Chapter 15
Global Biomass Supply and Sustainable Development

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Abstract Biomass – in form of nutritional energy and energy-rich material – is not accounted for in conventional energy statistics. It constitutes a neglected energy carrier although it has ever since provided the basis for human life and activity. In this work, we assess current global draw on the earth's biomass resources by examining the indicators 'Ecological Footprint' and 'Human Appropriation of Net Primary Production', quantifying humankind's biomass demand and the earth's biomass supply. It is revealed that humankind appropriates about 20–30% of the ecosystem's supplying capacity. Other definitions partly suggest lower and higher values. We then use the energetic metabolism accounting concept to acquire data on biomass supply for the past centuries to complement conventional energy statistics. It is disclosed that the actual energy supply to humankind is about twice as high as conventional energy statistics essentially suggest. Depending on the approach taken, current biomass supply amounts to 10–12 TW or to 14–15 TW. Against the results yielded, ideas like substituting fossil resources with biomass in the future for the provision of energy services to mitigate the current energy and climate crisis might be controversial to the achievement of sustainability.

Keywords Historic primary energy supply · Biomass · HANPP · Ecological Footprint · Energetic metabolism accounting

1 Introduction

When the energy supply of a certain country or region is analyzed, it is customary to refer to energy statistics or balances. However, this refers to commercial energy only, i.e. to commercially-traded energy that is used in technical devices for the provision of energy services (Haberl 2001:11; compare also OECD 2011; BP 2011).

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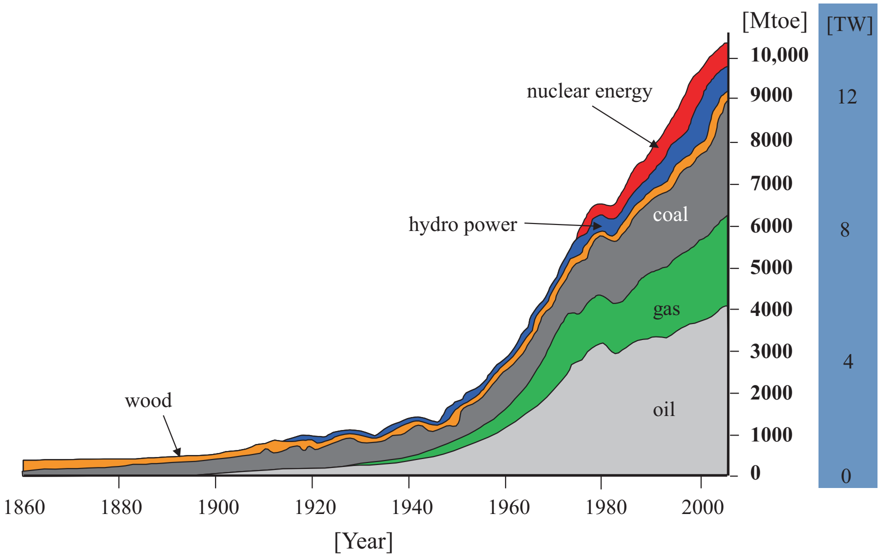

Fig. 15.1 Conventional primary energy supply in the industrial era (Mtoe = million tonnes of oil equivalent; TW = 10^{12} W.)
Source: Adapted from Paeger (2011)

They most notably include fossil energy carriers like coal, crude oil, and gas, as well as alternatives such as nuclear and regenerative energy carriers (compare Fig. 15.1).

Considering the development pictured in Fig. 15.1, it seems like people having lived before 1860 hardly had any noticeable energy at their disposal. Such a conclusion would be incorrect as biomass – organic material produced in the photosynthesis process by the primary producers' transformation of solar into chemical energy – has always provided the vital energy source for almost all life on earth. While the total amount of chemical energy produced by photoautotrophic organisms (like green plants) of an ecosystem within a certain time period is called gross primary production (GPP), part of this energy is used for the primary producers' own metabolic processes. The remaining fixed energy is the net primary production (NPP) and is either used for the buildup of biomass stocks or for the feeding of the ecosystem's consumers (Campbell and Reece 2003:1434; Haberl et al. 2004:280).

The human economic system, being a subsystem of the ecosystem, draws from many resources and services provided by the latter: resource supply, waste absorption and the provision of space to be occupied by human infrastructure. An ecosystem's NPP, the amount of which depends on factors like solar influx, nutrient and water availability, the composition of plant species and soil quality, provides nutritional energy and energy-rich material for the socioeconomic stocks of a human society, which are humans, domesticated animals as well as artefacts (Haberl et al. 2004:280; Haberl 2006:88).

For a comprehensive analysis on global energy supply, energy values from conventional energy statistics must be completed with values on biomass supply. This is particularly important in order to assess humankind's current draw on the earth's NPP, so that ideas like substituting fossil resources with biomass in the future for the provision of energy services to mitigate the current energy and climate crisis can be critically evaluated. Although the need to capture data on biomass quantities supplied to the economic system to complement conventional energy statistics was recognized as early as in 1952 by the United Nations (for instance UN 1952:101), only in the very last decades have scientists/institutions worked at the systematic development of accounting tools to be employed for the acquisition of data on humankind's demand for the ecosystem's NPP.

In this chapter, we pursue two purposes. The first consists of examining two different approaches that quantify humankind's biomass demand and the earth's biomass supply. Such juxtaposition helps to assess the global draw on the earth's NPP. We, therefore, start by taking a macro-perspective approach and examine the metric Ecological Footprint (EF), being followed by the measure Human Appropriation of Net Primary Production (HANPP) and alternative studies on NPP appropriation. The second purpose consists of complementing the conventional energy statistics with values on biomass in order to assess the actual energy supply to humankind. We, therefore, continue by taking a micro-perspective approach and analyze the energetic metabolism accounting concept, being based on energy flow accounting and allowing for the tracing of (per capita) energy flows through a defined societal compartment. The basic questions pervading the examination of EF, HANPP and the energetic metabolism accounting concept are: What is revealed by the defined concept with regard to demand for and supply of biomass? To what extent can the information provided be used to assess global draw on the earth's NPP and to complement conventional energy statistics with biomass estimates?

This analysis is structured as follows. In Sect. 2, approaches to the estimation of biomass supply are presented. In Sect. 2.1, the Ecological Footprint is examined, being followed by Human Appropriation of Net Primary Production in Sect. 2.2. Section 2.3 is devoted to the energetic metabolism accounting concept, the presentation of two diverse approaches to the approximation of global biomass supply and the complementation of conventional energy statistics with biomass supply. The key findings established in Sects. 2.1–2.3 are juxtaposed in Sect. 2.4. Section 3 brings our considerations to a close.

2 Approaches to the Estimation of Biomass Supply

2.1 Ecological Footprint (EF)

The metric Ecological Footprint (EF)[1] was conceived in the early 1990s by the University of British Columbia's academics Wackernagel and Rees (Ewing et al. 2010:9). Both researchers were convinced that human actions cannot be seen as activities that are independent from nature; in contrast, they believed that any form of growth must take place within nature's ecological limits. Following the idea that humankind lives ecologically unsustainably and will experience a decline in well-being in the long run when it consumes more ecological products and generates more wastes than can be provided and absorbed by the ecosystem, the EF was created as "an indicator of human demand for ecological goods and services linked directly to ecological primary production" (Ewing et al. 2010:90). In analogy to bank statements, it juxtaposes "human demand on ecological assets", i.e. the EF and "the ability of these assets to meet this demand", i.e. the biocapacity (Ewing et al. 2010:8). To quantify the EF, the amount of biologically productive land and water area that is required for the generation of all resources currently used and for the absorption of all wastes produced – given the prevalent resource management practices and technology – is measured.[2] The biocapacity, representing the supply of biological materials that are demanded for by human activities is assessed by the quantification of bioproductive areas available to secure provision thereof (GFN 2012). Thereby, it is indifferent where the bioproductive areas are located. The EF thus provides an insight into "how much bioproductive area is needed exclusively to sustain the activities of a given society" (Haberl et al. 2004:284). Both demand and supply are measured in hypothetical area units, namely the global hectare (gha); this means that the global EF can actually exceed the earth's biocapacity, a situation called ecological overshoot (Ewing et al. 2010:104; van den Bergh and Verbruggen 1999:64).

