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ORIGINAL PAPER

Refining the ecological footprint

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Abstract Ecological footprint measures how much of the biosphere's annual regenerative capacity is required to renew the natural resources used by a defined population in a given year. Ecological footprint analysis (EFA) compares the footprint with biocapacity. When a population's footprint is greater than biocapacity it is reported to be engaging in ecological overshoot. Recent estimates show that humanity's footprint exceeds Earth's biocapacity by 23%. Despite increasing popularity of EFA, definitional, theoretical, and methodological issues hinder more widespread scientific acceptance and use in policy settings. Of particular concern is how EFA is defined and what it actually measures, exclusion of open oceans and less productive lands from biocapacity accounts, failure to allocate space for other species, use of agricultural productivity potential as the basis for equivalence factors (EQF), how the global carbon budget is allocated, and failure to capture unsustainable use of aquatic or terrestrial ecosystems. This article clarifies the definition of EFA and proposes several methodological and theoretical refinements. Our new approach includes the entire surface of the Earth in biocapacity, allocates space for other species, changes the basis of EQF to net primary productivity (NPP), reallocates the carbon budget, and reports carbon sequestration biocapacity. We apply the new approach to footprint accounts for 138 countries and compare our results with output from the standard model. We find humanity's global footprint and ecological overshoot to be substantially greater, and suggest the new approach is an important step toward making EFA a more accurate and meaningful sustainability assessment tool.

Keywords Ecological footprint · Sustainability · Net primary productivity · Natural capital

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Abbreviations

EF	Ecological footprint
EFA	Ecological footprint analysis
EF-GAEZ	Ecological footprint based on GAEZ suitability indices
EF-NPP	Ecological footprint approach that employs net primary productivity
EQF	Equivalence factor
FAO	United Nations Food and Agricultural Organization
GAEZ	Global agricultural ecological zone
GDP	Gross domestic product
GFN	Global Footprint Network
GHA	Global hectare
Gt C	Gigatons of carbon
HA	Hectare
IPCC	Intergovernmental Panel on Climate Change
NPP	Net primary productivity
RP	Redefining Progress

1 Definitions and background

The ecological footprint is a largely heuristic tool that has been widely used in sustainability analyses for over a decade. In addition to its heuristic value, the power of the ecological footprint is thought to lie not only in the absolute numbers it yields, but in its ability to compare resource demands of different populations in a common currency of global productivity (Ferguson, 1999). According to Wackernagel and Loh (2002) the ecological footprint is ‘‘[a] measure of how much productive land and water an individual, a city, a country, or humanity requires to produce the resources it consumes and to absorb the waste it generates, using prevailing technology’’. According to Wackernagel et al. (2005, p. 5) ecological footprint accounts document how much of the annual regenerative capacity of the biosphere is required to renew the resource input of a defined population in a given year. We draw from these definitions. As referenced in this paper, the ecological footprint is a standardized estimate of the Earth’s biological carrying capacity required to support humanity’s resource use and waste production.[1]

Ecological footprint analysis (EFA) compares the ecological footprint with available biocapacity. It compares biological capacity used against what is available on a renewable basis. Distinguishing between EFA and the footprint is important. By itself, the footprint tells us little about sustainable resource use, it is simply a

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[1] Two clarifications are in order. First, the footprint does not provide a way to measure the environmental area impacted from pollution directly, so these should not be inferred from our definition. Secondly, the freshwater footprint does not account for human water consumption, it only accounts for our use of inland fisheries. The first version of footprint ever circulated in academic circles by Dr William Rees and Mathis Wackernagel at the University of British Columbia in the 1990s did attempt to account for fresh water appropriation, but the approach was deemed inadequate and abandoned.

measure that increases or decreases as our demands on the environment increase or decrease without telling us whether or not those demands are sustainable. EFA, on the other hand, is purported to measure sustainability. As noted by Wackernagel et al. (2002) EFA provides a way to "compare renewable natural resource consumption with nature's biologically productive capacity".

When humanity's footprint is smaller than global biocapacity it is considered sustainable. When it is larger, it is reported to be engaging ecological overshoot or running a negative ecological balance. Currently, leading global footprint practitioners estimate the amount of ecological overshoot to be roughly 23% (Loh & Wackernagel, 2004). Hence, "[w]hen we compare the current Ecological Footprint with the capacity of the Earth's life supporting ecosystems, we must conclude that we no longer live within the sustainable limits of the planet" (Loh & Wackernagel, 2004).

In part, because the footprint embodies a vast amount of information in a single quantitative measure and attempts to operationalize well-known concepts of carrying capacity and sustainability its popularity is burgeoning amongst sustainability analysts and practitioners in academic, government, non-profit, education, and business circles. Nonetheless, EFA faces a number of conceptual and practical challenges that may ultimately hinder its broader acceptance and utility as a sustainability assessment tool if it is given serious scrutiny in a policy-making setting, for example. On a conceptual level, Lélé and Norgaard (2005) note that the footprint is "relevant only with respect to a particular choice of ultimate values or variables of interest, or to particular notions of how disparate values should be aggregated". For example, EFA is thought to reflect an implicit optimism in technology to replace lost biocapacity by boosting forest, crop, and fish yields without incurring any long-term ecological costs (van den Bergh & Verbruggen, 1999). Perhaps, but the larger problem we identify is that despite its evolution within an objective scientific framework, EFA reflects an anthropocentric orientation that excludes significant aspects of sustainability that might be given due from a different theoretical approach. To be sure, leading practitioners in the field have promoted the anthropocentric theory of footprint (Wackernagel et al., 2005). EFA, however, need not be so.

Given that EFA purports to measure consumption of resources within the context of sustainability, it seems appropriate to expand the theoretical basis of EFA from people to the rest of nature by refining EFA to signal when our consumption is jeopardizing the long-term viability of non-human life—thank you very much Aldo Leopold. Thus, it is our contention that a study of the human footprint on the environment *should* begin from an ecologically based theoretical perspective. From this perspective, EFA provides framework for estimating the Earth's biological carrying capacity that is required to support humanity's resource use and waste production, and maintain a healthy ecological support systems for all life. Of course, this approach also comes with value laden baggage, for which we the authors are willing to suffer the slings and arrows that may come against our contention that a study of the human footprint on the environment *should* begin from an ecologically based theoretical perspective.

On a practical level, there has been ample criticism of EFA's assumptions, methods, and data. Among our chief concerns include the exclusion of large areas of the Earth from biocapacity, failure to allocate space for the needs of non-human species, use of agricultural productivity potential as the basis for equivalence factors (EQF) used to normalize disparate land types, allocation of the carbon budget, and failure to capture unsustainable use of forests, fisheries, crop land, pasture land, toxins, and fresh water.

At a time when the need and demand for sustainability analysis tools appears to be rapidly escalating, it is critical to address these concerns in a rigorous and systematic manner.

In this paper, we propose refinements to EFA that begin to address these shortcomings and offer a research agenda for further advancements. Our new approach (EF-NPP) includes the entire surface of the Earth in biocapacity, allocates space for other species, changes the basis of EQF to net primary productivity (NPP), reallocates the carbon budget, and reports carbon sequestration biocapacity. The footprint provides an excellent framework for measuring the extent (area) of humanity's ecological influence within the context of sustainability. The originators, and our colleagues as global leaders in the field, have done much in the way of making continuous valuable advances to EFA (Wackernagel et al., 2005). Our hope is that the new approach (EF-NPP) discussed in this paper contributes to this process by adding to the breadth of the concept and subtleties of the methodology. We suggest that an NPP-based approach may be useful in addressing some of the problems with standard EFA that may thwart broader and deeper acceptance and use of EFA as an objective and meaningful sustainability analysis framework. The remainder of our paper is organized as follows.

In Sect. 2, we underscore the need for changes to EFA in the face of new demands for its use in research and as a tool for evaluating the sustainability of public policies, business practices, and personal lifestyles. In Sect. 3, we review pertinent aspects of the standard ecological footprint methodology and discuss critiques. In Sect. 4 we introduce the new methodology. In Sect. 5, we apply the approach, calculate the footprints of 138 countries and explain differences between our approach and the standard approach using cross sectional multivariate regression analysis. In Sect. 6, we offer concluding thoughts and discuss future refinements to EFA.

2 The need for change to ecological footprint analysis

While major critiques of EFA have been in existence since the late 1990s, there are three major trends that underscore the need to make significant changes to EFA at this time: (a) greater demands for EFA in academic research and as a tool for evaluating the sustainability of public policies, business practices, and personal lifestyles; (b) growing abundance of modified footprint methods that cloud the distinction between EFA and other kinds of sustainability analyses, and (c) concerted attempts to set international standards for EFA based on an approach that has not substantively addressed major criticisms in the literature.

There are many recent applications of EFA in both natural and social sciences that illustrate the degree to which it has permeated sustainability analyses across disciplines and in an ever-growing variety of research settings. For example, Rosa, York, and Dietz (2004) explored the effects of two anthropogenic drivers—population and affluence—on a wide variety of global environmental impacts, including greenhouse gas emissions, emissions of ozone depleting substances, and the ecological footprint. Dias de oliveira, Vaughan, and Rykiel (2005) compared the benefits and environmental impacts of ethanol fuel in Brazil and in the United States using the ecological footprint tool. Warren-Rhodes, Sadovy, and Cesar (2003) used EFA to evaluate live reef fish food product consumption in major Asian economies.

EFA has also been applied to social science research. In a cross national study, Jorgenson and Andrew (2003) developed a recursive indirect effects model to estimate the direct, indirect, and total effects of world-system position, domestic inequality, urbanization, and literacy rates on the size of average ecological footprints. York, Rosa, and Dietz (2003) tested theoretical propositions derived from human ecology, modernization, and political economy using stochastic formulation to assess what factors were driving the ecological footprint. Hubacek and Jiljum (2003) used EFA to calculate direct and indirect land requirements for the production of exports from 15 European Union countries to the rest of the world.

