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Ocean fertilization and other climate change mitigation strategies: an overview

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ABSTRACT: In order to evaluate ocean fertilization in the larger context of other proposed strategies for reducing the threat of the global warming, a wide range of different climate change mitigation approaches are compared in terms of their long-term potential, stage of development, relative costs and potential risks, as well as public acceptance. This broad comparative analysis is carried out for the following climate change mitigation strategies: supply-side and end-use efficiency improvements, terrestrial and geological carbon sequestration, CO_2 ocean disposal and iron fertilization, nuclear power, and renewable energy generation from biomass, passive solar, solar thermal, photovoltaics, hydroelectric and wind. In addition, because of the inherent problems of conducting an objective comparative cost–benefit analysis, 2 non-technological solutions to global warming are also discussed: curbing population growth and transitioning to a steady-state economy.

KEY WORDS: Ocean fertilization · Climate change mitigation technologies · Efficiency · Carbon sequestration · Renewable energy · Cost–benefit analysis · Population growth · Economic growth

INTRODUCTION

Anthropogenic emissions of carbon dioxide from the combustion of fossil fuels have significantly increased atmospheric CO_2 concentrations during the last century, which, in turn, is expected to bring about climate change together with both predictable and unforeseen negative consequences for both humans and the environment. In order to reduce the threat of global warming, drastic reductions in carbon emissions, currently amounting to ~7.1 Gt C yr^{-1}, are needed. According to the so-called 'Kaya' equation, the magnitude of net carbon emissions to the atmosphere (Net C) is a function of multiple driving forces (Huesemann 2006):

$$\text{Net C} = P\,(GDP/P)\,(E/GDP)\,(C/E) - S \qquad (1)$$

where P is the size of the human population, GDP/P is the per capita gross domestic product, often referred to as 'affluence', E/GDP is the energy required per gross domestic product, also called energy intensity, which is the inverse of energy efficiency, C/E is the carbon emitted per unit energy generated, i.e. the carbon intensity of the fuel mix used to drive the economy, and S is the natural and induced removal of carbon as CO_2 from the atmosphere, also referred to as carbon sequestration. In summary, the Kaya equation states that the size of total carbon emissions is the product of a nation's population, its per capita economic output, its energy utilization efficiency, and the carbon quality of the fuel used, minus any carbon that is sequestered in terrestrial biomass, geologic formations, or oceans. It is the objective of this paper to provide a broad comparative cost–benefit analysis of all climate change mitigation technologies, including ocean fertilization, and also consider non-technological solutions to global warming, such as curbing population growth and transitioning to a steady-state economy.

COMPARISON OF CLIMATE CHANGE MITIGATION STRATEGIES

A comparison of different climate change mitigation technologies, in terms of their long-term potential,

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Table 1. Comparison of different climate change mitigation in terms of their long-term potential, stage of development, relative costs and potential risks. R&D: research and development, C: carbon, tech: technology, med: medium

Mitigation technology	Long-term potential	Stage of development	Relative cost[a]	Potential risks	Other issues
Efficiency improvements					
Supply-side efficiency	2-fold improvement	Current tech	Low to med	None	Market imperfections
End-use efficiency	>10-fold (?) improvement	R&D	Low to med	None	Market imperfections
Carbon sequestration					
Terrestrial	Approx. 200 Gt C	Current tech	Low	None	Competition with food, fiber and fuel wood
Geological					
Coal seams, Oil & gas fields	Several 100 Gt C	R&D, pilot study	Med to high	Environmental health	Leakage, only power plants
Saline aquifers	Up to 10 000 Gt C	R&D, pilot study	Med to high	Environmental health	Leakage, only power plants
Ocean					
CO_2 disposal	Several 1000 Gt C	R&D, pilot stopped	Med to high	Acidification of marine biota	Public resistance, legality
Iron fertilization	~0.2 Gt C yr^{-1}	R&D, pilot study	Low to med	Marine environment	Public resistance, legality
Carbon intensity reduction					
Decarbonization of fossil fuels	Decarbonize all fossil fuels	Current tech	Low to med	Carbon sequestration	–
Renewable energy sources					
Biomass	Several-fold increase	Current tech, some R&D	Low	Environment, food availability	Land-use conflicts
Passive solar	>10-fold increase	Current tech	Very low	None	Market imperfections
Solar thermal	>10-fold increase	Current tech, some R&D	Low to med	Desert ecosystems	–
Photovoltaics	>10-fold increase	Current tech, some R&D	Low to med	None or very limited	–
Hydroelectric	No further increase	Current tech	Low	Aquatic ecosystems	Public resistance
Wind power	>10-fold increase	Current tech, some R&D	Low to med	Noise, bird kills	Aesthetics, public resistance
Nuclear energy	Several-fold increase	Current tech, some R&D	Low to med	Radioactivity, catastrophe	Waste proliferation

