to an Optimum Population with Appropriate Technologies

The human population has enormous potential for rapid growth because of the young age distribution both in the U.S. and throughout the world (PRB 2008). Future population growth is highly dependent on the path that future fertility takes (WPP 2006). If the whole world agrees on and adopts a policy of only two children per couple, it would be more than 100 years before the world population finally stabilizes at approximately 13 billion (Weeks 1986). A more daunting projection is that if fertility remains at present levels, the population will reach nearly 13 billion by 2050 (Cohen 2003).

However, a population policy ensuring that each couple produces an average of only one child would be necessary to achieve the goal of reducing world population from the current 6.8 billion to an optimal population of approximately 2 billion in slightly more than 100 years. Even with the United Nation's projection of declining fertility rates, population will reach 9.1 million by mid-century (UN 2005).

Our suggested 2 billion population carrying capacity for the Earth is based on a European standard of living for everyone and sustainable use of natural resources. For land resources, we suggest 0.5 ha of cropland per capita (the level that existed in 1960) with an intense agricultural production system (~8 million kcal/ha) and a diverse plant and animal diet for the people. In addition, approximately 1.5 ha of land would be required per capita for a renewable energy system. At the same time, the goal would be to have approximately 1 ha each for forest and pasture production per capita. Of course, all current land degradation associated with soil erosion would have to stop (Pimentel *et al.* 1995), but technologies are currently available for soil conservation in agricultural and forest production which only need to be implemented (Troeh *et al.* 2004b). In recent years there has been a growth in the adoption of "conservation tillage" and "zero-tillage" systems. These systems maintain a crop residue cover of the soil, rather than leaving the soil unprotected, as in conventional production, which increases organic matter decomposition that contributes to global warming.

Balancing the population-resource equation will be difficult because current overpopulation, poor distribution of resources, and environmental degradation are already causing serious malnourishment and poverty throughout the world, especially in developing countries (Gleick 1993; WHO 2005a, b). Wheat demand is projected to increase by 40% by 2020 and most demand will be from developing countries (Pingali and Rajaram 1999). The current shift to wheat and rice based diets is most apparent in developing countries, which are projected to have a per capita increase of 6%, from 62 kg per capita in 1993 to 66 kg per capita in 2020 (Rosegrant *et al.* 1999). In the future, more food will have to be produced on less land and with fewer water resources. Based on the estimate that 0.5 ha per capita is necessary for an adequate and diverse food supply, it would be possible to sustain a global population of approximately 2 billion humans. Cropland land is being degraded and lost at a rate of more than 20 million ha per year. At this rate, in just 42 years there will be sufficient arable land for a population of only 2 billion. It is critical to adopt soil and water conservation techniques to protect the soil resources that currently produce more than 99.7% of the world's food.

A reduction in the world population to approximately 2 billion, in addition to a reduced per capita consumption rate, would help reduce the current severe pressure on surface and groundwater resources and decrease water pollution. If water shortage and pollution problems were reduced, agricultural production would improve and degradation of aquatic ecosystems would decline. Appropriate technologies that conserve soil and water resources, and reduce pollution in soil, water, and atmospheric resources would help avert the alarming extinction rates of almost all species (Kellert and Wilson 1993), which in turn would protect and preserve most of the essential functions provided by natural biodiversity (Pimentel *et al.* 1997).

With the exhaustion of fossil fuels and associated increases in costs and pressure from global climate change, significant changes will also have to take place in energy use and practices. Fossil fuel shortages and global warming problems will force a transition to renewable energy sources within the next 100 years. Research on ways to convert solar energy into usable energy, for example, and research to develop other new power sources will have to be given a much higher priority. Although many solar technologies have been investigated, most are only in limited use. The most promising of renewable sources of energy include: solar thermal receivers, photo-voltaics, solar ponds, wind-power, hydropower, and biomass (Pimentel 2008).

Global warming caused by CO_2 and other greenhouse gases is a major challenge facing humans (Vorosmarty *et al.* 2000). The IPCC (2007) states that "warming of the climate system is unequivocal, as is now evident from observation of increase in global temperature, widespread melting of snow and ice and rising global average sea level." Greenhouse gases are essential to maintaining a reasonable temperature on earth; without the gases, the planet would be so cold as to be uninhabitable. However, an excess of greenhouse gases can raise the temperature of the planet to high levels. Efforts underway to reduce the CO_2 emissions have been to date unsuccessful. A 1% increase in the population results in a 1% increase in carbon dioxide emissions. Consumption of energy and other human activities contribute to the greenhouse gas problems (Shi 2003).

The adjustment of the world population from 6.8 billion to 2 billion could be achieved over approximately a century, but only if the majority of people agree that protecting human health and welfare is vital, and are willing to work towards a stable quality of life for themselves and their children. Although a rapid reduction in population numbers to 2 billion humans could cause social, economic, and political problems, continued rapid growth to 13 billion people will result in a dire situation with major starvation and disease outbreaks. Worldwide catastrophic health and environmental problems will reduce human numbers but with major disturbances in human lives and welfare.

Conclusion

Clearly, the world's human population cannot continue to increase indefinitely. Natural resources are critically limited, and there is emerging evidence that natural forces are already starting to control human population numbers through malnutrition and other severe diseases. More than 3.7 billion people worldwide are malnourished, and 3 billion are living in poverty; grain production per capita has been declining since 1984; irrigation per capita has been declining since 1978; arable land per capita has been declining since 1948; fish production per capita has been declining since 1980; fertilizer supplies essential for food production have been declining since 1989; loss of food to pests has not decreased below 52% since 1990; and pollution of water, air, and land has increased, resulting in a rapid increase in the number of humans suffering from serious, pollution-related diseases.

Fifty-eight academies of science, including the U.S. National Academy of Sciences, recognize that "Humanity is approaching a crisis point with respect to the interlocking issues" of population, natural resources, and sustainability (NAS 1994). The report points out that science and technology have a limited ability to meet the basic needs of a rapidly growing human population with rapidly increasing per capita demands. Unfortunately, most individuals and government leaders appear unaware, unwilling, or unable to deal with the growing imbalances between human population numbers and the energy and environmental resources that support all life. The interdependence among the availability of life-supporting resources, individual standard of living, quality of the environment, environmental resource management, and population density are neither acknowledged nor easily understood. Although we humans have demonstrated effective environmental conservation in certain cases (e.g., water), overall we have a disappointing record in protecting essential resources from over-exploitation in the face of rapidly growing populations (Pimentel and Pimentel 2008).

Historically, decisions to protect the environment have been based on isolated crises and catastrophes. Instead of examining the problem in a holistic, proactive manner, these ad hoc decisions have been designed to protect and/or promote a particular resource or aspect of human well-being in the short-term. Our concern, based on past experience, is that these urgent issues relating to human carrying capacity of the world may not be addressed holistically until the situation becomes intolerable or, possibly, irreversible.

Through the use of a population policy that respects individual rights, and effective resource use policies, as well as science and technology to enhance energy supplies and protect the integrity of the environment, an optimum population of 2 billion people can be achieved. With a concerted effort, fundamental obligations to ensure the well-being of future generations can be attained within the twenty-first century. Individuals will then be able to live free from poverty and starvation, in an environment that is capable of sustaining human life with dignity. We must avoid allowing the human population to continue to increase beyond the limit of the Earth's natural resources, which will inevitably lead to increased disease, malnutrition, and violent conflicts over limited resources.

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References

American Physical Society. (2008). Energy Future: Think Efficiency. Retrieved September 2009 from http://www.aps.org/energyefficiencyreport/

Arrow, K. J., Dasgupta, P., Goulder, L. H., Daily, G. C., Ehrlich, P., Heal, G., Levin, S., Maler, K., Scheider, S. H., Starrett, D., and Waler, B. (2004). Are We Consuming Too Much? The Journal of Economic Perspectives 18(3): 147–172.

Bartlett, A. A. (1997-98). Reflections on Sustainability, Population Growth, and the Environment—Revisited. Renewable Resources Journal 15(4): 6–23.