Interest in international, national, and local policy applications of EFA are growing, as well. Torras (2003) applied EFA to the problem of debt relief, exploring the possibility of compensatory policy that makes pecuniary transfers from rich to poor countries based on ecological footprints and balances. Barrett (2001) demonstrated the value of EFA as a regional planning tool. According to Barrett, Cherret, and Birch (2004), ‘‘there are a growing number of local authorities that have conducted an ecological footprint for their local authority area and are applying the results’’. For example, the City of Santa Monica used EFA to gauge the effects of past policies on the footprint (Venetoulis, 2004). In policy settings, the ecological footprint is increasingly relied upon to model land use scenarios and to guide sustainable development.

Corporate leaders are increasingly concerned about ecological footprints and this concern has led to a profusion of studies exploring ways to reduce the footprint of companies and entire sectors. For example, several studies have addressed ways that the ecological footprint of tourism can be reduced (Cole & Sinclair, 2002; Goessling, Hansson, Hoerstmeier, & Saggel, 2002). Using EFA Holden and Høyer (2005) demonstrate that ‘‘the environmentally friendly car truly exists’’. The ecological footprint of aquaculture is the subject of intensive ongoing research (Kautsky, Berg, Folke, Larsson, & Troell, 1997; Wolowicz, 2005). Recent announcements of footprint reduction programs by Wal-Mart and British Petroleum are clear indications that EFA may play an increasingly important role in corporate sustainability analyses.

Finally, at the personal level, there is rapidly growing interest in personal lifestyle choices that minimize an individual's ecological footprint. According to Seyfang (2003) the ecological footprint is a ‘‘touchstone for understanding the obligations of ecological citizens as a justice based account of how we should live’’. Millions of visitors each year take the popular ‘‘footprint quiz’’ to understand how their consumption choices can be made more sustainable.[2]

With increasing interest and use of EFA have come demands for revised methodologies to guarantee EFA's ongoing usefulness. For example, Aall and Norland (2005) argue for adjustments in the footprint methodology when shifting from a national to a local policy context to ensure the indicator‘s applicability in local politics and administration. Bastianoni, Pulselli, and Tiezzi (2004) used the ecological footprint methodology as a basis for developing a ‘‘consumer responsibility approach’’ to assigning responsibility for greenhouse gas emissions. Sonak (2004) has developed a tool called the Ecological Footprint of Tourism to gauge the sustainability of development activities. A diversity of approaches is warranted, given that some applications are sensitive to local context. However, there are studies carried out and reported under the banner of EFA that are something else entirely.[3]

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[2] See www.myfootprint.org.

[3] For example Staples, an office supply company in North America, recently released its corporate sustainability assessment report, with an emphasis in the text on the ‘‘environmental’’ footprint. However, the report presented raw descriptive data and no footprint calculations were performed.

In response to the proliferation of EFA adaptations, one of the major organizations conducting ecological footprint research is circulating a draft set of international standards with ratification expected in 2006. According to the Global Footprint Network (GFN), "[t]he value of the Footprint as a trusted sustainability metric depends not only on the scientific integrity of the methodology but on consistent application of the methodology across analyses".[4] While we may agree that standards can be a useful way to preserve the integrity of a metric in the face of multiple approaches and misuse, it may be imprudent to set such standards without addressing problems with the most widely used (and for all practical purposes, the informal standard) approach noted in the literature.

3 The standard approach and core critiques

The most up to date and detailed treatment of the theory, assumptions, and methodology of standard EFA is found in Wackernagel et al. (2005). Other helpful expositions include Ferguson (1999) and Loh and Wackernagel (2004).

3.1 Salient aspects of the standard approach

As discussed below, the standard EFA methodology is based largely on Food and Agriculture Organization (FAO) global agricultural ecological zone (GAEZ) suitability indices. For simplicity we hereafter refer to the standard approach as "EF-GAEZ". Aspects of EF-GAEZ most pertinent here involve: (a) the choice of land areas included in biocapacity; (b) EQF used to compare and aggregate disparate land types in a common metric, and (c) assumptions about carbon sequestration rates.

EF-GAEZ is acknowledged by Wackernagel and Silverstein (2000)—one of the co-originators and leaders of EFA worldwide—to be derived from a mechanistic worldview that draws heavily from utility theory and an anthropocentric version of environmentalism. EF-GAEZ is "utilitarian resource accounting...within a positivist's (if not mechanistic) framework" (Wackernagel & Silverstein, 2000). Because of this, EF-GAEZ is exclusively focused on human demands and needs, and thus counts biocapacity only in terms of portions of the Earth which can be of direct use by people. As argued by Monfreda, Wackernagel, and Deumling (2004), "[b]y focusing the measure on biologically productive areas that provide particular functions to people, rather than on the total amount of photosynthesis generated, the measure becomes sensitive to the quality of the biomass generation and its usefulness for the human economy". Excluded from biocapacity calculations in the standard EFA methodology are 36 billion hectares of land considered too unproductive to support agriculture or aquaculture as well as the outer reaches of the oceans. Under EF-GAEZ, it does not matter if such areas—which include mountains, deserts, tundra, ice sheets, and most of the ocean—are degraded or destroyed because such areas are not counted as areas from which humanity derives sustenance.

Another related aspect of the EF-GAEZ approach is the assumption that all biocapacity is available for sustainable human use, and that none of this capacity is needed to sustain other species which may indirectly contribute to the amount and

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[4] See http://www.footprintnetwork.org/gfn_sub.php?content=standards.

quality of renewable resources available to future generations. While other species have been given considerable attention by leaders in the field, formal inclusion in the methodology has been limited to one EFA variant (Chambers, Simmons, & Wackermenagel, 2000). In theory, humanity could appropriate 100% of the Earth's biocapacity counted in EF-GAEZ and still have a sustainable footprint.

A second methodological aspect of interest here involves carbon sequestration rates. EF-GAEZ expresses a population's fossil energy footprint in terms of forest hectares needed to sequester carbon emissions after deducting 35% of those emissions sequestered by oceans. The sequestration rate is based on averages from samples of 26 forests biomes in 1980 and 1990 and is assumed to be 0.95 metric tonnes of carbon (t C) per hectare per year. Thus, for every metric tonne of carbon emitted over and above the amount sequestered by oceans, EF-GAEZ assumes a footprint of 1.05 ha.

A final concern we raise has to do with the EQF, which allow footprint practitioners to compare ecological values of disparate land types with a common metric. EF-GAEZ's EQF are based on agricultural potential using United Nations' FAO data. To compare different types of land, EF-GAEZ first creates broad aggregations of land types or ''biomes'' including crop land, pasture land, forest land, energy land, built space, and marine and inland fisheries and then derives a common denominator from FAO's GAEZ data set. That common denominator is the GAEZ estimate for the potential of different land types to be converted into agriculturally productive land. Such potential is evaluated with respect to soil, temperature, slope, precipitation, and other factors regardless of whether the land in question is currently covered by trees, grass, or water. The result is a suitability index for land areas.

Global agricultural ecological zone suitability indices provided the basis for EQF which, in turn, are used to estimate biocapacity for each biome. The most recent biocapacity estimates of EF-GAEZ are presented in Table 1. In the first column land area reported by FAO is presented on a hectares per capita basis. This area is multiplied by the respective EQF to derive the available biocapacity area, reported in global hectares. Note that no biocapacity is explicitly considered available for the absorption of carbon. One reason for not including carbon sequestration (energy) land explicitly may have to do with one of the core assumptions of EF-GAEZ: that land can only serve one purpose. In other words, if a forest produces wood, the assumption is that it cannot also serve other functions, such as carbon sequestration,

Table 1 EF-GAEZ biomes, equivalence factors (EQF), and biocapacity

Biome	Actual land area (ha per capita)	EQF	Biocapacity (gha per capita)
Crop land	0.25	2.11	0.53
Pasture land	0.58	0.47	0.27
Forest land	0.64	1.35	0.86
Built space	0.05	2.11	0.10
Marine and inland fisheries	0.39	0.35	0.14
Energy land	0.00	1.35	0.00
Average	–	–	–
Total	1.90	–	1.90

Derived from Table 3 in ''The World's Ecological Footprint and Biocapacity 1999'', Redefining Progress, Oakland, California, and Loh and Wackernagel (2002) soil stabilization, or wildlife habitat. Nonetheless, it appears that carbon dioxide absorption factors are internalized in EF-GAEZ calculations, but not made explicit.

3.2 Core critiques

The most comprehensive critiques are summarized by van den Bergh and Verbruggen (1999). It is not our intent to replicate these discussions. Instead, we focus on critiques of greatest relevance to our suggested advances: (a) by excluding significant natural areas from estimates of biocapacity, national footprint accounts fail to recognize the interdependent nature of all ecosystems; (b) EQF, which influence biocapacity estimates, fail to take into account substantive ecological and bioregional disparities; (c) multiuse land is excluded; (d) calculation of the energy footprint is entirely based on forest carbon sequestration rates; and (e) there is no difference drawn between sustainable and unsustainable land use.

A year later, several authors echoed these concerns in an *Ecological Economics* edition devoted entirely to EFA. One commentator went so far as to recommend against the use of EFA as a measuring rod for sustainability and especially its use as a way of gauging the environmental merits or demerits of activities, projects, and policies (Opschoor, 2000). Answering these critiques, an EFA proponent concluded that, "[d]espite its limitations the ecological footprint describes a minimum condition for ecological sustainability: footprints must be smaller than the [total] available ecological capacity" (Wackernagel & Silverstein, 2000). While both points of view have merit, to this date, important theoretical and methodological weaknesses of EF-GAEZ have yet to be dealt with in a productive way. Instead of taking sides by disregarding or wholly embracing the EF-GAEZ, our intent here is to begin the process of making advances to EFA so as to make it more compatible with ecological realties, more scientifically robust, and more useful as a sustainability evaluation tool.

