Recasting Marine Ecological Fishprint Accounts[1]

By

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Abstract

The ecological footprint is a ubiquitous sustainability indicator used in academic, policy, and educational settings. Ecological footprints measure how much of the Earth's annual regenerative capacity is required to renew the resources used by a defined population in a given year. Ecological footprint analysis (EFA) compares the footprint with the biological capacity provided by forests, crop land, pasture land, and fisheries. While standard EFA shows humanity's footprint overshooting Earth's overall biocapacity by 22%, it indicates our fisheries are sustainable. Clearly, this finding is at odds with the reality of collapsing fish stocks and marine ecosystems throughout the world's oceans.

As a remedy, this paper suggests several modifications to the "fishprint" component of standard EFA. We expand the scope of the fishprint to include the entire ocean since fishing on the high seas is becoming an increasingly important component of the global catch. To address changes in mean trophic levels, we change the basis for calculating the fishprint from tonnes to tonnes of primary productivity required. We modify the basic EFA equations to include an ecological sustained yield threshold and to reflect declining biocapacity when this threshold is breached. We also modify biocapacity to account for marine protected areas. Our new approach suggests that humanity's fishprint exceeded the Earth's marine biocapacity beginning in 1970. By 2003, we report a global overshoot of 157%. Important factors contributing to country-level fishprint differences include EEZ size, fishing intensity, mean trophic level of the catch, fisheries export value, and region.

Keywords: ecological footprint analysis, sustainability, fisheries, primary productivity

Abbreviations

EEZ – Exclusive economic zone
EFA – Ecological footprint analysis
ESYT – Ecological sustained yield threshold
FAO – Food and Agriculture Organization of the United Nations
GAEZ – Global agriculture ecological zone
LME – Large marine ecosystem
LPR – Living Planet Report
MEA – Millennium Ecosystem Assessment
MPA – Marine protected area
MSY – Maximum sustained yield
NOAA – National Oceanic and Atmospheric Administration
NPP – Net primary productivity
PPR – Primary productivity required
RRCI – Relative rate of catch increase
WWF – World Wildlife Fund

1.0 From Footprint to Fishprint

Ecological footprints provide a spatial measure of humanity's use of nature in terms of standardized hectares of average global productivity and with respect to four major biomes: crop land, pasture land, forest land, and marine and inland fisheries. Ecological footprints also calculate the spatial demands of lands occupied by built space and the area needed to sequester our carbon emissions. By comparing ecological footprints with renewable biological capacity ecological footprint analysis (EFA) provides a largely heuristic tool for assessing the degree to which humanity's use of nature is sustainable. When humanity's ecological footprint exceeds biological capacity we are said to be engaging in unsustainable ecological overshoot and depleting stocks of natural capital on which we rely for renewable natural resource flows. Semi-annual *Living Planet Reports* (LPR) published by the World Wildlife Federation and the Global Footprint Network provide the most authoritative calculations of the ecological footprint on a global, continental, and national basis. According to the 2004 LPR report, humanity's ecological footprint was calculated to be 2.2 global hectares (gha) per person while biocapacity was estimated to be 1.8 gha – an overshoot of 22%. 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 and Wackernagel, 2004 pg. 1).

In part because EFA corroborates an increasingly vast pool of scientific evidence suggesting that we have breached the ecological limits of the planet, it has earned widespread popularity in academic, policy, and educational settings. It is now considered one of the most ubiquitous measures of ecological sustainability. According to the Untied Nations Convention on Biological Diversity, EFA "provides a valuable form of ecological accounting that can be used to assess current ecological demand and supply, set policy targets, and monitor success in achieving them" (UNEP, 2005).