2.1.1 Assumptions Underlying Ecological Footprint Accounts

There are six fundamental assumptions providing the basis for EF and biocapacity calculations, i.e. for the ecological footprint accounts (Kitzes et al. 2007:3; Ewing et al. 2010:8–9):

- It is possible to track all resources consumed and wastes produced in a given territory per time unit in physical form as tons, joules or m^3.
- Most of these material flows can be attributed to the bioproductive areas that are needed for the resources' provision and the wastes' removal. Resource and waste

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[1] http://www.footprintnetwork.org/en/index.php/GFN/page/at_a_glance/

[2] It should be noted here that carbon dioxide emissions are so far the only waste product included in national footprint accounts (Ewing et al. 2010:14).

flows that cannot be quantitatively captured in terms of biologically productive areas are ignored in the assessment.
- Worldwide diverse bioproductive areas can be converted into a mutual unit, the global hectare (gha). Global hectares represent hectares "with world-average productivity for all biologically productive land and water" (GFN 2012) and are used to express both the EF and the biocapacity.
- The entire demand can be aggregated by the merging of all mutually exclusive areas generating resources and absorbing wastes. Such an addition is guaranteed through the conversion of physical hectares into gha and is also valid for the determination of supply, i.e. biocapacity.
- When expressed in gha, humankind's demand for natural capital (EF) can be directly compared to its supply (biocapacity).
- If human demand for the resources of a specific ecosystem exceeds this ecosystem's regenerative capacity, an overshoot is present and ecological assets are being reduced.

2.1.2 Methodology of Ecological Footprint Accounts

The EF is calculated through the capture of all individual resource requirements over several bioproductive area categories and the conversion into the standardized area unit gha by means of yield and equivalence factors (Kitzes et al. 2007:1–2). The comprehensive data points needed to calculate a territory's footprint or biocapacity are provided by global databases, primarily by the UN's Food and Agriculture Organization FAOSTAT, UN's Comtrade, and OECD's International Energy Agency. Also, satellite imaging is used, for instance with regard to built-up land (Ewing et al. 2010:8–9/12–13).

In ecological footprint accounts, six diverse bioproductive area categories or land types are distinguished (Ewing et al. 2010:13–14/100):

- Cropland, the most bioproductive land type delivering food, fodder, rubber and fiber.
- Grazing land, providing above-ground biomass for livestock to deliver meat and dairy products, wool produces and hide.
- Fishing grounds, delivering catch from continental shelves and inland water areas. Catch estimates are converted into an equivalent quantity of primary production, according to the species' trophic levels.
- Forest land, supplying lumber, timber products, fuelwood and pulp.
- Built-up land, which does not provide any resources but – in contrast – prevents any resource provision given human urban and infrastructural development. It is assumed that built-up land replaces the biologically most productive area category, i.e. cropland.
- Carbon dioxide land, describing the biologically productive area that is necessary to absorb the anthropogenic carbon dioxide emitted into the atmosphere through the combustion of fossil fuels, land-use change, industrial processes, and transport. It is the only EF component that is dedicated to mere waste (i.e. carbon

dioxide) absorption. In ecological footprint accounts, all carbon dioxide emissions not sequestered by oceans are translated into the amount of bioproductive forestland needed to absorb the remaining emissions. Carbon dioxide land is thus actually forestland needed for carbon dioxide uptake.

For the purpose of identifying the original area needed to provide resources for processed products, the latter “are converted into primary product equivalents” (Kitzes et al. 2007:4) and translated into gha by means of extraction rates in order to account for the individual nation’s transformation efficiencies. The energy required for processing is also considered in ecological footprint accounts and is eventually represented in the carbon footprint (Ewing et al. 2010:11–12).

In order to compare the various area categories by a common denominator, physical hectares (ha) needed for resource provision and waste absorption are converted into gha; the conversion from a physical ha into a gha is undertaken by means of two factors, which are valid both for the EF and the biocapacity (GFN 2012; Kitzes et al. 2007:6–7).

- Yield factors describe the extent of a national land type’s biological productivity in comparison to this area category’s global average productivity. They are used to convert one physical ha of any land type into the equivalent quantity of world-average hectares through the multiplication of the physical hectare by the appropriate national yield factor of the area category in question. This implies that a yield factor indicates the amount of world-average ha existent within a physical hectare of the defined national area category.
- Equivalence factors specify the productivity potential of a certain area category in relation to the global average productivity of all area categories. They allow for the conversion of one world-average ha of any land type into the corresponding quantity of gha through the multiplication of the world-average ha by the appropriate equivalence factor. This implies that an equivalence factor indicates the amount of gha existent within a world-average ha of a specified land category.

2.1.3 The EF as a Tool for the Assessment of Humankind’s Draw on the Earth’s NPP

With regard to the purpose of using global EF and biocapacity data, as provided by the EF concept for an assessment of humankind’s draw on the earth’s NPP, some adjustments must be made to avoid drawing false conclusions. According to the Global Footprint Network (GFN), humankind needs 1.5 planets to uphold its standard of living: the hypothetical area needed to supply products and services is larger than the bioproductive area needed to meet this demand, or its regenerative capacity; natural capital is depleted as a consequence. The current exploitation of the planet’s renewable biological resources thus amounts to 150% (GFN 2012). However, this percentage includes the carbon footprint, which is related to the deficiency of single service accounting:

- The concept of ecological footprint accounting is designed in such a way that any given land type can solely render a single ecological service. This assumption is questionable because various land types do provide multiple services and allocation difficulties are almost certainly predestinated (van den Bergh and Verbruggen 1999:65). This is particularly valid with regard to forestland. Forestland does not only provide wooden products but it absorbs much of the carbon dioxide emissions caused by human activities. The EF distinguishes forestland and carbon dioxide land as mutually exclusive areas. In this respect, the forestland's footprint, being caused by human demand for wooden products, is juxtaposed with the biocapacity provided by forests, the single service of which is the supply of the products demanded for. However, the biocapacity provided by forests also absorbs much of the carbon dioxide. As the EF concept is designed in such a way that each land area can solely render a single service, no "corresponding carbon sequestration biocapacity" (Venetoulis and Talberth 2008:452) is additionally allocated. This implies that the demand for land area to absorb carbon dioxide (characteristically exactly forestland) is included in the acquisition of a territory's footprint and expressed as a carbon dioxide land, the supply of bioproductive area to do so, however, is neglected in the accounting framework (due to the conceptual decision that multiple land uses are not considered). This conceptual decision clearly affects the result of a territory's footprint and biocapacity, making the draw on earth's natural resources seem more intense.

