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Population crash: prospects for famine in the twenty-first century

Carleton Schade · David Pimentel

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Abstract For centuries famine arose as a seemingly endless series of acute, regional and unanticipated events; it has transformed into a phenomenon, global in scale and continuous in nature. Half the world's human population perpetually suffers some form of malnourishment, from either a scarcity of calories, protein or micronutrients or from a combination of these. Sheer population size has rendered the scale of suffering unprecedented. Perpetual famine has emerged during an era of abundant and relatively inexpensive soil, water and energy resources, improving crop yields, and a benign climate. However, the twentieth century trends of resource degradation, diminishing growth in crop yields and a warming atmosphere will likely continue, latently and perhaps synergistically impacting agricultural production, and therefore, threatening food security in the twenty-first century. Assuming some proportional relationship between food security and these resources, famine is here projected to greatly increase in the coming decades, severely impacting billions of people.

Keywords Perpetual famine · Population crash · Food security · Agriculture · Global warming

1 Famine: past, present and future

Unlikely as the chances for global famine may appear from our present perspective, hunger and famine have plagued humanity since agriculture's beginnings (Cohen 1989; Larsen 2006). Famine is featured in the book of Genesis of the Hebrew Bible and it has been recorded in the texts of the great civilizations of Egypt, China, Greece, India, and Rome

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C. Schade (✉)
P.O. Box 2888, Sag Harbor, NY 11963, USA
e-mail: namahshivaya@msn.com

D. Pimentel
Cornell University, 5126 Comstock Hall, Ithaca, NY 14853, USA

(Sen 1982; Golkin 1987; Arnold 1988). Its evidence has been found in the bones and archeological remains of the Mayan, Aztec, Anasazi, Indus, Mesopotamian, Andean, Polynesian, and Easter Island societies (Hole 1966; Sabloff and Willey 1967; de Montellano 1978; Manzanilla 1997; Yoffee 1997; Taylor and Davies 2004; Diamond 2005; Aimers 2007; Alum et al. 2007). Western Europe suffered mightily for 1,000 years between 500 and 1,500; then Eastern Europe for the following 200 years; India and China for the next 200 years after that (Arnold 1988; Smil 2001; O Grada 2007). As the world's population steadily rose through the centuries, so did the number of deaths due to famine. During the twentieth century more people died in famines than from the two World Wars combined (Devereux 2000; Meng and Qian 2006). Holland, Japan, the Ukraine, the Soviet Union, Kazakhstan, the Caribbean, China, Ethiopia, Sudan, North Korea, Bangladesh, Burma, India, and some 40 other countries experienced famines (Sen 1982; Golkin 1987; Arnold 1988; Devereux 2000; O Grada 2007).

Famine has been defined in terms of both extreme food scarcity and as widespread life-threatening hunger, irrespective of food's availability (Ravallion 1996). Using the latter definition, we find ourselves in a time of unprecedented food abundance as well as in an era of perpetual famine. More people have suffered in the past decades from protein and calorie malnutrition than ever before. Until 1800, there had never even been 850 million people on the planet at any one time, but now that many go to bed hungry every day (Sanchez and Swaminathan 2005; FAO 2006). Of these, about 85 million people worldwide suffer *acute* hunger, starving slowly, wasting away, victims of war, famines, and natural disasters (Sanchez and Swaminathan 2005). More than nine million actually starve to death each year or die of diseases their malnourished bodies cannot fight (Serageldin 2002; WWPA 2003; FAO 2006). In a given year, a billion feel the pangs of chronic hunger (Darwin et al. 2005). Somewhere between 2.2 and 4.5 billion people are deficient in protein and calorie intake and in the micronutrients iron, iodine, vitamin A, folate, and zinc (FAO 1993; Underwood 2003; WHO 2004). Stunted physically and mentally, they suffer from considerable brain damage, cretinism, goiter, blindness, anemia, and die early of cancer, malaria, measles, and other diseases (FAO 1997; Marx 1997; Ames 1999, 2001; Black, M 2003; Black, R 2003; Pimentel 2003; Underwood 2003; Sanchez and Swaminathan 2005).