[a]The quantification of exact costs or cost ranges is difficult for the following reasons: (1) for many currently existing technologies (e.g. solar photovoltaics), costs are expected to decrease substantially due to economies of scale if they were to be widely adopted; (2) for mitigation strategies that exhibit some type of saturation phenomenon (e.g. planting trees on limited land), marginal costs increase as opportunities for applying them decreases; (3) for technologies that are still in the research and development stage (e.g. geological sequestration, iron fertilization), costs are difficult to estimate because the final system or end-product is not yet known; (4) for technologies that transfer costs and risks to future generations (e.g. nuclear energy, geological sequestration), present-day cost estimates may be significantly underestimated

stage of development, relative costs and potential risks, is given in Table 1. As indicated by Eq. (1), climate change mitigation technologies fall into 3 general categories: energy efficiency improvements, carbon sequestration and carbon intensity reduction. Within each of these 3 general categories, a number of different technologies or mitigation approaches exist. For example, energy efficiency improvements can further be classified as either supply-side or end-use efficiency improvements. Supply-side efficiency is defined as the ratio of useful energy output (e.g. work, heat, electricity) to primary energy input (e.g. coal, oil, uranium, biomass) and is currently about 37 % at the global scale (Jochem 2000), but could in theory be further increased ~2-fold (Jochem 1991). Further improvements are unlikely, given intrinsic thermodynamic and practical constraints (Jochem 1991). Most increases in supply-side efficiency could be achieved with current technologies, making them relatively cost effective and risk free.

End-use efficiency is defined as the ratio of economic output resulting from energy services (measured as gross domestic product, or GDP) to useful energy input and could, in certain specific cases, be increased substantially, possibly by 1 order of magnitude or more. For example, compared to traditional incandescent lights, the amount of lighting service (lumens) provided per electric energy input has risen significantly with the use of light-emitting diodes (LEDs). Since continued research and development will be needed to further increase end-use efficiencies, relative costs are intermediate, but risks are low or nonexistent.

Despite the fact that efficiency improvements are a risk-free solution to climate change and that many could easily be implemented at no additional cost (Lovins & Lovins 1991), there are a number of barriers, such as absence of economic incentives, lack of consumer information, insufficient capital, slow technology diffusion, and general cultural inertia (Huesemann 2006). However, the primary reason for not realizing theoretically achievable efficiencies are market imperfections that are created when the cost of energy is kept artificially low by subsidies or by externalizing environmental and national security costs, thereby encouraging wasteful energy use by consumers and providing no incentives for energy conservation via efficiency measures (Sioshansi 1991, Jochem 2000). Finally, it is important to note that energy efficiency improvements alone will not reduce total energy use and carbon emissions if the size of the global economy continues to grow (see also Huesemann 2006, Huesemann & Huesemann 2008).

Carbon sequestration involves either the capture and secure storage of power plant CO_2 emissions in geologic formations or deep oceans, or the removal of CO_2 from the atmosphere by terrestrial or marine photosynthesis and the subsequent, long-term storage of the carbon-rich biomass (US DOE 1999). Terrestrial carbon sequestration consists of the photosynthetic fixation of atmospheric CO_2 by plants (e.g. trees, crops, grasses, etc.) and the long-term accumulation and storage of both standing and below-ground biomass. Rates of terrestrial carbon sequestration can be increased by reforestation and afforestation, and by implementing alternative soil management practices, such as no-till agriculture to promote the formation and retention of soil organic matter. The terrestrial biosphere currently stores approximately 2000 Gt C (ca. 600 Gt in plant biomass and 1400 Gt in soil humus) (US DOE 1999) and this carbon pool could possibly be increased by approximately 200 Gt C, to its pre-1750 size, via reforestation and improved farming practices (Scholes & Noble 2001). Terrestrial carbon sequestration can be carried out with current technology, is low in cost and carries few risks — in fact, it should result in a significant improvement in previously degraded ecosystems. The main challenge to implementing terrestrial carbon sequestration on a large scale is the ever-increasing and competing demand for food, fiber, and fuel wood by growing human populations.