Despite its popularity, EFA has several theoretical and methodological problems that may ultimately hinder its more widespread acceptance in policy settings (Van den Berg and Verbruggen, 1999; Venetoulis and Talberth, 2006). Of particular concern is the fact that while global EFA accounts published in the LPR reveal that overshoot is evident at an aggregated, global level, they do not show overshoot for crop land, pasture land, forest land, or marine and inland fisheries, implying that our use of these biomes is within biological carrying capacity and that depletion of natural capital is not occurring (Loh, 2002; Loh and Wackernagel, 2004). Of course, the evidence shows otherwise. As the recent Millennium Ecosystem Assessment (MEA) report concludes, human actions are depleting Earth's natural capital and "putting such strain on the environment that the ability of the planet's ecosystems to sustain future generations can no longer be taken for granted" (MEA, 2005, pg. 5).

With respect to fisheries, the inconsistency is particularly troubling. The United Nations' most recent *State of the World Fisheries and Aquaculture* report found that 76% of all marine fish stocks are fully exploited, overexploited, depleted, or recovering (FAO, 2004). Myers and Worm (2003) suggests that the ocean has lost more than 90% of large predatory fishes. Clearly, to serve as a basis for evaluating the sustainability of humanity's use of the seas, the ecological footprint needs to be brought in line with these rather alarming realities and reflect the ecological overshoot known all too well by fisheries biologists throughout the world.

As a first step, this paper suggests several modifications to the fisheries component of standard EFA – hereafter, the "fishprint." The modifications address the fishprint's failure to signal marine fisheries overshoot and the phenomenon of "fishing down food webs" (Pauly et al.,

1998) as well as other problems in catch data and geographic scope. We expand the scope of the fishprint to include the entire area of the ocean since fishing on the high seas is becoming an increasingly important component of the global catch. To address changes in mean trophic levels, we change the basis for calculating the fishprint from tonnes to tonnes of primary productivity required using data from the University of British Columbia's *Sea Around Us* project. We modify the basic fishprint equations to include an ecological sustained yield threshold and to reflect declining biocapacity when this threshold is breached. We also modify biocapacity to account for suggested extent of marine protected areas.

The remainder of the paper is organized as follows. In Section 2, we review EFA's role in previous work related to sustainable fisheries and aquaculture. In Section 3, we document EFA's failure to capture unsustainable use of the world's fisheries at both a global and country level and other problems related to geographic scope and catch data. In Section 4, we review the standard fishprint methodology and propose a series of modifications in the context of four separate models. In Section 5, we apply these models to *Sea Around Us* data and develop new global fishprint accounts for 1950 to 2003 as well as country level accounts for 2003. In Section 6, we conduct a multivariate cross sectional analysis of the new accounts to test assumptions about differences in country level fishprints. Conclusions and suggestions for future research are set forth in Section 7.

2.0 Fishprints in Previous Work

The science and practice of calculating marine ecological fishprints has been evolving since the late 1980s. As noted by Warren-Rhodes et al. (2004), fishprints "measure the marine ecosystem area appropriated by human populations to supply seafood and other marine products and services." Fishprint methods have been as diverse as the fisheries they study. They vary with respect to activities addressed, metrics, scale, and scope. The vast majority of studies have considered fishprints of specific activities, such as mariculture or capture fisheries on an aggregate or species specific basis. Mariculture studies have addressed both intensive and semi-intensive systems. For example, Folke (1998) found that production of the fish content of dry pellets fed to cage-farmed salmon demands a supporting marine production area 40,000 to 50,000 times the surface area of cultivation. Larsson et al. (1994) estimated the spatial ecosystem support required to produce food inputs, nursery areas, and clean water to semi-intensive farming of shrimps in the Bay of Barbacoas to be 35-190 times larger than the surface area of individual farms. Tyedmers (2000) addressed the fishprint per tonne of four species of captured and culture salmon and considered biological, labor, fossil fuel, and electricity inputs. Fishprints for captured salmon species ranged from 5.03 to 10.17 hectares per tonne while fishprints for farmed salmon ranged from 9.2 to 15.8.