4 An EFA approach based on net primary productivity

In this section, we propose an initial set of changes to the theory and methodology of standard footprinting that respond to some of the basic critiques outlined by van den Bergh and Verburggen (1999). Because NPP is critical to a number of assumptions and calculations inherent to the new approach, hereafter, we refer to it as EF-NPP. According to Running et al. (2004, p. 547) "NPP marks the first visible step of carbon accumulation; it quantifies the conversion of atmospheric CO_2 into plant biomass". Thus, NPP is a rate process that tracks the net flux of carbon from the atmosphere into green plants per day, week, or year. NPP is highly variable year to year and seasonally. For some seasons and biomes NPP may be negative, indicating that plant respiration is greater than the uptake of carbon by plants, as during months when vegetation is stressed by drought conditions or low temperatures. In addition, succession can influence NPP though allocation of fixed carbon to maintenance rather than growth. So even within a single biome type there is a high degree of variability.

Net primary productivity provides the basis for maintenance, growth, and reproduction of all consumers and decomposes. Because of this, NPP is also referred to as a measure of the ‘‘total food resource’’ available on the planet (Vitousek, Ehrlich, Ehrlich, & Matson, 1986). Because human beings appropriate NPP to fuel production and consumption activities and because these activities, in turn, affect NPP availability in the future, NPP is particularly relevant in sustainability analyses and seems useful as the basis for EFA accounts that attempt to put disparate types of land into a common currency. In fact, it has been suggested that human appropriation of NPP is ‘‘a more explicit measure of the intensity of human pressure on ecosystem use than the ecological footprint, which focuses more explicitly on demand’’ (UNEP, 2005). On the other hand, proponents of EFA argue that human appropriation of NPP fails to indicate anything useful about sustainability thresholds and that EQF based on GAEZ agricultural productivity data are more robust than actual NPP (Haberl et al., 2004; Wackernagel et al., 2005).[5] A comparative study of EFA and NPP was conducted by Haberl et al. (2004). They suggest that EFA and NPP serve different functions—EFA measures society’s utilization of biologically productive area while human appropriation of NPP maps the intensity of that use. Rather than extending this debate about the relative merits and drawback of the two approaches, what we offer here is a methodology that combines the two by integrating NPP into the EFA framework.

Net primary productivity can be incorporated into EFA in a number of useful ways. This section suggests four primary changes to EF-GAEZ based on NPP: (a) including the entire surface of the Earth in biocapacity; (b) reserving a fraction of NPP for other species; (c) changing assumptions about carbon sequestration rates; and (d) using NPP as the basis for new EQF.

4.1 Including the entire surface of the Earth in biocapacity

As previously discussed, EF-GAEZ excludes areas where resources do not appear (in the data set) to be directly utilized for the purpose of human consumption and waste assimilation. This exclusion, however, disregards the role these areas provide in generating global biocapacity or supporting critical ecosystem services that sustain both human and non-human life on the planet. To illustrate this point, productive forests at mid-elevations in western North America are ecologically linked to alpine tundra above and deserts below through the hydrological cycle, wildlife migration, and soil movements, yet EF-GAEZ excludes both deserts and tundra from biocapacity because these areas are determined to have no or extremely low potential for agricultural productivity in the FAO’s GAEZ assessments.

From an NPP perspective, however, the entire surface of the Earth is relevant. Because most of the Earth’s surface participates in the carbon cycle, the first change in the methodology is to include all land and water area on the Earth as part of biocapacity. The proposed change adds about 36 billion hectares of biocapacity not counted in EF-GAEZ, and primarily consists of areas with relatively low levels of NPP as compared to tropical forests, pasture lands, or crop land. This change acknowledges the interconnectedness of the biosphere and is offered as a step

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[5] It is also worth noting that the FAO considers GAEZ data to be of uneven quality and reliability and though various modes have been pursued for ground-truthing and verifying GAEZ suitability analyses, there is an acknowledged need for further validation of results and underlying databases (FAO STAT 2005).

toward addressing one of the core critiques of EF-GAEZ (van den Bergh & Verbruggen, 1999).

4.2 Reserving habitat for other species

Our second change is meant to provide a formal accommodation for other species. As noted earlier, EF-GAEZ takes an explicit anthropocentric stance. As a consequence, the portion of the Earth's biocapacity needed to sustain the diversity of non-human life is not removed from the realm of sustainable human appropriation. Nor does EF-GAEZ take other species' needs into account in the context of yield factors used to convert any particular nation's stock of crop land, pasture land, or forest land into global hectares. Because of this, EF-GAEZ has failed to capture the world's biological diversity crisis, indicating that lands we use to meet our demands for food, fiber, timber, and fish are all managed sustainably, while all remaining lands are ignored, suggesting that they have no ecological significance.

According to GFN's 2004 *Living Planet Report* global biocapacity for crop land, forest land, pasture land, and fishing grounds is 1.74 global hectares (gha) per capita while humanity's footprint within these biomes is 0.94, *implying that humanity can nearly double its consumption of food, fiber, timber, and fish without exceeding ecological limits* (Loh & Wackernagel, 2004). This lapse is one of the chief drawbacks of EFA noted by leading ecologists. For example, collapsing cod, salmon, and tuna stocks and numerous scientific assessments cast serious doubt on EF-GAEZ's conclusions that fisheries yields were sustainable from 1960 to 1999 (Jackson et al., 2001; Pauly & Watson, 2001).

While other species are not included in the EF-GAEZ approach to biocapacity estimates, by expanding the (ecological and ethical) boundaries of the biological community as the basis of the EF-NPP approach, an initial step is offered here. Conceptually, since NPP is a food source available to all species it follows that a certain amount must be removed from the realm of human appropriation to meet other species' needs for food and habitat. A recent scientific assessment found that humans presently appropriate approximately 32% of planetary NPP, a ''remarkable level of co-option for a species that represents roughly 0.5% of the total heterotroph biomass on Earth'' (Imhoff et al., 2004; Rojstaczer, Sterling, & Moore, 2001). Considering just those areas accessible to humans, Sunquist (2005) found this figure to range between 89 and 96%. Regardless, evidence strongly suggests that by appropriating the lion's share of NPP on the planet, we have endangered vast numbers of other species and contributed to an extinction rate up to 1,000 times greater than background levels (Levin & Levin, 2002).

Within the EFA framework, addressing other species' needs can be accomplished in several ways. From a NPP standpoint, it would be necessary to convert all spatial measures of footprint and biocapacity into NPP equivalents (i.e., appropriated vs. available NPP) then ''reserve'' some percentage of average annual NPP within each biome for other species by deducting that amount from biocapacity. The amount of reserved NPP would have to be based on biome and sub-biome specific estimates of ecological sustained yield (ESY). It may be possible to make use of well-established relationships between NPP removal and biological diversity losses to develop these ESY benchmarks for crop land, pasture land, marine and inland fisheries, and forests. If the footprint exceeds these ESY thresholds, it would signal that appropriation of NPP had passed a level commensurate with sustainability of ecosystem health. To be most useful, global EFA accounts would have to provide these signals in advance of ecosystem collapse. Daniel Pauly and others at the Sea Around Us project at the University of British Columbia have taken one important step in this direction by converting catch data now reported in tonnes into tonnes of primary productivity required to support that catch. However, there are formidable hurdles to this overall approach.

For example, there are situations where intensive land uses such as monocropping increase NPP but harm plant and animal diversity. In addition, large-scale disturbances such as stand-replacing fires may significantly decrease NPP in the short term, but result in improved productivity and species diversity over longer time scales. This makes absolute NPP figures a difficult basis for estimating ESY thresholds in an EFA framework.

In lieu of an NPP reservation strategy, EF-NPP takes a habitat-based approach and sets aside a portion of biocapacity in each biome for other species based on recent global hot spot and gap assessments. According to the latest global assessment by Mittermeier et al. (2005), 34 areas totaling 2.3% of the world's surface qualify as biodiversity hot spots—severely threatened places with exceptional endemism and in need of immediate conservation attention. These are largely tropical or subtropical forests threatened by human activities. Average NPP within these areas exceeds the global average of 1.77 pedagrams carbon (Pg C) per year by a factor of at least two and up to nine in some areas. By applying EQF discussed below to the actual composition data reported in Mittermeier et al. (2005) we estimate that 15.1% of the Earth's biologically productive space would need to be removed from biocapacity accounts to protect these few hot spot areas. Global gap analysis is another form of global conservation needs assessment. Existing gap studies suggest that if approximately 13.4% of the terrestrial land on Earth were protected, 55% of all species that are significantly threatened with extinction would meet targets for survival (Rodrigues et al., 2003). In regions "with high levels of species richness and endemism...larger percentages of their territory [require protection]" (Rodrigues et al., 2003).

In lieu of more thorough needs assessments based on combinations of NPP density studies, gap, hot spots, and other, more site-specific approaches, we use the conservative gap estimate as a starting point and deduct 13.4% of each biome from biocapacity. We would suggest that this is a conservative estimate of the amount of aquatic and terrestrial space actually needed to ensure the well-being of non-human life. Nonetheless, it is an adjustment that recognizes the critical importance of providing space for other species within the EFA framework to avoid the pitfalls inherent to EF-GAEZ.

4.3 Changing assumptions about carbon sequestration

EF-NPP makes two changes with respect to carbon sequestration: (1) reassigning the carbon budget from forests alone to the entire surface of the Earth, and (2) changing the assumed rate of carbon sequestration. One of the more problematic aspects of EF-GAEZ is its assumption that land only serves one purpose at a time (van den Bergh & Verbruggen, 1999). The most conspicuous manifestation of this problem is in the way EF-GAEZ treats carbon emissions. In particular, EF-GAEZ assigns the biosphere's entire carbon footprint to forests, but reports no corresponding carbon sequestration biocapacity (Table 1). This is because forests are already counted in biocapacity for their role in supplying wood products. EF-NPP resolves this quandary by allowing for multiple land uses. The extent to which multiple land uses are operationalized under EF-NPP is limited to the carbon absorption service—i.e., a hectare of forest can now produce paper *and* absorb carbon. We also recognize the carbon sequestration function provided by all other biomes so we reassign the carbon budget from just forests to include the entire globe and report it as biocapacity in the footprint–biocapacity accounts (Table 3). Of course, this means that EF-NPP biological capacity is nearly twice the area of the planet since every hectare (after deducting 13.4% for other species) is now counted twice—once for its primary function and once for its carbon sequestration function. While this may be difficult to comprehend, we feel that it better reflects the fact that each hectare of land or sea provides multiple ecosystem services.