Geological carbon sequestration involves the storage of CO_2 in deep underground reservoirs, such as depleted oil and gas fields, unmineable coal seams, and saline aquifers (US DOE 1999, Bruant et al. 2002). Prior to sequestration, the CO_2 must first be separated from the flue gases of centralized fossil fuel-fired power plants and then transported via pipeline to geologic reservoirs. The total world-wide carbon storage capacity is estimated to be tens to hundreds Gt C for coal seams, hundreds to 10 000 Gt C for saline aquifers, and several hundred Gt C for depleted oil and gas fields (Herzog 2001, Bruant et al. 2002). The primary difficulty with geologic carbon sequestration is the potential leakage of CO_2 from the reservoirs and subsequent adverse effects to human health and the environment (Herzog 2001, Bruant et al. 2002, Wilson et al. 2003). Thus, given that some leakage is unavoidable — because it would be very difficult, if not impossible, to detect, monitor and to control all potential CO_2 escape routes — geologic carbon storage is not truly permanent. Slow, chronic leakage could result in the dissolution of CO_2 in shallow aquifers, causing the acidification of groundwater and undesirable changes in geochemistry (e.g. mobilization of toxic metals), water quality (e.g. leaching of nutrients), and ecosystem health (e.g. pH impacts on organisms) (Bruant et al. 2002). A sudden catastrophic release of large amounts of CO_2, as a result of either reservoir fracturing by earthquakes or pipeline failures, could result in the immediate death of both people and animals, particularly since CO_2 is odorless, colorless, and tasteless, and thus is likely to escape detection (Bruant et al. 2002). The US Department of Energy is currently conducting a number of field pilot studies to evaluate the efficacy and safety of geologic carbon sequestration (US DOE 2007). Because of the need for gas separation, transport, injection and long-term monitoring, sequestration costs will likely be intermediate to high.

Two different types of ocean carbon sequestration schemes have been proposed: (1) the disposal of CO_2 in mid- or deep oceans, and (2) the addition of fertilizers to stimulate the growth of phytoplankton, part of the latter is expected to sink to the ocean floor and thus sequester C there. Proposed CO_2 ocean disposal strategies include the release of dry ice cubes from a stationary ship, the introduction of liquid CO_2 onto a seafloor depression forming a 'deep lake,' the release of CO_2-enriched seawater at 500 to 1000 m depth, and the injection of liquid CO_2 at 1000 to 1500 m depth from a stationary outlet or from a pipe towed by a moving ship (Herzog et al. 1996, Caulfield et al. 1997, US DOE 1999). The rationale for injecting CO_2 into the oceans, which have a combined storage capacity of several thousand Gt C (Herzog 2001), is to accelerate the transfer of CO_2 from the atmosphere to the deep ocean, a process which occurs naturally at an estimated rate of 2 Gt C yr^{-1}. The main problem with CO_2 ocean disposal is that the resulting seawater acidification and pollution with CO_2 impurities such as NO_x, SO_x, and trace metals (US DOE 1999) could adversely affect highly sensitive marine organisms, many of which have adapted to the very stable deep sea environment and therefore are ill-suited to adjust to drastic changes in seawater chemistry (US DOE 1999, Tamburri et al. 2000, Seibel & Walsh 2001). In addition, CO_2 disposal may also negatively affect microbial populations and thus cause changes or disruptions in marine biochemical cycles (Seibel & Walsh 2001, Huesemann et al. 2002), which may have large negative consequences, many of them secondary and difficult to predict (US DOE 1999). Because of these environmental issues, mounting public opposition and legal concerns, 2 proposed small-scale CO_2 disposal experiments off the coasts of Hawaii and Norway were cancelled in 2002 (Burke 2002), making the future of CO_2 ocean dumping uncertain.

