

# Harvesting the Biosphere: The Human Impact

VACLAV SMIL

THE HUMAN SPECIES has evolved to become the planet's dominant organism in what has been, on the biospheric time scale of billions of years, a very brief period. Less than 2.5 million years have elapsed since the emergence of our genus (with *Homo habilis*), and *Homo sapiens* became identifiable about 200,000 years ago (Lewin 2005). The shift from subsistence foraging (hunting and gathering) to settled existence energized by cultivated plants and domesticated animals began shortly after the end of the last glaciation (less than 10,000 years ago); afterward our capacities for expansion, extraction, production, and destruction began to grow rapidly with the emergence of the first complex civilizations (Cochran and Harpending 2010). After millennia of slow gains during the Pleistocene era and the early part of the Holocene,<sup>1</sup> global population began to multiply as it commanded increasing flows of energy owing to many technical and social innovations. Quantitative reconstructions of these long-term trends are uncertain but they capture the magnitude of specific advances and their relentless growth.

Five thousand years ago the Earth most likely contained fewer than 20 million people; at the beginning of the common era the total was about 200 million; a millennium later it had risen to about 300 million; in 1500, at the onset of the early modern era, it was still less than 500 million, and one billion was passed shortly after 1800. In 1900 the total was about 1.6 billion, in 1950 2.5 billion, in 2000 6.1 billion, and in 2010 it approached 7 billion. Consequently, there has been a 350-fold increase in 5,000 years, more than a 20-fold gain during the last millennium, and roughly a quadrupling between 1900 and 2010.

Energy use in the earliest complex civilizations was limited to burning wood and crop residues, and even during the first centuries of the common era the average annual energy consumption in the Roman Empire was no higher than 10 billion joules (GJ) per capita (Smil 2010).<sup>2</sup> By 1800 the British mean, the world's highest, reached about 50 GJ per capita (Warde 2007), and in 1900 the average US per capita energy supply (fossil fuels and wood) had

surpassed 130 GJ (Schurr and Netschert 1960). A century later the largest EU countries were, much like Japan, at about 170 GJ, while the US and Canadian per capita supply of primary energy was around twice that rate (BP 2011). All of these rates are for gross energy inputs: because of vastly improved energy conversion efficiencies, the levels in terms of actually available useful energy were in all of these instances at least three times higher.

Life expectancy at birth among the citizens of the Roman Empire was less than 25 years (Scheidel 2007; Woods 2007), and not until 1900 did the average for both sexes surpass 50 years in the United States and various European countries; by 2010 it stood around 80 years in the world's most affluent countries and exceeded 70 years even in China (UN 2011). And while per capita GDP is an imperfect measure of economic well-being, its reconstructions for the Roman Empire (Maddison 2007; Scheidel and Friesen 2009) yield only US\$500–1,000 in today's money, similar to the levels now prevailing in the poorest countries of sub-Saharan Africa, while the 2010 averages in large economies ranged from more than \$40,000 for the US, Japan, and the EU's richest countries to about \$4,000 for China (IMF 2010).

These comparisons make it clear that the human species has been highly productive. In its quotidian mental detachment from nature, modern civilization sees that its fortunes depend on securing incessant and affordable supplies of modern forms of energy in general and fossil fuels in particular (hence the concerns about “running-out” or “peak oil”), and on the availability of a wide range of non-energy minerals. But first things first: photosynthesis will always remain the most important energy conversion on Earth, and without newly formed plant tissues (phytomass) no heterotrophic life—whether the simple unicellular solitary organisms or complex insect, mammalian, and human societies—would be possible.<sup>3</sup>

Our phytomass harvests go beyond the metabolic needs to secure raw materials (wood, fibers, pulp) and energy (fuelwood, charcoal, straw) whose inputs remain indispensable even in the age of metals, concrete, synthetics, and fossil fuels.<sup>4</sup> The biosphere has paid a considerable price for these human gains as both its total stock of standing phytomass and its overall productivity have declined by significant margins.<sup>5</sup> And because we are an omnivorous species we have also been harvesting a wide variety of zoomass by collecting and hunting animals as foragers and eventually also deliberately raising them as pastoralists and farmers. These actions have reduced the stocks of wild terrestrial and marine animals while massively expanding the stocks of cattle, water buffaloes, horses, camels, sheep, pigs, and poultry.

This attempt to quantify these well-known changes in the global biomass will proceed along two different (but complementary) paths: first, by contrasting the history of anthropogenic destruction of standing phytomass (caused by deforestation and conversion of other ecosystems to croplands, pastures, settlements, and industrial uses) and the accompanying losses of wild zoo-

mass with the concurrent expansion of the anthropomass and the mass of domesticated animals; second, by expressing the level of current human phytomass harvests as a share of the biosphere's productivity. This approach has the advantage of directing attention to both the status and the process, to biomass stocks existing at different periods of time, and to the changing rates of their decline or rise. In closing, I offer some reflections on the meaning of these realities and note some opportunities that could be pursued to moderate future human claims on biomass.

## Biomass changes

Satellite monitoring has provided fairly accurate and up-to-date means of global mapping of land cover, but calculating the standing phytomass still requires field studies to assess densities and species composition of representative plant formations.<sup>6</sup> Even with these advances, the global estimates of total terrestrial phytomass stocks at the end of the twentieth century spanned a wide range from less than 300 billion to as much as 900 billion tonnes of carbon (Gt C), with the most likely total between 400 and 700 Gt C.<sup>7</sup> Further monitoring advances in the past decade—most notably the deployment of satellite-borne LIDAR (light detection and ranging) to reveal the vertical structure of forests (NASA 2010)—have helped to reduce the uncertainty.

The latest appraisal of phytomass in tropical rain forests has been by far the most comprehensive evaluation of the single largest repository of living matter (Saatchi et al. 2011). The study combined data from nearly 4,100 inventory plots with LIDAR monitoring and high-resolution (1-km) optical and microwave imagery to estimate the global tropical forest carbon stock at 247 Gt C, with nearly 80 percent (193 Gt C) above ground and the rest in roots. Assuming that the tropical rain forests contain at least 40 percent or as much as 50 percent of the global terrestrial phytomass, the storage would be between 500 and 615 Gt C.

There is no doubt that the most recent ice age reduced the Earth's plant cover and that the global phytomass stocks subsequently rebounded with deglaciation. Global storage peaked sometime during the mid-Holocene (about five millennia ago) before the more extensive human interferences (due to shifting and permanent cultivation, grazing of domestic animals, higher incidence of fires, and extension of settlements) began to change the natural land cover and reduce the phytomass stores. These processes accelerated during the past two centuries, and the substantial post-1950 return of temperate forests has not eliminated the net loss of post-glacial woody phytomass.