In order to offset this deficiency, we decide to omit the carbon footprint in our assessment of humankind's draw on natural biomass resources. This is target-aimed to the effect that we want to determine the quantity of biological products that is appropriated for the maintenance of global society's socioeconomic metabolism.[3] When the carbon footprint, amounting to 54% of global EF (GFN 2012), is subtracted from the current rate of use of planet earth, namely 150%, the exploitation of the planet's resources is reduced to ~70%. Moreover, the estimate of the carbon footprint, amounting to 54% of global EF, should be seen with certain skepticism, as aggregation inaccuracies might be existent:

- In ecological footprint accounts, all carbon dioxide emissions not sequestered by the oceans are translated into the amount of bioproductive forestland needed to absorb the remaining emissions. However, depending on the kind of forest (mature vs. immature, for instance), the net carbon dioxide uptake can differ and the carbon footprint is likely to be falsely aggregated (Herendeen 2000:357). Most notably, ecosystems other than forests also take up emissions and the "carbon budget from just forest" should be reassigned "to the entire globe" (Venetoulis and Talberth 2008:452).

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[3] The term 'metabolism' refers to the functioning of living organisms, the internal (chemical and physical) processes of energy-rich material intake to enable sustenance and reproduction as well as output in form of entropy and waste (Ayres 1994:xi/3). Analogous to the biological notion, the socioeconomic metabolism approach examines these processes within certain human societies and between such societies and their natural environment.

Also, we want to contrast human demand for biological resources with the NPP instead of the biocapacity:

- In ecological footprint accounts, the global EF is contrasted with the biocapacity. In contrast to the NPP, the biocapacity only embodies areas that deliver products and render services that are of direct productive use to humankind (Ewing et al. 2010:12). This anthropocentric point of view neglects ~36 bn hectares of land (from 51 bn hectares in total) like mountains, tundra, deserts, ice sheets and most of the ocean, because – according to the EF concept – these areas are too unproductive to provide any economically useful biological materials or services (Venetoulis and Talberth 2008:446/449/452). Although the NPP of land types like deserts is below that of biologically more productive areas like tropical forests or crop land, the complete omission of these land types' productivity does not only disregard their role in global biocapacity provision and carbon dioxide sequestration (Venetoulis and Talberth 2008:449) but also leads to a downward bias of the biocapacity available.

Following these considerations, the draw on biological resources caused by human demand can be deduced from the information given on the EF. When the current rate of use of planet earth amounts to 150% and the biocapacity is indicated to include 15 bn gha, the present EF actually corresponds to 22.5 bn gha. When thereof 54% are subtracted in order to neglect the carbon footprint, the EF is reduced to ~10 bn gha. Setting in relation this quantity with the global bioproductive area, namely the 51 bn ha that generate NPP, the proportion of biological resources drawn from the earth's ecosystems' NPP amounts to ~20%. However, as the additional 36 bn ha of bioproductive area are not weighted according to their NPP's usefulness for humans and the lands' characteristics have a lower NPP than the land area accounted for in the biocapacity, the corresponding value of 51 bn ha expressed in gha would be lower; the appropriation of 20% can thus be regarded as a minimum.

2.2 Human Appropriation of Net Primary Production (HANPP)

The indicator HANPP was elaborated by Haberl (1997) and is based on the belief that human activities disturb the ecosystem's functioning by altering vital ecological energy flows and reducing the NPP available. Measuring in physical units (dry matter biomass, Joule, carbon) the quantity of NPP appropriated by humans in a defined land area, the indicator HANPP discloses the intensity of land use and examines the changes in energy flows that result from human use of the ecosystem's services. It can thus be used for an evaluation of the extent of human domination in a given territory (Haberl et al. 2004:280/286; Krausmann and Haberl 2002:181).

The definition of HANPP was formulated after a concept given by Wright (1990), stating that the biomass appropriated by humans through land use is the energy that would be potentially available without the presence of human beings. More precisely, HANPP is defined as the difference between the potential NPP (NPP_0), i.e. the NPP that would prevail in the ecosystem "in the absence of human intervention" (Haberl et al. 2007a:12942) and the NPP actually remaining in the ecosystem after harvest has been completed (NPP_t). NPP_t is calculated by subtracting the NPP harvested and destroyed in the harvest process by human beings (NPP_h) from the current, actual vegetation (NPP_{act}). HANPP is thus $NPP_0 - NPP_t$ with $NPP_t = NPP_{act} - NPP_h$. If the difference between NPP_0 and NPP_{act} is denoted as ΔNPP_{LC}, namely being "NPP changes induced by soil degradation, soil sealing, and ecosystem change" ($\Delta NPP_{LC} = NPP_0 - NPP_{act}$), then "HANPP becomes equal to $NPP_h + \Delta NPP_{LC}$" (Haberl et al. 2007b:3). ΔNPP_{LC} thus embraces productivity changes (losses or gains) compared with potential vegetation (Haberl et al. 2007a:12945).

Methodologically, NPP_h (i.e. the biomass harvested and destroyed in the harvest process) is quantified on the basis of statistical data on agricultural yields, livestock and wood harvest, mainly delivered by the UN's FAO or other agricultural statistics as well as on the basis of "spatially explicit data on land use in grid-based geographical information systems" (Haberl et al. 2007a:12946). NPP_{act} (i.e. the NPP that currently prevails in the ecosystem) is assessed on the basis of existing statistical datasets on land use and land cover stemming from gridded geographical information systems databases (Haberl 2007a:12942). Also, dynamic global vegetation models (DGVM) are being made use of, more precisely the Lund-Potsdam-Jena DGVM, simulating biogeochemical processes and productivity of global vegetation. If there is a lack of reliable and consistent data, harvest indices are used or assumptions made (Haberl et al. 2007b:5). Data for the determination of potential terrestrial NPP, i.e. NPP_0 is either derived from the Lund-Potsdam-Jena DGVM or from extrapolation of typical NPP values per defined unit and year given by literature sources (Haberl et al. 2007a:12946; Haberl et al. 2007b:4).

In their study, Haberl et al. (2007a) quantify and map HANPP in the earth's above- and belowground terrestrial ecosystems. They reveal that HANPP amounted to 15.6 Pg C/yr. around year 2000; this equals 18.3 TW.[4] It is the sum of NPP_h (9.6 TW), ΔNPP_{LC} (7.4 TW) and NPP appropriated in human-induced fires (1.3 TW), the latter being separately shown in the authors' calculation.

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[4] Pg C/yr. = 10^{15} g carbon per year. For better assessment of this chapter's contents as well as on grounds of uniformity, all original units used in various studies are converted into the unit of power, namely Watt (W) (1 W = 1 J/s; TW = 10^{12} W). Conversions are undertaken using the following factor: 1 kg dry matter biomass equals 0.5 kg carbon or 18.5 MJ (Haberl et al. 2007b:6). All figures stipulated hereafter derive from exact conversions and are only as precise as the original data.

2.2.1 Further 'HANPP' Estimates

As terms, scope of consideration and methods for the assessment of HANPP are not (yet) standardized – the standardization being the aim of Haberl et al. (2007a:12945) – estimates on the appropriation of NPP generated by other authors cannot be directly juxtaposed to each other because 'HANPP' is defined differently in every study. Therefore, we attempt to systematically classify and synthesize alternative definitions of NPP appropriation with the corresponding estimates, therewith providing an overview of the amount of biomass that is taken from the ecosystem to meet human needs.

a. **Classification**

From a conceptual point of view, it is Wright's (1990) study that is most comparable to HANPP. This is based on the fact that Haberl (1997) adopts Wright's idea of NPP appropriation being compared "with the amount of photosynthetic energy that would flow through natural ecosystems in the absence of human impact" (Wright 1990:189):

- In his assessment of NPP appropriation, Wright (1990) focuses on long-term effects on the ecosystem's productivity that result from human activities. Such long-term effects are produced by habitat destruction like the conversion of natural vegetation into ecosystems serving human purposes as cropland and urban areas. In contrast to Haberl et al. (2007a), he neglects short-term effects like losses of plant biomass that are caused by burning or timber harvest. Wright argues that such biomass losses only have a minimal impact on the NPP that remains in ecosystems to be consumed by wild species (the implications for species endangerment being Wright's main object of research). Productivity losses caused by habitat degradation, like desertification or the conversion of forest into pasture as well as fodder consumed by domesticated animals, are included in Wright's estimate. His study suggests a NPP appropriation of 20.8 TW from aboveground terrestrial ecosystems around year 1988.