Ocean fertilization involves the addition of limiting micronutrients, such as iron, to stimulate the growth of phytoplankton (US DOE 1999, Chisholm et al. 2001). While most of the additional photosynthetically fixed biomass carbon will be recycled in the photic zone, a small fraction will sink to the ocean floor, where it will become incorporated into deep-sea sediments, thereby preventing its reentry into the global carbon cycle for some time. Although there are significant scientific and technical problems with quantifying the exact amounts of carbon that would be sequestered in deep-ocean sediments (Gnanadesikan et al. 2003, Buesseler et al. 2004), it is estimated that about 200×10^6 t C (i.e. ca. 3% of current annual CO_2 emissions) could be sequestered per year by fertilizing 10^8 km^2, an area corresponding to the size of the entire Southern Ocean (Buesseler & Boyd 2003). Because large-scale ocean fertilization would involve the manipulation of immense expanses of ocean surface waters, there are serious concerns about potential unexpected negative consequences to marine ecosystems and biogeochemical cycles. For example, large-scale eutrophication could result in the depletion of oxygen, leading to deep ocean anoxia, which, in turn, would shift the microbial community structure towards organisms that produce methane and nitrous oxide, i.e. greenhouse gases with much higher warming potentials than CO_2 (US DOE 1999, Chisholm et al. 2001, Gnanadesikan et al. 2003). In addition, it will be difficult to predict all secondary and higher order effects of ocean fertilization on the ocean food web structure and dynamics, including changes in the biogeochemical cycling of important elements, such as carbon, nitrogen, phosphorus, silicon and sulfur (US DOE 1999, Boyd et al. 2007). Despite increasing interest by private companies in selling carbon credits by fertilizing large expanses of ocean, the International Maritime Organization recently announced at their 2007 London Convention that, 'knowledge about the effectiveness and potential environmental impacts of ocean fertilization is currently insufficient to justify large-scale operations.' (IMO 2007).

In addition to efficiency improvements and carbon sequestration, a third climate mitigation approach is to reduce the carbon intensity of the energy mix[1], which can be brought about by (1) decarbonization of fossil fuels, (2) increased use of renewable energy, and (3) greater utilization of nuclear power (see Table 1). Decarbonization of fossil fuels involves the generation of the carbon-free energy carrier hydrogen and CO_2, the latter of which must be sequestered in geologic formations or deep oceans, an approach that is neither inexpensive nor risk-free (see above). The increased use of renewable energy sources such as biomass, wind, photovoltaic, solar thermal, and hydroelectric energy is often seen as an easy and obvious solution to climate change but, as has been reviewed in great detail elsewhere (Huesemann 2003, Huesemann 2006), there are likely to be significant environmental impacts if renewable energy generation were to be implemented on a large scale.

Biomass energy can be generated in many cases at relatively low cost using technologies that are already available or currently under development. The main problem with biomass energy is that large areas of productive land are required. Consider, for example, that anthropogenic activities already appropriate 30 to 40% of the terrestrial primary productivity (i.e. photosynthetically fixed carbon) worldwide (Vitousek et al. 1986, Rojstaczer et al. 2001), indicating that two-fifths of the land's productive capacity is tightly controlled and managed for supplying food, fiber and energy. In the USA, total energy use (ca. 100 quads) is almost twice as large as the energy captured by all vegetation (58 quads), about half of which (28 quads) is already harvested as agricultural crops and forest products and therefore not available for energy production (Huesemann 2006). For example, if ethanol from corn were to be substituted for 100% of the gasoline consumption in the USA, all of the available USA cropland would have to be devoted to ethanol production, leaving no land for food production (Kheshgi et al. 2000). Thus, increased biomass energy production will lead to com-

[1]Energy mix is defined as the proportional relationship between all utilized energy sources

petition for scarce agricultural land and will intensify ethical conflicts regarding the use of crops for food versus fuel. Indeed, in response to the rising demand for corn-based ethanol, prices for corn and other basic staples have already increased significantly, placing the world's poorest people at serious risk of malnutrition and starvation (Muller et al. 2008). A possible solution to these problems is to cultivate microalgal biomass for biofuel conversion employing land and water resources not used for agriculture. Because of the high solar conversion efficiencies of microalgae, their cultivation has a 10-fold smaller environmental footprint than agricultural biomass; however, significant research and development will be needed to make biofuels from microalgae economically competitive (Huesemann & Benemann 2008). According to a recent analysis by van Harmelen & Oonk (2006), approximately 100×10^6 t CO_2 (27×10^6 t C) could be removed annually by microalgae starting around 2020. If microalgal biofuels were to be produced at this scale for 50 yr, about 1.35 Gt C would be abated, which amounts to approximately 5% of the climate stabilization wedge proposed by Pacala & Socolow (2004).