Quantifying all of this is another matter. The best conclusion is that during the last glacial maximum, the land plants stored up to 200 Gt less carbon than they did in the year 2000 (Adams et al. 1990). Substantial Holocene gain—an estimate of a doubling does not seem excessive, as the total area of tropical

forest had roughly tripled between 18,000 and 5,000 years before the present and the area of cool-temperature forests expanded more than 30-fold (Adams and Faure 1998)—could have raised the stocks to more than 1,000 Gt C, and the subsequent land use changes had reduced it, most likely, to between 750 and 800 Gt C by the eighteenth century. Plant carbon losses during the last two centuries probably amounted to 150–200 Gt C, lowering the late-twentieth-century terrestrial stocks to no more than 650 Gt C and very likely below 600 Gt C (Houghton 2003; Saatchi et al. 2011). Human actions may have thus reduced the biosphere's stock of phytomass by as much as 45 percent during the last two millennia, and during the twentieth century the net reduction of global phytomass was about 110 Gt C, or about 17 percent of the 1900 total (Table 1).

We are on a firmer ground when appraising the conversion of natural ecosystems to fields and the global expansion of cropping driven by growing populations and by the universal dietary transition from vegetarian diets to higher shares of animal protein. By the middle of the eighteenth century farmland was still only about 350 million hectares (Mha). By 2010 land used for annual and permanent crops surpassed 1.5 billion hectares (Gha). Crop-lands amount to about 12 percent of all ice-free land but their peak seasonal pre-harvest phytomass is less than 0.5 percent of all terrestrial plant mass (Richards 1990; HYDE 2011; FAO 2011).

These gains came at the expense of temperate grasslands and tropical forests. After 1850 most of North America's and Russia's new cropland came from plowing-up grasslands, and in the tropics most new fields came from deforestation. In total, ecosystem conversions led to the loss of at least 150 Gt of plant carbon between 1850 and 2000 (Houghton 2003). Perhaps the most instructive way to illustrate the extent of human impacts on the stocks of global organic matter is to trace the gains and losses of mammalian biomass—that is,

**TABLE 1** Some important long-term global trends

Year	Population (million)	Energy use (GJ/capita)	Economic product (1990\$/capita)	Life expectancy (years)	Global phytomass stock (Gt C)
5000 bp	20	<3	<100	20	>1,000
0	200	<5	500	<25	1,000
1000	300	<10	500	<30	900
1800	900	23	600	35	750
1900	1,600	27	1,200	40	660
2000	6,100	75	6,500	67	550

NOTE: bp = before present. All of these values (with the exception of post-1900 population, energy, and life expectancy) are approximations of the most likely values with substantial margins (generally >20 percent) of error. Population series are available in McEvedy and Jones (1978), Demeny (1990), and HYDE (2011). Average per capita energy use based on Smil (2008 and 2010). Economic product estimates based on Maddison (2007). Global phytomass stocks derived from Adams et al. (1990), Adams and Faure (1998), Matthews et al. (2000), Saugier, Roy, and Mooney (2001), Houghton (2003), and Houghton and Goetz (2008).

the increasing mass of humanity (anthropomass) and domesticated animals and the declining zoomass of wild terrestrial animals, particularly of the largest herbivores and anthropoid primates. Once again, quantification of these variables rests on chained assumptions, but conservative calculations reveal the magnitude of secular trends and produce some surprising comparisons.

## Global anthropomass and domesticated zoomass

Calculations of global anthropomass must take into account differences in age compositions and average body weights of constituent populations. For example, in 2010 40 percent of Africa's population was younger than 15 years and the continent's median age was 19.7 years, while the corresponding numbers for Europe were 15 percent and 40.2 years (UN 2011). Five-year-old children in the United States are 3–4 kg heavier than in India, and by age 15 the difference is twice as big (Ogden et al. 2004; Sachdev et al. 2005); and different obesity rates result in a relatively large body mass range even among the affluent countries. In 2005 the prevalence of obesity (defined as body mass index higher than 30) was as low as 3.9 percent in Japan and as high as 33 percent in the US, with the European shares ranging from 10 percent in Italy to about 23 percent in England (NOO 2009).

These wide ranges explain why, in calculating the global anthropomass in 2000, I chose four different weighted means of body averages: for North America with its overweight population of more than 300 million people; for all of the other high-income countries (about 800 million, dominated by Europe); for modernizing countries (4.2 billion, dominated by China and India); and for the world's poorest economies (about 700 million, mostly in Africa). Age and sex structures are available for these four population categories (UN 2011), and I used average body masses derived from anthropometric studies and growth curves for populations of four representative countries: the United States, Germany, China, and India (Schwidetzky, Chiarelli, and Necrasov 1980; Sachdev et al. 2005; Zhang and Wang 2010). These data yield a weighted global mean of about 50 kg, which indicates that the total live weight of the global anthropomass of 6.1 billion people in 2000 was about 300 million tonnes (Mt). Water content of the human body averages 60 percent (Ellis 2000), and with 45 percent of carbon in the dry mass that total yields about 55 Mt C.

Since the late nineteenth century, better diets among increasingly urban populations have resulted in higher average body weights: for example, average male weight at age 20 in Japan rose from 53 kg in 1900 to 65.4 kg in 2000 (Ōkawa, Shinohara, and Umemura 1987–88; SB 2010). As a result, the total biomass of our species increased at a somewhat faster rate than did the overall population, which was about 3.7 times higher in 2000 than it was in

1900. Assuming a weighted global body mass mean of 45 kg and an approximate population total of 1.65 billion gives an estimate of 13 Mt C in human biomass in 1900: global anthropomass had thus more than quadrupled over the twentieth century.

Even the largest species of wild terrestrial vertebrates now have aggregate zoomass that is only a small fraction of the global anthropomass. Minuscule remnants of once-enormous herds of bison, America's largest surviving mega-herbivore, total only about 40,000 t C.<sup>8</sup> The latest continent-wide count of African elephants enumerated 470,000 individuals in 2006 (Blanc et al. 2007). With average body mass of 2.6 t, this equals only about 1.2 Mt of live weight, and with 55 percent water and 45 percent C in dry matter, it equals only about 250,000 t C, an equivalent of about 0.5 percent of the global anthropomass.