Berk, R., and Rothenberg, S. (2003). Water Resource Dynamics in Asian Pacific Cities. Department of Statistics, University of Southern California. Los Angeles, California. Retrieved September 2009 from http://repositories.cdlib.org/uclastat/papers/2003050101/

Botsford, L. W., Castilla, J. C., and Peterson, C. H. (1997). The Management of Fisheries and Marine Ecosystems. Science 277 (5325): 509–515.

Brown, L. (2008). World facing huge challenge on food front: Business-as-usual not a viable option. Plan B Update #72. Retrieved April 2009 from http://www.earth-policy.org/index.php?/plan_b_updates/2008/update72

Butler, R. (2009). As rain forests disappear, a market solution emerges. Environment 360. Yale University, New Haven. Retrieved September 2009 from http://e360.yale.edu/content/feature.msp?id=2097

Cantrell, K. B., Ducey, T., Ro, K. S., and Hunt, P. G. (2008). Livestock Waste-To-Bioenergy Generation Opportunities. Bioresource Technology 99(17): 7941–7953.

Cassman, K. G., Dobermann, A., Walters, D. T., and Yang, H. (2003). Meeting Cereal Demand While Protecting Natural Resources and Improving Environmental Quality. Annual Review of Environment and Resources 28: 315–358.

Chiras, D. (2006). Environmental Science, 7th ed. Jones and Bartlett, Sudbury.

Cohen, J. (2003). Human Population: The Next Half Century. Science 302: 1172–1175.

Covich, A. P. (1993). Water Ecosystems. In Gleick, P. H. (ed.), Water in Crisis. Oxford University Press, New York, pp. 40–55.

Crosson, P. (1997). Will Erosion Threaten Agricultural Productivity? Environment 39(8): 4–9. 29–31.

Daily, G. C., and Ehrlich, P. R. (1996). Socioeconomic Equity, Sustainability, and Carrying Capacity. Ecological Applications 6: 991–1001.

Daily, G., Ehrlich, A., and Ehrlich, P. (1994). Optimum Human Population Size. Population and Environment 15: 469–475.

Desvaux, M. (2009). Current population is three times the sustainable level. From Balanced View, 2007–2008. World Population Balance newsletters. Retrieved September 2009 from http://worldpopulationbalance.org/3_times_sustainable

Döös, B. R. (1994). Environmental degradation, global food production and risk for large-scale migrations. Ambio 23(2): 124–130.

Döös, B. R. (2002). The Problem of Predicting Global Food Production. Ambio 31(5): 417–424.

Earth Policy Organization. (2008). Why Ethanol Production Will Drive World Food Prices Even Higher in 2008. Table 5. World Grain Consumption and Stocks, 1960–2007. Retrieved February 2009 from Earth Policy Institute http://www.earth-policy.org/Updates/2008/Update69_data.htm#table5

Ehrlich, P. R., and Ehrlich, A. H. (1997). The Population Explosion: Why We Should Care and What We Should Do About It. Environmental Law 27: 1187–1208.

EIA. (2008). World Proved Reserves of Oil and Natural Gas, Most Recent Estimates. Energy Information Agency, U.S. Department of Energy, Washington, DC. Retrieved September 2009 from http://www.eia.doe.gov/emeu/international/reserves.html

EPA. (1994). Quality of Our Nation's Water 1994. Washington, DC, U.S. Environmental Protection Agency. Retrieved September 2009 from http://www.epa.gov/305b/94report/index.html

Exploring the Future. (2001). Energy Needs, Choices and Possibilities. Scenarios to 2050. Global Business Environment. Shell International 2001. Retrieved September 2009 from http://www.cleanenergystates.org/CaseStudies/Shell_2050.pdf

FAO. (1998). Agriculture's use of water. FAO Corporate Document Repository. Natural Resources Management and Environment Department. Food and Agricultural Organization, United Nations. Rome.

FAO. (2003). Food and Agricultural Organization of the United Nations. Food Balance Sheets. Retrieved September 2009 from FAO http://faostat.fao.org/site/368/default.aspx#ancor

FAO. (2006). FAO, Agricultural Statistics Global Outlook. FAO Statistics Division. Food and Agricultural Organization, United Nations, Rome. Retrieved September 2009 from FAO http://faostat.fao.org/portals/_faostat/documents/pdf/world.pdf

Ferguson, A. (1998). "World Carrying Capacities." Optimum Population Trust, 12 pages. Copies can be requested from Optimum Population Trust. http://www.optimumpopulation.org/

Ferguson, A. (2008). Photovoltaics, Batteries, Tractors, Horses, and Biofuels. Optimum Population Trust 8(2): 7–13.

Fischer, G., Shah, M., Tubiello, F. N., and Velhuizen, H. V. (2005). Socio-economic and Climate Change Impacts on Agriculture: an Integrated Assessment, 1990–2080. Philosophical Transactions of the Royal Society of London, B 360: 2067–2083.

Giampietro, M., and Pimentel, D. (1994). Energy Utilization. In Arntzen, C. J., and Ritter, E. M. (eds.), Encyclopedia of Agricultural Science, vol. 2. Academic, San Diego, pp. 63–76.

Gilau, A. M., Van Buskirk, R., and Small, M. J. (2007). Enabling Optimal Energy Options Under the Clean Development Mechanism. Energy Policy 35(11): 5526–5534.

Gleick, P. (ed.) (1993). Water in Crisis: a Guide to the World's Fresh Water Resources. Oxford University Press, New York.

Gleick, P. (2008–2009). The World's Water 2008–2009: The Biennial Report on Freshwater Resources. Pacific Institute for Studies in

Development, Environment and Security, Island Press, Washington D.C.

Gleick, P. H., Wolff, E. L., and Chalecki, R. R. (2002). The New Economy of Water: The Risks and Benefits of Globalization and Privatization of Freshwater. Oakland, CA: Pacific Institute for Studies in Development, Environment, and Security. 48 pp. Retrieved September 2009 from http://www.pacinst.org/publications/

Goklany, I. M. (2001). Modern Agriculture. Property and Environment Research Center Reports 19(1): 12–14. Retrieved September 2009 from PERC http://www.perc.org/search.php

Ho, S. P. S., and Lin, G. C. S. (2004). Converting Land to Nonagricultural us in China's Coastal Provinces: Evidence from Jiangsu. Modern China 30(1): 81–112.

Hotez, P. J., and Pritchard, D. T. (1995). Hookworm Infection. Scientific American 272(6): 68–74.

IFFCO. (2008). Developments in Ammonia Production Technology. Indian Farmers Fertiliser Cooperative Limited. Retrieved December 2008 from IFFCO http//www.iffco.nic.in/applications/iffcoweb5.nsf/0/4c4c41bda8dce6c7652570c40047bd41?OpenDocument

IFIA. (2008). International Fertilizer Industry Association. Statistics. Infoacosan. 2005–2006. Retrieved August 2009 from http://www.fertilizer.org/iea/overview.html

International Energy Annual. (2007). International Energy Annual. World Energy Overview. Retrieved from Energy Information Administration http://www.eia.doe.gov/iea/overview.html [access date].

IPCC. (2007). Climate change 2007. Synthesis Report 2007. Available from IPCC Fourth Assessment Report. Retrieved January 2009 from http://www.ipcc.ch/pdf/assessment_report/ar4/syr/ar4_syr_spm.pdf

Kellert, R. S., and Wilson, E. O. (1993). The Biophilia Hypothesis. Island Press, Washington.

Kendall, H. W., and Pimentel, D. (1994). Constraints on the Expansion of the Global Food Supply. Ambio 23(3): 198–205.

Kloverpris, J., Wenzel, H., and Nielsen, P. H. (2008). Life Cycle Inventory Modeling of Land Use Induced by Crop Consumption. Part 1: Conceptual Analysis and Methodological Proposal. Assessment 13(1): 13–21.

Kondratyev, K. Y., Krapivin, V. F., and Varotsus, C. A. (2003). Global Carbon Cycle and Climate Change. Springer-Verlag, Berlin.