In terms of metrics, fishprint studies fall into two categories: spatial to spatial fishprints and spatial to weight fishprints (Wolowicz, 2005). Spatial to spatial fishprints are most common in mariculture settings and calculate the marine ecosystem area in hectares required by either one or the total number of hectares of surface cultivation. The Larsson et al. (1994) study is an example. Another is Berg et al. (1996), who found that the fishprint required for food production in intensive tilapia cage farming in Lake Kariba, Zimbabwe is 10,000 times larger than the area of the cages. Spatial to weight (or vice versa) fishprints calculate the area needed to produce a specified weight of fish either produced or captured. Tyedmers (2000) provides one example. Weber (2004) found that for every metric tonne of cultured Atlantic salmon, 10.6 hectares of marine area and 3.0 hectares of terrestrial area was required. Bunting (2001) converted spatial to spatial fishprints calculated by Berg et al. (1996) as well as Robertson and Phillips (1995) into weight to spatial metrics and found, for example, that to produce 1 kilogram of tilapia in a semi-intensively managed pond requires an ecosystem area of 1.78 square meters and an additional square meter for phosphorous assimilation and oxygen production. Contrary to findings from spatial to spatial area studies, Bunting (2001) demonstrated that from a weight to spatial area framework, semi-intensive systems have larger fishprints.

The scale of fishprint studies has ranged widely from individual operations and individual fisheries to production and consumption patterns of cities, regions, nations, and the world. Most mariculture studies noted above have been conducted at the scale of individual operations. Folke (1998) was among the first to consider the fishprint of an entire fishery in a region by calculating the primary production required in the North Sea and Baltic Sea required by captured and cultured salmon. Folke and Kautsky (1989) extended these results to addresss Norway's salmon consumption. They found that an annual production of 8×10^7 kilograms of farmed salmon in Norway would require roughly 15% of the primary production of the fishable area of the North Sea. Folke et al. (1996) estimated that the largest cities of the Baltic Sea drainage basin appropriate a "marine shadow" area of at least 133 times their actual area. Later, Folke et al. (1997) found that 25% of globally available shelf, coastal, and upwelling areas are appropriated to supply seafood to 20% of the global human population living in large cities.

Finally, fishprint studies differ in scope. Most consider fishprints by themselves to provide comparisons between alternative fisheries management systems or consumption patterns without reference to biological capacity. Others compare the fishprint with biological capacity as a rough guide to sustainability, more in keeping with the overall EFA methodology. For example, Folke et al. (1997) considered the per capita seafood consumption of inhabitants of the world's largest cities and found that the rest of the world could not consume similar amounts of marine resources since it would mean that, “the world’s productive marine ecosystems would be exploited beyond their full capacity.” Warren-Rhodes et al. (2004) estimated the marine ecosystem area appropriated by Hong Kong’s total reef fish consumption and grouper consumption. They also calculated the percentage of ecological sustained yield appropriated under “optimistic” and “pessimistic” scenarios. They found that Hong Kong appropriates an area 6,500 to 13,000 times the size of its own coral reef and that grouper demand for Hong Kong alone exceeds total sustainable grouper production throughout Southeast Asia by 40 to 160%. This study is one of the first to incorporate sustainable yield thresholds into fishprint analysis.

In their semi-annual *Living Planet Reports* Loh (2000, 2002) and Loh and Wackernagel (2004) provide global and national level fishprint estimates along with estimates of biological capacity for marine and inland fisheries. These are the only published fishprint studies of which we are aware that address the world’s entire catch. As we explain in this next section, the last two LPR reports suggest that per capita fishprints equal biocapacity for the marine and inland fisheries biome, implying that humanity’s consumption of fish is sustainable. This article suggests a new approach for calculating these global accounts that incorporates, in part, the general approach outlined by Warren-Rhodes (2004).