Another extremely cost-effective way of providing renewable energy for space heating and hot water is through 'passive' solar energy capture by buildings specifically designed for this purpose. Tremendous potential exists for capturing more solar energy by buildings with current technologies with no or minimal environmental impacts. Solar energy can also more 'actively' be captured by either solar thermal receivers consisting of computer-controlled sun-tracking parabolic mirrors that focus sunbeams to generate steam for electric power generation or by photovoltaic cells that convert light into electricity. While some limited amount of energy is already being generated with these active solar capture technologies, more research and development will be needed to make them economically competitive. For significant fractions of the total energy demand to be supplied by these technologies, very large land areas (e.g. thousands of square miles) would have to be covered with these solar energy capture devices, which could potentially result in adverse environmental impacts (Huesemann 2006). Hydroelectric dams generate annually about 3% of the USA's total energy demand, but hydropower generation is unlikely to be expanded because all suitable sites have already been exploited and there are increasing concerns about deleterious environmental impacts to aquatic species (Huesemann 2006). Finally, large windmills — if deployed by the millions — could also provide a fraction of carbon-free power. However, given that millions of ha would have to be covered with windmills to provide even a small fraction of the USA's electricity demand, it is unlikely that the public will tolerate huge wind farms, given concerns about blade noise and aesthetics (Huesemann 2006).

In addition to renewable solar energy generation, carbon-free energy can also be produced in a relatively cost-effective way by nuclear power plants using existing technologies. Although nuclear power currently supplies about 6% of energy in the form of electricity worldwide, further expansion of nuclear energy generation will be problematic because of limited uranium reserves, waste disposal and weapons proliferation concerns associated with breeder reactors, nuclear reactor safety, long-term storage of radioactive wastes, and intense public resistance against the construction of new nuclear power plants (Huesemann 2006).

Finally, a number of innovative 'geo-engineering' or 'planetary engineering' approaches have been proposed to counteract global warming by reducing the quantity of sunlight reaching the earth surface. More commonly proposed geoengineering strategies include (1) the dispersal of sulphate aerosols and/or dust into the atmosphere, thereby effectively simulating volcanic eruptions that have historically been demonstrated to cause 'global cooling,' (2) large-scale cloud seeding to increase cloud cover, and (3) the installation of a 2000 km diameter space-mirror deflecting about 2% of earth-bound solar radiation (Teller et al. 1997, Hoffert et al. 2002). Although these geoengineering technologies are presently only at the conceptual stage of development, there is already considerable concern about potentially unknown and even intrinsically unknowable negative long-term consequences of the large-scale modification of planetary processes (Kintisch 2007).

INHERENT PROBLEMS OF COMPARATIVE COST–BENEFIT ANALYSIS

Based on the above cursory analysis of potential climate change mitigation options (Table 1), it appears that the best approaches are those which can employ existing technologies, are low cost, and have minimal risk, thereby being readily acceptable to the public. Using these selection criteria, efficiency improvements, terrestrial carbon sequestration, passive solar, and a very cautious expansion of renewable solar energy sources such as biomass, active solar, and wind power are probably some of the best choices for reducing the risk of global climate change. However, because of the limited potential of these few options, it will be necessary to carry out a more rigorous comparative cost–benefit analysis (CBA) of all climate change mitigation approaches.

As shown in Fig. 1, a comprehensive and systematic CBA involves at least 9 different steps (Boardman et

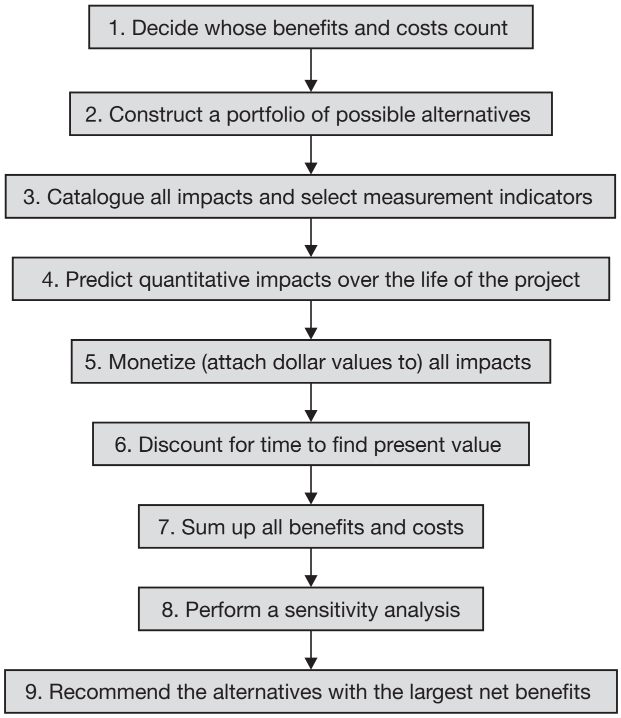

Fig. 1. Procedural steps involved in performing comprehensive and systematic cost–benefit analyses (Boardman et al. 1996)