Lal, R. (1997). Degradation and Resilience of soils. Philosophical Transactions of the Royal Society of London 352(1356): 997–1010.

Larsen, J. (2003). Population growth leading to land hunger. Earth Policy Institute, January 23, 2003. Retrieved February 2009 from Earth Policy Institute http://www.earth-policy.org/index.php?/plan_b_updates/2003/update21

Leach, G. (1995). Global Land and Food in the 21st Century. Stockholm: International Institute for Environmental Technology and Management. Retrieved from Earth Policy Institute http://www.earth-policy.org/index.php?/Plan_b_updates/2003/update21 [access date].

Mann, D. (2009). Essay on a sustainable economy. NPG Forum Series. Retrieved July 2009 from NPG http://www.npg.org/forum_series/sus_econ_91.htm

Matson, P. A., Parton, W. J., Power, A. G., and Swift, M. J. (1997). Agricultural Intensification and Ecosystem Properties. Science 277: 504–509.

McNeely, J. A. (1999). Imagine Tomorrow's World. International Union for Conservation of Nature, Gland

Meadows, D. (2000). "Population, Poverty, And Planet Earth" *in* Birth, Sex & Death. In Context: A Quarterly of Humane Sustainable Culture (#31): Human Family Planning. Last Updated 29 June 2000. Retrieved January 2009 from http://www.context.org/ICLIB/IC31/Meadows.htm

Montgomery, D. R. (2007). Dirt: The Erosion of Civilizations. University of California Press, Berkeley.

Morrison, F. B. (1946). Feeds and Feeding: a handbook for the student and stockman. 21th Edition, unabridged. Morrison Publishing Co., Ithaca.

Murray, C. J. L., and Lopez, A. D. (1996). The Global Burden of Disease: A Comprehensive Assessment of Mortality and Disability from Diseases, Injuries, and Risk Factors in 1990 and Projected to 2020. Harvard School of Public Health, Cambridge.

Muvirimi, F., and Ellis-Jones, J. (1999). A farming systems approach to improving draft animal power in sub-Saharan Africa. In Starkey, P. and Kaumbutho, P. (eds.), Meeting the Challenges of Animal Traction: A resource book of the Animal Traction Network for Eastern and Southern Africa (ATNESA). Intermediate Technology Publications, London, pp. 10–19. Retrieved January 2009 from ATNESA http://atnesa.org/challenges/challengesmuvirimifarmingsystems.pdf

Myers, N. (1990). The Nontimber Values of Tropical Forests. Forestry for Sustainable Development Program, University of Minnesota, November, 1990. Report 10.

National Academy of Sciences (1989). Alternative Agriculture. National Research Council. National Academy of Sciences Press, Washington.

National Academy of Sciences (1994). Population Summit of the World's Scientific Academies. National Academy of Sciences Press, Washington.

National Academy of Sciences (2003). Frontiers in Agricultural Research: Food, Health, Environment and Communities. National Academy of Sciences, Washington.

NASA/C3P. (2008). International Workshop on Pollution Prevention and Sustainable Development. Retrieved September 2009 from http://www.teerm.nasa.gov/workshop2008.html

Nash, L. (1993). Water Quality and Health. In Gleick, P. (ed.), Water in Crisis: A Guide to the World's Fresh Water Resources. Oxford University Press, Oxford, pp. 25–39.

Netherlands Environmental Assessment Agency. (2008). China Now No. 1 in CO_2 Emissions; USA in Second Position. Retrieved September 2009 from http://www.pbl.nl/en/dossiers/Climatechange/moreinfo/Chinanowno1inCO2emissionsUSAinsecondposition.html

Nearing, M. A., Pruski, F. F., and O'Neal, M. R. (2004). Expected Climate Change Impacts on Soil Erosion Rates: A Review. Journal of Soil and Water Conservation 59(1): 43–50.

Oldeman, L. R., Hakkeling, R. T. A., and Sombroek, W. G. (1990). World map of the status of human-induced soil degradation: an explanatory note. Global Assessment of Soil Degradation (GLASOD). International Soil Reference and Information Centre (ISRIC) and United Nations Environment Programme (UNEP).

Oreke, E. C., and Dehne, H. W. (2004). Safeguarding production–losses in major crops and the role of crop protection. Crop Protection 23(4): 275–285. Retrieved February 2009 from Science Direct http://www.sciencedirect.com/science/article/B6T5T-4B84XHC-1/2/e55ee6dbbb31f42ef43b7eb26066e907

Patzek, T. (2009). Personal Communication, University of Texas.

Pimentel, D. (1997). Pest Management in Agriculture. In Pimentel, D. (ed.), Techniques for Reducing Pesticide use: Environmental and Economic Benefits. Wiley, Chichester.

Pimentel, D. (1998). Economics Benefit of Natural Biota. Ecological Economics 25: 45–47.

Pimentel, D. (2000). Konsequenzen der weltweiten Bordenerosion und-degradation. In Haber, W., Held, M., and Schneider, M. (eds.). Nachhaltiger Umang mit Boden: Initiative fur eine internationale. Bodenkonvention, pp. 11–27.

Pimentel, D. (ed.) (2002). Biological Invasions: Economic and Environmental Costs of Alien Plant, Animal and Microbe Species. CRC Press, Boca Raton.

Pimentel, D. (2006). Soil Erosion: A Food and Environmental Threat. Environment, Development and Sustainability 8: 119–137.

Pimentel, D. (2008). Renewable and Solar Energy Technologies: Energy and Environmental Issues. In Pimentel, D. (ed.), Biofuels, Solar and Wind as Renewable Energy Systems: Benefits and Risks. Springer, Dordrecht, pp. 1–17.

Pimentel, D., and Wen, D. (2004). China and the World: Population, Food and Resource Scarcity. In Tso, T. C., and He, K. (eds.), Dare to Dream: Vision of 2050 Agriculture in China. China Agricultural University Press, Beijing, pp. 103–116.

Pimentel, D., and Wilson, A. (2004). World Population, Agriculture, and Malnutrition. Worldwatch Magazine 17(5). Retrieved October 2009 from the Worldwatch Institute http://www.worldwatch.org/node/554

Pimentel, D., and Patzek, T. (2008). Ethanol Production Using Corn, Switchgrass and Wood; Biodiesel Production Using Soybean. In Pimentel, D. (ed.), Biofuels, Solar and Wind as Renewable Energy Systems: Benefits and Risks. Springer, Dordrecht, pp. 375–396.

Pimentel, D., and Pimentel, M. (2008). Food, Energy and Society, 3rd ed. CRC Press (Taylor and Francis Group), Boca Raton, p. 380.

Pimentel, D., Stachow, U., Takacs, D. A., Brubaker, H. W., Dumas, A. R., Meaney, J. J., O'Neil, J. A. S., Onsi, D. E., and Corzilius, D. B. (1992). Conserving Biological Diversity in Agricultural/ Forestry Systems. Bioscience 42: 354–362.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurtz, D., McNair, M., Crist, S., Spritz, L., Fitton, L., Saffouri, R., and Blair, R. (1995). Environmental and Economic Costs of Soil Erosion and Conservation Benefits. Science 267: 1117–1123.

Pimentel, D., Wilson, C., McCullum, C., Huang, R., Dwen, P., Flack, J., Tran, Q., Saltman, T., and Cliff, B. (1997). Economic and Environmental Benefits of Biodiversity. Bioscience 47(11): 747–757.

Pimentel, D., Bailey, O., Kim, P., Mullaney, E., Calabrese, J., Walman, L., Nelson, F., and Yao, X. (1999). Will Limits of the Earth's Resources Control Human Numbers? Environment, Development and Sustainability 1(1): 19–39.

Pimentel, D., Hertz, M., Glickstein, M., Zimmerman, M., Allen, R., Becker, K., Evans, J., Hussain, B., Sarsfield, R., Grosfeld, A., and Seidel, T. (2002). Renewable Energy: Current and Potential Issues. Bioscience 52(12): 1111–1120.