The second change deals with carbon sequestration rates. For every ton of carbon emitted, EF-GAEZ apportions a 1.05 ha footprint based on the uptake potential of relatively young forests during two points in time (1980 and 1990), and as noted above no land is presented as available biocapacity. In addition, EF-GAEZ does not acknowledge carbon sequestered by 36 billion hectares of land and sea excluded from FAO's GAEZ data. In EF-NPP, we consider the net total potential uptake from the entire surface of the Earth as biocapacity for carbon sequestration, and use recent sequestration rates estimated by the Intergovernmental Panel on Climate Change (IPCC). According to IPCC's models, the total combined carbon sequestration of Earth is estimated to be 3.0 gigatons of carbon (Gt C) annually with oceans sequestering an estimated 2.3 Gt C (IPCC, 2004). Net terrestrial uptake is estimated to be 0.7 Gt C annually. Terrestrial uptake potential is actually higher, but land use changes (e.g., deforestation) have decreased this potential. Of the Earth's 51 billion hectares, oceans cover about 36.7 billion and land covers 14.4. By taking a weighted average of net sequestration potential of the land and sea we arrive at the average carbon absorption rate for EF-NPP: 0.06 tonnes of carbon per hectare per year. This means that for every tonne of carbon emitted EF-NPP assigns a footprint of 16.65 ha, a significant increase over EF-GAEZ. Moreover EF-NPP makes explicit the addition of 8.27 ha of carbon sequestration land per capita to biocapacity.

4.4 Using NPP as the basis for new EQF

The fourth major modification to EF-GAEZ deals with EQF, which are the denominators in biocapacity estimates. Recall that EF-GAEZ EQF were based on potential agricultural yields as determined by GAEZ data. Here, we replace the GAEZ suitability indices with NPP. As shown in Table 2, EQFs for EF-NPP are the ratio of each biome's NPP per unit of area to the global average. NPP figures for each biome are based on Table 2 from Amthor (1998, p. 16) which provides area, annual NPP, plant carbon content, and soil carbon content for 16 distinct biomes. These estimates are based on several decades of research after Ajtay, Ketner, and Duvigneeaud (1979), Post, Emanuel, Zinke, and Stangenberger (1982), Botkin and Simpson (1990), Gorham (1995), and FAO (1997). According to Amthor (1998, p. 16), their NPP figures assumed "[p]otential gains and losses are semiquantitative, based on perceived productivity stimulation due to increasing CO_2 and losses that

Table 2 Equivalence factor (EQF) calculations for EF-NPP

Biome	Area ($\times 10^{12}$ m^2)	Total NPP (Pg/year)	NPP/area	EQF
Crop land	14.80	6.28	0.4243	2.1214
Forest land	36.10	23.76	0.6583	3.2916
Pasture land	29.80	14.41	0.4835	2.4176
Built space	2.00	0.20	0.0997	0.4984
Less productive land	66.10	13.75	0.2080	1.0400
Marine and inland fisheries	21.30	11.38	0.5344	2.6719
Open ocean	343.60	32.95	0.0959	0.4795
Average	–	–	0.20	–
Total	513.70	102.73	–	–

Table 3 World biocapacity estimates for EF-NPP

Biome	Area (ha/cap)	Area adjusted for other species (-13.4%)	Equivalence factor	Biocapacity (gha per capita)
Crop land	0.25	0.22	2.12	0.46
Forest land	0.62	0.54	3.29	1.77
Pasture land	0.57	0.49	2.42	1.20
Built space	0.05	0.04	0.50	0.02
Less productive land	0.87	0.75	1.04	0.78
Marine and inland fisheries	0.38	0.33	2.67	0.87
Open ocean	5.60	4.85	0.48	2.34
Energy land	n/a	n/a	n/a	8.27
Average	–	–	–	–
Total	8.34	7.22	–	15.71

Figures may not add up due to rounding

could occur due to warming stimulated increases in decomposition and reduced productivity due to increasing stress...''

Clearly, the science of NPP mapping is evolving rapidly and is now reaching the point where continuous satellite-derived mapping is possible (Running et al., 2004). As we discuss in Sect. 5, a key future refinement to EFA would be to incorporate this real time information. For now, however, we simply use the Amthor (1998) estimates to demonstrate the technique of using NPP to provide a more accurate measure of relative ecological productivity across biomes that the GAEZ data. To illustrate how EQFs were derived, consider the 2.12 EQF for cropland. Table 2 shows that global NPP for cropland is 6.3 Pg C over an area of 14.8×10^{12} square meters or 0.43 Pg C per square meter. The crop land EQF of 2.12 is simply 0.43 Pg C divided by the global average NPP figure of 0.20 Pg C. Thus, EQFs for EF-NPP represent the ratio of productivity of one land type to the average, where productivity is measured in NPP.

Table 2 also displays EQFs for less productive lands and open oceans—areas excluded by EF-GAEZ. Also note the change in the relative values of each biome. For example, EF-GAEZ had built space as more biologically productive than forest land, pasture land, and marine and inland fisheries. EF-NPP shows the converse. Because of this, we suggest that EF-NPP is more closely aligned with basic scientific understanding of the relative ecological ‘‘value’’ of different land types. As a related point, we suggest that EF-NPP better captures the ecological impacts of built space. Recall from Table 1 that EF-GAEZ assigns identical EQFs to crop land and built space because of the underlying assumption that all built space is displaced cropland (Wackernagel et al., 2005). In contrast, EF-NPP captures variability in the impacts of built space by deducting from future biocapacity global hectares that are more closely aligned with the actual land type being lost, regardless of whether such lands are crop lands, pasture lands, forests, or desert.

All of the changes discussed in this section affect biocapacity, which rises from about 1.9 gha per capita under EF-GAEZ to 15.71 gha under EF-NPP. Table 3 provides a breakdown of EF-NPP's biocapacity estimates for crop land, pasture land, forest land, marine and inland waters, open oceans, less productive land, built space, and energy land. As compared with EF-GAEZ, energy land is the greatest addition (8.27 gha per capita) since EF-GAEZ assigns no biocapacity to this function. EF-NPP also adds 3.11 gha per capita to biocapacity for less productive lands and open oceans where EF-GAEZ assigns none.

4.5 Changes to the EFA template

All of the changes discussed in this section were incorporated into the basic EF-GAEZ excel-based template used to create global footprint accounts. The template finds its origin in Rees and Wackernagel (1994). In subsequent years, the EF-GAEZ template has been refined at two U.S.-based non-governmental organizations—Redefining Progress (RP) and the GFN both in Oakland, California. Both organizations are informal leaders in producing the global and national footprint accounts based on the standard (FAO) approach. Both have also published the international footprint accounts with World Wildlife Federation International. Slight variations in the EF-GAEZ methodology incorporated in the template used by RP and GFN have developed over the last several years. However, both approaches remain fundamentally the same and show nearly identical results.

Land use, production, and consumption data primarily from the FAO Statistical Database, International Energy Agency, and IPCC form the primary inputs into that template. The template contains EQF and algorithms for estimating yield factors based on these data. As previously discussed, EQFs form the basis for biocapacity calculations. Yield factors form the basis for footprint calculations. For example, at the global level the unadjusted (i.e., before conversion to global hectares) footprint calculation for beans can be expressed as the ratio of cropland area devoted to bean production divided by its yield factor. When that land area is converted into global hectares the size of the footprint changes accordingly. For example, if the EQF goes down 1 year, so does the footprint because less biocapacity is assumed to be utilized. A more thorough discussion of the data and template operations underlying EF-GAEZ can be found online[6] and in Wackernagel et al. (2005).

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[6] See www.rprogress.org/newprojects/ecolFoot/methods/.

5 Application of EF-NPP to the footprint of nations

In this section we compare global biocapacity and footprint accounts for 2001, as well as global trends between 1961 and 2001, using EF-NPP and EF-GAEZ. We also describe some key differences at the country level and use multivariate regression analysis to systematically evaluate differences in ecological balances under the two approaches.

5.1 Global 2001 snapshot

Use of EF-NPP results in significant changes to global footprint accounts. Table 4 shows global per capita biocapacity, footprint, and ecological balances (biocapacity–footprint) for both EF-NPP and EF-GAEZ. EF-NPP shows negative ecological balances (overshoot) in 2001 in four biomes: crop land, marine and inland fisheries, built space, and energy land. EF-GAEZ shows overshoot for energy land alone, a finding corroborated by GFN's 2004 *Living Planet Report*.[7] Changes made to EQFs and biocapacity as well as deductions made for other species help explain why EF-NPP shows negative ecological balances for more biomes than EF-GAEZ. On a per capita basis, global cropland is determined to have a higher EQF using EF-NPP (2.12 vs. 2.11). However, deductions made for other species offset this effect so that biocapacity is significantly lower relative to EF-GAEZ (0.461 gha vs. 0.527 gha). The net effect is an overshoot of 0.060 gha per capita while EF-GAEZ results indicate a zero ecological balance. For marine and inland fisheries, EF-NPP shows a significantly greater EQF (2.67 vs. 0.35), biocapacity (0.873 gha per capita vs. 0.132 gha per capita), and footprint (1.045 gha per capita vs. 0.138 gha per capita). The net effect is an overshoot of 0.173 gha per capita. EF-GAEZ results indicate a zero ecological balance. For built space, EF-NPP has a significantly lower EQF (0.50 vs. 2.11), biocapacity (0.02 gha per capita vs. 0.1 gha per capita), and footprint (0.046 gha per capita vs. 0.1 gha per capita), but overall shows net overshoot of 0.026 gha per capita. Again, EF-GAEZ shows a zero ecological balance.