3.0 Troubled Waters – Something’s Fishy with Global Fishprint Accounts

Table 1 reprints the results from the LPR global accounts for 2000, 2002, and 2004 as well as a recent calculation by Venetoulis and Talberth (2006) based on a proposed refinement to EFA methodology. For each biome, Table 1 provides LPR calculations of biocapacity and ecological footprint per capita as well as the resulting ecological balance (biocapacity – footprint). Note that LPR reports in 2002 and 2004 show no ecological overshoot (negative ecological balance) for any of the major biomes. In each report, humanity’s per capita use of forest land, crop land, pasture land, and marine and inland fisheries is shown to be at or below biological capacity, implying that our use of these biomes is sustainable. In fact, it is only because carbon emissions are assigned a footprint and not biological capacity that there is any overshoot reflected by these LPR reports at all. Findings reported in the LPR 2000 are the same, with one notable exception. Here, fisheries biocapacity was reported to be .03 gha per capita while the fishprint was reported to be .04 gha. Correspondingly, "[t]he total fishing ground footprint of the world's population therefore exceeded the availability of the world's fishing grounds by approximately 30%" (Loh, 2000, pg. 20). Significant changes to the methodology occurred in subsequent LPR reports, and the 2002 and 2004 reports remain the most authoritative figures. In those reports, biocapacity and fishprints for the marine and inland fisheries biomes are balanced at .14 gha in 2002 and .13 gha in 2004 (Loh, 2002, pg. 22-23; Loh and Wackernagel, 2004, pg. 24-25).

Of course, these findings belie the fact that marine and inland fisheries are in crisis and that depletion of fish stocks is occurring throughout the world's oceans and have been occurring since fishing first became industrialized in the late 19th century (Ludwig et al., 1993). The United Nations Food and Agriculture Organization (FAO) estimates that at least 24% of all fish stocks are overexploited, depleted, or recovering from depletion (FAO, 2004). As little as 10% of large predatory fish remain in the oceans (Myers and Worm, 2003). To compensate, nations are increasingly fishing down food webs by capturing greater quantities of smaller fish lower on the food chain prompting fears that fish populations previously thought immune to overfishing will suffer the fate of higher trophic level species (Pauly et al. 1998; Pauly and Palomares, 2005). In fact, according to Pauly and Palomares (2005, pg. 207), the fishing down phenomenon is "ubiquitous and much stronger than previously believed."

The LPR reports also provide fishprint and biocapacity estimates on a country by county basis. These country level fishprint accounts also seem at odds with well known facts about the plight of fisheries by showing positive ecological balances for countries known to be engaging in overfishing and stock depletion. For example, the LPR accounts for 2004 show that the United States has a marine and inland fisheries biocapacity of 0.36 gha per capita and a fishprint of just 0.23 (Loh and Wackernagel, 2004, pg. 28-29). This is in contrast with reports from the National Oceanic and Atmospheric Association (NOAA) indicating that roughly 30% of assessed federally managed ocean fish stocks are overfished to levels below those which would support the maximum sustainable yield on a continuing basis (NOAA, 2004). As another example, the LPR fishprint accounts show both Norway and the Russian Federation as running positive ecological balances (Loh and Wackernagel, 2004, pg. 30). However, both nations have significantly overfished cod to the point where the International Council for the Exploration of the Sea (ICES) recommended a full stop to coastal cod fishing in the Russian and Norwegian waters in 2003 (WWF, 2004).

Other problems with global fishprint accounts include limited consideration of biocapacity and failure to capture differences in mean trophic levels of country level catches. In terms of biocapacity, the most recent LPR global fishprint accounts assume that only 1.9 billion hectares (i.e. continental shelves) is fished out of an ocean area of over 36.3 billion hectares (Loh and Wackernagel, 2004). Given that the high seas' constitute over 90 percent of the oceans and about 40% of fish are caught outside the continental selves, it seems illogical to not include the entire ocean area. In terms of trophic level, the LPR accounts assign an equal fishprint to countries with the same raw weight of catch. This, of course, overlooks important trophic level differences and the fishing down effect discussed by Pauly et al. (1998) and Pauly and Palomeres (2005).