And even a liberal estimate of the total zoomass of wild terrestrial mammals at the beginning and the end of the twentieth century yields no more than about 50 Mt of live weight (about 10 Mt C) in 1900 and 25 Mt of live weight (about 5 Mt C) in 2000, a decline of 50 percent.<sup>9</sup> In contrast, during the same time, the global anthropomass rose from roughly 13 to 55 Mt C. This means that the global anthropomass surpassed the wild mammalian terrestrial zoomass sometime during the second half of the nineteenth century, that by 1900 it was at least 30 percent higher, and that by 2000 the zoomass of all wild land mammals was only about a tenth of the global anthropomass (see Table 2).

The zoomass of wild vertebrates is now vanishingly small compared to the biomass of domestic animals. In 1900 there were some 1.6 billion large domesticated animals, including about 450 million head of cattle and water buffalo (HYDE 2011); a century later the count of large domestic animals had surpassed 4.3 billion, including 1.65 billion head of cattle and water buffalo and 900 million pigs (FAO 2011). Calculations using these head counts and average body weights (they have increased everywhere since 1900, but the differences between larger body masses in North America and Europe and lower weights elsewhere persist) yield estimates of at least 35 Mt C of domesticated zoomass in 1900 (more than three times the total of all wild land mammals) and at least 120 Mt C in the year 2000, a 3.5-fold increase in 100 years (and 25 times the total of wild mammalian zoomass). And cattle zoomass alone is now at least 250 times greater than the zoomass of all surviving African elephants, which in turn is less than 2 percent of the zoomass of Africa's nearly 300 million bovines (Table 2).

For humans the comparisons with zoomass are just as striking. Anthropomass densities supported by modern intensive farming have far surpassed the highest possible densities of wild mammals and have risen orders of magnitude above those of anthropoid primates. Chimpanzee zoomass (live weight) of some communities surpasses 1 kg/ha but is typically less than half that rate.<sup>10</sup> Densities of many early human foraging societies were similar (at

**TABLE 2 Global anthropomass and zoomass of wild and domesticated animals, 1900 and 2000 (Mt C)**

Year	Humans	Wild terrestrial mammals	Elephants	Domesticated animals	Cattle
1900	13	10	3.0	35	23
2000	55	5	0.3	120	80

NOTE: Estimates shown are the best approximations of global totals; those for the anthropomass and the zoomass of domesticated animals and cattle in 2000 are relatively the most accurate.

less than 0.5 kg/ha), but the most productive traditional agricultures could eventually support more than five people, or more than 200 kg, per hectare of arable land (Smil 1994, 2008). Even more remarkably, by 2000 the most intensively farmed regions could support more than 15 people/ha, or in excess of 250 kg of dry-weight anthropomass per hectare, while the total dry matter zoomass of soil fauna in such fields is usually less than 100 kg/ha (Coleman and Crossley 1996).

This means that the normal composition of heterotrophic biomass—the trophic pyramid with a large base of soil fauna and a narrow vertebrate apex—has been greatly altered as intensive cropping in many agricultural regions now supports a mass of people larger than the mass of all soil invertebrates. In some countries domestic animals have reached unprecedented densities. In 2009 the Netherlands had nearly 4 million head of cattle, more than 12 million pigs, and 1.1 million sheep and goats (PVE 2010). The live weight of this zoomass equaled about 1.3 t/ha of crop and grazing land, three times as great as the average anthropomass per hectare, and in some parts of the country the difference was twice as big. Even more remarkably, this high density of domesticated zoomass was an order of magnitude greater than the biomass of all soil invertebrates and was surpassed only by the mass of soil bacteria. Even very high Dutch crop yields cannot support such densities of domesticated zoomass, and the country is a major importer of animal feed (Galloway et al. 2007).

## Photosynthetic productivity

Anthropogenic (i.e., human-caused) loss of vegetation had to result in diminished primary productivity. Current intensity of this loss can be expressed as a share of the biosphere's overall photosynthetic output. The numerator—most often measured in mass per unit area (t/ha is the norm in agriculture), although foresters often prefer volume per unit area (m<sup>3</sup>/ha)—requires some arbitrary decisions as to what constitutes a harvest. The commonly used denominator is a variable that cannot be directly measured: this baseline is the biosphere's net terrestrial primary productivity (NPP).

Gross primary productivity (GPP) includes all new phytomass that was photosynthesized during a given period of time (usually in one year). A large share of GPP is promptly re-oxidized during autotrophic respiration ( $R_A$ ) in order to provide energy for synthesis of biopolymers (complex plant tissues) from their monomers (simple sugars), transport photosynthates within plants, and repair diseased or damaged tissues. Autotrophic respiration is an indispensable metabolic bridge between photosynthesis and plant structure and function (Amthor and Baldocchi 2001; Trumbore 2006).<sup>11</sup> The difference between gross primary productivity and autotrophic respiration is the net primary productivity ( $NPP = GPP - R_A$ ), the amount of phytomass that is available to heterotrophic organisms, be they bacteria, insects, or humans.

NPP is only the potentially harvestable phytomass: what is actually harvestable depends on the amount of litter fall (leaves, buds, blooms, fruits, twigs, and branches), root death, emissions of volatile organic compounds (in copious volumes from some trees), other exudates (sap, resins, and waxes), methane produced by methanogenic bacteria, and carbon supplied to root symbionts. Over longer periods of time and on larger scales the accounts must also include the phytomass losses due to such natural disturbances as fires and destructive floods that can cause substantial episodic destruction of plant growth (effects of drought should be reflected in reduced GPP).

All of these processes can be combined in the category of non-respiratory losses (L). Heterotrophic respiration ( $R_H$ ) includes all pre-harvest phytomass consumption by bacteria, fungi, insects, reptiles, amphibians, birds, and mammalian herbivores. Net ecosystem productivity (NEP) is thus  $NPP - (L + R_H)$ . This term corresponds to actual yield only when entire plants (or at least all of their above-ground tissues) are harvested, as is the case with whole tree utilization or alfalfa or hay harvests; in all other cases parts of the phytomass either are not harvested or are left on site (tree tops, branches, stumps; cereal and leguminous straws, roots).

The standard method of determining NPP through frequent harvesting of sample plots is restricted by logistics and cost to small areas (typically  $<10^2 \text{ m}^2$ ), and it captures only the above-ground share of the overall productivity and ignores either the below-ground increment or the carbon losses that do not involve respiratory flows. The most difficult-to-measure component of below-ground productivity is the often voluminous but always short-lived fine root turnover (Fahey and Knapp 2007). A more complete appraisal of  $\text{CO}_2$  fluxes can now be derived from gas exchange techniques that are fairly easily applied to small plant plots but are much more difficult with forest growth (they require erection of tall towers, use of tethered balloons, or regular sampling with aircraft). But even these techniques are unable to distinguish the autotrophic components (derived from roots) and heterotrophic components (derived from bacteria) of soil respiration and do not quantify non- $\text{CO}_2$  losses. Total  $\text{CO}_2$  flux methods

should yield productivity estimates that are perhaps 20–50 percent higher than the standard values.<sup>12</sup>

## Quantifying phytomass harvests

Global assessments of phytomass harvests and their comparisons to the biosphere's total primary productivity began only in the 1970s. Accounting for the phytomass that is actually harvested by humans—which is removed annually from natural ecosystems or from agroecosystems and tree plantations to be used as food, feed, fuel, or raw material—is a conceptually straightforward task, and the quantification can be fairly reliable because an overwhelming majority of these harvests are now a part of national and global markets, and most of their transactions are closely monitored. But some major uncertainties remain, hence any claims of high accuracy must be suspect.