Energy land is by far the largest footprint category under both EF-NPP and EF-GAEZ, but the EF-NPP footprint is nearly 17 times greater. This is largely a function of including the entire Earth in the biocapacity sequestration estimates thereby reducing carbon sequestration rates from 0.95 to 0.06 t C/ha. EF-NPP also adds 8.27 gha of energy land per capita to biocapacity. The result is an overshoot of 11.1 gha. EF-GAEZ shows an overshoot of 1.14 gha.

Both approaches show positive ecological balances for pasture land and forest land, with EF-NPP showing greater balances due to its higher EQFs for these biomes. Unfortunately, neither approach accounts for desertification of grasslands from over-grazing, salinization of crop land, or loss of forests from unsustainable logging and land conversions. For example, neither approach captures the 1.5 million hectares of crop land lost to salinization each year (Wood, Sebastian, and Scherr 2000) or the 140 million hectare decline in forest area covering the Earth from 1961 to 2001 (FAOSTAT, 2005). While such declines may be reflected in lost biocapacity

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[7] The EF-GAEZ model seems to show a net negative footprint for fisheries. This, given the model assumptions, appears to be an indication of an error in the model or in the data. It amounts to about 0.0056 gha per capita. This may not have been reported previously due to rounding or could, in fact, be a relatively minor flaw.

Table 4 Global footprint accounts: EF-NPP and EF-GAEZ

Biome	Biocapacity		Footprint		Ecological balance	
	EF-NPP	EF-GAEZ	EF-NPP	EF-GAEZ	EF-NPP	EF-GAEZ
Crop land	0.461	0.527	0.521	0.527	–0.060	0.000
Forest land	1.775	0.833	0.464	0.189	1.311	0.644
Pasture land	1.197	0.267	0.470	0.091	0.726	0.176
Built space	0.020	0.100	0.046	0.100	–0.026	0.000
Less productive land	0.779	–	0.000	–	0.779	–
Marine and inland fisheries	0.873	0.132	1.045	0.138	–0.173	–0.006
Open ocean	2.337	–	0.000	–	2.337	–
Energy land	8.265	–	19.357	1.142	–11.092	–1.142
Total	15.707	1.859	21.903	2.187	–6.197	–0.328

All figures in gha per capita, 2001 data

in the future, they are not reflected in negative ecological balances in the present because EFA data is not "real time". Future EFA iterations may benefit from remotely sensed data increasingly available from NASA Data Centers that captures changes in land cover at extremely fine temporal scales on a seasonal and annual basis. Incorporation of these data into EFA is an exciting possibility in the years ahead. In the mean time, EFA does not reflect lost biocapacity from these land use changes and, instead, assumes that biocapacity "breaks even" as a result of higher yields obtained from smaller areas. Of course, higher yields are often associated with ecologically tenuous practices, such as when native forests are converted into tree plantations or plants and animals are injected with growth hormones. EFA's general failure to differentiate between ecologically sustainable and unsustainable practices remains one of its major shortcomings. We lay out an NPP-based research agenda for addressing these and other concerns in our concluding section.

As previously noted, EF-NPP allocates 3.11 gha per capita of less productive and ocean space for biocapacity, while EF-GAEZ fails to assign any. At this time, EF-NPP does not calculate footprints within these biomes. Future advances in EFA data and methods may make this possible. For now, these areas remain unqualified additions to biocapacity.

In the final tally, EF-NPP shows 15.71 gha of total biocapacity, most of which is carbon sequestration land. EF-GAEZ shows about 1.86 gha per capita. The respective footprints are 21.90 and 2.19 gha per capita. Both approaches show a negative ecological balance, or overshoot. EF-NPP: –6.20 gha per capita; EF-GAEZ: –0.33. On a per planet basis, if you will, EF-GAEZ shows a footprint of 1.18 planets. That is, humanity's ecological footprint would require biocapacity the size of another planet that is 18% the size of Earth (at average biocapacity levels) to be sustainable. EF-NPP shows a footprint of 1.39 planets, a 21% increase over EF-GAEZ.

5.2 Global trends over time

Figure 1 illustrates trends in biocapacity and ecological footprints under both approaches between 1961 and 2001. Both EF-GAEZ and EF-NPP show no significant change in biocapacity through the period. Global ecological footprints have risen steadily under both approaches, but more steeply under EF-NPP. Both

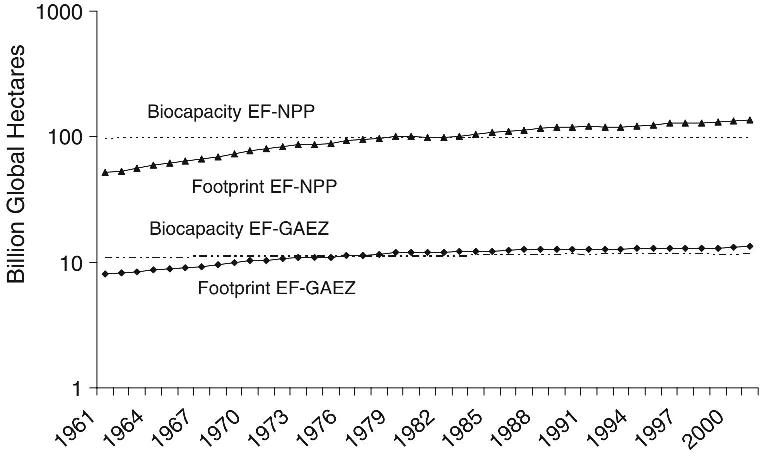

Fig. 1 Ecological footprint and biocapacity 1961–2001

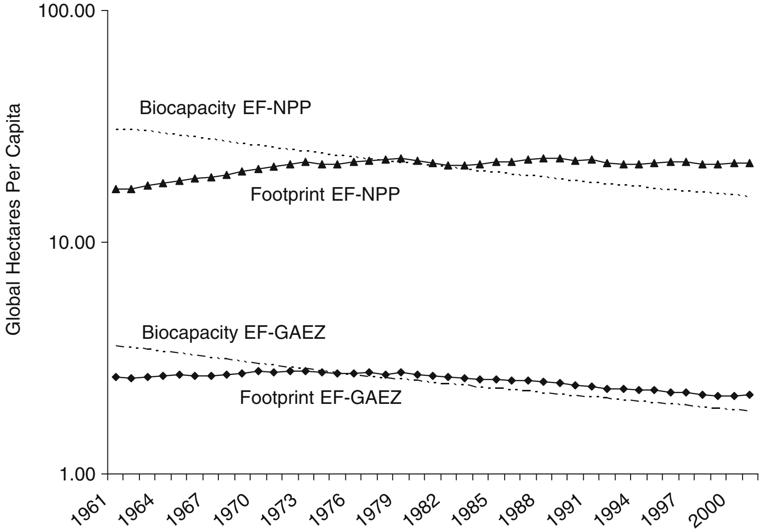

Fig. 2 Ecological footprint and biocapacity per capita 1961–2001

illustrate that ecological overshoot began in the late 1970s. Thereafter, overshoot has increased to about 18% with EF-GAEZ and 39% with EF-NPP.

On a per capita basis EF-NPP and EF-GAEZ footprints diverge to a considerable extent. Figure 2 shows EF-GAEZ and EF-NPP biocapacity and footprints per capita from 1961 to 2001. With EF-GAEZ, there is a rise in the footprint (from 2.61 to 2.79) between 1961 and 1973, then a fairly steady decline through 2001 (from 2.79 to 2.19). This could be due to several factors, including rising population or increases in yield factors. EF-NPP shows per capita footprint increasing over the first 20 years and then becoming fairly stable within the range of 21–23 gha per capita thereafter. Under both approaches biocapacity declines by roughly half.

Table 5 provides EF-NPP footprint, biocapacity, and ecological balance estimates for 138 countries based on 2001 data and indicates differences from EF-GAEZ. Regionally, Africa, Asia-Pacific, Latin America, and the Caribbean fare better. As compared with EF-GAEZ, these regions show significant gains in their ecological balances. In these regions, the biocapacity of the countries tended to exceed their ecological footprint. In contrast, the Middle Eastern, Central Asian, North American, and European regions tend to show lower ecological balances. Here, EF-NPP shows that most countries are exceeding their biological capacities by a significantly greater margin than what EF-GAEZ suggests. On a country-by-country basis, 75 countries showed greater ecological balances, 63 showed lower balances. Mongolia's ecological balance gained the most, rising from 25.17 gha per capita under EF-GAEZ to 163.12 under EF-NPP—a gain of 137.95. The United Arab Emirates saw the most precipitous decline in ecological balance, from –13.77 gha per capita (EF-GAEZ) to –213.43 (EF-NPP)—a drop of 199.66.

Allow us to offer a word of caution concerning these results. The size of the ecological overshoot is largely due to the heavy-weight carbon emissions are given in the basic EFA model. While anthropogenic carbon emissions are contributing to a very troubling ecological problem—global climate change—the predominance of the carbon footprint over all other environmental concerns could be construed as presumptuous, and not scientifically defensible. As such, biome-specific accounts may have just as much meaning as the global tally, especially if credible sustainability criteria can be developed.

5.3 Cross sectional regression analysis

To systematically account for ecological balance differences between EF-GAEZ and EF-NPP and to shed light on variables relevant to models that may utilize EF-NPP data in the future, we ran a multivariate cross sectional regression on the 2001 data. Given the methodological changes embodied in EF-NPP, we can expect that ecological balances would tend to fall in nations that use relatively less energy, have larger land masses, and have greater shares of their biological capacity in pasture, forest, or marine and inland fisheries and tend to rise in smaller nations with relatively higher energy use and greater shares of biological capacity devoted to built space. This is because EF-NPP drastically reduced carbon sequestration rates (which boosts the energy footprint), made significant increases to EQFs for pasture land, forest land, and marine and inland fisheries (which increases biological capacity, especially for large countries), and significantly decreased the EQF for built space (which decreases biological capacity in highly urbanized countries).