Venetoulis and Talberth (2006) proposed a modification to the basic EFA methodology that responded to earlier critiques offered by Van den Bergh and Verbruggen (1999) and others. These critiques, in part, called attention to the fact that EFA global accounts underreported biocapacity and failed to distinguish between sustainable and unsustainable use of key biomes. The new EFA approach suggested by Venetoulis and Talberth (2006) includes the entire surface of the Earth in biocapacity, allocates space for other species, changes the basis of equivalence factors to net primary productivity (NPP), reallocates the carbon budget and reports carbon sequestration biocapacity. While their results show a 20% overshoot for the marine and inland fisheries biome at a global level – mainly due to the deduction of biocapacity for other species – they left sustainability criteria and other deeper fishprint issues for future research. In Section 4, we attempt to tackle these issues in the context of an alternative fishprint accounting method.

4.0 Beyond Bait and Tackle: A New Fishprint Methodology

Before we describe the fishprint methodology used in this study, the basics of the most widely used approach are briefly explained. Recall that ecological footprint analysis (EFA) measures the area of forest, pasture land, crop land, and marine and inland fisheries needed to support our consumption patterns and assimilate our wastes all in terms of standard global hectares of average biological productivity. For each biome footprints are compared with biocapacity to gauge whether or not humanity is overshooting its ecological limits. Here, we are interested in the marine fisheries biome alone. We further restrict our analysis to capture or wild fisheries, since the methodology for aquaculture is still under development.

4.1 Fishprints and biocapacity under the standard approach

For an individual country, the marine fishprint measures the ocean area needed to support the amount of wild fish consumed by the population within its borders. The standard fishprint is calculated with three pieces of information: (1) tonnes of various species of fish consumed by a given country (T); (2) a global yield factor (YF_G) in tonnes per hectare, and (3) an equivalence factor (EQF) needed to convert a hectare of marine fisheries into standard global hectares (Wackernagel et al., 2005). For country N in year y the fishprint (FP) is simply:

$$[1] \qquad FP_{N_y} = \frac{T_{N_y}}{YF_{G_y}} \times EQF$$

T_N is taken from annual FAO statistics. YF_G is global fish catch divided by the global area fished in a given year. The reason for using a global yield factor here is that fish consumed in any particular country in a given year are caught in various places on the planet with various levels of productivity. Because it is cumbersome to calculate different yield factors associated with imports from each country from which those imports are received, a global average is used. Under the standard approach, *EQFs* are calculated for each biome by dividing a biome's average productivity by the world average where productivity is measured in terms of its agricultural potential as determined by FAO's Global Agricultural Ecological Zone (GAEZ) data. The standard fishprint approach assigns marine fisheries an EQF of 0.35, implying that the productivity of marine fisheries is 35% of the global average.

For biocapacity, the standard approach is also calculated with three pieces of information: (1) the area a country has exclusive rights to fish (A); (2) a ratio of a country's per hectare yield to the global average (YFR_n), and (3) the marine fisheries equivalence factor (EQF). For country N in year y then, marine fisheries biocapacity (BC) is:

[2] $$BC_{N_y} = A_{N_y} \times YFR_{N_y} \times EQF$$

As stated in the *Living Planet Reports*, A_N is the area of a country's exclusive economic zone. YFR_N is the tonnes of fish caught by country N divided by its fishing area (A) all divided by YF_G. The reason for including this country-specific yield factor ratio is to reflect the fact that fishing grounds of individual countries vary widely in terms of productivity. YFR, then, can be thought of as a *within*-biome equivalence factor. In contrast, EQFs are for comparisons *between* biomes.

4.2 Fishprints and biocapacity under the new approach

In this section, we introduce modifications to fishprint and biocapacity calculations. We begin by incorporating an entirely new set of data published by the University of British Columbia's *Sea Around Us* project (www.seaaroundus.org) which provides time series catch data for each country from 1950 to 2003. These data alter the basis for reporting from tonnes to tonnes of primary productivity, thereby capturing differences in the mean trophic level of global and country level catches. The primary production required (PPR) by catches is a function of the trophic level of the species that are caught. Thus, far more primary production is required to produce one tonne of a high-level trophic fish, for example tuna, than of a low level- trophic fish, for example sardine. This is because the transfer efficiency between trophic levels is in the ocean relatively low, 10 % on the average (Pauly and Christensen, 1995). To calculate the primary productivity of a given tonnage of fish caught by country N in year y, we need the mean trophic of the catch (TL) an assumption about trophic efficiency (here 10%) and the equation:

[3] $$PPR_{N_y} = T_{N_t} \times 10^{TL-1}$$

The catches used here are based mainly on statistics from FAO and other sources disaggregated spatially and taxonomically as outlined in Watson et al. (2004). To date, these catches represent mainly “nominal landings”, as discarded by-catch, illegal and other unreported catches have been estimated for only a few countries. These data are constantly being improved, and the footprints will change accordingly when the data becomes available. Also, the PPR corresponding to imports of fish and other seafood will be added where appropriate. PPR is calculated separately for each species (or group of species) for the fleets of all countries operating in the EEZ of the country in question (or in a Large Marine Ecosystem (LME) or High Sea Area), expressed in terms of the primary production in that EEZ, LME or High Sea Area. The combined pressure of different countries fishing in a given area can thus be assessed, as can the footprint of a country that exploits its EEZ, the EEZs of other countries, and the High Seas.

To incorporate these data into the fishprint framework, we begin by substituting tonnes of primary production (TPP) required by the catch of each country in each year for (T) in equation [1]. Note also that by doing this, we move away from a consumption-based fishprint to a fishprint based on catches. This is an intermediate step due to the lack of import and export data at this point in time. With PPR-based import and export data currently being compiled by the *Sea Around Us* project, we will be able to revert to a consumption based fishprint approach since with that data, a country’s consumption can be determined by subtracting exports and adding imports to its catch.

We also make two modifications to $YF_{G.}$ First, we use global TPP instead of raw tonnes. Secondly, we divide TPP by the entire biocapacity of the oceans, not just the area of the continental shelves to acknowledge the fact that significant fishing activity does take place outside the continental shelves. Finally, we incorporate a new equivalence factor (EQF_{NPP}) for marine fisheries based on net primary productivity (NPP) rather than GAEZ. As suggested by Venetoulis and Talberth (2006), an NPP based approach for equivalence factors is more closely aligned with basic scientific understanding of the relative ecological "value" of different biomes. Under their NPP approach, the EQF for exclusive economic zone areas is 1.66 while the EQF for open oceans is 0.48. The weighted average of the two (EQF_{NPP}) is 0.94.

Under this modified approach, the fishprint of country N in year y is:

$$[4] \qquad FP_{N_y} = \frac{TPP_{N_y}}{YFPP_{G_y}} \times EQF_{NPP}$$

Again, under the new fishprint approach, the global yield factor ($YFPP_G$) is calculated by dividing the total primary productivity required by the global catch in each year by the global marine fisheries biocapacity (BC_G). Global marine fisheries biocapacity is calculated by multiplying the area of open oceans with the open ocean equivalence factor and area of EEZ with the EEZ equivalence factor. Table 2 provides the relevant calculations, and indicates a marine biocapacity of 33.94 billion global hectares (gha). From the *Sea Around Us* data, we estimate PPR for the global catch in 2003 to be 47.06 billion tonnes. Thus, we estimate the 2003 $YFPP_G$ to be 1.39 tonnes per global hectare.

Determining marine fisheries biocapacity for individual countries is more complex. The standard approach, described by equation [2] allocates biocapacity from the continental shelf area contained in a country's exclusive economic zone. This approach neglects the fact that a given country's fishing fleet may capture fish in many different parts of the world. Japan is a case in point. According to *Sea Around Us* project data, Japan's fishing fleet landed a total of 4.5 million tonnes of fish in 2003, only 47% of which was caught in its own EEZ. The remainder was caught on the high seas and in other country's EEZs. In fact, countries are often entitled to areas outside their EEZ through international or bilateral agreements, which allows them to fish in a much larger area. Another obvious disadvantage to the standard approach is the implication that landlocked countries have no biocapacity –a fact that will, by default, cause their fishprints to be unsustainable.