At the same time, over a billion people are considered overfed, overweight and obese (Kopelman 2000; O'Brien and Dixon 2002), and billions of the world's newly affluent are eating higher on the food chain, eating more meat, and taking in more calories, a phenomenon referred to as "diet globalization" and the "nutrition transition" (Bender 1994; Myers 1997; Harris 2001; Tilman et al. 2002; Naylor et al. 2005; FAO 2006). Assuming the continued rise in food consumption per capita and the 2.5 billion additional people projected by 2050 (UNPD 2007), global food demand is expected to double—perhaps even triple—by mid-century (Bongaarts 1996; Crosson 1997; Matson et al. 1997; Daily et al. 1998; Doos and Shaw 1999; Harris 2001; Vance 2001; Ruttan 2002; Tilman et al. 2002; Green et al. 2005; Lal 2007).

In order to support a far smaller 20th century population—with a mean of about four billion people between 1950 and 2000—humanity overwhelmed a majority of the planet's ecosystem services (MEA 2005), destroyed much of its life, both in number and diversity, and have taken control of a significant portion of the Earth's biological, geological, and chemical cycles (Wilson 1989, 2006; Blaustein et al. 1994; Leaky and Lewin 1996; Vitousek et al. 1997; Ricciardi and Rasmussen 1999; Jackson et al. 2001b; Collins and Storfer 2003; Burney and Flannery 2005; Ceballos et al. 2005; Lotze et al. 2006; Becker et al. 2007; Kareiva et al. 2007). Every environmental indicator of global proportions has steadily worsened. Not one, not even the ozone damage—humanity's one ecologic victory—has actually improved (IPCC 2007: 145). Some time between 1970 and 1980, the human footprint exceeded Earth's capability to sustainably provide for humanity's combined needs and wants (Wackernagel et al. 1999). Even with all this damage—which by definition will be unsustainable in the long run—billions have remained malnourished and close to a billion people were perpetually hungry. At the United Nation's 2006 World Food Summit (WFS), it was recognized that "…the number of undernourished people remains stubbornly high…," and, "Virtually no progress has been made towards the (1996) WFS target of halving the number of undernourished people by 2015" (FAO 2006).

The question becomes whether the Earth will be able to provide the necessary resources and ecosystem services (Foley et al. 2007) in a world of growing food demand and decreasing carrying capacity. A review of some of agriculture's limiting influences—namely land, water, energy, and climate—suggests that the Earth will not meet our demands and that the perpetual famine will worsen in the coming decades.

2 Land

From 1950 to 1999, land area devoted to crops increased from 1.2 billion to 1.5 billion ha (Groombridge and Jenkins 2002). Global crop area is still increasing at the rate of 5 million ha a year (Pimentel et al. 1999; Young 1999). At this rate, crop area will increase another 200 million ha by 2050 and almost 450 million ha by century's end. Projecting present needs as a constant does not take into account diminishing returns on fertilizer and pesticide masking effects (Cassman and Harwood 1995; Smil 2000a; FAO 2003), diminishing soil quality (Harris 2001), or the projected increases in consumption (Daily et al. 1998; Harris 2001), and so likely produces a low value.

To compensate for only a doubling of food requirements by 2050 without an increase in cropland would require a near doubling of global yield (Borlaug 1997; Trewavas 2002). On the other end of the spectrum, if yields-per-acre suddenly stagnated, we would need about double the 1.5 billion ha now cropped (Goklany 2003). More realistically, an average annual 1% growth in yield through mid-century will result in serious shortfalls, and 2% or more would deliver surfeit (Waggoner 1996; Postel 1998; Frink et al. 1999). Between 1950 and 1995, growth in global grain yields per acre averaged more than 2% a year (Postel 1998). Since then, yield growth has declined (Matson et al. 1997; Postel 1998; Harris and Kennedy 1999; Mann 1999; Trewavas 2002; Pimentel and Pimentel 2006). An annual 1% yield growth through 2050—as projected by Balmford et al. 2005—will satiate about half our projected needs. So, if half the food needed in the coming decades comes from yield increases (intensive means), the other half must come from farming more land (extensive means), increasing the area cropped an extra 0.75 billion ha by 2050. These two estimates (200 million and 750 million ha) fall comfortably within the range of previous projections for the additional farmland needed by 2050 (Waggoner 1996; Frink et al. 1999; Tilman et al. 2001; Vance 2001; Goklany 2003; FAO 2003; Balmford et al. 2005; Lal 2007).