al. 1996). Although this step-wise procedure appears to be straightforward at first sight, many difficult problems arise as soon as one actually tries to carry out a particular comparative CBA. (1) It is difficult to determine whose benefits and costs should be counted (Step 1). Should it be a selected group of people, all people presently living, future generations, certain animal species, all animals, all plants, etc.? The answer to these questions cannot be found by an objective analysis but depends on value judgments, thus greatly increasing the probability of value conflicts among different stakeholders. (2) The cataloging of all potential impacts and the selection of measurement indicators (Step 3) is affected by the boundaries of the analysis. Should local or global, present or future impacts be considered? In addition, many impacts may not be foreseeable. Similarly, the selection of measurement indicators depends on our current state of knowledge, which, because of its perpetual incompleteness, could result in a situation in which the most important impacts would not be measurable. (3) Even if all potential effects could be identified and measured, quantitative prediction (Step 4), from the present into the distant future, is almost certainly impossible given the inherent limitations of current mechanistic, reductionist science (Huesemann 2001). (4) The monetization of all costs and benefits (Step 5) is highly problematic because it is exceedingly difficult to assign a price for non-marketed values such as the life of humans or animal species. (5) The discounting of the future to obtain the present value (Step 6) is ethically questionable because potential negative consequences to future generations may be greatly underestimated. (6) The entire process of CBA, which is based on utilitarian philosophy, is an attempt to maximize overall benefits to society (Step 7) while at the same time ignoring issues of equity and justice, i.e. CBA is insensitive to the fact that benefits may accrue to some individuals or groups at the expense of others.

Because of these inherent procedural uncertainties, it is intrinsically impossible to conduct a truly objective, comparative CBA of different climate change mitigation technologies. Instead, the most powerful stakeholders often define the problem and influence the procedure in such a way that the outcome of the CBA will be biased towards a particular favored technology. Thus, the selection of the best climate change mitigation approaches is not just a technical exercise but a highly political process.

CURBING POPULATION GROWTH AND TRANSITIONING TO A STEADY-STATE ECONOMY

According to Eq. (1), net carbon emissions are affected to a significant degree by the size of the human population (P) and per capita affluence (GDP/P), 2 factors that are rarely considered in the climate change mitigation debate. Several studies have shown that the projected population growth between 1985 and 2100 accounts for more than 33% of the future growth in CO_2 emissions globally and close to 50% in developing nations (Bongaarts 1992, UNPC 1994). If global fertility could be reduced by only 0.5 births per woman to achieve the United Nation's low variant population projection of 5.6×10^9 (Gaffin 1998), the projected population would decrease by 18% in 2050 and by 46% in 2100, which could translate into similar reductions in energy demand and greenhouse gas emissions (Gaffin & O'Neill 1998).

Respecting human rights, global fertility could be easily and cost-effectively reduced by (1) increasing the education of women, (2) offering financial incentives for small families and disincentives for large ones, (3) providing social security and universal health care in order to reduce dependence on adult children, (4) making family planning services available, and (5) changing cultural norms with regard to ideal family size (Huesemann 2006, Huesemann & Huesemann 2008). Compared to most climate change technologies discussed above (Table 1), controlling population growth is one of the cheapest methods to avoid future CO_2 emissions. According to the analysis of Birdsall (1994), the costs of reducing births through family planning and female education are $US4 to $US11 and $US3 to $US9 t^{-1} of carbon avoided, respectively, which is lower than the US Department of Energy's ambitious goal of $10 per ton of carbon sequestered or avoided (US DOE 2007).

All other things being equal, the size of the per capita GDP, commonly referred to as 'affluence' or 'material standard of living,' is directly related to the magnitude of net carbon emissions (see Eq. 1). According to estimates by the Intergovernmental Panel on Climate Change (IPCC), the size of the world economy is expected to increase 12- to 26-fold by 2100, and per capita affluence 4- to 19-fold, depending on scenario conditions (Huesemann 2006). This continuing growth in economic output and material affluence is likely to significantly lessen any gains in net carbon emission reductions that will be made by the various technological mitigation approaches discussed above (see Table 1). Thus, unless there is a conscious effort to transition from our current growth-oriented economy to a steady-state economy in which material affluence is maintained at constant and sustainable levels, it will be extremely difficult to reduce carbon emissions sufficiently to achieve permanent climate stabilization.