A remedy to the country-level biocapacity issue would require a more detailed analysis of actual areas each country is entitled to fish as well as yield factors associated with such areas. Conceptually, the S*ea Around Us* data provides the first step toward doing this because the data is reported in terms of tonnes of catch and PPR for that catch within a country's own EEZ, the high seas, and all other country EEZs where it fishes. However, refining biocapacity along these lines still fails to address the question of whether land-locked countries are entitled to biocapacity. In lieu of a more complete treatment of the biocapacity question, here we opt for a rather simplistic approach based on the concept of "fair earth share," which states that each and every individual on the planet is entitled to an equal portion of the Earth's biological productivity (Rees and Wackernagel, 1996). However, we make one necessary caveat – since we are for the time being restricted to a production fishprint approach, we cannot calculate fishprints for non-producing countries so we need to restrict our analysis to the population in countries with EEZs. Thus, marine fisheries biocapacity for country N in year y under our new approach is a function of global biocapacity (BC_G), global population (POP_G), and country N*'s* population (POP_N):

[5] $$BC_{N_y} = \frac{BC_G}{POP_{G\,y}} \times POP_{N_y}$$

4.3 Sustainability thresholds in the global fishprint model

Under the standard fishprint approach, an individual country's fishprint can exceed its biocapacity if the global hectares associated with both domestic production and imported fish exceed the area of its fishing grounds. At the global level, however, it is mathematically impossible (but not conceptually) for the fishprint to exceed biocapacity. As discussed in Section 2, this is one of the major flaws in EFA in general, and one that has cast doubt on its usefulness as a tool for evaluating the sustainability of fisheries management either at a global or country level. The reason why fishprints cannot exceed biocapacity at the global level is easy to see by examining equations [1] and [2] together, which are reproduced below in equation [6] with the fishprint on the left hand side and biocapacity on the right hand side.

$$[6] \qquad \frac{T_{N_y}}{YF_{G_y}} \times EQF \leq A_{N_y} \times YFR_{N_y} \times EQF$$

First, recall that YFR_N is a ratio of a particular country's yield factor to the global average. At the global level, the ratio reduces to 1 (i.e. global yield/ global yield). Since the marine fisheries equivalence factor (*EQF)* appears on both sides of the equation, it can be factored out. And since T is now global and not country specific, it follows that dividing T by the global yield factor simply gives back area fished or A, which, at its maximum value, can only equal and not exceed the entire area of the ocean or A from the biocapacity side of the equation. Thus, it is mathematically impossible for standard fishprint analysis to show unsustainable use of fisheries at the global level. This is why the fisheries component of the global ecological footprint is always at or below biological capacity. In the most recent analysis, both fishprint and biological capacity were calculated to be .13 global hectares per capita (Loh and Wackernagel, 2004).

As a remedy, we present four separate global fishprint models, each involving an additional layer of complexity and each permitting an imbalance between fishprints and biocapacity at the global level. As a preliminary matter, we suggest three broad criteria for evaluating the usefulness of a modified fishprint model consistent with the realities of unsustainable global fisheries management and consistent with the overall footprint framework: (1) the model should distinguish between sustainable and unsustainable use of global fisheries; (2) biological capacity should remain fixed at its maximum extent until ecological overshoot begins, decline in periods of overfishing, and rise as fishing pressure is reduced, and (3) assuming constant ecological productivity, the fishprint should rise as the global fish catch rises.

The first condition is self explanatory and is, of course, the most important fix to global fishprint analysis offered here. The second condition is simply an outgrowth of the footprint framework – unless the fishprint exceeds biological capacity, biological capacity is not eroded. If the fishprint does exceed biocapacity, it means we are drawing down natural capital stocks, and depleting biocapacity. Finally, reducing the intensity of resource use should allow biological capacity to restore itself assuming no irreversible thresholds have been breached. The third condition is intuitive. Assuming ecological productivity of our fisheries remains the same, the more fish we consume, the greater the fishprint. A model that satisfies any one of these conditions opens the door to a possible imbalance between the fishprint and biocapacity at the global level. Each of the four models discussed below introduces factors into the standard fishprint equations that create such imbalances.