To capture energy footprint effects, the regression model uses total gross domestic product (GDP) as a proxy for the absolute level of energy consumption and a nation's energy footprint share (enfpshr) under EF-GAEZ.[8] To capture changes in biocapacity, a nation's EF-GAEZ share of biocapacity in pasture and marine and inland fisheries (pafishr) and built space (bsshr), as well as the log of its total land area (ln area) are employed as independent variables. EF-GAEZ shares

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[8] GDP is an indirect measure of the absolute magnitude of energy consumption in a nation while the share of energy in the overall footprint is a relative measure. We included GDP in lieu of a more direct measure of energy consumption due to multicolinearity concerns with energy share and also because GDP is highly correlated with the overall size of the consumption footprint.

Table 5 Ecological footprint per capita in gha (EF-NPP Method)

	Cropland	Pasture	Forests	Fisheries	Built space	Energy	Total FP	Biological capacity	Ecological balance		Difference
									NPP	GAEZ	
World	0.52	0.47	0.46	1.05	0.05	19.36	21.91	15.71	–6.20	–0.33	–5.87
Africa	0.45	0.80	0.38	0.73	0.04	5.07	7.48	27.51	20.03	2.05	17.98
Algeria	0.64	0.49	0.18	0.13	0.03	13.73	15.21	20.11	4.91	–1.09	6.00
Angola	0.32	0.38	0.22	0.79	0.02	4.68	6.41	44.71	38.30	7.74	30.56
Benin	0.41	0.29	0.49	0.55	0.04	1.28	3.06	10.24	7.18	0.19	6.99
Botswana	0.36	1.91	0.31	0.20	0.02	13.62	16.42	63.61	47.19	2.37	44.82
Burkina Faso	0.57	1.31	0.50	0.11	0.07	0.49	3.05	12.46	9.42	0.44	8.98
Burundi	0.29	0.14	0.62	0.19	0.03	0.23	1.50	7.36	5.86	–0.03	5.89
Cameroon	0.62	0.74	0.37	0.80	0.05	1.85	4.43	18.66	14.23	3.14	11.09
Central African Rep	0.63	1.89	0.45	0.49	0.04	0.69	4.19	47.40	43.21	6.12	37.09
Chad	0.47	1.74	0.46	1.26	0.04	0.24	4.21	32.96	28.75	0.60	28.15
Congo	0.22	0.12	0.31	1.61	0.05	1.15	3.46	55.90	52.44	13.11	39.33
Cote Divoire	0.48	0.20	0.43	0.50	0.06	2.17	3.84	14.52	10.68	1.57	9.11
Egypt	0.48	0.13	0.21	1.14	0.19	10.15	12.30	9.25	–3.05	–0.93	–2.12
Eritrea	0.25	0.84	0.28	0.30	0.04	1.08	2.79	13.63	10.83	0.60	10.24
Ethiopia	0.26	0.14	0.68	0.03	0.04	0.42	1.56	8.53	6.97	–0.24	7.22
Gabon	0.67	0.16	0.24	2.54	0.03	20.43	24.06	120.20	96.15	31.22	64.92
Gambia	0.54	0.73	0.31	0.89	0.04	1.28	3.78	10.64	6.86	0.08	6.78
Ghana	0.42	0.12	0.54	0.87	0.05	1.24	3.23	10.78	7.54	0.39	7.16
Guinea	0.31	0.84	0.73	0.68	0.05	0.90	3.51	21.10	17.59	2.17	15.42
Guinea-Bissau	0.42	1.08	0.32	0.62	0.02	1.20	3.65	28.60	24.95	3.13	21.82
Kenya	0.22	1.51	0.37	0.04	0.04	1.69	3.87	12.70	8.83	0.74	8.09
Lesotho	0.25	1.25	0.45	0.00	0.02	0.75	2.72	12.41	9.69	0.57	9.11
Liberia	0.23	0.06	0.72	0.56	0.04	0.59	2.20	20.39	18.19	2.88	15.31
Libya	0.89	0.37	0.12	0.57	0.03	37.51	39.50	71.09	31.60	–2.20	33.79
Madagascar	0.28	1.54	0.28	0.59	0.04	0.73	3.46	23.85	20.39	2.08	18.30
Malawi	0.29	0.08	0.25	0.48	0.05	0.71	1.86	8.50	6.64	0.24	6.40
Mauritania	0.37	4.32	0.24	0.46	0.04	5.84	11.28	79.77	68.49	0.81	67.67
Mauritius	0.57	0.40	0.23	2.01	0.08	19.02	22.31	58.41	36.11	–0.93	37.04

Table 5 continued

	Cropland	Pasture	Forests	Fisheries	Built space	Energy	Total FP	Biological capacity	Ecological balance		Difference
									NPP	GAEZ	
Morocco	0.51	0.32	0.08	0.56	0.03	4.73	6.22	10.65	4.43	–0.14	4.56
Mozambique	0.23	0.10	0.47	0.18	0.02	0.48	1.49	23.99	22.50	2.83	19.68
Namibia	0.99	1.93	0.00	3.40	0.07	3.28	9.67	106.96	97.30	3.18	94.11
Niger	0.70	0.34	0.16	0.14	0.04	0.54	1.92	26.84	24.91	–0.02	24.93
Nigeria	0.56	0.24	0.34	0.63	0.05	4.02	5.84	9.04	3.20	–0.03	3.23
Rwanda	0.33	0.26	0.48	0.11	0.04	0.44	1.65	7.13	5.48	0.01	5.47
Senegal	0.44	1.17	0.37	1.52	0.04	2.43	5.98	14.46	8.48	0.66	7.82
Sierra Leone	0.25	0.25	0.56	1.12	0.04	1.05	3.27	14.15	10.87	0.79	10.08
South Africa	0.65	1.62	0.60	0.51	0.06	37.19	40.62	20.80	–19.81	–0.32	–19.50
Sudan	0.45	1.68	0.33	0.18	0.04	1.56	4.23	18.99	14.76	1.05	13.71
Tanzania	0.24	1.25	0.34	0.96	0.05	0.55	3.39	15.81	12.42	1.34	11.08
Togo	0.59	0.25	0.60	0.49	0.03	1.87	3.83	9.05	5.23	–0.13	5.35
Tunisia	0.84	0.20	0.26	0.86	0.04	8.14	10.35	10.70	0.35	–0.66	1.01
Uganda	0.51	0.35	0.83	1.62	0.05	0.19	3.55	10.00	6.44	0.05	6.39
Zambia	0.52	0.53	0.41	0.77	0.03	0.63	2.89	30.40	27.51	3.77	23.74
Zimbabwe	0.28	1.11	0.39	0.17	0.02	7.06	9.03	16.35	7.32	1.19	6.13
Middle East and Central Asia	0.58	0.55	0.17	0.61	0.05	39.65	41.61	13.55	–28.06	–1.75	–26.32
Armenia	0.38	0.70	0.03	0.05	0.03	4.01	5.20	7.55	2.36	–0.36	2.72
Azerbaijan	0.52	0.96	0.08	0.04	0.03	18.98	20.60	11.64	–8.96	–0.80	–8.17
Georgia	0.41	1.11	0.01	0.04	0.02	6.01	7.60	9.36	1.76	–0.12	1.87
Iran	0.51	0.64	0.04	0.48	0.05	23.65	25.36	12.45	–12.91	–1.04	–11.87
Israel	0.83	0.41	0.50	2.29	0.09	52.30	56.42	6.55	–49.87	–4.14	–45.73
Jordan	0.53	0.28	0.18	0.53	0.06	14.06	15.64	9.06	–6.58	–1.30	–5.29
Kazakhstan	0.71	0.97	0.06	0.04	0.02	33.87	35.66	34.61	–1.05	–0.11	–0.94
Kuwait	0.54	0.35	0.27	0.63	0.15	152.98	154.91	8.41	–146.50	–9.43	–137.06
Kyrgyzstan	0.56	0.85	0.03	0.02	0.03	8.70	10.19	10.19	0.00	8.83	–8.83
Lebanon	0.65	0.24	0.36	0.33	0.07	22.24	23.90	6.33	–17.57	–1.96	–15.62
Saudi Arabia	0.85	0.29	0.22	0.75	0.09	65.89	68.10	23.19	–44.91	–3.31	–41.60
Syria	0.57	0.21	0.06	0.19	0.06	17.27	18.36	7.98	–10.39	–0.85	–9.54
Tajikistan	0.27	0.31	0.02	0.00	0.02	4.02	4.64	9.65	5.01	–0.29	5.30