Furthermore, these endpoints (*200* million and *750* million ha) have the added advantage of reflecting the likely range of conditions. The lower number corresponds to a future where yields experience negligible (0.3%) increases and consumption per capita remain flat, and the higher number reflects a world—projected by most analysts—where yields average 1% per year and consumption doubles by 2050 (Bongaarts 1996; Ruttan 2002; Tilman et al. 2002; Balmford et al. 2005). When added to the 1.5 billion ha presently cropped, we will be farming between 1.7 and 2.25 billion ha by mid-century.

However, since farming tends to cause soil degradation, humanity will need far more land than merely that being farmed at any one time. Within the last 1,000 years, agriculture has degraded and destroyed a combined two billion ha of once productive land (UNEP 1986; Oldeman et al. 1991). This is more land than the 1.5 billion ha globally cropped. And consistent with all the trends, most of the damage has occurred within the past couple of generations, since the time of industrial agriculture (Smil 2000a). Over 60% of this damage—1.2 billion ha, an area equal to the combined landmasses of India and China—has been assessed as moderate, severe or extreme (Oldeman et al. 1991). At best, these soils have suffered such damage that recovery can come only at great cost. At worst, the damage is complete and irreversible. Since 1960, alone, a third of the world's farmland has been abandoned because it has been degraded beyond use (Lal 1990; Kendall and Pimentel 1994; Pimentel and Pimentel 2008). We continue destroying ~10 million ha each year (Lal and Stewart 1990; Rosanov et al. 1990: 205; Oldeman et al. 1991; Goklany 1998; Pimentel et al. 1999; Young 1999). To be conservative, we will not consider the 0.7 billion ha of drylands abandoned (Daily 1995), the 0.3–0.4 billion ha already lost to human settlement and infrastructure (Young 1999; Wackernagel et al. 2002) or the additional 0.1–0.3 billion arable ha that will be similarly lost by 2050 (Goklany 1998; Young 1999). Using a constant and conservative rate of 10 million ha/year loss over a 40-year period (2010–2050) suggests that 0.4 billion additional ha of natural lands will have to be brought into production just to maintain the status quo. This brings projected additional farmland required by 2050 to 0.6–1.2 billion ha. Added to the 1.7–2.25 billion ha projected to be in production, humanity's farmland needs by 2050 will likely total somewhere between 2.1 and 2.7 billion ha.

From where will this land come? Of the Earth's land surface, 37% is under farm and pasture and almost 33% is unusable—ice caps, mountains, deserts, cities, etc. (Livi-Bacci 2001). That leaves the 30% of the Earth's surface that is still covered—however, imperfectly—in forest. Asia, Europe, and North America have very little of this land (Fischer and Heilig 1997; FAO 2003). More than 90% of all the land available for future farming exists now as tropical forests and rangelands in South America and Africa (Fischer and Heilig 1997; FAO 2003). Ignoring for the moment the obvious biological tragedy being contemplated, these low-latitude lands also exhibit serious limitations as farm and pasture (FAO 2003). In the temperate forests of North America and Europe, most of the life is underground, harbored in the soil. In the tropics, most of the life is above, in tree, vine and foliage. Tropical soils are thus thin and easily spent. This is why, we are going through it so quickly—between 5 and 15 million ha a year (Pimm et al. 1995; Achard et al. 2002; FAO 2003).

The lands farmed and already destroyed are the Earth's most fertile (Tilman et al. 2002). Remaining lands considered arable are increasingly unsuitable for farming, being either swampy or too dry, or with slopes too steep or soils sandy or thin, or roads few and far from market (Cassman and Harwood 1995; Crosson 1997; Eswaran et al. 1999; Harris 2001; Doos and Shaw 1999; Pimentel et al. 1999; Tilman et al. 2002; FAO 2003). To put this land into production will be costly beyond anything so far experienced (Cassman and Harwood 1995; Crosson 1997; Doos and Shaw 1999; Pimentel et al. 1999; FAO 2003), and it will degrade with increasing rapidity (Larson and Frisvold 1996; Doos and Shaw 1999; Pimentel et al. 1999; FAO 2003). Not only are these some of the Earth's most fragile lands, but they are also the settings for some of the world's worst poverty, disease and malnutrition, further suggesting their unsuitability (Hillel 1991; FAO 2006). Numerically, of the 1.8 billion ha considered even remotely arable, far less can actually provide any affordable sustenance—perhaps some 300–500 million ha, and then only briefly (Fischer and Heilig

1997; Eswaran et al. 1999; Young 1999; Tilman et al. 2001; FAO 2003). This leaves a 0.1–0.9 billion hectare deficit by 2050.