Pimentel, D., Berger, B., Filiberto, D., Newton, M., Wolfe, B., Karabinakis, B., Clark, S., Poon, E., Abbett, E., and Nandagopal, S. (2004). Water Resources: Agricultural and Environmental Issues. Bioscience 54(10): 909–918.

Pimentel, D., Petrova, T., Rley, M., Jacquet, J., Ng, V., Honigman, J., and Valero, E. (2006). Conservation of Biological Diversity in Agricultural, Forestry, and Marine Systems. In Burk, A. R. (ed.), Focus on Ecology Research. Nova Science, New York, pp. 151–173.

Pimentel, D., Cooperstein, S., Randell, H., Filiberto, D., Sorrentino, S., Kaye, B., Yagi, C. J., Brian, J., O'Hern, J., Habas, A., and Weistein, C. (2007). Ecology of Increasing Diseases: Population Growth and Environmental Degradation. Human Ecology 35(6): 653–668.

Pimentel, D., Williamson, S., Alexander, C. E., Gonzalez-Pagan, O., Kontak, C., and Mulkey, S. E. (2008a). Reducing Energy Inputs in the U.S. Food System. Human Ecology 36(4): 459–471.

Pimentel, D., Marklein, A., Toth, M. A., Karpoff, M., Paul, G. S., McCormack, R., Kyriazis, J., and Krueger, T. (2008b). Biofuel Impacts on World Food Supply: Use of Fossil Fuel, Land and Water Resources. Energies 1: 41–78; DOI: 10.3390/en1010041 Retrieved December 2008 from http://www.mdpi.org/energies/papers/en1020041.pdf

Pingali, P. L., and Rajaram, S. (1999). Global wheat research in a changing world: Options for sustaining growth in wheat productivity. In Pingali, P.L. (ed.), CIMMYT 1998–99 World wheat facts and trends, Global wheat research in a changing World: Challenges and Achievements. CIMMYT, Mexico, DF, pp. 1–18. Retrieved September 2009 from http://www.cimmyt.org/research/economics/map/facts_trends/wheatft9899/htm/wheatft9899.htm

Pollution Problem. (2009). From 90% to 95% of sewage in developing countries is placed in rivers and lakes. Retrieved August 2009 from http://www.infoforhealth.org/pr/m14/m14chap4_1.shtml

Postel, S. (1997). Last Oasis: Facing Water Scarcity. W.W Norton, New York.

PRB (1996). World Population Data Sheet. Population Reference Bureau, Washington.

PRB. (2008). World Population Data Sheet. Population Reference Bureau, Washington, D.C. Retrieved August 2009 from PRB http://www.prb.org/Publications/Datasheets/2008/2008wpds.aspx

PRB. (2009). World Population Data Sheet. Population Reference Bureau, Washington, D.C. Retrieved October 2009 from PRB http://www.prb.org/Publications/Datasheets/2009/2009wpds.aspx

Reid, W. V., and Miller, K. R. (1989). Keeping Options Alive: The Scientific Basis for Conserving Biodiversity. World Resources Institute, Washington.

Rijsberman, F. (2004). The Water Challenge. Copenhagen Consensus. pp. 1–37. 3. May 2004. Retrieved November 2008 from http://www.copenhagenconsensus.com/files/filer/cc/papers/sanitation_and_water_140504.pdf

Ro, K. S., Cantrell, K., Elliott, D., and Hunt, P. G. (2007). Catalytic Wet Gasification of Municipal and Animal Wastes. Industrial and Engineering Chemistry Research 46(26): 8839–8845.

Rosegrant, M., Leach, N., and Gerpacio, R. (1999). Alternative Futures for World Cereal and Meat Consumption. Proceedings of the Nutrition Society 58: 219–234.

Sanchez, P. A. (2002). Soil Fertility and Hunger in Africa. Science 295: 2019–2020.

Science Daily. (2008). Economic Value of Insect Pollination Worldwide. Estimated at U.S. $217 Billion. Retrieved February 2009 from Science Daily http://www.sciencedaily.com/releases/2008/09/080915122725.htm.

Shetty, P. S., and Shetty, N. (1993). Parasitic Infection and Chronic Energy Deficiency in Adults. Supplement to Parasitology 107: S159–S167.

Shi, A. (2003). The impact of population pressure on global carbon dioxide emissions, 1975–1996: evidence from pooled cross-country data. Ecological Economics 44(2003): 29–42.

Stillwaggon, E. (2006). The Ecology of Poverty: Nutrition, Parasites, and Vulnerability to HIV/AIDS. In Gillespie, S. (ed.), AIDS, Poverty and Hunger: Challenges and Responses. International Food Policy Research Institute, Washington, pp. 167–180.

Soil and Water Conservation Society. (2003). Conservation Implications of Climate Change: Soil Erosion and Runoff from Cropland. Soil and Water Conservation Society, Ankeny, IA. Retrieved February 2009 from SWCS http://www.swcs.org/en/publications/conservation_implications_of_climate_change/

Sustainable World (2002). Water. Retrieved August 2009 from http://www.sustainableworld.org.uk/water_res.htm

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W. H., Simberloff, D., and Swackhamer, D. (2001). Forecasting agriculturally driven global environmental change. Science 292: 281–284.

Troeh, F., Hobbs, J., and Donahue, R. L. (2004a). Soil and Water Conservation for Productivity and Environmental Protection, 4th ed. Prentice Hall, New Jersey.

Troeh, F. R., Hobbs, J. A., and Donahue, R. L. (2004b). Soil and Water Conservation for Productivity and Environmental Protection. Prentice Hall, New Jersey.

UN. (2005). UN News Centre. UN News Service. World population to reach 9.1 billion in 2050, UN projects. United Nations. Geneva. Retrieved September 2009 from http://www.un.org/apps/news/story.asp?NewsID=13451&kwi=billion8Kw2=9.1t&Kw3=

UNFPA (1991). Population and the Environment: The Challenges Ahead. United Nations Fund for Population Activities. United Nations Population Fund, New York.

USCB (2002). Statistical Abstract of the United States: 2002, 122nd ed. U.S. Census Bureau, Washington.

USCB (2008). Statistical Abstract of the United States: 2008, 127th ed. U.S. Census Bureau, Washington.

USCB (2009). Statistical Abstract of the United States: 2009, 128th ed. U.S. Census Bureau, Washington.

USDA (2007). Agricultural Statistics. U.S. Department of Agriculture, Washington.

Vietmeyer, N. (1995). Applying Biodiversity. Journal of the Federation of American Scientists 48(8): 1–8.

Vorosmarty, C., Green, P., Salisbury, J., and Lammers, R. (2000). Global Water Resources: Vulnerability from Climate Change and Population Growth. Science 289: 284–288.

Weeks, J. R. (1986). Population: An Introduction to Concepts and Issues, 3rd ed. Wadsworth Publishing Co, Belmont.

Wen, D., and Pimentel, D. (1992). Ecological Resource Management to Achieve a Productive, Sustainable Agricultural System in Northeast China. Agriculture, Ecosystems & Environment 41: 215–230.

West, L. (2008). U.S. Autos Account for Half of Global Warming Linked to Cars Worldwide. Retrieved October 2009 at About. com http://environment.about.com/b/2008/06/02/us-autos-account-for-half-of-global-warming-linked-to-cars-worldwide.htm

Western, D. (1989). Conservation without peaks. In Western, D., and Pearl, M. C. (eds.), Wildlife in Rural Landscape in Conservation for the Twenty-first Century. Oxford University Press, New York, pp. 158–165

Wheal, C. (1991). Freshwater Pollution. Global Environment Monitoring System, Nairobi, Kenya, United Nations Environment Programme.

WHO. (1992). Our Planet, our Health: Report of the WHO Commission on Health and Environment, Geneva, World Health Organization. Environment and Urbanization 4(1): 65–76. Retrieved from http://eau.sagepub.com/cgi/content/abstract/4/1/65 [access date].