Table 5 continued

	Cropland	Pasture	Forests	Fisheries	Built space	Energy	Total FP	Biological capacity	Ecological balance		Difference
									NPP	GAEZ	
Turkey	0.82	0.53	0.28	0.56	0.06	14.01	16.25	9.08	–7.17	–0.77	–6.40
Turkmenistan	0.60	0.76	0.01	0.04	0.03	26.42	27.86	25.40	–2.46	–0.59	–1.88
United Arab Emirates	1.18	0.42	0.83	4.22	0.08	226.13	232.86	19.43	–213.43	–13.76	–199.66
Uzbekistan	0.31	0.42	0.01	0.02	0.04	19.78	20.58	20.58	0.00	–1.10	1.10
Yemen	0.28	0.40	0.03	0.68	0.04	3.43	4.87	12.45	7.58	–0.33	7.91
Asia-Pacific	0.53	1.09	0.51	1.69	0.04	15.55	19.42	29.97	10.55	2.15	8.40
Australia	1.85	1.84	1.57	2.10	0.05	71.63	79.05	110.21	31.16	4.36	26.80
Bangladesh	0.23	0.03	0.10	0.68	0.03	1.27	2.33	6.50	4.17	–0.14	4.31
Cambodia	0.31	0.50	0.34	0.09	0.03	0.24	1.51	10.56	9.05	0.78	8.28
China	0.39	0.12	0.21	1.18	0.04	10.53	12.46	8.36	–4.10	–0.33	–3.77
India	0.29	0.02	0.15	0.19	0.02	4.15	4.83	6.93	2.10	–0.10	2.20
Indonesia	0.32	0.15	0.28	0.87	0.03	6.39	8.03	12.54	4.50	0.93	3.58
Japan	0.48	0.20	0.61	4.09	0.09	47.73	53.21	8.77	–44.44	–3.62	–40.82
Korea DPRP	0.29	0.01	0.20	0.75	0.03	42.66	43.93	9.11	–34.82	–1.76	–33.06
Korea Republic	0.50	0.16	0.46	3.61	0.07	34.89	39.69	9.04	–30.65	–2.57	–28.07
Laos	0.27	0.76	0.58	1.28	0.03	0.34	3.26	23.81	20.55	4.64	15.91
Malaysia	0.59	0.30	0.44	4.04	0.04	30.07	35.48	17.10	–18.38	0.44	–18.82
Mongolia	0.38	15.05	0.26	0.01	0.01	11.05	26.77	189.89	163.12	25.17	137.95
Myanmar	0.41	0.05	0.39	0.73	0.03	0.98	2.58	11.99	9.40	1.06	8.35
Nepal	0.28	0.22	0.31	0.08	0.03	0.68	1.60	7.54	5.93	0.12	5.81
New Zealand	2.91	2.85	2.72	6.45	0.10	33.51	48.54	84.73	36.18	2.47	33.72
Pakistan	0.30	0.02	0.13	0.39	0.02	3.84	4.69	7.07	2.39	–0.29	2.67
Papua New Guinea	0.26	0.18	0.80	2.03	0.03	1.81	5.11	70.08	64.97	14.69	50.28
Philippines	0.27	0.17	0.32	2.13	0.03	5.63	8.55	7.99	–0.56	–0.45	–0.11
Sri Lanka	0.26	0.19	0.23	1.76	0.03	3.58	6.04	8.25	2.21	–0.36	2.57
Thailand	0.31	0.10	0.27	1.89	0.03	13.35	15.95	9.67	–6.27	–0.14	–6.13
Vietnam	0.27	0.06	0.24	1.21	0.05	2.31	4.12	9.14	5.02	0.20	4.82
Latin America and Caribbean	0.49	1.95	0.57	0.64	0.05	13.20	16.90	22.22	5.31	1.67	3.64
Argentina	1.04	3.12	0.28	0.76	0.05	17.81	23.05	39.26	16.20	4.24	11.96
Bolivia	0.40	3.28	0.21	0.10	0.03	6.97	11.00	48.60	37.60	8.63	28.97

Table 5 continued

	Cropland	Pasture	Forests	Fisheries	Built space	Energy	Total FP	Biological capacity	Ecological balance		Difference
									NPP	GAEZ	
Brazil	0.66	2.92	1.02	0.59	0.05	8.88	14.11	29.16	15.05	4.67	10.38
Chile	0.52	1.46	1.85	1.25	0.08	14.28	19.44	39.84	20.40	1.41	18.98
Colombia	0.29	2.70	0.18	0.37	0.05	7.57	11.17	18.57	7.41	1.92	5.48
Costa Rica	0.38	1.42	1.05	0.28	0.08	11.11	14.32	18.85	4.54	0.58	3.96
Cuba	0.59	0.32	0.15	0.40	0.03	11.61	13.10	9.60	–3.50	–0.48	–3.02
Ecuador	0.35	1.59	0.73	1.00	0.04	9.86	13.56	15.92	2.36	1.03	1.33
El Salvador	0.34	0.92	0.55	0.20	0.03	5.53	7.57	7.43	–0.14	–0.59	0.45
Guatemala	0.31	0.87	0.67	0.04	0.05	5.69	7.64	10.33	2.69	0.25	2.44
Haiti	0.26	0.41	0.15	0.12	0.02	1.18	2.15	7.18	5.03	–0.23	5.26
Honduras	0.37	1.38	0.75	0.10	0.04	5.79	8.44	13.54	5.11	0.39	4.72
Jamaica	0.44	0.73	0.48	1.18	0.04	23.02	25.90	11.49	–14.41	–1.72	–12.69
Mexico	0.75	1.58	0.34	0.63	0.04	19.80	23.14	14.34	–8.81	–0.66	–8.15
Nicaragua	0.66	1.25	0.52	0.13	0.04	4.81	7.42	19.41	11.99	2.05	9.93
Panama	0.55	2.01	0.28	0.59	0.04	18.85	22.32	22.84	0.51	1.32	–0.81
Paraguay	0.47	3.34	1.19	0.55	0.04	4.27	9.86	34.37	24.51	5.44	19.07
Peru	0.43	1.20	0.19	1.48	0.05	3.71	7.06	30.11	23.05	5.16	17.89
Trinidad and Tobago	0.47	0.31	0.28	1.35	0.04	59.87	62.31	11.53	–50.78	–3.92	–46.86
Uruguay	0.58	8.12	1.00	1.29	0.04	11.60	22.64	44.42	21.77	4.58	17.19
Venezuela	0.43	2.06	0.14	1.04	0.05	25.08	28.80	19.75	–9.05	0.99	–10.04
North America	1.72	1.01	2.69	1.59	0.15	88.83	95.99	53.16	–42.83	–0.93	–41.90
Canada	1.90	1.06	2.74	1.31	0.12	75.91	83.03	85.95	2.92	3.12	–0.21
United States of America	1.53	0.96	2.65	1.86	0.18	101.76	108.95	20.37	–88.58	–4.99	–83.60
Western Europe	0.98	0.53	1.78	2.87	0.11	54.45	60.70	16.84	–43.86	–2.73	–41.13
Austria	0.82	0.60	1.92	1.04	0.06	46.69	51.13	9.94	–41.19	–3.07	–38.12
Belgium and Luxembourg	0.85	0.44	0.00	2.02	0.13	65.43	68.87	7.19	–61.69	–4.64	–57.05
Denmark	1.26	0.45	3.28	1.69	0.11	55.04	61.84	16.28	–45.56	–2.64	–42.92
Finland	1.03	0.10	5.69	1.98	0.25	35.44	44.48	32.16	–12.33	2.12	–14.45
France	1.13	0.63	1.10	2.51	0.10	60.36	65.82	11.29	–54.54	–3.29	–51.25
Germany	0.73	0.22	0.87	1.22	0.14	49.04	52.21	8.44	–43.77	–2.75	–41.02

Table 5 continued

	Cropland	Pasture	Forests	Fisheries	Built space	Energy	Total FP	Biological capacity	Ecological balance		Difference
									NPP	GAEZ	
Greece	1.16	1.16	0.51	2.43	0.07	62.53	67.85	11.79	–56.06	–3.68	–52.38
Ireland	1.21	0.62	1.19	1.64	0.07	60.69	65.42	27.02	–38.40	–1.48	–36.92
Italy	0.86	0.49	0.69	1.75	0.03	37.68	41.51	8.05	–33.46	–2.65	–30.81
Netherlands	0.93	0.51	0.98	1.39	0.09	65.19	69.09	7.96	–61.13	–4.58	–56.54
Norway	0.76	0.16	2.40	5.91	0.09	83.81	93.13	48.89	–44.24	–2.90	–41.34
Portugal	0.93	0.66	1.02	10.03	0.09	36.47	49.20	16.33	–32.88	–3.58	–29.30
Spain	1.10	0.69	0.84	4.58	0.05	43.42	50.68	10.44	–40.24	–3.19	–37.05
Sweden	1.20	0.34	5.34	2.51	0.24	57.13	66.76	26.38	–40.38	–0.93	–39.45
United Kingdom	0.71	0.81	0.81	2.33	0.09	57.81	62.56	10.45	–52.11	–3.73	–48.38
Central and Eastern Europe	0.96	0.53	0.86	0.67	0.04	28.30	31.36	12.45	–18.91	–0.99	–17.92
Albania	0.65	0.44	0.13	0.20	0.04	8.43	9.90	8.29	–1.61	–0.55	–1.05
Belarus	0.89	0.75	0.45	0.42	0.03	32.62	35.17	12.23	–22.94	–0.79	–22.15
Bosnia Herzegovina	0.59	0.97	0.70	0.26	0.03	18.64	21.20	8.13	–13.07	–1.67	–11.40
Bulgaria	1.07	0.52	0.36	0.19	0.04	31.47	33.65	10.76	–22.88	–1.33	–21.56
Croatia	0.90	0.45	0.71	0.78	0.05	25.75	28.64	12.87	–15.77	–0.80	–14.97
Czech Republic	0.99	0.25	1.29	0.98	0.06	43.67	47.24	9.95	–37.30	–2.09	–35.21
Estonia	1.24	0.51	3.31	1.39	0.04	23.36	29.84	20.97	–8.88	–0.11	–8.77
Hungary	0.73	0.32	0.69	0.51	0.06	32.62	34.93	9.28	–25.65	–1.10	–24.55
Latvia	2.06	0.65	2.66	-0.12	0.03	18.83	24.11	18.75	–5.36	0.63	–6.00
Lithuania	1.40	0.36	0.82	2.33	0.04	32.56	37.51	12.41	–25.10	–1.22	–23.88
Macedonia	0.67	1.05	0.38	0.54	0.03	23.24	25.92	8.32	–17.60	–1.74	–15.86
Moldova Republic	0.64	0.24	0.09	0.15	0.03	8.37	9.52	7.73	–1.79	–0.21	–1.59
Poland	1.00	0.29	0.70	0.88	0.05	31.38	34.31	9.18	–25.13	–1.54	–23.59
Romania	0.78	0.67	0.42	0.19	0.04	26.84	28.94	8.24	–20.71	–1.65	–19.05
Russia	1.28	0.82	0.70	1.87	0.03	43.65	48.35	35.94	–12.42	0.69	–13.11
Slovakia	0.79	0.42	0.95	0.45	0.04	33.56	36.22	10.73	–25.48	–1.19	–24.29
Slovenia	0.70	0.42	0.88	0.48	0.05	36.05	38.57	10.88	–27.69	–1.34	–26.35
Ukraine	0.97	0.42	0.18	0.48	0.04	38.36	40.46	9.52	–30.94	–1.75	–29.19

were selected since the EF-GAEZ ecological balance is the baseline from which the ecological difference was calculated. For a given country *n*, the specified model is:

$$\mathrm{diff}_n = \mathrm{GDP}_n + \ln \mathrm{area}_n + \mathrm{enfpshr}_n + \mathrm{pafishr}_n + \mathrm{bsshr}_n + e_n,$$

where diff is the difference in ecological balances as reported in Table 5, *e* is the error term, and all other variables are as defined above.