Broad brushstrokes of simple ratios would suggest that of the 9.2 billion people projected to be alive in 2050 (UNPD 2007), there will not be enough food for between a half and 3 billion (Table 1). It is unlikely that 6 billion will take all the food and 3 billion will receive none. More likely, distribution will mirror present conditions, where the top billions are well fed and the bottom billions suffer from hunger, disease, physical and mental stunting, etc. And so, the perpetual global famine will likely worsen.

3 Irrigated land

Of the 1.5 billion ha we crop, about 18% is irrigated, and yet these 275 million ha grow 40% of the world's food (WWI 2007). Irrigated land is, on average, 3.3 times as productive as rain-fed land, and so has been duly credited for half of the Green Revolution miracle (Hawken et al. 1999). Of the food grown in the United States, 16% comes from irrigated land (USDA 2002). In India and China, it is about 50% (WWI 2007). We will need more in the future and we are quickly losing what we have.

Global food security depends on irrigating at least 350 million ha by 2050 (Vance 2001; FAO 2003). Meanwhile, 1.5 million ha of irrigated land are lost annually to salinization, alone (Foley et al. 2005), and four million ha a year are being lost to the combined effects of salinization, waterlogging and erosion (FAO 2003), although values as high as 10 million ha a year have been reported (Thomas and Middleton 1993). Using the lower estimate for the sake of prudence, 160 million ha of irrigated land will likely be abandoned in the next 40 years. Therefore, total irrigated land requirements by 2050 will reach 510 (350 + 160) million ha. Beyond the 275 million ha presently irrigated, there is ~150 million ha considered additionally suitable (Doos and Shaw 1999; Gilland 2002; FAO 2003), for a total of 425 million ha available for irrigation. This leaves an 85 million (510–425) ha deficit by mid-century. Because of irrigation's 3.3-fold productivity, this deficiency equals 280 million ha of rain-fed land. In order to avoid any double-counting of the previously considered land deficits, 195 million ha will be used to translate this deficit into the number of people potentially affected. Simple proportions would suggest that by 2050 food deficits from deficient irrigated land, alone, will total 760 million people. Most gravely impacted will be the heavily irrigated, highly populated countries, such as China, India, Pakistan, Mexico, and Egypt.

Added to the previous estimates from rainfed land, worldwide food deficits may total 1.2 to nearly 4 billion people. Should farming methods remain unchanged, humanity's prospects will continue to disintegrate. Because the new land will be of diminishing

Table 1 Land deficit and human dieback (9.2 billion people projected in 2050)

	Land farmed now (billion ha)	Additional land needed (billion ha)	Land available (billion ha)	Deficit (billion ha)	Ratio: deficit versus total land needed	Deficit as a %	Billion people into which this % translates
Best case	1.5	0.6	0.5	0.1	0.1:2.1	5	0.46
Worst case	1.5	1.2	0.3	0.9	0.9:2.7	33	3.1

quality, it will be costly to work and it will degrade with accelerating speed (Goklany 1998). Each year afterwards, humanity will lose—from irrigated land, alone—the capacity to feed another 40 million people. That comes to another two billion people by 2100. At century's end, population is projected to hover at over nine billion (ESA 2004), but—given present trends—there will be food for only three to six billion. This means that the other three to six billion people will either die from malnutrition and its effects or will not be born.

Granted, these numbers are conjectural, accepting many assumptions and unknowns. Assumptions include, but are not limited to, the persistence of present trends and a globally averaged relationship of cropland to production. Innovations, policy changes, and singularity events cannot be foreseen. Assessments of land degraded and land available, of food grown, and of malnourishment all suffer their inaccuracies. The possible permutations are endless. For example, people's ability to adapt to fewer calories when necessary (Smil 2000a) may be offset by the changing demographic structures, whereby an aging population will require more calories (FAO 2006). Even here, malnourishment is far more complex than simply considering calories. Given the inherent limitations, calculations cannot be taken as predictions, but they can serve to illustrate the impending land-scarcity crisis. And so, they provide insight into the enormity of the human predicament.

If available lands were the only natural factor limiting humanity's unchecked growth, the necessary changes would be likely affected. Innovative solutions would be employed, destructive behaviors modified, efforts concentrated. However, there are other equally powerful constraints, and, among them, there is none as critical as the issue of water.