Historical records of crop harvests are good enough to trace centuries of very low and stagnating yields. Plant improvement proceeded very slowly until the eighteenth century, and it really took off only after Mendelian genetics opened new opportunities (Kingsbury 2010). The most important result of these improvements has been a steady rise of harvest indexes, and the most obvious outcome of that trend has been the shortening of cereal straws. Even in 1900 many wheat cultivars were still more than one meter tall, while today the shortest varieties are only about 50 cm tall (Smil 1999). Higher harvest indexes, denser planting, optimum nutrient supply and applications of herbicides and pesticides boosted cereal yields during the twentieth century, with national averages often more than doubling. Better data enable fairly reliable global reconstructions of crop harvests for the entire twentieth century.

In 1900 worldwide harvests of food and feed crops amounted to about 400 Mt of dry matter; by 1950 that total had doubled, and by 1975 it had doubled again. At the beginning of the twenty-first century, the global harvest of food, feed, and fiber crops was about 2.7 Gt; their residues added about 3.7 Gt and forage crops equaled about 1.2 Gt, for a global total of about 7.6 Gt of above-ground phytomass available for harvest.<sup>13</sup> Roughly half of this phytomass was fed to animals, and it produced (in fresh weight) nearly 300 Mt of meat, almost 700 Mt of milk, and 65 Mt of eggs. Annual harvests of woody phytomass (fuelwood, industrial roundwood and pulpwood, and biomass destroyed or abandoned during harvesting) had reached about 8 Gt by 2000.<sup>14</sup>

During the first decade of the twenty-first century the annual harvest (and direct destruction) of terrestrial phytomass had thus added up to more than 15 Gt of dry matter, or nearly 8 Gt C. For comparison, combustion of all coal and hydrocarbons has recently surpassed 8 Gt C/year, hence the annual extraction of fossil carbon is very similar to the annual harvest of fresh phytomass (in annual crops) or only slightly aged phytomass (in trees).<sup>15</sup> Harvesting estimates can be also used to trace long-term growth of phytomass

supply—revealing a nearly seven-fold increase during the twentieth century compared to just four-fold gain in global population—but standing alone they tell us nothing about the relative intensity of these human claims. To achieve that perspective requires analyzing phytomass harvests in terms of the human appropriation (or co-option) of global net primary production.

### Human appropriation of net primary production

The first assessment of human appropriation of net primary production (HANPP), in a report by P. M. Vitousek and colleagues, defined appropriation by resorting to three levels of intervention (Vitousek et al. 1986). The low estimate included only the share of NPP that people use directly as food, fuel, fiber, or timber. This low calculation assumed that during the late 1970s people consumed annually 910 Mt of biomass (including 760 Mt of phytomass and 150 Mt of zoomass), that it took about 2.9 Gt of phytomass to produce all animal foodstuffs, and that the annual wood harvest was 2.2 Gt. This equaled about 5.2 Gt of phytomass, or roughly 4 percent of annual terrestrial NPP as estimated by Ajtay et al. (1979).

The intermediate calculation added the NPP of all croplands (15 Gt/year) and all pastures that have been converted from other ecosystems (9.8 Gt/year); to this was added phytomass of natural grasslands that was either consumed by grazing livestock (800 Mt) or destroyed in anthropogenic fires (1 Gt). The forest share included all phytomass cut and destroyed during wood harvesting and during shifting cultivation and establishment of plantations (total of 13.6 Gt). The grand total of 40.6 Gt of “co-opted” terrestrial phytomass amounted to about 31 percent of the estimate of global NPP by Ajtay et al. Finally, the high estimate also included all productive capacity lost as a result of land use changes. These additions brought the grand total to 58.1 Gt, equivalent to about 39 percent of global NPP. This finding led to the most quoted sentence of the entire report: “Thus, humans now appropriate nearly 40 percent of potential terrestrial productivity . . .” (Vitousek et al. 1986: 372); and the authors added that human activities also affect much of the remaining 60 percent, “often heavily.”

The second quantification of HANPP calculated that 23.5 percent of the Earth’s annual potential production was appropriated by humans (Wright 1990). The third attempt was essentially an update of the 1986 assessment, but one with estimated uncertainty ranges for all parameters based on (arguably inadequate) literature references (Rojstaczer, Sterling, and Moore 2001). Its mean HANPP—39 Gt of dry matter or 20 Gt C—was put at 32 percent of terrestrial NPP, nearly the same as the intermediate value estimated by Vitousek et al. (1986). This was a mere coincidence because most of the parameters used in this analysis had substantially different values. More importantly, the authors concluded that the variance in their estimates of

**TABLE 3** Comparison of the global estimates of the human appropriation of net primary productivity

Authors	Approximate period of the estimate	Human appropriation of NPP (%)	
		Mean	Range
Vitousek et al. (1986)	late 1970s	27	4–39
Wright (1990)	1980s	24	
Rojstaczer et al. (2001)	1990s	32	10–55
Imhoff et al. (2004)	1990s	20	14–26
Haberl et al. (2007)	2000	24	

parameters resulted in a poorly constrained confidence interval of  $\pm 27$  Gt (14 Gt C) and hence in more than a fivefold HANPP range of 12–66 Gt of dry matter, or as little as 10 percent and as much as 55 percent of all terrestrial products of photosynthesis.

The fourth attempt to quantify HANPP defined the measure as the amount of terrestrial NPP required to produce foodstuffs and fibers consumed by humans, including harvesting and processing losses (Imhoff et al. 2004). Its low, intermediate, and high variants amounted, respectively, to 8, 11.54, and 14.81 Gt C; annual NPP was assumed to be 56.8 Gt C, and appropriations thus represented about 14 percent, 20 percent, and 26 percent of the biosphere's annual primary production. Continental averages of HANPP ranged (for intermediate values) from only about 6 percent for South America to 80 percent for South Asia, with Western Europe just above 70 percent and North America just below 25 percent.