WHO (1993). Global health situation, Weekly Epidemiological Record. World Health Organization 68(12 February): 43–44.

WHO. (2004). World Health Report. World Health Organization. Retrieved October 2008 http://www.who.int/whr/2004/

WHO. (2005a). World Health Report on Infectious Diseases, Removing the Obstacles to Healthy Development, World Health Organization, Geneva. Retrieved September 2009 from http://www.who.int/infectious-disease-report/index-rpt99

WHO. (2005b). Malnutrition Worldwide. World Health Organization. Retrieved February 2009 from http://www.mikeschoice.com/reports/malnutrition_worldwide.htm

WHO. (2008). The global burden of disease: 2004 Update. World Health Organization. Retrieved December 2008 http://www.who.int/healthinfo/global_burden_disease/2004_report_update

Wiens, M. J., Entz, M. H., Wilson, C., and Ominski, K. H. (2008). Energy Requirements for Transport and Surface Application of Liquid Pig Manure in Manitoba, Canada. Agricultural Systems 98(2): 74–81.

Willett, W. C., Sacks, F., Trichopoulou, A., and Drescher, G. (1995). Mediterranean Diet Pyramid: A Cultural Model for Healthy Eating. The American Journal of Clinical Nutrition 61(6): 1402S.

WPP. (2006). The 2006 Revision (2006). UN-Social and Economic Affairs. Retrieved January 2009 from http://www.un.org/esa/population/publications/wpp2006/WPP2006_Highlights_rev.pdf

WRI. (1993). World Resources 1992–93: Guide to the Global Environment. World Resources Institute, Washington, DC. Retrieved December 2008 from the World Resources Institute http://www.wri.org/publication/world-resources-1992-93-guide-global-environment

Yao, X.-J. (1998). Personal Communication, Cornell University.

Youngquist, W. (2008). Personal Communication, Petroleum Geologist. Eugene, Oregon.

Zweibel, K., Mason, J., and Fdthenakis, V. (2007). Solar Grand Plan. By 2050 Solar Power Could End U.S. Dependence on Foreign Oil and Slash Greenhouse Gas Emissions. Scientific American 289: 37–48.

POPULATION GROWTH AND AUSTRALIA'S 2020 GREENHOUSE GAS EMISSION COMMITMENTS

Bob Birrell and Ernest Healy

The Australian Government has stated an unconditional commitment to reduce greenhouse gas emissions by five per cent on year 2000 levels by 2020. However, in the absence of new abatement measures, Treasury-led modelling indicates that Australia's emissions will grow from 553 million tonnes in 2000 to 774 million tonnes in 2020. This article disaggregates the Treasury modelling in order to estimate the contribution of population expansion to this growth. It shows that 83 per cent of the forecast increase in greenhouse emissions to 2020 will be attributable to population growth. The article concludes that it is very unlikely that Australia will achieve the five per cent reduction target by 2020 in the absence of attention to the population growth factor.

In its White Paper on the Carbon Pollution Reduction Scheme (CPRS) published in December 2008, the Australian Labor Government laid down its greenhouse gas abatement commitments and aspirations.[1]

It affirmed the Labor Party's long-standing aspiration to reduce greenhouse emissions in Australia by 60 per cent on year 2000 levels by 2050. It also announced a new commitment to reduce Australia's greenhouse emissions by between five and 15 per cent below 2000 levels by 2020. These two endpoints are defined in the White Paper as CPRS-5 and CPRS-15 respectively. Henceforth, they will be referred to in these terms.

The White Paper states that:

> The top of this range (5 per cent below 2000 levels) represents a minimum (unconditional) commitment to reduce emissions by 2020, irrespective of the actions by other nations. The bottom of the range (15 per cent below 2000 levels) represents a commitment to reduce emissions in the context of global agreement where all major economies commit to substantially restrain emissions and all developed countries take on comparable reductions to that of Australia.[2]

In this paper, the focus is on the Australian government's 'unconditional' commitment to a five per cent reduction in greenhouse emissions on year 2000 levels (which were 553 million tonnes) by 2020, that is, CPRS-5. For this to occur, Australia's greenhouse emissions would have to fall to 525 million tonnes in 2020. The White Paper acknowledges that even this apparently modest goal will not be easy to achieve. It states that:

> Australia's social and economic characteristics, especially our growing population and relatively emissions-intensive economy, mean that we will have higher adjustment costs than many other developed countries to reach ostensibly similar goals.[3]

It is easy to see why Australia will have difficulty arresting the growth of greenhouse emissions. Per capita economic growth has been growing rapidly, and so too has Australia's population, with the consequence that overall real economic growth (or Gross Domestic Product—GDP) has been growing by three to four per cent per annum, at least until the economic crisis beginning in 2008. Meanwhile, as the White Paper notes, Australia's 'relatively emissions-intensive economy' ensures that rapid economic growth translates into increased greenhouse emissions.

As part of the preparation for the White Paper, the Australian Government issued a separate report entitled *Australia's Low Pollution Future* (ALPF) in 2008.[4] This reports the Treasury-led modelling for the 'business as usual' outlook for greenhouse emissions to 2020 and 2050. Subsequent references to the Treasury's modelling contribution to the White Paper refer to this report. The 'business as usual' or reference case (as it will be referred to subsequently) indicates Treasury forecasts of greenhouse emissions in the absence of new abatement measures, including the proposed CPRS or any other form of carbon tax. The forecast for this reference case is that Australia's greenhouse emissions will grow from 553 million tonnes (expressed as CO_2 equivalent gases) in 2000 to 774 million tonnes by 2020 or by 221 million tonnes.

The Treasury reference case is a product of highly detailed computable general equilibrium modelling, which takes into account a multitude of variables. However in presenting the results in ALPF, the Treasury summarises or reduces these variables to three factors. They are per capita economic growth, population growth and greenhouse emissions per dollar of GDP.

As is shown below, the Treasury expects both per capita economic growth and population growth to increase significantly to 2020 and 2050. On the other hand, it expects emissions per dollar of GDP to fall over the same period, even in the absence of the proposed CPRS. Since the expectation is that there will be overall growth in emissions of 221 million tonnes by 2020 it is evident that the forecast per capita economic growth and population growth offsets the expected decline in emissions per unit of GPD.

The reference case provides a measure of how difficult it will be to achieve any reduction at all on year 2000 greenhouse gas emission levels. Both the Labor Government and the Coalition opposition are committed to maximising Australia's per capita economic growth and neither have shown any inclination to challenge Australia's current high rate of population growth. The Labor Government has proposed that the CPRS will serve as a mechanism to lower Australia's greenhouse gas emissions. But as discussed below, the Government has struggled to gain acceptance of this mechanism from either industry or the opposition parties.

Given this situation it is timely to investigate what the relative role of per capita economic growth, population growth and emissions intensity is in the reference case outlook for Australia's greenhouse emissions. The Treasury does not provide this information in ALPF. This paper seeks to fill the gap. It provides an estimate of the contribution of population growth to the forecast increase in greenhouse emissions of 221 million tonnes over the period 2000 to 2020. It does so by disaggregating the Government's modelling in order to indentify the role of population growth in the level of greenhouse emissions by 2020 relative to other factors considered in the modelling.

There is a growing awareness about the lack of government attention to population growth in Australia's greenhouse abatement policy. As the climate scientist David Karoly has recently declared:

> Australian governments' policies on population growth, encouraging immigration and an increasing birth rate, also make it more difficult to reduce emissions. This encouragement for increasing population in Australia is completely at odds with the claimed aims of tackling climate change.[5]

But, how important is the population factor? At present, the interested public is flying blind on the issue. Before proceeding with the analysis, we digress to examine the treatment of the population factor in recent policy discussions of Australia's greenhouse gas emissions.