Another study that includes long-term productivity losses in the assessment of NPP appropriation is the one by Vitousek et al. (1986). In addition to ΔNPP_{LC}, they account for the entire NPP that is lost from a defined ecosystem due to its human occupation:

- Vitousek et al. (1986) produce an estimate on the amount of NPP that is appropriated by humankind in above- and belowground terrestrial ecosystems. Their so-called 'high estimate' includes the entire NPP of "lands devoted to human activities" (Vitousek et al. 1986:368) and productivity losses compared to potential NPP as a consequence of human interference in the ecosystem. Productivity losses as defined by Vitousek et al. can be relatively clearly juxtaposed with the HANPP component $\Delta NPP_{LC.}$ However, the acquisition of the entire NPP of "lands devoted to human activities" does indeed include the entire NPP that is produced in a defined human-dominated ecosystem – regardless of whether the NPP is actually withdrawn through harvest or logging or whether it actually remains there. In this context, the definition suggests that the estimate also includes onsite backflows of harvested biomass to nature (like killed roots or grazing animals' feces) and the often very productive vegetation in urban and infrastructural areas (like gardens, parks or roadside greening) (Haberl et al. 2007a:12943; Haberl et al. 2007b:5). Haberl et al. (2007a) only capture the NPP that is effectively withdrawn for further processing, thus distinguishing between NPP_h and NPP_t. According to Vitousek et al.'s (1986) 'high estimate', humankind appropriated 34.1 TW of terrestrial NPP in the 1980s.

Other estimates omit the consideration of ΔNPP_{LC} and define NPP appropriation solely as the entire NPP of human-dominated lands. A distinction between NPP_h and NPP_t is thus again not made.

- Besides the 'high estimate', Vitousek et al. (1986) also produce an 'intermediate estimate', which is the result of the subtraction of ΔNPP_{LC} from the 'high estimate'. Vitousek et al.'s 'intermediate estimate' for above- and belowground terrestrial ecosystems suggests an appropriation of 23.8 TW in the 1980s.
- The study by Rojstaczer et al. (2001) is oriented towards the 'intermediate estimate' generated by Vitousek et al. (1986). This means that their approximation accounts for the entire productivity of all human-dominated land, including the biomass directly and indirectly consumed. Rojstaczer et al. reassess the estimate on NPP appropriation by using more recent data – compared to Vitousek et al. (1986) – and by conducting stochastic simulations to incorporate estimates of uncertainty. According to their reassessment, the NPP appropriated in above- and belowground terrestrial ecosystems amounted to 22.9 TW, presumably in the 1990s. The 95% confidence interval accounts for ±15.8 TW.
- Imhoff et al. (2004) produce a regular estimate on NPP_h (see below), but point out that this regular estimate would increase to 24.4 TW if all the NPP of land dominated by humans was included. In this case, the amount and content appropriated are similar to the 'intermediate estimate' by Vitousek et al. (1986) and the reassessment estimate by Rojstaczer et al. (2001).

Imhoff et al. (2004) commonly define NPP appropriation as all biomass harvested for further processing. From a content point of view, their estimate compares to NPP_h:

- Imhoff et al. (2004) define NPP appropriation as the sum of the terrestrial NPP needed to produce biomass products demanded for by humankind and the NPP that is lost during harvest, logging and processing and that is consequently no further used economically. Their study suggests that NPP appropriation in aboveground (and partly belowground; belowground NPP of grazing land is not included) terrestrial ecosystems amounted to 13.5 TW around year 1995.

There are further estimates based on the definition that NPP appropriation solely includes biomass that is directly consumed by humans or animals; losses occurring during the process of harvesting or logging are not included:

- In this respect, Whittaker and Likens (1973) produce an estimate accounting for the quantity of food (terrestrial and aquatic) and timber directly consumed by humans. They suggest a direct NPP appropriation of 2 TW. The exclusion of aquatic food from the calculation does not have any noticeable effect; direct NPP appropriation remains at a value of 2 TW. The authors do neither specify whether their estimate refers to above- or belowground ecosystems nor what year they refer to. It might be as early as 1950.
- Vitousek et al. (1986) produce a 'low estimate' that only incorporates the NPP that is directly consumed by humans and animals in form of food (terrestrial and aquatic) as well as timber. Their result reveals a direct NPP appropriation of 4.2 TW in the 1980s; when aquatic food is omitted, direct NPP appropriation is reduced to 3 TW.

b. **Synthesis**

Depending on scientists referred to and the corresponding definitions taken, appropriation estimates differ. In the following, we synthesize the individual estimates on terrestrial NPP appropriation classified above. We start with the estimate accounting for least NPP components and end with the most comprehensive estimate. All estimates but the one by Wright (1990) – and possibly Whittaker and Likens (1973) – refer to above- and belowground ecosystems.

- *Estimates on appropriated NPP through direct consumption*: According to Whittaker and Likens (1973), an amount of 2 TW was appropriated in the 1970s through direct consumption. The 'low estimate' produced by Vitousek et al. (1986) suggests an amount of 3 TW in the 1980s, consumed by humans and domesticated animals.
- *Estimates on appropriated* NPP_h: Haberl et al. (2007a) indicate an appropriation of $\mathrm{NPP_h}$ of 9.6 TW around year 2000. Imhoff et al. (2004) suggest an amount of 13.5 TW around year 1995.
- *Estimates on HANPP*: Wright (1990) suggests a NPP appropriation of 20.8 TW around year 1988. Haberl et al. (2007a) quantify a NPP appropriation of 18.3 TW around year 2000.
- *Estimates on appropriated NPP of human-dominated lands*: Estimates range from 22.9 TW presumably in the 1990s (Rojstaczer et al. 2001) to 23.8 TW in the 1980s (Vitousek et al. 1986) to 24.4 TW around year 1995 (Imhoff et al. 2004).
- *Estimate on appropriated NPP of human-dominated lands +* ΔNPP_{LC}: Vitousek et al. (1986) suggest an appropriation amounting to 34.1 TW in the 1980s.