4 Water

The above discussion assumes the existence of all the necessary water. This assumption may be unfounded. Because food production is expected to double by 2050, water use will likely need to double, as well (Postel 1998; Marris 2008). But a doubling of surface waters—streams, rivers, and lakes—is beyond the theoretical available "ceiling" (Stolntitz 2000). Consequently, much of this water will have to come from underground. Already aquifers below are being drained by explosive populations above—in the Indian states of the Punjab, Rajasthan, and Tamil Nadu, California's Central Valley, in Egypt, Mexico, China's northern plain, Southeast Asia, and the strip of dry lands across North Africa and the Middle East (Kendall and Pimentel 1994; Postel 1997; Jackson et al. 2001a, b; Yang et al. 2003; Smil 2005). Many of the biggest grain-growing areas have suffered significant declines in their aquifers, causing concern of aquifer longevity and food security (Beaumont 1985; Postel 1997, 1998; Jackson et al. 2001a, b; Yang et al. 2003).

Despite enormous effort, the appropriation of surface waters and the mining of underground water reserves have failed to fully satiate either humanity's hunger or its thirst. At least two billion people are suffering some form of malnutrition, over a billion people lack safe drinking water, and more than three billion suffer from improper sanitation (Kendall and Pimentel 1994; Postel 1997; Jackson et al. 2001a, b; Underwood 2003; WHO 2004; Marris 2008; Shannon et al. 2008). There are nearly four billion annual cases of disease in developing countries attributed to water-borne causes: 2–6 million of them die each year (Pimentel et al. 1995; Gleik 2003a; WWI 2006; Shannon et al. 2008). In 1995, 1.4 billion people lived in water *stressed* conditions, which means they have access to less than the annual 1,700 m^3 considered necessary to supply all one's needs, including food (Postel 1998; Smil 2000a). Only 10 years later, the number had shot up to 2.4 billion

(Oki and Kanae 2006). By 2025, that number is expected to double to as many as five billion people, a full two-thirds of the projected population (FPA 2003; Havener et al. 2005). And a billion people scattered among 30 countries will live in water *scarce* conditions, meaning that a country's annual supplies will average <1,000 m^3 per capita (Smil 2000a; Fairless 2008). Even so, humanity will be collectively appropriating 70% of surface waters potentially available (Postel 2000). The prospects for 2050—when water requirements will have presumably doubled—seem dire beyond reckoning. By some estimates, nearly 75% of the world's population will face conditions of water scarcity (Hightower and Pierce 2008).

Increasing competition for remaining waters promises to put a further strain on agricultural productivity. Food crops require tremendous quantities of water. In the United States, for instance, corn transpires six million liters of water per hectare during a growing season, and soil evaporation accounts for another 1–2.5 million l/ha (Pimentel et al. 2004). Globally, irrigation accounts for 70% of all human water use and for 85% of water consumption, this latter representing water that is no longer available for other uses (Pimentel et al. 1997a; FAO 2003; Gleik 2003b; Oki and Kanae 2006). Following what has become a global trend, farmers in the American West and Midwest are losing the "water wars" to far wealthier municipalities and industry (Brown 2004a). With population and wealth per capita continuing its upward course, households and industry may double their share of water in the coming years (Postel 2000). Agriculture will be losing water as it needs it ever more dearly.

The most water-starved countries (for example, Algeria, Egypt, Mexico, Israel, Saudi Arabia, Yemen, China) have already taken to another, less costly strategy, that of importing enormous quantities of "virtual water" by importing food, instead (Postel 1998; Dyson 1999; Yang et al. 2003, Oki and Kanae 2006; Liu 2008; Marris 2008). Since it takes about a 1,000 kg of water to produce a kilogram of grain, it becomes far less expensive to forgo the complexities of arid-land farming and to simply buy the food (Postel 2000; Smil 2005). For poor countries with exploding populations, this will increasingly become the only alternative (FAO 2006). Third World countries will be importing between two and three times as much food in 2030 as they did in 2000 (Harris and Kennedy 1999; FAO 2003). China's imports have been steadily increasing and are projected to be as much as 200 million tons of grain by 2030, requiring, by itself, most of the world's exports (Brown 1995; Shenggen and Ageaoili-Sombilla 1997; Huang et al. 1999).