Finally, Haberl et al. (2007) followed Wright's (1990) suggestion and defined HANPP as the difference between the net productivity of an ecosystem that would be in place in the absence of humans (potential NPP, labeled  $NPP_0$ ) and the net productivity that actually remains in an existing ecosystem (labeled  $NPP_c$ ).<sup>16</sup> Aggregate global HANPP totaled 15.6 Gt C, or nearly 24 percent of potential NPP, with 53 percent of the total attributable to phytomass harvests, 40 percent to land-use-induced changes in primary productivity, and 7 percent to anthropogenic fires. Regional breakdown showed HANPP values ranging from 11 percent for Australia to 63 percent for South Asia, with Western Europe averaging 40 percent and North America 22 percent.

Comparisons of these five quantification exercises show a mean value of about 25 percent and the extreme shares as low as 4 percent and as high as 55 percent (see Table 3).

## Deconstructing appropriation

There has been no uniform approach to calculating HANPP, and the published values are usually cited without specifying what they represent. *A sensu stricto*

definition of human appropriation of photosynthetic products includes all crop harvests (whether directly for food or for animal feeding, raw materials, or medicinal or ornamental uses) and all harvests of woody phytomass (whether for fuel, construction timber, or roundwood to be made into plywood and furniture or pulped to make cardboard and paper for packaging, printing, and writing). That is the first, low-estimate, choice by Vitousek et al. (1986). A *sensu lato* definition is much more elastic: there is no clear natural cutoff for inclusion, while many impacts that should clearly be included are difficult to quantify.

Grazing by domestic animals should be included. Yet when grazing is done in a sustainable manner (with appropriately low animal densities), it does not diminish the overall photosynthetic capability of a site: in fact, it may promote growth. And the phytomass not consumed by domesticated herbivores would not necessarily be “appropriated” by other vertebrates: the ungrazed grass would die during winter or arid season and be eventually decomposed. Moreover, domesticated grazers also return much of the partially digested phytomass in their wastes, actually promoting grassland productivity. There should be other adjustments. Conservation tillage and no-till practices either recycle most of the residual phytomass (straws, stalks) or do not remove any of it, leaving it to decomposers and other heterotrophs. Significant shares of cereal straws removed for bedding and feeding of ruminants are returned to fields (made available to soil heterotrophs) as manures. And most logging operations do not remove tops of trees, branches, and stumps from forests.

By a logical extension, regular burning of grasslands to prevent re-establishment of woody phytomass should also be included in HANPP, as should all phytomass burned by shifting cultivators and all forest fires caused by human negligence or arson. A comprehensive global estimate of phytomass consumed in anthropogenic fires used the best available published estimates of the share of human-induced large-scale vegetation fires in different countries (mostly between 80 and 95 percent in the tropics but only 15 percent in Canada) and a set of assumptions to calculate the biomass burned in small (shifting cultivation) fires (Lauk and Erb 2009). The exercise resulted in estimates of annual burning of 3.5–3.9 Gt of dry matter, with one-third (1–1.4 Gt) attributed to shifting cultivation, and with the sub-Saharan Africa’s grassland fires accounting for the largest share of the total (2.2 Gt/year).

Other studies of African burning demonstrate the uncertainty of that total. Median burning interval is about four years, but some grasslands in the Sahel are not burned for up to 20 years, while annual fires are common in the Guinean zone. This causes substantial year-to-year fluctuations, and different assumptions regarding the density of the burned phytomass result in annual aggregates varying more than eight-fold, 0.22 vs. 1.85 Gt/year (Barbosa, Stroppiana, and Grégoire 1999). The latest published annual rate is for the years 2001 to 2005, estimating that about 195 Mha of African grasslands were burned annually, releasing about 725 Mt C (Lehsten et al. 2009).

But adding this uncertain total to the HANPP is questionable because nearly all of the released carbon will be incorporated into new grass growth following the burning, and because many tropical and subtropical grasslands have always been subject to widespread natural seasonal fires and it would not be easy to quantify only the net increase in fire activity resulting from deliberate burning. Further, productivity of many fire-adapted ecosystems benefits from regular burning (storage in fire-adapted forests may actually increase after a fire, as fast-growing new trees have lower autotrophic respiration than does old-growth forest), and it would be very difficult to quantify only that part of deliberate burning that reduces overall productivity.

Moreover, analysis of global sedimentary charcoal data shows that the recent rates of anthropogenic burning are much lower than in the past (Marlon et al. 2009).<sup>17</sup> Another perspective illustrating a comparatively large extent of pre-1800 fires was offered by Stephens, Martin, and Clinton (2007): they estimated that fires ignited by lightning and native Americans in the territory of today's California consumed annually about 1.8 Mha. That amounts to nearly 90 percent of the total area affected annually by wildfires in the entire US during the years 1994–2004, a decade characterized as having “extreme” wildfire activity. Such a description aptly illustrates how ignorance of historical realities affects the perception of recent natural and anthropogenic phenomena.

Higher productivities of both field crops and well-managed forests may result in smaller areas devoted to these managed harvests, and as natural vegetation fills the vacated space the national HANPP will decline. This has indeed been the case in three countries for which HANPP trends are available: Austria, Britain, and Spain. At the same time, intensively managed cropland and high-yield tree plantations will experience greater environmental burdens (higher fertilizer, pesticide, and herbicide applications; increased nitrogen losses, including greater leaching and resulting eutrophication of waters) and may be subject to less desirable agronomic practices (increased monocropping, reduced crop rotation, and soil compaction by heavier machinery): such a decline of HANPP cannot be seen as wholly desirable.

The next major concern about HANPP estimation is the problematic denominator chosen to calculate the appropriation ratio. As explained, NPP is a theoretical concept, not a physical entity that can be left alone or harvested; hence it is incorrect to say that people can use it, directly or indirectly. Moreover, some global NPP estimates are only for above-ground production, but that restriction is not always clarified. Using only the above-ground NPP is particularly misleading in the case of grasslands, as those biomes store more phytomass under than above ground. Their below-ground NPP is, in most cases, considerably higher than their shoot productivity: its share is roughly 50–65 percent in tall grasses, 60–80 percent in mixed grass prairie, and 70–80 percent in short-grass ecosystems (Stanton 1988).