It could be argued that it is practically and politically impossible to abolish our addiction to infinite economic growth and ever-rising material affluence. That may be so. But it should be kept in mind that as soon as basic material needs have been satisfied, further increases in the material standard of living do not result in greater happiness (Lane 2001). For example, although the average income after taxes more than doubled in the USA from 1960 to 1990, the fraction of people who consider themselves 'very happy' remained virtually constant at around 35% (Myers & Diener 1996). The reasons for this paradox are that (1) human desires are inherently insatiable, (2) relative rather than absolute income determines one's social position and feeling of achievement, and (3) the pursuit of materialism deprives people of opportunities to engage in social, cultural, and spiritual activities that are known to promote feelings of happiness and well-being (Huesemann & Huesemann 2008).

In conclusion, while there are a number of promising climate change mitigation technologies, it is highly unlikely that global warming will be successfully averted unless we seriously reconsider our commitment to unlimited economic growth and consumption, and instead find fulfillment in less materialistic ways. Should we continue along a path that not only aggravates global warming but also does not improve our sense of well-being? It is time to re-examine our priorities.

LITERATURE CITED

Birdsall N (1994) Another look at population and global warming. In: Population, environment, and development: Proceedings of the United Nations expert group meeting on population, environment, and development, held at the United Nations Headquarters, 20–24 January 1992. United Nations, New York, p 39–54

Boardman AE, Greenberg DH, Vining AR, Weimer DL (1996) Cost–benefit analysis: concepts and practice. Prentice Hall, Upper Saddle River, NJ

Bongaarts J (1992) Population growth and global warming. Popul Dev Rev 18:299–319

Boyd PW, Jickells T, Law CS, Blain S and others (2007) Mesoscale iron enrichment experiments 1993–2005: synthesis and future directions. Science 315:612–617

Bruant RG, Celia MA, Guswa AJ, Peters CA (2002) Safe storage of CO_2 in deep saline aquifers. Environ Sci Technol 36:240A–245A

Buesseler KO, Boyd PW (2003) Will ocean fertilization work? Science 300:67–68

Buesseler KO, Andrews JE, Pike SM, Charette MA (2004) The effects of iron fertilization on carbon sequestration in the Southern Ocean. Science 304:414–417

Burke M (2002) Sequestration experiment is drowning. Environ Sci Technol 36(21):401A

Caulfield JA, Auerbach DI, Adams EE, Herzog HJ (1997) Near field impacts of reduced pH from ocean CO_2 disposal. Energy Convers Manage 38(Suppl):S343–S348

Chisholm SW, Falkowski PG, Cullen JJ (2001) Dis-crediting ocean fertilization. Science 294:309–310

Gaffin SR (1998) World population projections for greenhouse gas emission scenarios. Mitig Adapt Strategies Glob Change 3:133–170

Gaffin SR, O'Neill BC (1998) Combat climate change by reducing fertility. Nature 396:307

Gnanadesikan A, Sarmiento JL, Slater RD (2003) Effects of patchy ocean fertilization on atmospheric carbon dioxide and biological production. Global Biogeochem Cycles 17(2):1050

Herzog HJ (2001) What future for carbon capture and sequestration? Environ Sci Technol 35:148A–153A

Herzog HJ, Adams EE, Auerbach D, Caulfield J (1996) Environmental impacts of ocean disposal of CO_2. Energy Convers Manage 37:999–1005

Hoffert MI, Kaldeira K, Benford G, Criswell DR and others (2002) Advanced technology paths to global climate stability: energy for a greenhouse planet. Science 298: 981–987

Huesemann MH (2001) Can pollution problems be effectively solved by environmental science and technology? An analysis of critical limitations. Ecol Econ 37:271–287

Huesemann MH (2003) The limits of technological solutions to sustainable development. Clean Technol Environ Policy 5:21–34

Huesemann MH (2006) Can advances in science and technology prevent global warming—a critical review of limitations and challenges. Mitig Adapt Strategies Glob Change 11:539–577

Huesemann MH, Benemann RJ (2008) Biofuels from microalgae: review of products, processes, and potential, with special focus on *Dunaliella* sp. In: Ben-Amotz A, Polle JEW, Subba Rao DV (eds) The alga *Dunaliella*: biodiversity, physiology, genomics, and biotechnology. Science Publishers, Enfield (in press)

Huesemann MH, Huesemann JA (2008) Will progress in science and technology avert or accelerate global collapse?