This state of affairs will amplify global reliance on high productivity in the world's major breadbaskets and on the continuance of a benign geological, meteorological, and political climate. Only seven countries actually produce substantially more food than they consume—the United States, Canada, France, Australia, Thailand, and Argentina (Dyson 1999; Gilland 2002; Brown 2004b). About 193 countries must import at least some of their food (Pimentel et al. 1997). Some, like China, Egypt, Mexico, and Nigeria, whose populations are still surging, import more every year (Pimentel, Huang, et al. 1997; Yang et al. 2003; Brown 2004a). Since grains constitute—directly or indirectly, via livestock—80% of the world's calorie consumption, grain production, and consumption remain telling indices for food security. Per capita grain production has declined continuously since 1984 (FAO 2007), and despite bumper crops and high-yielding hybrid cereals, the world's grain reserves have steadily dropped, from 130 days in the peak year of 1986 to 55 days in 2007 (EPI 2008). Should some coincidence of unfortunate events strike several of the world's breadbaskets, we have stored, as a species, <2 months of back-up grain. In these best of times, of high yields, benign climate and geological quietude, humanity is but one disastrous year away from severe global famine.

5 Oil

Modern agriculture is no less dependent on fossil fuel than is the rest of civilization. During the 20th century, the six-fold increase in crop production was made possible by a 150-fold increase in fossil fuel use (Smil 2000b). To insure the high yields of modern industrial agriculture, fertilizers, pesticides, irrigation, and tractors are required in abundance, and these have in every way depended on oil. From plow to plate, food accounts for 20% of America's enormous fossil fuel consumption (Plienninger 2007). Industrial agriculture now inputs three-to-ten times more energy into food than food returns (Giampietro and Pimentel 1993; Hawken et al. 1999).

Of the three main fossil fuels, oil will likely have the shortest lifespan (Smil 2000b). A trillion barrels of oil have been burned, most of it in the past 50 years (Hall et al. 2003). There are only one or two trillion recoverable barrels left, and most of it will be functionally gone by mid-century (Salameh 1999, 2002; Hall et al. 2003; Kerr 2005, 2007a). All projections indicate that by 2050, oil will have long passed peak, and production will be fast declining (Wood et al. 2004). Costs will surely rise over the long term. Beyond the market psychology of a diminishing resource comes the real costs of producing oil. The EROI (energy returned on energy invested) was a hundred-to-one in 1930s America; by 2006, it has dropped to seventeen-to-one (Hall et al. 2003). In the 7 years between 1999 and 2006, costs for discovery and developing oil rose three-fold (NYT 2007). Because, as with land and water, we have tapped the best and cheapest oil (Hall et al. 2003).

Rising oil prices will most severely impact the poor, as many people in the developing world spend 60–80% of their income on food (Economist 2008). The skyrocketing oil prices of 2007 and 2008 gave us a window into the future. In 2007, wheat and rice prices rose 77 and 16%, respectively, and rice prices rose another 141% in the first third of 2008. According to *The Economist* (2008), this crisis is "affecting people not usually hit by famines. For the middle classes … it means cutting out medical care." For those billions living on $2 and less a day, simple diets became simpler, many subsisting only on cereals. "And for those on 50 cents a day, it means total disaster." Rising grain prices pushed as many as a hundred million more people into poverty, according to World Bank President Robert Zoellick (WB 2008), a concern raised by earlier studies (Chen and Katz 1994; Parry et al. 2001; Eakin 2005). These were the results not of food scarcity, but simply of rising food prices due mainly to rising oil prices.

The world's poor will be further squeezed as rising oil prices force energy-hungry nations like the United States and Brazil to increase the cropland devoted to producing biofuels. The International Energy Agency found that, "Conventional biofuel production requires about 1% of all arable land and yields about 1% of global transportation fuels" (IEA 2006: 289). To fill global transportation needs would, therefore, require all present farmland. It has been estimated that by 2050, one-third of the world's farmland may be devoted to ethanol production (Cline 2007). Given the impact that the 1% has already had on food prices and diet, any substantial diversion of acreage from food to fuel will likely reverberate like an earthquake throughout the world.