Grazing herbivores rarely remove below-ground phytomass, hence calculating the HANPP of grasslands by considering only shoot NPP and shoot

consumption by grazers misrepresents the dynamics of primary productivity in grasslands. In contrast, harvests of above-ground tissues of annual crops leave behind dead roots. Imhoff et al. (2004) included roots among human appropriation; but Haberl et al. (2007) excluded them from HANPP because the dead phytomass is fully available to decomposers and soil heterotrophs. And, obviously, any study using only above-ground NPP should logically exclude the harvesting of below-ground tubers, roots, and seeds.<sup>18</sup>

On the most general semantic level, we should ask what is meant by saying that humans “appropriate” (or “co-opt”) a certain share of the Earth’s annual photosynthetic production. To appropriate may be a felicitous choice of a verb intended to capture the entirety of human intervention: it is superior to “consume” as the latter verb evokes first food, and on second thought also wood for construction and pulp. But even before humans begin any harvesting, the NPP of crops and forests is reduced, often substantially, by incessant heterotrophic deprecations. Here the realities of phytomass harvests clash with both the choice of the analytical denominator (NPP) and the correct understanding of the key operative term (appropriation).

HANPP may be defined in ways that subsume not only direct harvests of phytomass for food, feed, and fuel but also many indirect claims that humans make on the biosphere’s photosynthetic production: annual burning of grasslands to maintain open pastures for domesticated animals is the spatially most extensive example of such interventions. But the standard definition of appropriation—to take exclusive possession of—also indicates that the way the term was used by Vitousek et al. (1986) is not accurate: the biosphere operates in ways that make it impossible for humans to take exclusive possession of any phytomass.

Viral, bacterial, and fungal infections affect all crops; insect deprecations can reduce the yield or claim virtually the entire productivity of tree stands on scales ranging from local to semi-continental: such long-standing pests as the mountain pine beetle and spruce budworm and the Asian longhorned beetle are common examples of massive, large-scale, and chronic damages inflicted by invasive invertebrates. To these must be added periodically devastating impacts of locust swarms on crops. Vertebrate attacks range from elephants eating and trampling African crops to deer and monkeys feeding on corn, and birds picking off ripe grapes in vineyards around the world. And highly variable shares of crop phytomass may remain unharvested because of lodging of stalks (particularly common in grain crops), shattering, and pre-harvest sprouting of grain.

Even in modern, highly managed agroecosystems, where much effort is spent on minimizing losses caused by heterotrophs, NPP and NEP are far from identical: pre-harvest heterotrophic consumption will never be eradicated. The correct denominator in assessing the intensity of harvests should be NEP, not NPP. But we would have to know actual NEP values at the time of harvest in a

particular year because considerable variabilities of weather and pest infestations result in annual NEP averages that fluctuate  $\pm 10$  percent even around a short-term mean and often as much as +10 percent and -40 percent in the long term.<sup>19</sup> Harvested phytomass is subject to a second wave of losses during storage: bacteria, fungi, insects, and rodents assert their claim before the feed or food harvests can be consumed. Improperly stored grain in low-income countries is particularly vulnerable (more than 5 percent of it may be lost before consumption), and tubers in the tropics sustain even higher pre-consumption losses. A case can be made that these storage losses should be classed under human appropriation, but their obvious beneficiaries are the bacteria, fungi, insects, and rodents, and this reality contradicts the claim of an “exclusive possession” of phytomass harvested by humans for their own use.

Even if NPP were not a debatable choice of denominator, one would still face the problem of choosing a value that can only be modeled and indirectly estimated. More than a decade ago, comparison of global NPP models used to simulate actual annual production showed a substantial range of results, with the highest global value twice the lowest value; even after excluding four extreme values, the remaining 12 assessments differed by as much as 40 percent (Cramer et al. 1999). Ito's (2011) recent meta-analysis of all recent global NPP estimates showed a mean of 56.4 Gt C/year and uncertainty of about  $\pm 15$  percent, or 8–9 Gt C. If both the total of the harvested (appropriated) phytomass and the total (actual or potential) NPP have minimum unavoidable errors of just  $\pm 15$  percent, then the extreme HANPP shares would be about 26 percent less and 34 percent more than the mean rate of 25 percent, bracketing a nearly twofold spread of 18–34 percent. Unfortunately, references to the studies of global HANPP in the mass media have almost completely ignored these complexities and uncertainties and reported just a single value for the appropriated or co-opted phytomass.

But perhaps the most serious charge against the exercise of calculating an HANPP share is that the result is a purely quantitative expression without the slightest consideration of the qualities of the affected phytomass. Harvesting food crops grown in optimized rotation on land that has been cultivated for centuries is clearly a very different appropriation of phytomass from cutting down one of the last remaining forest stands in such biodiversity hotspots as Brazil's *Mata Atlântica* or Guinean forests of West Africa (Conservation International 2011). Similarly, as already noted, the periodic burning of African savanna, whose phytomass will regenerate the very next season, is very different from conversion of the same grassland to crop monoculture (especially to a row crop such as corn, where the soil remains open to heavy erosion until the plant canopies protect it from rain).

Marine harvests provide an even better illustration of this complete absence of qualitative appraisal. By 2000 reported harvests averaged 93 Mt/year, and that total should be enlarged by about 17 Mt (18 percent of the

reported total) of illegal landings and 8 Mt of discarded by-catch. Such a harvest required annual consumption of at least 2.8 Gt C of phytoplankton and aquatic plants—and with the global aquatic NPP of about 50 Gt C, this would be equal to less than 6 percent of the marine NPP.<sup>20</sup> Such a low share of the human appropriation of oceanic NPP might appear to indicate that oceans are only lightly affected. It tells us nothing about the actual dismal state of the world's fisheries (Pauly 2009): as far as all large carnivorous fishes are concerned, virtually all major fishing areas are either exploited to their full capacity or are overexploited.

In sum, human appropriation of global net primary production is not just a poorly defined measure whose quantification depends on an abstract modeled value and on a concatenation of variables whose values have considerable margins of error. More fundamentally, it is a concept whose unambiguous formulation would be very difficult, whose practical applications are questionable because of some of the necessary underlying assumptions, and whose final ratio reduces many complex processes into a single figure that is hard to interpret. As is true for so many other compound indexes and global measures, it does not offer any special insight as a basis for effective guidance.<sup>21</sup> Its published values are too dependent on the concept's definition, and, perhaps most importantly, many qualitative implications and multifaceted ecosystemic and social impacts of the phytomass harvests are completely beyond its scope.

### Implications, concerns, and possibilities

What do these efforts to quantify the human exploitation of the biosphere tell us? I would argue that the comparisons of changing biomass stocks are particularly revealing as they record the unprecedented domination by a single species and its associated domesticated zoomass. Barring a severe pandemic or a global thermonuclear war, this new reality cannot be reversed rapidly, and it creates an unprecedented demand for the products of photosynthesis. On the other hand, frequently invoked NPP appropriation rates carry less weight because the absence of a clear definition can make the claim minor (<10 percent of NPP) or very worrisome (>40 percent) and because the measure ignores qualitative aspects of biomass harvests.