Disregarding the estimates on NPP appropriation through direct consumption on grounds of their relatively limited acquisition of NPP components from a content point of view, it is revealed that humankind appropriates – depending on the definition in question – between 10 TW (the estimate on appropriated $\mathrm{NPP_h}$ by Haberl et al. 2007a) and 34 TW (the estimate on appropriated NPP of human-dominated lands + $\Delta \mathrm{NPP_{LC}}$; i.e. the "high estimate" by Vitousek et al. 1986) of above- and belowground terrestrial NPP. Vitousek et al.'s (1986) 'high estimate' outranges all others due to the very broad conception of NPP appropriation, accounting for the

Table 15.1 Diverse NPP appropriation estimates

Classification of NPP appropriation definitions	Absolute appropriation [TW]	Terrestrial NPP_{act} [TW]	Appropriation of NPP_{act} [%]	Sources
Appropriated NPP through direct consumption	2	63	3.2	Whittaker and Likens (1973)
	3	77	3.9	Vitousek et al. (1986) "low estimate"
Appropriated NPP_h	9.6	70 (77)*	13.7(12.5)**	Haberl et al. (2007a)
	13.5	70	19.3	Imhoff et al. (2004)
HANPP (NPP_h + ΔNPP_{LC})	18.3	70 (77)*	26.1 (23.8)**	Haberl et al. (2007a)
	20.8	76 (89)*	27.4 (23.4)**	Wright (1990)
Appropriated NPP of human-dominated lands	22.9 (±15.8)	70	32.7 (± 22.6)	Rojstaczer et al. (2001)
	23.8	77	30.9	Vitousek et al. (1986) "intermediate estimate"
	24.4	70	34.9	Imhoff et al. (2004)
Appropriated NPP of human-dominated lands + ΔNPP_{LC}	34.1	77	44.3	Vitousek et al. (1986) "high estimate"

*the figures in brackets refer to NPP_0
**the figures in brackets refer to the appropriated % of NPP_0
Source: Adapted from Whittaker and Likens (1973), Vitousek et al. (1986), Wright (1990), Rojstaczer et al. (2001), Imhoff et al. (2004), and Haberl et al. (2007a)

entire NPP of human-dominated land areas and all "land-use-induced productivity changes" (Haberl et al. 2007a:12945) caused by human existence. It is also shown that estimates on ΔNPP_{LC} range from 7.4 TW (Haberl et al. 2007a) to 9.7 TW (Vitousek et al. 1986).

A systematic overview of the results by absolute numbers is provided in Table 15.1.

2.2.2 The Earth's Supply of NPP

So far, we have disclosed estimates on human demand for terrestrial biomass. What is the earth's supply of terrestrial NPP? This information is necessary to establish approximations on human draw on biological resources, which can be used as additional assessments to the Ecological Footprint considerations.

Haberl et al. (2007a:12942) distinguish between NPP_{act} (i.e. the NPP that currently prevails in terrestrial ecosystems) and NPP_0 (i.e. the terrestrial NPP that would prevail in absence of human civilization).

- *NPP_0 of terrestrial ecosystems*: Estimates on NPP_0 are provided by Haberl et al. (2007a:12943) and Wright (1990:189), only. Their corresponding estimates amount to 77 TW and 89 TW, respectively.
- *NPP_{act} of above- and belowground terrestrial ecosystems*: Estimates on NPP_{act} range from a minimum of 63 TW (Whittaker and Likens 1973:358; Smil 1991:52) to a maximum of 77 TW (Vitousek et al. 1986:369), with numerous scientists assuming a NPP of 70 TW (Rojstaczer et al. 2001:2552; Imhoff et al. 2004:872; Krausmann et al. 2008:481; Haberl et al. 2007a:12943).[5]

These approximations seem to be validated by estimates on gross primary production (GPP) that are believed to amount to an absolute maximum value of 150 TW with regard to terrestrial ecosystems (Dyke et al. 2011:155–156). Following the assumption that actual NPP amounts to ~50% of GPP (Kleidon 2012:1030), terrestrial ecosystems produce a maximum NPP of 75 TW.

2.2.3 The Appropriation Percentage of NPP

Again, disregarding the estimates on NPP appropriation through direct consumption, a juxtaposition of the estimates on terrestrial NPP appropriation with the corresponding estimates on terrestrial NPP supply reveals that humankind appropriates a minimum of 13.7% (NPP_h by Haberl et al. 2007a) and a maximum of 44.3% (the "high estimate" given by Vitousek et al. 1986) – depending on the definition. However, it might be more plausible to assume a range of 20–35% due to the following reasons. First, Haberl et al. (2007a) regard NPP_h only as one component of HANPP that must be completed with ΔNPP_{LC}. When the appropriated amount of 18.3 TW is juxtaposed with NPP_{act}, humankind appropriates 26.1% of the NPP produced by earth's terrestrial ecosystems. When the absolute appropriation is juxtaposed with NPP_0, the percentage declines to 23.8%. Wright (1990) has similar results, with an appropriation of 27.4% of NPP_{act} and 23.4% of NPP_0. Second, the estimate on appropriated NPP in human-dominated lands + ΔNPP_{LC}, i.e. Vitousek et al.'s (1986) "high estimate" might be too elevated because the production capacity lost (ΔNPP_{LC}) is not juxtaposed with a corresponding estimate on potential NPP production (NPP_0; due to a lack of data provision by Vitousek et al. (1986)). Also, there is no distinction between the NPP actually harvested (NPP_h) and the NPP actually remaining in the ecosystems (NPP_t). This latter argumentation is in fact also valid for the estimates on appropriated NPP in human-dominated lands, all showing an appropriation percentage of up to 35%. These appropriation estimates are higher than HANPP, suggesting that NPP_t must actually account for a quite substantial

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[5] NPP_{act} of the entire ecosystem (terrestrial and aquatic) is quantified at a minimum of 94 TW (Whittaker and Likens 1973:358) to a maximum of 130 TW (Vitousek et al. 1986:369).

quantity. If these are neglected and solely the estimates on HANPP are regarded, humankind's draw on the terrestrial ecosystem's NPP amounts to 20–30%. Table 15.1 summarises the diverse definitions classified, the corresponding absolute appropriation estimates, approximations on terrestrial NPP and the appropriation percentage yielded.

2.3 The Energetic Metabolism Accounting Concept

The examination of the EF, HANPP and of the alternative definitions of NPP appropriation has provided a snapshot of current demand for and supply of the earth's biological resources. We have therewith completed the first purpose of our paper, namely the assessment of global draw on the earth's NPP. In order to assess the actual energy supply to humankind, we now turn to the second purpose of our paper, namely the complementation of conventional energy statistics with values on biomass. We thus need estimates on the amount of biomass that has throughout the time been directly and indirectly consumed by humans; the estimates on NPP_h as provided by HANPP deliver a global approximation for today, only. In order to acquire estimates for years in the past, we proceed with the examination of the energetic metabolism accounting concept, which allows for the tracing of the (per capita) energy flows of different societies.

The accounting concept allowing for the tracing of energy flows through a societal compartment (energy flow accounting) was developed by Haberl following the presently applied methods of material flow accounting (Krausmann and Haberl 2002:179). Being based on the same system boundaries and concepts, a methodologically stringent quantification of a society's energetic metabolism is ensured. Thereby, all energy-rich material that enters the socioeconomic unit under consideration is accounted for. In contrast to conventional energy statistics, this includes nutritional energy for humans and domesticated animals and all other biomass inputs regardless of their purpose. The term input, as used in energy flow accounting methodology, can be compared with the term supply: It is the energy supplied to a defined system. The prerequisites of energy flow accounting are summarised in Fig. 15.2 and read as follows.

Total primary energy input refers to the total amount of energy that is mobilised by a societal compartment. Total primary energy input includes hidden flows: Energy flows that are mobilised for the procurement of the direct energy input but not crossing the boundary between society and environment. Hidden flows can thus be compared with the losses occurring during biomass harvest; total primary energy input thus with NPP_h (ΔNPP_{LC} is neglected in the energetic metabolism accounting concept). The direct energy input is the amount of energy actually entering into the societal compartment under consideration. When exports are subtracted from the direct energy input, domestic energy consumption is calculable.

After several conversion processes, primary energy becomes final energy, which includes power and fuels but also human food and the draught animals' nutrition.