6 Climate change

Since land, water, and oil scarcity will each, by themselves, threaten global famine by mid-century, maximizing crop potential and food security, itself, will increasingly depend on favorable climates. Instead, average global temperatures are expected to rise about 1.5°C by 2050, and then another 1.1–6.4°C (IPCC 2007: 749). As the atmosphere heats up, the fluid systems that balance the energy fluxes through the air and oceans will adjust themselves (Broecker 1997; Visbeck 2002). Regional climates will change, impacting and—in many places—hampering agricultural productivity (Moffat 1992; FAO 2003; Lal et al. 2005; IPCC 2007; Cline 2007; Lobell et al. 2008). Climate change is, as one analyst has put it, "the straw that may break the camel's back" (Goklany 2003). Some 30% of wildlife species face an increased threat of extinction in the next century due to global warming, alone (IPCC 2007; Thomas et al. 2004). Given that hybrid cereals have been bred to thrive under very specific conditions, the impact to our domesticated food plants may be much greater (Brown and Funk 2008; Lobell et al. 2008).

Global warming, even at its most benign, will impact crops from numerous directions. Floods, droughts, drying climates, increased evaporation, and dryer soils will all exacerbate problems in many regions (Doos and Shaw 1999; Jackson et al. 2001a, b; Oki and Kanae 2006; IPCC 2007; Brown and Funk 2008; Lobell et al. 2008). Of all the variables, food security will revolve most critically around the water cycle. Since continental interiors will heat up much more than the global average, evaporation will increase (Kendall and Pimentel 1994; FAO 2003; IPCC 2007; Schiermeier 2008). Drier soils lose fertility and structure, reducing infiltration and increasing erosion (Jackson et al. 2001a, b; Alley et al. 2003; FAO 2003; Kaiser 2004; Oki and Kanae 2006; IPCC 2007; Schiermeier 2008). Desertification is expected to further spread across Africa, China, India, and Australia (Kaiser 2004; IPCC 2007; Brown and Funk 2008), and deserts will likely expand, most imminently in the American Southwest (Seager et al. 2007). Increased evaporation may drop river flows in dry regions by 40%, severely impacting irrigation (Schiermeier 2008). By 2050, all continents but Antarctica are expected to suffer drier summers, the season that crops grow their most and are accordingly thirstiest (Jackson et al. 2001a, b; Schiermeier 2008). Droughts are expected to increase in frequency and in intensity, impacting continental interiors, the tropical (densely populated) latitudes and the already dry regions of the Earth (Dai and Trenberth 1998; Jackson et al. 2001, b; Shiva 2002; FAO 2003; Stewart 2005: IPCC 2007; Brown and Funk 2008; Lobell et al. 2008). This factor, alone, may place an extra one to two billion people into the category of water stressed (Jackson et al. 2001a, b; IPCC 2007; Kerr 2007b). Crop and livestock productivity will decline in Africa, Asia, Latin America, the Mediterranean Basin countries, and Australia, impacting the lives of billions (FAO 2003; IPCC 2007).

Climate models suggest increased rain, as well, but rains will not be spread idyllically across the growing season. They will be less frequent but more intense (Goswami 2006; FAO 2003; Schiermeier 2008). Flooding is expected to increase, damaging crops at any stage of the growing season, increasing soil erosion and hastening soil death due to waterlogging (Jackson et al. 2001a, b; Oki and Kanae 2006; IPCC 2007).

To make matters worse, the accelerated melting of glaciers in the Himalayas, Andes, Cascades, Rockies, Alps, and many others mountain belts may imperil the lives of the billions of downstream denizens who depend on their meltwaters for drinking and irrigation during the dry seasons (Pearce 2006; Shannon et al. 2008; UNEP 2008). By mid-century, summer flows of the Brahmaputra, Indus, Ganges, Yangtze, Yellow, Irrawaddy and Mekong rivers, all of whose headwaters begin in the icy heights of the Himalayas and Tibetan Plateau—will be intermittent (Pearce 2006; Shannon et al. 2008).

Some high latitude countries such as Canada, Russia, and Northern Europe may initially benefit from longer growing seasons; however, crops will suffer in the low latitude, highly populated countries of Africa, Southern China, South and Southeast Asia, and Latin America (Rosenzweig and Parry 1994; FAO 2003; Stewart 2005; IPCC 2007). Studies indicate that increased atmospheric carbon dioxide improves crop yields and temperature depresses them (Moffat 1992; Evans 1998; Smil 2000a; FAO 2003; Easterling 2005; Lal 2005). Overall the effect is negative (Thompson 1975; Conroy et al. 1994; Ziska et al. 1997; Ferris et al. 1998; Peng et al. 2004; Plaut et al. 2004; Lal 2005; Long et al. 2006; Cline 2007; Lobell et al. 2008).