DEALING WITH THE POPULATION FACTOR

It is sometimes argued that the growth of greenhouse emissions in Australia due to the immigration component of population growth is not relevant because greenhouse emissions are a global problem and the particular national context in which the emissions occur does not matter. This is not true in Australia's case because of our very high per capita emissions level (see Table 1). As is shown below (Table 3) the bulk of Australia's projected population increase will come from net migration. Most of our migrants come from Europe, China, India and other parts of Asia, where per capita emission levels are a third or less of those in Australia. Once here, migrants rapidly adopt Australian consumption patterns and thus move to a similar greenhouse footprint to that of other Australian residents.

Given that it is Australian Government policy to maintain a very high migration program, one might think that the government would be attracted to emission reductions based on per capita targets, rather than to those expressed in aggregate national terms. Rapid population growth, as is documented in this paper, makes the attainment of even modest reductions to overall greenhouse emissions in Australia very difficult to achieve.

The per capita reduction strategy was recommended by Ross Garnaut in the *Garnaut Climate Change Review* presented to the government in September 2008. Garnaut's thinking is transparent. He has been an advocate of high migration levels for decades. He does not want to see immigration policy coming under critical scrutiny in the context of greenhouse gas abatement policy. Thus, at the outset of his inquiry, he excised population from the range of factors to be considered in achieving the ambitious targets that his inquiry ultimately recommended.[6]

As a consequence, Garnaut's final report has nothing to say about population, except to declare that the report assumes that Australia's population will reach 47 million by 2100. There is no analysis of the contribution that population growth makes to the growth of emissions in his reference case, nor of the effect that any contraction in the 47 million assumption would have on greenhouse emissions in Australia.

Nonetheless, Garnaut was aware of the contribution population growth makes to Australia's emission growth profile and thus of the difficulty of achieving reductions in Australia's total greenhouse emissions. His solution is to recommend per capita emission targets. The key paragraph is as follows:

> Australia's ongoing strong immigration and population growth means that it will be easier to cut emissions in per capita rather than absolute terms. Australia's population growth rate is above the world average. The Garnaut-Treasury reference case suggests that Australia's population will increase proportionately by almost three times global population through this century. If emissions entitlements and targets are framed in per capita terms, countries with growing populations will receive greater absolute allocations. Population growth considerations are centrally

Table 1: Emissions (tonnes CO_2e) per capita, 2005

United States	23.9
European Union	10.7
Australia	28.9
Rest of Annex B[1]	12.3
China	5.4
India	1.6
Rest of world	4.2
World average	6.0

Source: Treasury estimates in *Australia's Low Pollution Future*, Chapter 3, p. 6.

Notes: [1] There are 39 Annex B countries under the Kyoto protocol. Under the protocol, these are emissions-capped industrial countries or economies in transition with legally binding emission reduction obligations.

important to equitable distribution of the adjustment burden among Australia and other developed countries.[7]

Garnaut appears to assume that the world will look kindly on the desire of Australian policy elites to rapidly increase the population and that the rest of the world will allocate the necessary greenhouse-emission indulgences to accommodate this aspiration.

In the event, the Labor Government's did not accept Garnaut's recommendation to make per capita emission targets the basis for evaluating Australia's progress on the issue. The White Paper does not explicitly say this. Rather, it simply ignores Garnaut's recommendations on the matter. The White Paper's proposals are all expressed in terms of national-level aggregate emission targets.

It may be that the politics of following Garnaut's recommendations frightened the Government. Garnaut recommended a strategic path of 'contraction and convergence' to the per capita emission levels prevailing in most undeveloped countries of around three to four tonnes per head by 2050.[8] If this level was to be achieved it would require an implausible reduction in per capita emissions in Australia of almost 90 per cent. Not that Garnaut ever believed that such a contraction was possible in Australia. He assumes that by 2050, Australian polluters will be heavily reliant on the purchase of emission permits in the international carbon-permit market place.

A REPLICATION OF THE TREASURY REFERENCE CASE

The focus here, however, is not on the Garnaut review but on the Treasury's reference case to 2020 as published in ALPF. This is a product of highly detailed modelling. However, as noted, in presenting its analysis to the public, the Treasury reduces the factors shaping greenhouse emission levels to three. The first is the projected rate of growth in per capita GDP. The more rapidly this grows, the greater the production of goods and services in Australia will be by 2020. If there is no change over this period in the amount of energy used and the carbon content of the fuel used in supplying this energy for the production of these goods and services, there will be a parallel increase in per capita greenhouse emissions.

The second is the number of Australian residents. The more their number grows, again, other things being equal, the more greenhouse emissions will grow. These two factors amplify each other, since Treasury assumes that any expansion of per capita GDP will apply to new residents as well as those currently present in Australia. The aggregate of these two factors is total GDP. This is obtained by multiplying the projected per capita GDP in 2020 by the projected population in that year.

The third factor is the greenhouse emission levels resulting from each dollar of GDP. This ratio has been falling, largely as a result of structural change in the Australian economy, as the share of services in total economic activity increases relative to goods. The production of services normally involves a much lower input of energy per unit of activity than is the case with goods. The Treasury led modelling also projects that there will be improvements in technology which will lead to less energy per unit of output, whether of goods or services.[9]

Greenhouse emissions in Australia by 2020 in the reference case are calculated by multiplying total GDP by Treasury's estimate of the weight in kilograms of greenhouse gases per dollar of GDP by 2020. As is detailed in Table 2, the total emissions by 2020 are forecast to be 774 million tonnes (up from 553 million tonnes in 2000).

In order to calculate the contribution of each of the three factors to the forecast greenhouse emission growth, information is required on each of these factors at the starting date of 2000 and the completion date of 2020. Some of this information is provided in ALPF,[10] though not the number of people that Treasury assumes will be resident in Australia by 2020, nor per capita GDP by 2020. As a result, an interested citizen would have difficulty doing any disaggregation of the Treasury forecasts. However Treasury did provide, on our request, the necessary information on the population and GDP per capita assumptions to 2020. The relevant data for the starting point in 2000 (shown in Table 2) were derived from publicly available Australian Bureau of Statistics releases. The estimate for emissions per dollar of GDP in 2000 is our calculation. It is computed by dividing total greenhouse emissions in 2000 by GDP in 2000. The estimate for greenhouse emissions in 2000 was provided by the Treasury.

As Table 2 shows, the Treasury assumes Australians will be very much richer (on average) by 2020 than we were in the year 2000. Real GDP per capita is projected to grow from $44,532 in 2000 to $62,357 in 2020. This outcome reflects Treasury's assumption that real GDP per capita will grow by 1.4 per cent per annum. Treasury also assumes that Australia's population will reach 25.2 million in 2020 and 33.0 million by 2050 (up from 19.2 million in 2000). As a result, aggregate real GDP almost doubles between 2000 and 2020 from $885 billion to $1,571 billion.

It will come as no surprise that this huge increase in economic activity results in significant growth in greenhouse emissions in the reference case. However as Table 2 shows, the impact of this additional economic activity is offset somewhat by the results of the Treasury led modelling on greenhouse emissions per dollar of GDP. These are projected to fall from 0.625 kilograms per dollar of GDP in 2000 to 0.4927 kilograms by 2020.

Table 2: Treasury assumptions for the calculation of the reference case level of greenhouse gases in 2020

	2000	2020
Population (million)	19.2	25.2[1]
GDP per capita (A$)	44,532[2]	62,357[3]
GDP (A$ billions)	885[4]	1571[5]
Greenhouse emissions per $GDP (kg)	0.625[6]	0.4927[7]
Emissions (millions of tonnes CO_2e)	553[8]	774[9]
Per capita emissions (tonnes CO_2e)	28.8	30.7

Sources: [1] Australian Government Treasury, <www.treasury.gov.au/lowpollutionfuture/spreadsheets/report_charts/Annex%20B/Chart%20B.3%20-%20Australian%20population.xls>
[2] ABS, Australian National Accounts: National income, expenditure and product, 5206.0, June 2009, Table 1
[3] Australian Government Treasury, <www.treasury.gov.au/lowpollutionfuture/spreadsheets/report_charts/Chapter%203/Chart%203.29%20-%20Australian%20GDP%20and%20GNP%20levels.xls>
[4] GDP per capita multiplied by population
[5] GDP per capita multiplied by population
[6] Greenhouse emissions divided by GDP
[7] Australian Government Treasury, personal communication
[8] Australian Government Treasury, personal communication
[9] GDP multiplied by greenhouse emissions per dollar of GDP

Note: CO_2e means CO_2 equivalent greenhouse gases

THE ROLE OF POPULATION GROWTH IN THE EXPANSION OF GREENHOUSE GAS EMISSIONS IN AUSTRALIA

The replication of the Treasury modelling outcomes allows a calculation of the contribution of population growth, growth in per capita GDP and reductions in emissions per dollar of GDP to the growth of greenhouse emissions in the reference case. The contribution of population growth can be assessed by asking what total greenhouse gas emissions would be in 2020 if per capita GDP and emissions per dollar of GDP were to reach the levels projected by the Treasury to 2020, but Australia's population were to remain unchanged at the 2000 figure of 19.2 million.