Consequently, appropriation rates are best seen (once properly interpreted) as a trend indicator helping to illustrate the human transformation of the Earth. This process has resulted not only in a complete loss of natural ecosystems and in the continuing expansion of almost purely anthropogenic landscapes, but also in the emergence of natural ecosystems that are either dominated or affected by human actions. Ellis and Ramankutty (2008) claim that these anthropogenic biomes (anthromes), where nature is embedded within human systems, now cover more than 75 percent of all ice-free land and incorporate 90 percent of all terrestrial NPP. While these shares are debatable (anthrome coverage is based on computerized classification of satellite

images, leaving considerable room for error), hybrid landscapes are ubiquitous, a reality that forces us to make choices about the “naturalness” of ecosystems and consider the question of authenticity in nature (Dudley 2011).

Most long-range global population forecasts expect only a relatively modest increase before an eventual stabilization (and possible downturn),<sup>22</sup> but potential increases in per capita consumption throughout the modernizing world may lead to large gains (if not a doubling) of today’s phytomass harvests by the middle of the twenty-first century. If current appropriations were already on the order of 35–40 percent, future high harvesting gains could easily push them well over 50 percent, leaving less than half of the terrestrial NEP outside the human reach. Such levels of phytomass harvesting would restrict largely undisturbed natural ecosystems to areas too small to sustain a desirable degree of biodiversity and adequate provision of various environmental services, including protection against soil erosion, water storage, and the capacity for capture and neutralization of various air- and waterborne pollutants.

But even if current appropriations were only on the order of 20 percent, their qualitative impact has already been worrisome enough (Millennium Ecosystem Assessment 2005) to argue for a dedicated effort to minimize the impact of future harvests. This effort should rely on the combination of two strategies: to reduce typical rates of consumption and to use resources more efficiently. Opportunities for the first strategy abound in affluent countries given their wastefully high per capita supply of food, high degree of carnivory, excessive food intakes, and rising incidence of obesity. The second strategy holds enormous potential everywhere, both during the production phase and throughout the post-harvest food chain.

The best agronomic practices—with optimized irrigation and fertilization (particularly nitrogen applications) and the use of pesticides, with reduced tillage and with crop rotations rather than monocultures—should limit the environmental consequences of cropping intensification. Post-harvest (storage and distribution) food and feed losses remain unacceptably high. A significant proportion of food purchased by households, eateries, and institutions in both the United States and China is wasted.

Excess supply and food-chain losses on a national level can be determined as the differences between food available at the retail level and food that is actually consumed; the first set of daily averages is readily available in FAO’s annually updated national food balance sheets (FAO 2011), while actual food intakes are based on estimates derived from irregular short-term food consumption surveys (often involving unreliable dietary recalls) in a limited number of countries. A more accurate approach is the one used by Hall et al. (2009) to model metabolic and activity requirements in order calculate the most likely food intake of the US population between 1974 and 2003. Their best estimate is that the average intakes ranged from about 2,100 kcal/day to nearly 2,300 kcal/day; during the same period the average food supply rose

from about 3,000 kcal/day to 3,700 kcal/day, which means that America's food waste increased from 28 percent in 1974 to about 40 percent three decades later. A detailed survey of British food waste found that UK households waste about 31 percent of purchased food (WRAP 2009); if the supermarket losses and wastes in institutional eateries and restaurants are added, the total would come close to the US rate.

Given the very high average per capita food supplies in all other major EU economies—ranging from 3,500 kcal/day in Germany to 3,700 kcal/day in Italy, with France at 3,600 kcal/day—and the fact that actual intakes in those countries cannot exceed about 2,100 kcal/day, it is obvious that similarly high, or even slightly higher, levels of food waste (40–45 percent of the total supply) must prevail in most EU countries. Even Japan, the least wasteful affluent country, now loses about 25 percent of the total daily food supply (Smil and Kobayashi 2012). A surprisingly high share of food is now also wasted in urban China, where average per capita food supply surpasses 3,000 kcal/day. On the other hand, any savings from curtailing waste could be negated by reckless expansion of biofuel crops.

The greatest savings of woody phytomass could result from a universal adoption of efficient rural wood stoves, such as those that have been widely diffused in China (Smil 2004); by whole tree utilization and expanded production of engineered timber (Williamson 2001); by even higher rates of paper recycling (McKinney 1994); and by further shift from paper-based records to purely electronic files.<sup>23</sup> Looking further ahead, expansion of crop and wood harvests may not require conversion of substantially larger undisturbed areas to cropping or to wood plantations thanks to new high-yielding transgenic plants. These realistic opportunities for moderated use and improved efficiency of biomass resources allow us to make a prudent and encouraging claim: improvements in quality of life for the world's still-growing population can be made without exerting a perilously large claim on the biosphere's fundamental and irreplaceable energy flow—its photosynthetic productivity.

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## Notes

1 The Pleistocene era began nearly 3.6 million years ago and lasted until 11,700 years before the present; its final 100,000 years coincided with the most recent glaciations of northern continents. The Holocene era's relatively stable climate allowed the evolution and diffusion of agriculture and the rise of complex societies.

2 The following energy values provide some helpful comparisons: daily food intake of an average adult is about 10 million joules

(MJ); burning a kilogram (kg) of air-dried wood releases about 17 MJ; a kg of oil contains 42 MJ, which means that a tonne of oil has 42 GJ. As a historical comparison, per capita burning of wood during the Roman Empire averaged an equivalent of 250 kg of oil a year; the US mean annual per capita commercial energy consumption is now about 8,000 kg (8 t) of oil.

3 Life's chief dichotomy is between autotrophs, organisms that can nourish themselves

(all plants and photosynthesizing bacteria), and heterotrophs, lifeforms that must feed on other organisms or on their particular tissues. Heterotrophs survive and reproduce only by ingesting fully formed organic compounds synthesized by autotrophs, whether by eating them directly (as is the case with herbivores, and with vastly more numerous bacteria and fungi consuming dead phytomass) or indirectly by eating other heterotrophs (carnivores); omnivores do not discriminate. Imperatives of energy metabolism dictate that the global biomass of heterotrophs is only a small fraction of all autotrophs, but (much as in the case of photosynthesizing organisms, whose size ranges from sequoias to oceanic nanoplankton) heterotrophic bodies range over eight orders of magnitude from microbial decomposers to the largest marine mammals.

4 Traditional biomass fuels (fuelwood, charcoal, cereal straws, dried dung) still dominate the rural energy supply in the poorest regions of Asia, Africa, and Latin America, and annual consumption of these fuels amounts to nearly 10 percent of all primary energy (fuels and hydro, nuclear, solar, and wind electricity) consumed worldwide (Smil 2008).