A critical analysis and policy recommendations. Environ Dev Sustain (in press) doi: 10.1007/s10668-007-9085-4
Huesemann MH, Skillman AD, Crecelius EA (2002) The inhibition of marine nitrification by ocean disposal of carbon dioxide. Mar Pollut Bull 44:142–148
IMO (International Maritime Organization) (2007) Convention on the prevention of marine pollution by dumping of wastes and other matter, 1972 and its 1996 protocol—Statement of concern regarding iron fertilization of the oceans to sequester CO_2. Ref. T5/5.01, LC-LP1/Circ. 14, 13 July. Available at: www.imo.org/home.asp?topic_id=1488
Jochem E (1991) Long-term potentials of rational energy use—the unknown possibilities of reducing greenhouse gas emissions. Energy Environ 2:31–44
Jochem E (2000) Energy and end-use efficiency. In: Goldemberg (ed) World energy assessment: energy and the challenge of sustainability, Chap. 6. United Nations Development Programme, United Nations Department of Economic and Social Affairs, World Energy Council. United Nations, New York, p 174–217
Kheshgi HS, Prince RC, Marland G (2000) The potential of biomass fuels in the context of global climate change: Focus on transportation fuels. Annu Rev Energy Environ 25:199–244
Kintisch E (2007) Should we study geoengineering? A Science magazine panel discussion. Science 318:1054–1055
Lane RE (2001) The loss of happiness in market democracies. Yale University Press, New Haven, CT
Lovins AB, Lovins LH (1991) Least-cost climatic stabilization. Annu Rev Energy Environ 16:433–531
Muller A, Schmidhuber J, Hoogeveen J, Steduto P (2008) Some insights in the effect of growing bioenergy demand on global food security and natural resources. Water Policy 10(Suppl 1):83–94
Myers DG, Diener E (1996) The pursuit of happiness. Sci Am 274:70–72
Pacala S, Socolow R (2004) Stabilization wedges: solving the climate problem for the next 50 years with current technologies. Science 305:968–972
Rojstaczer S, Sterling SM, Moore NJ (2001) Human appropriation of photosynthesis products. Science 294:2549–2552
Scholes RJ, Noble IR (2001) Storing carbon on land. Science 294:1012–1013
Seibel BA, Walsh PJ (2001) Potential impacts of CO_2 injection on deep-sea biota. Science 294:319–320
Sioshansi FP (1991) The myths and facts about energy efficiency. Energy Policy 19:231–243
Tamburri MN, Petzer ET, Friederich GE, Aya I, Yamane K, Brewer PG (2000) A field study of the effects of CO_2 ocean disposal on mobile deep animals. Mar Chem 72:95–101
Teller E, Wood L, Hyde R (1997) Global warming and ice ages. I: Prospects for physics-based modulation of global change. Proc 22nd Int Seminar on Planetary Emergencies, Erice (Sicily), Italy, 20–23 August, 1997. Available at: http://www.osti.gov/accomplishments/documents/fullText/ACC0229.pdf
UNPC (United Nations Population Council) (1994) Future population growth and global warming. In: Population, environment, and development: Proceedings of the United Nations expert group meeting on population, environment, and development held at the United Nations headquarters, 20–24 January 1992. United Nations, New York, p 280–285
US DOE (United States Department of Energy) (1999) Carbon sequestration—state of the science. DOE Carbon Sequestration Research and Development Report. Available at: www.netl.doe.gov/publications/press/1999/seqrpt.pdf
US DOE (United States Department of Energy) (2007) Office of Fossil Energy, carbon sequestration R&D overview. Available at: www.fossil.energy.gov/sequestration/overview.html
van Harmelen T, Oonk H (2006) Microalgae biofixation processes: application and potential contributions to greenhouse gas mitigation options. TNO Built Environment and Geosciences, The Netherlands
Vitousek PM, Ehrlich PR, Ehrlich AH, Matson PA (1986) Human appropriation of the products of photosynthesis. Bioscience 36:368–373
Wilson EJ, Johnson TL, Keith DW (2003) Regulating the ultimate sink: managing the risks of geologic CO_2 storage. Environ Sci Technol 37:3476–3483

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