The answer is that if Australia's population had remained at 19.2 million in 2020, GDP would have been $1,197 billion (19.2 million multiplied by per capita GDP of $62,357). If emissions of greenhouse gases per unit of GDP fell to 0.4927 kilograms, as projected by the Treasury, total greenhouse emissions in 2020 would have been 590 million tonnes, an increase of only 37 million tonnes on the 2000 figure.

The implication is that the combined effect of Treasury's projected changes in GDP per capita and emissions per unit of GDP have only added 37 million tonnes to the the 553 million tonne starting point in 2000. The rest of the 221 million tonne projected increase to 774 million tonnes, or 184 million tonnes, is a consequence of the extra six million people Treasury projects will be added to Australia's population between 2000 and 2020. That is, population growth is responsible for 184 million tonnes of the projected 221 million tonne increase, or 83.3 per cent.

The reason for the relatively low growth in emissions under the stable population scenario is that most of the increase attributable to growth in GDP per capita is offset by the projected decline in emissions per unit of GDP.

GREENHOUSE EMISSIONS IN A STABLE POPULATION SCENARIO

If Australia's population were to remain stable between 2000 and 2020, there would be many differences in the pattern of economic activity by 2020, compared with what would occur as the result of an additional six million residents. These could affect emissions per dollar of GDP. We believe that emissions per dollar of GDP are likely to be lower in the stable population scenario. The reason is that the addition of six million persons is equivalent to adding an extra 17 Canberras to Australia's population (Canberra's population was 345,000 in 2008). These extra people would have to be accommodated and employed. The required city building activity would add a huge amount of energy-intensive economic activity to that which would otherwise occur should the population remain stable. If so, under the stable population scenario, greenhouse emissions are likely to be even lower than the 590 million tonne figure projected above.

Should Australia move towards a more stable population, this would deliver a double bonus in regard to lowering greenhouse emissions. Aggregate GDP would be lower, and so too would the emissions per dollar of GDP.

If Australia's population stabilised this might also affect the rate of per capita economic growth. The most recent thorough analysis of this effect is provided by the Productivity Commission's report on the *Economic Impacts of Migration and Population Growth*.[11] The Productivity Commission concluded that per capita annual income by 2024–25 would be slightly lower (by 0.71 per cent) in the absence of migration.[12] If so, greenhouse emissions are also likely to be slightly lower in per capita terms under the stable population scenario than under the rapid population growth scenario modelled by the Treasury.

IS POPULATION GROWTH AMENABLE TO POLICY ADJUSTMENT?

Population growth consists of natural increase and net migration components. The former, at least as far as births are concerned, is a product of individual family decisions, which government policy has only limited power to shape. Migration, however, is almost entirely a product of Australian Government policy, since the inflow of migrants can be micro managed by decisions about the rules shaping eligibility for family reunion, skilled and humanitarian entry, and whether this entry is permanent or temporary.

Table 3 shows the components of population growth between 2006 and 2020, and 2050, which are attributable to natural increase and to net overseas migration. The starting point is 2006 rather than 2000 because we wanted to replicate the Treasury projection, which starts from this date. The projection in Table 3 has been prepared by the Centre for Population and Urban Research (CPUR). We could not replicate the Treasury projection fully because of limited information as to the demographic assumptions incorporated within it. The endpoint at 2050 of 33 million matches the Treasury forecast. Our figure is a little lower for 2020 than the 25.2 million projected by the Treasury.

This is of no great consequence. What matters is the extent to which natural increase and net immigration contribute to the population growth forecast. Table 3 shows that, between 2006 and 2020, some 63 per cent of population growth is due to net overseas migration. After 2020, the Table indicates that almost all of Australia's population growth will derive from net overseas migration. This is because births and deaths converge after 2020.

PER CAPITA ECONOMIC GROWTH AND ENERGY EFFICIENCY FACTORS

The preceding analysis shows that Australian governments could have a major impact on controlling the growth of greenhouse emissions in Australia if the migrant intake was reduced. However, the Australian Labor Government and almost all of the green and climate advocate groups engaged in the climate-change debate have chosen to ignore the potential gains in reducing greenhouse gases through population policy adjustments. The implication is that they regard population growth as more important than the achievement of greenhouse abatement targets.

Our conclusion will be contested by climate abatement advocates. They believe that the CPRS-5 target can be achieved, even in a context of rapid population growth and rapid per capita growth in GDP. In other words, in their view, we can have it all ways. The basis for this belief is that it is possible to achieve a sharp and rapid reduction in emissions per dollar of GDP.

In principle they are right. If Australia's

Table 3: Population projections to 2020 and 2050, with and without net overseas migration ('000)

	2006	2020	2050
Population projection[1]	20,697	24,961	32,996
Projection with nil net migration	20,697	22,290	22,481
Population increase from 2006 due to natural increase	—	1,593	1,784
Population increase from 2006 due to NOM[2] of 180,000 per annum	—	2,671	10,515
Total population increase	—	4,264	12,299

Source: Centre for Population and Urban Research
Notes: [1] Assumes net overseas migration of 180,000 per annum and TFR of 1.8
[2] NOM = net overseas migration

coal-dependent economy was transformed to one using natural gas, nuclear and/or renewable energy, greenhouse emissions would contract sharply. A mandatory requirement for a sharp improvement in the energy efficiency of vehicles or in the fossil fuel energy used in buildings could similarly achieve major cutbacks. For example, if emissions per dollar of GDP in Australia were reduced from 0.4927 to 0.3 kilograms by 2020, Australia's greenhouse emissions would be 471 million tonnes by 2020 rather than 774 million tonnes, even if Australia's population reached the Treasury's projection of 25.2 million. If so, this would mean a reduction of 15 per cent below the year 2000 level of 553 million tonnes—which would be equivalent to meeting the CPRS-15 objective.

Emission levels per dollar of GDP at these levels are plausible. The Treasury report indicates that, within the European Union (EU), emissions per dollar of GDP were already at 0.37 kilograms in 2005. The Treasury projects that they will reach 0.3 kilograms per dollar of GDP in the EU by 2020.[13]

Sharp reductions in emissions in Australia could occur if the Labor Government legislates its proposed CPRS, including the emissions trading scheme (ETS) that is its centrepiece. The government will also have to implement a restrictive cap on the level of emissions allowed. This cap will have to fall to around 523 million tonnes by 2020 for CPRS-5 and around 464 million tonnes for CPRS-15.

However, as the Rudd Government has discovered, it is difficult to win acceptance of such legislation. There are too many powerful vested interests under threat. In addition, the cheapness of coal-based electric power in Australia relative to other sources of power generation, amplifies the cost penalties of an ETS (and associated restrictive cap on emissions) from the point of view of business. Reflecting these interests, the proposed ETS scheme, which failed to win parliamentary support in early December 2009, was full of loopholes providing free permits to coal-based electricity generators as well as to other big polluters, including the agricultural sector. This was before the government had stated what the cap would be. The proposed legislation just provides the authority to set a cap. The real test of the government's resolve will come if and when it sets a carbon cap that would put Australia on the path required for the CPRS-5 or CPRS-15 target.