5 Standing phytomass is measured either in absolutely dry plant mass per unit of area (in order to eliminate wide differences in water content of fresh phytomass) or in mass of carbon, the principal constituent of living matter that accounts for 45–50 percent of dry biomass; actual units used in this article are tonnes per hectare (t/ha) or tonnes of carbon per hectare (t C/ha). Photosynthetic (primary) productivity is expressed in the same units as an annual increment.

6 Plant formations are classified in an ascending order of communities, ecosystems, and biomes. Obviously, any averaging generalizations at the biome level (boreal forest, tropical rain forest) have very wide margins of error.

7 The main sources of these estimates are Matthews et al. (2000); Saugier, Roy, and Mooney (2001); and Houghton and Goetz (2008).

8 There are now fewer than 400,000 animals with average body mass of 500 kg and water content of 55 percent, an equivalent of anthropomass in a city of 4 million people.

For the history of bison virtual extinction and partial recovery see McHugh (1972); Branch (1929); and Isenberg (2000).

9 These estimates assume zoomass averages of 1 kg/ha in croplands, 2 kg/ha in low-productivity ecosystems (in both cases dominated by rodents), and 5 kg/ha (dominated by large herbivores) in the richest grasslands and forests and using the relevant historical land cover data (HYDE 2011). For the relationship between zoomass density and individual body mass, see Damuth (1981) and Silva and Downing (1995).

10 Tanzania's Gombe reserve (made famous by Jane Goodall's work) contains more than five animals per km<sup>2</sup> (Pusey et al. 2005), but this is an exceptionally high density because the community, habituated to humans, is now surrounded by inhabited and cultivated areas. Its former chimpanzee densities were between 1.29 and 1.93 individuals per km<sup>2</sup>, in line with typical counts in the forests of East and Central Africa: 1.45–2.43 and 1.45–1.95 in, respectively, Uganda's Kibale and Budongo forests, and 2.2 in Congo's Odzala forest (Bermejo 1999; Williams et al. 2002; Plumptre and Cox 2006).

11 Autotrophic respiration claims mostly between 30 and 65 percent of GPP in grasslands, between 55 and 75 percent in boreal and temperate forests, and even more in tropical rain forests. An average of 50 percent is commonly used as the first-order approximation, and this share was confirmed by four years of satellite observations: between 2000 and 2003 global terrestrial ecosystems had an NPP/GPP ratio of 0.52 (Zhang et al. 2009).

12 For example, the NPP of a Brazilian rain forest near Manaus is as high as 15.6 t C/ha, while a figure that neglected fine root turnover was nearly 40 percent lower (Geider et al. 2001). Scurlock, Johnson, and Olson (2002) believe that the harvest-based estimates of grassland NPP may be no more than 50 percent and perhaps as little as 20 percent of the real rate.

13 The most significant problem with FAO's regular production data, the principal source of these worldwide statistics, is that many published figures are not provided by the member states but are simply estimated in FAO's Rome headquarters. And, of

course, many national figures supplied to the FAO may be considerable over- or under-estimates.

14 Although illegal logging is common in many countries, global data for roundwood (timber) production are much more reliable than the estimates for annual harvests of phytomass fuels. Some of these fuels became part of larger-scale commercial exchange (charcoal and fuelwood for cities and industries), but most of them are collected by rural families for their immediate use in cooking or heating, and their annual totals must be estimated on the basis of limited short-term local or regional studies (Smil 2008).

15 Annually updated worldwide statistics of carbon emissions from fossil fuels can be found in CDIAC (2011).

16  $NPP_t$  is thus the difference between the NPP of the actual vegetation ( $NPP_{act}$ ) and the NPP harvested by humans ( $NPP_h$ ):  $NPP_t = NPP_{act} - NPP_h$  and the HANPP is  $NPP_0 - NPP_t$ .

17 The record shows a prolonged decline in biomass burning that lasted from the beginning of the common era to about 1750; this was followed by a marked rise peaking around 1870 and then by a sharp downturn. Yet the post-1870 period has seen the most rapid land use changes as well as rising temperatures, hence the downturn cannot be explained by reduced human activity or cooler climate: the most likely causes are fragmentation of vegetated areas, emergence of generally less flammable landscapes, and active fire suppression. These long-term trends of anthropogenic burning were confirmed for the last 650 years by analysis of concentrations and isotopic ratios of atmospheric CO preserved in a South Pole ice core (Wang et al. 2010): it shows a pronounced decline in southern hemisphere burning between 1350 and 1650; then came an undulating rise peaking during the late nineteenth century, followed by a decline to levels lower than at any time since 1350.

18 Tubers include massive harvests of white and sweet potatoes, yams, cassava, and taro totaling some 700 Mt worldwide; root harvests include sugar beets (now more than

200 Mt/year) and many vegetable root crops, ranging from carrots to celeriac; the most prominent component of the seed category is peanuts, whose harvest is now close to 40 Mt/year. The grand total of these underground harvests is now on the order of 1 Gt of fresh phytomass.

19 Above-average harvests are common during years that combine abundant precipitation with optimum temperatures needed for crop ripening: for example, average yields of corn, America's largest annual crop, were as low as 8.1 t/ha in 2002 and as high as 10.3 t/ha in 2009 (FAO 2011). In contrast, large yield losses are common during prolonged droughts, particularly those associate with La Niña circulation (ISU 2011).

20 I assume average carbon content at 12 percent of the fresh weight, average trophic index at 3.3 (herbivorous fish, such as herring, feed at trophic level 2.0, top-level carnivores, such as yellowfin tuna, at 4.6), and the mean feed energy transfer efficiency at 10 percent. For comparison, Pauly and Christensen (2002) calculated the phytomass requirement for the global fish catch at 8 percent of the marine NPP.

21 For example, we do not need to know the UNDP's Human Development Index for Sierra Leone (0.317) or Zimbabwe (0.140)—compared to 0.519 for India and 0.902 for the US—in order to appreciate the dire socioeconomic circumstances of those first two countries.

22 The latest version of the United Nations's *World Population Prospects* delays this peak until after 2100. Previous forecasts put the peak at about 9.2 billion in 2075, but the changed fertility assumptions result in the total surpassing 10 billion by the early 2080s and still slowly rising by 2100 (UN 2011).

23 This shift now includes electronic books: in May 2011 Amazon.com announced that its sales of e-books surpassed the sales of printed titles by 5 percent, and that balance is bound to shift rapidly (there are now some 30 companies making e-readers).

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