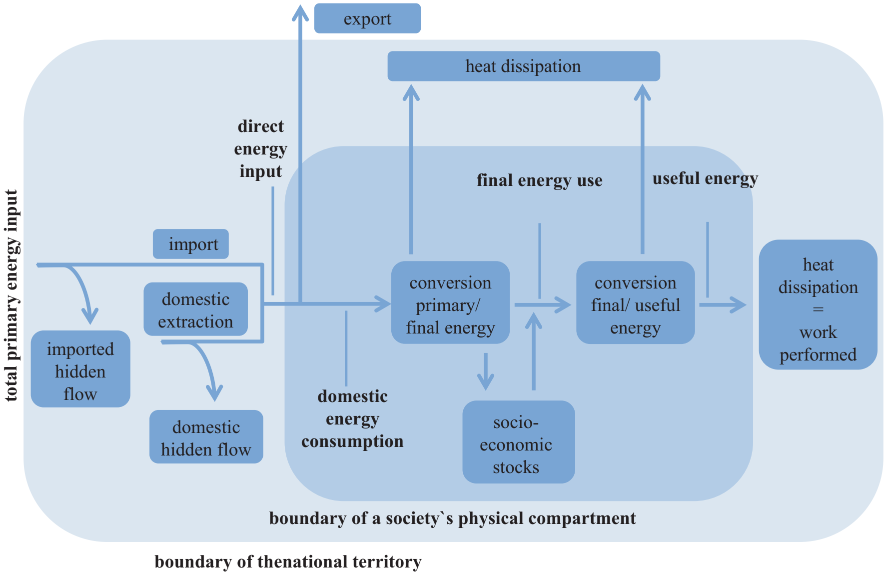

Fig. 15.2 The energetic metabolism accounting concept for a defined societal compartment
Source: Haberl (2002:73), Krausmann and Haberl (2002:180)

Haberl (2001:26) regards these components as final energy because he explicitly accounts for the conversion process from plant biomass (constituting the primary energy) to human food and fodder. In another conversion process also taking place within the societal compartment under consideration, useful energy is generated in the form of animate drive power. Useful energy, i.e. the energy that actually performs useful work eventually delivers energy services. The amount and quality of the energy services derived from energy inputs is often the decisive factor for the utility experienced by the society under consideration. The part of energy that is not immediately used for any energy provisions is often stored and maintained in the form of artefacts and thus contributes to a society's socioeconomic stocks. During every conversion process, energy gets lost in the form of heat, in accordance with the second law of thermodynamics (Haberl 2001:27–28).

2.3.1 Per Capita Estimates Given by Haberl (2002) and his Summation to Global Biomass Supply

On the basis of the energetic metabolism accounting concept, Haberl (2002) determines the average per capita quantity of biomass that is supplied to three archetypical societies. Thereby, losses occurring during harvest, logging or processing are also included, i.e. total primary biomass input per capita is regarded. All societies are characterised by a distinctive mode of subsistence:

- Hunter-gatherer societies: Haberl (2002:73–74) suggests that the primary energy supply to a typical hunter-gatherer society amounts to 10 GJ/cap/yr. Thereof, 3.5 GJ/cap/yr. are allocated to food supply. This corresponds to ~10 MJ/cap/day or 116 W/cap. Boyden (1992: 80) calls this amount of somatic energy, i.e. the energy flowing through the human body, the "human energy equivalent". Another ~10 MJ/cap/day are added by Haberl (2002) in order to account for the losses occurring during food collection and preparation. Further on, he estimates the extrasomatic energy, i.e. the "energy from sources other than human muscles" (Common 1995:68) consumed in form of firewood to be roughly equal to the energy consumed in form of nutritional energy (although the individual fire usage naturally depends upon environmental conditions and the tribes' behaviour). Nevertheless, this arguing lifts the total primary energy supply to hunter-gatherers to ~30 MJ/cap/day, or – as Haberl (2002) puts it – to 10 GJ/cap/yr. This corresponds to 317 W; the energy carrier being solely biomass.
- Agricultural societies: For an estimate on agricultural societies' energy usage, Haberl (2002) refers to a field study carried out by Grünbühel et al. (1999) in the north-eastern Thai village Sang Saeng in 1998. As in any ideal-typical agricultural society, the village's domestic energy extraction is exclusively biomass, which also constitutes the dominating primary energy input into the village. It is used as burning material (charcoal), nutritional energy for humans and domesticated animals and it is stored as energy-rich material in the form of artefacts. Haberl (2002:75) indicates a total biomass supply of 70 GJ/cap/yr. (2220 W/cap).

This estimate is validated by two alternative approximations yielded: On the basis of a case study carried out for year 1875 (Netting 1981), Fischer-Kowalski and Haberl (1997:69–70) estimate the biomass supply to the Swiss alpine village of Törbel to amount to 65 GJ/cap/yr (2061 W/cap). A calculation made for the energetic metabolism of Austria during the nineteenth century suggests an energy supply (being characterised to more than 99% by biomass and to less than 1% by coal) of 72 GJ/cap/yr. (2283 W/cap) (Krausmann and Haberl 2000). As "all these examples refer to societies at an early state of transition from agricultural to industrial society" (Haberl 2002:76), the author suggests believing in a range of biomass supply amounting to 40–70 GJ/cap/yr. (1268–2220 W/cap).

- Industrial societies: For an estimate on industrial societies' energy usage, Haberl (2002:76–78) presents a calculation for Austria in 1995. Austria's domestic biomass extraction with an amount of 59 GJ/cap/yr. is somewhat higher than that of the Thai agricultural village Sang Saeng (48 GJ/cap/yr.). Including domestic hidden flows, imported biomass and imported hidden flows, the total biomass supply rises to 84 GJ/cap/yr. (2664 W/cap). Whereas agricultural societies need a large portion of their biomass supply for fire pits and the nutrition of domesticated animals, industrial societies also consume much biomass in form of meat, for "non-energetic" purposes like the provision of furniture, pulp and paper as well as the realisation of construction work.

Haberl approximates graphically global biomass supply from 1800–2000 in several of his publications (compare Haberl 2000:39–41; Haberl 2006:93) by rather arbitrarily allocating a constant biomass supply of 70 GJ/yr. to each individual and multiplying this estimate by world population. When we numerally calculate global biomass supply according to this methodology and by taking reference to world population estimates given by McEvedy and Jones (1978), Maddison (2010) and the USBC (2011), global biomass supply amounted to 2 TW in 1800, to 3.5 TW in 1900, to 5.7 TW in 1950, to 13.5 TW in 2000 and to 15.3 TW in 2010.

2.3.2 Global Biomass Supply According to a Societal Composition Approach

The estimates produced by Haberl in the manner described are not only very crude (as admitted by the author (Haberl 2006:92) but neglect the complexity of today's societal composition: The earth accommodates all three typical societies, each disposing of a characteristic quantity of energy. We produce alternative global biomass supply estimates that are generated according to the following considerations (Dyckhoff et al. 2010).