It is likely that, with a booming economy stimulated further by the huge recent level of population growth, a carbon cap designed to meet either the CPRS-5 or CPRS-15 pathways would lead to such competition for carbon permits that the price would rise precipitously. In this context, it is hard to see the Rudd Labor Government or any subsequent government implementing such a cap.

WHY POPULATION GROWTH IS SUCH AN IMPORTANT DRIVER OF GREENHOUSE EMISSIONS

In developed countries, the extra emissions that flow from an increase in per capita GDP tend to be offset by improvements in energy efficiency, as measured by kilograms of emissions per dollar of GDP. The Treasury modelling confirms this pattern for Australia. Table 2 shows that per capita GDP in Australia is expected to grow from $44,532 to $62,357 over the years 2000 to 2020, or by a massive 40 per cent. Yet, as indicated, if population remains at the 19.2 level, greenhouse gas emissions only increase from 553 to 590 million tonnes over the same 20 years. The explanation is that growth in GDP (and thus consumer capacity to spend) is largely offset by the expected reduction in emissions per dollar of GDP.

This relationship has been evident for a long time. Calculations by the World

Resources Institute (WRI) show that in developed countries where population growth is low, as was the case across most of Western Europe during the 1990s and early 21st Century, that there was little increase in total greenhouse emissions. The WRI's disaggregation of the sources of growth in greenhouse emissions show that this is largely because per capita economic growth has been offset by improvements in energy efficiency per unit of GDP. By contrast, countries like Australia and Canada where population growth was relatively rapid, show much higher rates of greenhouse gas emission growth.[14] This is mainly because reductions in emissions per dollar of GDP in Australia and Canada tend to be negated by additional emissions attributable to population growth.

AUSTRALIA'S POLICY STANCE ON GREENHOUSE EMISSIONS

The Australian Labor Government likes to present itself as a global leader in the movement for greenhouse emissions reduction. Kevin Rudd has declared himself to be an impassioned believer in the need for a global compact on the issue in which developed nations state their willingness to cut greenhouse emissions. In a 6 November speech to the Lowy Institute, he attacked greenhouse sceptics as well as those who said Australia should wait until after the Copenhagen meeting before declaring its contribution. Rudd stated:

> As we approach Copenhagen, it becomes clearer that the domestic political pressure produced by the climate change sceptics now has profound global consequences by reducing the momentum towards an ambitious global deal. The argument that we must not act until others do is an argument that has been used by political cowards since time immemorial—both of the left and the right.[15]

The Labor Government even says that:

> It has committed to reduce Australia's carbon pollution by 25 per cent below 2000 levels by 2020 if the world agrees to an ambitious global deal to stabilise levels of CO_2 equivalent at 450 parts per million or lower by mid century.[16]

It is hard to see these commitments as anything more than symbolic goals, which no doubt the Government would like to achieve, but not at the price of threatening other valued ends.

This judgement stems from an evaluation of other policies which the government has pursued. The Labor Government has given the very highest priority to promoting aggregate economic growth in the interests of preserving and creating jobs. It has also shown great sensitivity about preserving Australia's emissions intensive export industries. Moreover, since taking office in November 2007 the Labor Government has pursued a record-high migration policy. The Prime Minister has stated that he welcomes the challenge this presents and values the 'big Australia' that will be the result. His government must know that this policy will diminish the likelihood that its greenhouse emission abatement policy will ever be fulfilled.

These priorities are evident in a recent statement by the head of the Treasury, Dr. Ken Henry, when discussing the forthcoming *Intergenerational Report* on Australia's population outlook. The *Report* projects that Australia's population will reach 35 million by 2049 and not 33 million as was assumed in the Treasury modelling discussed above. Dr. Henry expressed concerns about whether Australia's natural resource endowments are sufficient to sustain a population of 35 million, and about the loss of biodiversity. However, he had nothing to say about the implications of a population of 35 million for the attainment of the Australian government's emissions-abatement aspirations.[17]

CONCLUSION

The Australian Labor Government is in a diabolically difficult policy situation. It wants to be seen as an enlightened contributor to solutions to the global warming crisis. To this end it has given an 'unconditional commitment' to CPRS-5 by 2020 and flagged that it may be willing to introduce even greater cuts. It has the example of the EU which has committed to a 20 per cent cut in aggregate greenhouse emissions by 2020 relative to year 1990 levels. Even the United States Government has announced a commitment to reducing greenhouse gas emissions by 17 per cent by 2020 relative to 2005 levels.

The Australian Government will have to state its 'guaranteed emission targets' for 2020 by 31 January 2010 if it is to meet the terms of the Copenhagen Accord agreed to on 18 December 2009.[18] If the government is unwilling to go beyond the CPRS-5 goal to 2020 it will be exposed as a pretender in climate abatement circles. Those involved know that much more severe cuts are required if atmospheric greenhouse gases levels are even to be stabilised.

Yet as this paper has shown, there is little prospect of Australia achieving even the CPRS-5 objective. The Treasury-led modelling shows that, under the reference case, Australia's emissions will increase from 553 million tonnes in 2000 to 774 million tonnes by 2020. This expansion will be driven by a booming minerals-led economy, as well as rapid population growth. The Australian Government is riding this boom and thus is unlikely to enforce a cap on emissions which would achieve the CPRS-5 objective, even if it gets the CPRS legislation through the Parliament.

There is a relatively painless option available, which is a commitment to stabilising Australia's population. We have shown that population growth contributes 83 per cent to the total growth in greenhouse gases projected in the Treasury's reference case to 2020. Thus population stabilisation could massively ease the pain of achieving the CPRS-5 or even the CPRS-15 objective.

The simple arithmetic is as follows. If Australia's population had remained at 19.2 million to 2020 the achievement of the CPRS-5 goal would only have required a per capita reduction in greenhouse emissions from 28.8 tonnes per head in 2000 to 27.3 tonnes per head in 2020. But if Australia's population reaches 25.2 million by 2020 the achievement of CPRS-5 will require per capita emissions to fall to 20.8 tonnes. A fall of this magnitude over the next decade is not plausible.

The population option has been ignored by most participants in the greenhouse abatement debate, perhaps because few of them appreciate the crucial role of population growth in Australia's emission burden.

We hope that this article will at least remove the excuse of ignorance.

References

[1] Australian Government, *Carbon Pollution Reduction Scheme: Australia's Low Pollution Future*, White Paper, Volume 1, December 2008

[2] ibid., Executive Summary, p. xix

[3] ibid., p. 1.7

[4] Australian Government, *Australia's Low Pollution Future* (ALPF), 2008

[5] D. Karoly, 'Government fiddles around the edges while Australia burns', *The Age*, 27 November 2009, p. 19

[6] R. Garnaut, *The Garnaut Climate Change Review*, Interim Report to the Commonwealth, States and Territory Governments, Australia, February 2008, p. 30

[7] R. Garnaut, *The Garnaut Climate Change Review*, Final Report, Cambridge University Press, p. 205

[8] ibid, p. 208

[9] ALPF, op. cit., Chapter 3, Box 3.5: Energy efficiency

[10] ibid., Summary, p. 19

[11] Australian Government, Productivity Commission, *Economic Impacts of Migration and Population Growth*, Final Report, April 2006

[12] ibid., p. xxxii

[13] ALPF, op cit, Chapter 3, p. 34

[14] World Resources Institute, *Navigating the numbers: greenhouse gas data and international climate policy*, 2005

[15] Address to the Lowy Institute by the Prime Minister, 6 November 2009, p. 11

[16] Australian Government, Department of Agriculture Fisheries and Forestry, 'Carbon Pollution Reduction Scheme', 18 November 2009

[17] K. Henry, 'The shape of things to come: long run forces affecting the Australian economy in coming decades', speech to the Queensland University of Technology Business Leaders' Forum, 22 October, 2009

[18] United Nations Framework Convention on Climate Change, Draft decision, Copenhagen Accord, 18 December 2009