Table 6 reports the results. As expected, GDP, energy footprint share (enpfshr), and built space footprint share (bsshr) pull a nation's ecological balance down relative to EF-GAEZ, while land area (ln area) and pasture/fisheries share (pafishr) push that balance higher. All variables were significant at the 0.05 level or better, with an adjusted *R*-squared of 0.5396. Energy footprint share has the strongest impact, while GDP has the weakest effect. Thus, our hypothesis that countries with higher energy consumption, energy footprint share, and built space share fare worse under EF-NPP relative to EF-GAEZ while those with more land area, relatively larger shares of biocapacity in pasture and fisheries, and lower energy consumption fare better is supported by our findings.

In some cases, differences between the approaches were significant enough to cause nations with positive ecological balances under EF-GAEZ to show negative balances under EF-NPP and vice versa. For example under our EF-GAEZ model as well in Loh and Wackernagel (2004) the Russian Federation and Venezuela showed positive ecological balances. Under EF-NPP, these countries ran significant ecological deficits. The change in status was attributable, in part, to the rather large share energy consumption represented in these countries' EF-GAEZ footprints (56%). Conversely, under our EF-GAEZ model as well as in Loh and Wackernagel (2004) Mauritius and Yemen showed negative ecological balances. Under EF-NPP, these countries ran significant ecological surpluses. A key explanatory factor is EF-GAEZ pasture/fisheries footprint share, which was quite high in both at 63 and 46%, respectively. Such findings suggest that explanatory variables identified in our regression analysis may be important to any subsequent modeling completed with EF-NPP data.

6 Concluding thoughts and future refinements

At a time when applications of EFA are proliferating and international standards are under consideration, it is important to make changes to the basic methodology (EF-GAEZ) that respond to longstanding critiques that appear frequently in the literature. In this paper, we made four. First, we expanded the purview of EFA to include the entire Earth in biocapacity accounts. Second, we made a formal accommodation for other species by deducting 13.4% of each biome from biocapacity. Third, we changed the way in which carbon sequestration rates and the resulting footprint are calculated. Finally, we changed the basis for EQF from agricultural productivity potential to NPP. Using the new approach (EF-NPP), we constructed ecological footprint accounts for 138 countries between 1961 and 2001 and compared our results with EF-GAEZ. A regression model was used to systematically analyze differences in ecological balances.

At a global level, key differences between EF-NPP and EF-GAEZ are apparent in the significantly larger biocapacity and ecological footprints shown by the former. In addition, EF-NPP shows ecological overshoot (negative ecological balance) for

Table 6 Cross sectional analysis of ecological balance differences

Independent variables	Coefficients
GDP	–0.71*** (–3.00)
Ln area	4.23*** (3.02)
enfpshr	–77.12*** (–7.75)
pafishr	24.70** (2.16)
bsshr	–57.16** (–2.30)
Constant	–28.66 (–1.52)
R-squared	0.5396
Observations	134

Numbers in parentheses are *t*-statistics

** and *** denote significance at the 0.05 and 0.01 levels, respectively

crop land, built space, marine and inland fisheries, and energy land whereas EF-GAEZ reports overshoot only with respect to energy land, though no energy land biocapacity is explicitly included. Overall, EF-NPP shows a current ecological overshoot about 18% larger than EF-GAEZ. On a country-by-country basis, 75 countries had greater ecological balances under EF-NPP, while in 63, the ecological balance dropped. Cross sectional regression analysis supported the hypothesis that energy consumption, energy footprint share, and biocapacity shares for built space, pasture land, and marine and inland fisheries significantly affect the size and direction of ecological balance differences between the two approaches.

Our hope is that EF-NPP improves the accuracy and practical utility of EFA as a sustainability research tool. While EF-NPP represents a significant change, many more advances are warranted. One critical advance would be to establish sustainable yield benchmarks, as recommended frequently in ecological footprint literature. Mathematically, it is impossible for EF-GAEZ to show unsustainable use of forest land, crop land, marine and inland fisheries, or pasture land biomes on a global level due to the nature of the calculations and because EF-GAEZ fails to distinguish between sustainable and unsustainable yields (Ferng, 2005).[9] Site-specific sustainable yield factors for fisheries and forests have been estimated by ecologists (Ferng, 2005; Northcote & Hartman, 2004). It may be possible to develop others by considering the connection between NPP removal and declines in biological diversity or the “species energy hypothesis”.

According to this hypothesis, at levels above 50%, human appropriation of NPP has negative consequences in terms of biological diversity (Wright, 1990). Haberl et al. (2004) recently validated the hypothesis in a study of agricultural lands in eastern Austria. With further research, it may be possible to use NPP retention standards embodied in a representative sample of sustainable agriculture, forestry, and fishery systems from various regions across the world as a basis for ESY estimates applicable throughout entire crop land, forest land, pasture land, and marine

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[9] The proof is relatively straight forward. For crop land, a nation’s footprint = [crop production (C) in tons per year/global crop yield factor (G) in tons per hectare per year] × the crop land EQF (Q). Biocapacity = maximum crop land area (Am) × national crop yield factor (N) × the crop land EQF (Q) (Wackernagel et al., 2005). We can factor Q out of both sides of the equation, leaving [C/G] on the footprint side and AmN on the biocapacity side. We can rewrite N as [Y/G] since N is simply the ratio of a nation’s crop land yield (Y) to the global crop yield factor (G). For the world as a whole, however, $Y = G$ so this term is simply 1. This leaves C/G on the footprint side and Am on the biocapacity side. C/G cannot be greater than Am on a global basis because G is simply global production/global crop land area in production or C/Ap leaving Ap on the footprint side and Am on the biocapacity side, with $A\text{p} \leq A\text{m}$ by definition.

biomes. From there we can convert the disparity between sustainable yields and actual yields reported by FAO into deductions from biocapacity.

For example, with respect to agriculture, organic agriculture methods retain considerably more NPP and, in a recent long-term study, have been shown to reduce crop yields by roughly 20% but enhance long-term soil fertility and biological diversity (Mäder et al., 2002). If FAO reported yields are presumed to be 20% above an ESY then the area needed to produce that excess yield can be converted into global hectares and then deducted from biocapacity. While reserved NPP is clearly not a sufficient condition for preserving biological diversity or ensuring sustainable land use in any particular place—a feat dependent upon many other local factors such as the degree of fragmentation, presence of invasive species and responsiveness of public officials—it is, nonetheless, a necessary condition and one that continues to be explored in a variety of ecosystems and settings. Moreover, because NPP provides a common foundation applicable to all EFA biomes, it appears to be well suited for incorporating ecologically meaningful sustainability standards into EFA. Incorporating sustained yield factors into EFA raises some challenges because data over time and across all biomes does not appear to be readily available. Nonetheless, sustained yield benchmarks are critical to the long-term effectiveness of EFA and ought to be thoroughly researched. As it stands now EFA has a bias toward intensive (and potentially ecologically detrimental) production practices in the present over sustainability of ecosystems in the long run.

Net primary productivity can help fill other holes in EFA as well. Recent advancements in real time satellite mapping of NPP (or its derivative measures such as the Normalized Difference Vegetation Index) as well as human appropriation of NPP could also prove useful in estimating footprints for less productive lands and open oceans since these areas are not now linked to consumption data in the current EFA framework (Running et al., 2004). NPP can also be used to identify portions of aquatic and terrestrial ecosystems warranting removal from biocapacity due to specific threats or high species richness. Such mapping may prove to be a useful supplement to existing conservation needs assessments such as global biodiversity hot spots or gap analyses referenced in Sect. 4 (Bawa et al., 2002).

Additional refinements to EFA warranted by critiques and now being explored by the authors also include incorporating additional greenhouse gases, addressing the effects of environmental toxins, and modeling the footprint of water consumption. While carbon dioxide makes up the largest share of climate changing gasses from anthropogenic sources, analyses that link methane (CH_4), nitrous oxide (N_2O), and fully fluorinated compounds (PFCs, HFCs, and SF_6) to appropriation of biocapacity would represent a significant step forward in making EFA more comprehensive and meaningful with respect to the effects of climate change. At first glance, it appears very difficult, if not impossible, to convert the impacts associated with uranium, lead, arsenic, mercury, and other toxics into an area-based measure such as footprint. Footprinting is, after all, a quantitative indicator, not qualitative. Still, the relationship between concentrations of these toxins in a biome and its NPP may shed light on techniques to expand the scope of EFA to address these critical environmental concerns. Likewise, developing a defensible footprint for water consumption that captures aquifer depletion, loss of ecologically sustainable in-stream flows and degradation of water quality would represent a significant improvement in accounting for vital ecosystem services performed by lakes, rivers, streams, and underground water reserves. Before international standards for EFA are promulgated, we believe the modifications discussed in this paper as well as these additional refinements should be fully explored.

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