First, we generate ranges of per capita supply in order to avoid spurious accuracy. From the information provided by Haberl (2002), it is assumed that typical hunter-gatherer societies disposed of biomass amounting to 200–400 W/cap.[6] It was mainly supplied in form of somatic energy (food) and extrasomatic energy (mostly firewood but also clothing (furs) and tools (throw sticks)). Agricultural societies learned how to produce biomass, providing nutritional energy for themselves and for their livestock. Also, large amounts of wooden biomass were consumed: Private logging was effected in order to gain new soil that could be used for the growing of crops and much wood was needed for the maintenance of fire for cooking, heating, lighting and as base material for any devices. The per capita biomass supply of agricultural societies thus increased to 1200–2300 W.[7] The biomass supply of industrial societies augmented to 2500–3500 W/cap.[8] This augmentation can be explained by rising demand for a larger variety of food evoked by higher incomes. In this respect, the rising demand for animal products plays a major role. Also, so far increased demand has been met by expanded supply, which was facilitated through the industrialisation of the primary sector in the past decades, enabled by artificial fertilisers, agricultural chemicals (pesticides, herbicides), mechanisation and plantbreeding, which was optimised for energy-intensive agriculture following the 1950s (Beran

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[6] Other estimates on the hunter-gatherer's biomass supply fall into this range and thus seem to validate this spectrum (compare Boyden 1992:80; Malanima 2010:6–7; Cook 1971:136).

[7] Again, other estimates on the agricultural societies' biomass supply seem to validate this range (compare for instance Kumar and Ramakrishnan 1990:331–334).

[8] The higher limit of 3500 W also accounts for the biomass supply to more consumption-oriented societies, like Northern America, having a per capita biomass supply of ca. 3227 W (Krausmann et al. 2008:476–477).

and Dyckhoff 2012). As the range refers to the most advanced societies within each mode of subsistence, i.e. to societies having most sophisticated technologies at hand and thus employing the highest possible amount of primary energy, a 2:1 weighting scheme in favour of the lower value is used to adequately consider those societies that do not (yet) belong to the most advanced ones. Following this method, the per capita mean for hunter-gatherer societies amounts to 267 W, for agricultural societies to 1567 W and for industrial societies to 2833 W.

Second, we assess the share of people that has been living in one of the three modes of subsistence throughout human history. We assume the following process to have taken place:

- For a very long period of time, hunter gatherers were the only society on earth: They dominated earth until 10,000 BC. Braidwood and Reed (1957:23) classify the levels hunter-gatherer societies went through in terms of subsistence patterns as the "food-gathering of full Pleistocene times" and "the more specialised food collecting". Their population increased from 125,000 in 1,000,000 BC to 2 mio in 100,000 BC (Deevey Jr. 1960:196; McEvedy and Jones 1978:14).
- In 10,000 BC, first agricultural societies developed, experiencing with the cultivation of plants and animal husbandry (a level Braidwood and Reed (1957:23) refer to as "incipient agriculture"). We assume that in 10,000 BC, earth was home to 3.8 mio hunter-gatherers and 200,000 agriculturalists; or: 95% of the earth's population were hunter-gatherers and 5% agriculturalist. By 5000 BC, "primary village farming" (Braidwood and Reed 1957:23) communities came into existence, followed by "primary urban" and "various vegecultural-primary village-farming blends" (Braidwood and Reed 1957:23), being an intensification and diversification of the first village farming communities. "Pastoral nomadism" (Braidwood and Reed 1957:23) emerged in arid and semi-arid regions.
- By the Nativity in year zero, the earth was home to 170 mio people (McEvedy and Jones 1978:345) and we presume that the hunter-gatherers' share had meanwhile declined to roughly 0.3%; agricultural societies dominated the earth with a share of 99.7%. In this sense, 500,000 hunter-gatherers remained. However, they did not vanish from our planet but maintained their population size until today. The figure is a rough estimate, deriving from the assumption that there are about 400,000 Pygmies (Vidal 2007), the hunter-gatherers living in Central Africa and Southeast Asia as well as about 100,000 San (Wikipedia 2010), the Bushmen living in Southern Africa on earth nowadays. Pygmies and San represent the two classic hunter-gatherer groups these days (Lee and Hitchcock 2001:257). Although they are still nomadic, living more or less on the products of their environment, their living conditions have changed insofar that the art of trading to acquire different food or material items is probably well-known to them (Murdock 1975:13). Also, there are further groups like the Yanomanis and some native inhabitants, whose food income is, however, majorly secured through the cultivation of crops (Survival International 2011).

- By 1800, agricultural societies have grown to a population of 900 mio (McEvedy and Jones 1978:349). With the process of industrialisation, more and more countries changed from being characterised by agriculture to being characterised by industry and the share of industrial societies consequently increased – first in Europe and then in other regions of the world. Earth was no longer home to two societies but to three: To hunter-gatherers, to agricultural societies and to industrial societies.
- Following 1950, a time when world population amounted to 2.5 bn people (USBC 2011), industrialisation reached many developing countries, especially in Latin America and in Asia. Many agriculturalists migrated to the cities in order to find better living conditions. With this gigantic urbanisation, a new type of hunter-gatherers evolved: The slum hunter-gatherers, subsisting more or less on the spontaneous gathering of energy-rich material in the form of food and artefacts, findable on streets and sites for waste disposal. They majorly settled in large cities in regions such as South-central Asia, Eastern Asia, Sub-Sahara Africa, Latin America and the Caribbean. The slum hunter-gatherers' population increased in the second half of the twentieth century from virtually zero before industrialisation to more than a bn today (UN-HABITAT 2010). Thus, in addition to agricultural and industrial societies, the earth is home to two types of hunter-gatherers, the traditional and the slum hunter-gatherers.
- Today, about 7 bn people reside on earth. About 4 bn of them live in developing countries in agricultural societies. Their population increase is significant, as they have not concluded their demographic transition yet. More than 1.5 bn people live in developed countries in industrial societies (Kapitza 2006:149). Also, more than 1 bn people are of hunter-gatherer type, both traditional (like the Pygmies, San, Bushmen) and slum hunter-gatherers.

Third, estimates on global biomass supply are generated through the multiplication of the quantity of all humans living in one of the defined societies by the appropriate weighted biomass value used by each society under consideration. In contrast to Haberl's (2000:39–41; 2006:93) approach, this method explicitly considers the share of people having lived in each mode of subsistence in the course of time (Dyckhoff et al. 2010:277–278). Following this calculation approach, global biomass supply augmented from ~33 MW in 1,000,000 BC to ~1 GW in 10,000 BC. By the Nativity, it had reached the amount equalling ~270 GW and in year 1500 it accounted for ~670 GW. In 1800, global biomass supply reached 1.4 TW and increased to 2.8 TW in 1900, to 4.5 TW in 1950, to 10.1 TW in 2000 and by year 2010, the quantity had augmented to 11.5 TW. In comparison to the results yielded by Haberl's (2000:39–41; 2006:93) lump-sum calculation of global biomass supply, our values are lower as they take into account the share of people living in non-industrial standards that have less energy at their disposal.