There is no credible scenario showing that global warming will bring more food to the world's tables (Rosenzweig and Parry 1994; Stewart 2005). Rather, changes in temperature, precipitation, and evaporation patterns will likely amplify the shortages caused by humanity's reckless exploitation of soil, water and oil. It will surely get worse as the century proceeds (Cline 2007; Hansen et al. 2007a, b; IPCC 2007). By 2080, agricultural productivity in many of the tropical areas such as India, Africa, and Mexico may suffer 20–40% reductions (Cline 2007). Conservatively, global reductions due to climate change will average 3.2%; more likely, it will be 10–25% (Cline 2007). Simple ratios suggest that this could reduce the world's expected population by another half-billion to two billion people.[1]

7 Conclusion

A freeze frame of the present reveals a civilization at the peak of its power. Within the space of a few decades, humanity will have experienced peak population, peak oil, peak water, peak land, and perhaps even peak crop yields. Yet, even at the height of power, having taken virtual control of the biosphere and having turned the arable Earth into a vast feeding lot for our species, it still has not been enough. In what amounts to the greatest perpetual famine in human history, nearly three billion people are without proper food and water; 850 million lack the minimal bodily requirements of protein and calories; half the world is chronically deficient in at least one of the essential micronutrients; nine million die each year from starvation and diseases of malnourishment. Now, with deteriorating conditions of planetary forests, soil, water, oil, climate, and ecosystems, we are expecting to improve the quality of life for billions of more people in the coming decades. There is a flaw with the logic of our expectations—one which may well translate into billions of additional malnourished people by mid-century, or, indeed, could even augur a painful population crash.

Although there is as yet no evidence for a cessation or even amelioration of humanity's assault on the rest of nature, the potential continually exists. The solutions for an efficient, affordable, and environmentally friendly civilization are many, known and often already available; however, they have yet to be utilized (Waggoner 1996; Dyson 1999). For example, humanity's impact could be greatly diminished with a concerted effort to establish drip systems and other efficient delivery methods of irrigation (Postel 1998; Jackson et al. 2001a, b; Trewavas 2002), no-till plowing (Pimentel and Krummel 1987), information-intensive precision farming (Dyson 1999; Jackson et al. 2001a, b) on multifunctional farmland (Jordan et al. 2007), using efficient and appropriate technologies (Smil 1994; Harper 2004) and sustainable agricultural practices (Harris 2001; Tilman et al. 2002). Behaviorally, moderation in personal consumption (Myers 1997) and a voluntary one-child policy would have profound consequences. Eating nutritionally appropriate meat quantities

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[1] To avoid double-counting, dieback (1.2–4 billion people) from land constraints (as of 2050) were already considered. So, 10% of 5.2 billion for least impact and 25% of 8 billion for greatest impact equals ~0.5–2 billion.

would, alone, greatly reduce land needs (Bender 1994; Naylor et al. 2005). Equally, there are numerous regulatory policies that could be helpful, such as (a) eliminating subsidies for unwise practices such as for industrial fish fleets (Beddington et al. 2007), corn-ethanol production (Pimentel and Patzek 2008) and industrial agriculture (Jordan et al. 2007), (b) internalizing degradation, pollution, health and military expenditures into product costs (Hubbard 1991; Cassman and Harwood 1995; Myers 1997; Daily et al. 1998), (c) government funding of research and development of appropriate agriculture practices and energy technologies (Daily et al. 1998; Lobell et al. 2008; Brown and Funk 2008), in concert with the production incentives of the market place (Waggoner 1996).

Hoffert et al. (1998) called for an effort and urgency of Manhattan Project or Apollo space program scale to address the twin issues of energy needs and global warming, and Cassman and Harwood (1995) suggested that solving today's problems will require that long-term thinking replace short-term profit. According to many, what has been missing is the "political will." That will require both wise leadership and a citizenry aware and mature enough to demand the changes and to cope with the likely discomforts of the requisite societal transformations. As Pimentel et al. (1999) noted, environmental issues have been historically resolved only in isolated crises following catastrophe. In order to avoid that fate on a horrific global scale this century may well require a punctuated jump in awareness and maturity of the world's citizens. The scientific community can do its part by becoming more vocal, expressing its concerns through the powerful financial and media voices to promote the fundamental principles of sustainability and equity.

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