The results for the past decade yielded by our societal composition approach are very similar to the result of a study on global terrestrial biomass harvest carried out by Krausmann et al. (2008:471). Examining socioeconomic biomass flows and thereby focusing – among other issues – on $\mathrm{NPP_h}$, their study suggests a global

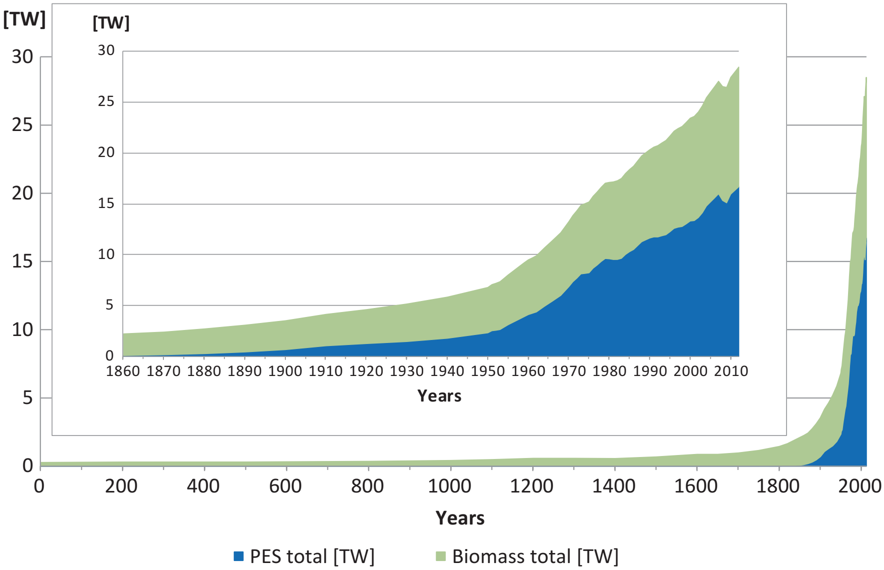

Fig. 15.3 Global primary energy supply
Source: Adapted from Dyckhoff et al. (2010:280)

NPP appropriation of 10.9 TW in above- and belowground terrestrial ecosystems in year 2000. Furthermore, our result of 10.1 TW in year 2000 compares to the approximations on NPP_h generated by HANPP, which amount to 9.6 TW (Haberl et al. 2007a) and 13.5 TW (Imhoff et al. 2004). In comparison to the absolute values on NPP appropriation generated by HANPP and other NPP appropriation definitions, the estimates produced on the basis of the energetic metabolism accounting concept are lower as they solely account for biomass that is embraced by the NPP_h component; they do neither include productivity changes compared to potential NPP (ΔNPP_{LC}) nor the NPP of human-dominated lands that actually remains in the ecosystem (NPP_t).

2.3.3 Completing Conventional Energy Statistics with Biomass Supply

The estimates on global biomass supply generated by the approach taking explicit account of societal composition are used to complement data on primary energy supply (PES) as stipulated by conventional energy statistics and balances. Figure 15.3 illustrates and clarifies humankind's actual energy supply from the Nativity until today, distinguishing between PES and biomass.

In correspondence with Fig. 15.1, conventional PES is reproduced below the supply of biomass to highlight the somehow absurd deduction that becomes established when the data from conventional energy statistics is extrapolated into the past: it seems as if people living before 1860 hardly had any noticeable energy at their disposal. In contrast, Fig. 15.3 demonstrates the long-lasting exclusivity of biomass as energy carrier as well as its importance and magnitude: Humankind's real energy supply is almost twice as high as estimates on conventional PES suggest.

While biomass increased due to changes in societies' subsistence patterns (compare Sects. 2.3.1 and 2.3.2), conventional PES increased due to a shift from the traditional solar energy system to a fossil energy system. After coal constituted the first energy carrier to provide a relative energy surplus and to eliminate the centuries-long shortages of energy (Sieferle 1997:140), oil and gas supplemented the energy mix substantially in the course of the twentieth century. While supply enlarged through progress in the discovery and extraction of resources as well as accessible prices, it was also strongly influenced by growing demand incited by economic activities in the transportation, industrial and commercial sectors. Thereby, oil has played an important role as it provided the basis for favorable transport, which accelerated the international division of labor and economic globalization in the late twentieth century, again leading to further transport processes and ultimately oil consumption.

2.4 Juxtaposition of Results

Both the EF and HANPP aim at the quantification of humankind's draw on the earth's natural resources by taking a macro perspective approach. We conclude that when the carbon footprint is subtracted from the global EF and when this resulting EF is juxtaposed with the actual NPP of the ecosystem, humankind's draw on the ecosystem's biological material amounts to a minimum of 20%. According to HANPP, humankind appropriates 20–30% of the earth's actual or potential NPP. Taking account of further studies that quantify appropriated NPP of human-dominated lands (thus including NPP_h and NPP_t), the percentage range can be widened to the interval [20; 35]. Further approaches to estimate generation are either very narrowly conceived (yielding an appropriation of 3–4% when solely direct biomass consumption is considered) or very comprehensively defined (yielding an appropriation of 44% when all the NPP of human-dominated lands + ΔNPP_{LC} is regarded).

With the energetic metabolism accounting concept, a micro-perspective approach is taken. Haberl (2000) acquires data on the per capita biomass supply to members of each archetypical society that accounts for the amount directly consumed and for all losses occurred during energy procurement. He establishes global totals by arbitrarily allocating a constant biomass value of 70 GJ/yr. to each individual and multiplying this per capita supply by world population. His method yields an estimate on global biomass supply amounting to 14–15 TW in the past decade. Our approach (Dyckhoff et al. 2010), explicitly considering the share of people that live in non-industrial standards either in agricultural or in hunter-gatherer (both traditional and slum) societies and multiplying the amount of people of each society by the corresponding weighted per capita biomass estimate, yields a result for the past decade of 10–12 TW. These global totals established on the basis of the energetic metabolism accounting concept are from a content point of view comparable to the HANPP component NPP_h. Thereby, it is particularly our approach that yields an estimate that is close to the NPP_h approximations of 9.6 TW and 13.5 TW.

3 Conclusions

The first purpose of our work was the examination of two different approaches that quantify humankind's biomass demand and the earth's biomass supply. We analyzed the macro-perspective approaches EF and HANPP, and conclude that the two indicators provide valuable information for the quantitative ascertainment of global draw on the earth's biological material. After some adjustments undertaken on our part, the EF suggests that a minimum of 20% of the earth's NPP are appropriated by humankind. Considering the information provided by HANPP, humankind appropriates 20–30%. Alternative definitions of NPP appropriation suggest assuming a range of 20–35% or even of 3–44%. The latter range, however, is based on a very narrowly conceived and a very comprehensively regarded NPP appropriation definition.

The second purpose of our work was the complementation of conventional energy statistics with values on biomass so that the actual energy supply to humankind could be assessed. We examined the micro-perspective concept of energetic metabolism accounting and conclude that its conceptual framework is conducive to the approximation of biomass supply to individuals living in one of the archetypical societies. Using these per capita estimates and multiplying them either generally by world population as done by Haberl (2000, 2006) or generating weighted per capita biomass values and multiplying those by the population living in each defined society as proposed by Dyckhoff et al. (2010), annual approximations of global biomass supply can be yielded over long periods of time. Conventional energy statistics can thus be complemented with humankind's most vital energy carrier in order to provide a more comprehensive picture of actual energy supplied by natural resources to the global economic system. It is revealed that humankind's actual energy supply is about twice as high as conventional energy statistics essentially suggest, with biomass supply in the past decade amounting to either 14–15 TW – following Haberl's (2000, 2006) approach – or to 10–12 TW – following the approach conceived by Dyckhoff et al. (2010).

It becomes evident that global draw on the earth's NPP is considerable and both direct and indirect effects thereof are well-known: land transformation; alterations of biogeochemical cycles; enhanced greenhouse gas emissions in the atmosphere; loss of biological diversity; species extinction; and even loss of entire ecosystems, etc. (Vitousek et al. 1997:494–498). Given the increasing population size and (aspired) growing standards of living, biomass extraction will increase. If biomass is to substitute (partly) the supply of fossil energy carriers in the future, its removal from the earth's ecosystems will be even more reinforced. Most likely, the increased demand evoked by humankind's growing activities in sectors like agriculture, international commerce, transportation, and industrial production will not be met without substantial ecological detriments, which might eventually turn into political conflicts on a national and international level. Humankind will impinge on the ecosystem's natural limits and conflict interface is existent.

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