Model 1

Our first model (Model 1) introduces the concept of an ecological sustained yield threshold (ESYT) for global fisheries into the fishprint framework. An ESYT is a level of global catch either in tonnes or primary productivity required (PPR) beyond which ecological sustainability is jeopardized. Using an ESYT on the fishprint side of the global equivalent of equation [4] makes it possible for the fishprint to exceed biocapacity when overfishing occurs. At the global level, the fishprint and biocapacity equivalents of equations [4] and [5] can now be expressed as:

[7] $$FP_{G_y} = \left(\frac{TPP_{G_y}}{YFPP_{G_y}} \times EQF_{NPP}\right) \times \frac{TPP_{G_y}}{ESYT_G} \leq\geq BC_{G_y} = A \times EQF_{NPP}$$

Importantly, in equation [7], the fishprint is multiplied by the ratio of a particular year's catch in PPR (TPP_G) to the ESYT for global fisheries ($ESTY_G$). This introduces a scaling factor for the fishprint that satisfies conditions 1 and 3 from above by insuring that catches below or above the ESYT translate into fishprints that are less than or greater than biocapacity and that fishprints rise with the global catch.

Of course, setting an appropriate ESYT is not an easy task. Given the heterogeneity of global fisheries and natural fluctuations in ecological productivity achieving scientific consensus on an ESYT is an elusive goal (FAO, 1996). Nonetheless, in a fishprint framework, it is perhaps the most straightforward way to cause fishprints and biocapacity to diverge at the global level in a manner consistent with global fishery trends, and therefore we do so by setting the global ESYT at a level equal to the average global fish catch during 1973-1976: 58.11 million tonnes of raw catch and 26.12 billion tonnes of primary productivity.[2]

Clearly, setting the ESYT at this level is simply a placeholder for a more accurate threshold derived from sophisticated modeling conducted on a fishery by fishery basis by fisheries biologists, not fishprint practitioners. Nonetheless, there are several good reasons why this period may serve as a useful reference point. First, we note that during the 1970s the relative rate of catch increase (RRCI) dropped to zero and below for the first significant stretch of time since 1950. The trend is reported in Figure 1 for the raw catch in tonnes, and Figure 2 for the catch expressed in terms of PPR. According to FAO (1996), RRCI is the percent increase or decrease in the current year's catch (C_t) with respect to the three year rolling average. In particular:

$$[8] \qquad RRCI_t = [C_t - [(C_{t-1} + C_{t-2} + C_{t-3})/3]/[(C_{t-1} + C_{t-2} + C_{t-3})/3]]$$

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[2] These global catch figures are based on the *Sea Around Us* estimates which take into account systematic errors in FAO landings data (Watson and Pauly, 2001).

As argued by Gaertner et al. (2001), in the absence of accurate data on fishing effort, the point where RRCI falls to zero can serve as a crude proxy for a maximum sustained yield threshold because beyond this point, stock depletion occurs. Of course, Gaertner et al. (2001) argued this from the vantage point of individual fisheries and not the global catch. At the global level, there may be many such zero points for RRCI as reflected by Figures 1 and 2 due to the constantly changing nature of fisheries. Nonetheless, RRCI may suggest something important about fundamental changes in global fisheries during the 1970s, especially when we consider RRCI side by side with other relevant indicators.

Two such indicators are mean trophic level and mean depth. Trophic level is a measure of the relative placement of the catch on the marine food web. The higher the trophic level, the more the catch is concentrated in top predators. Pauly et al. (1998) found that since the mid 1970s, the global trend in the trophic level of marine fisheries landings has been one of steady decline from landings of long lived, high trophic level, piscivorous bottom fish toward short lived, low trophic level invertebrates and planktivorous pelagic fish. Figure 3, taken from the Millenium Ecosystem Assessment (MEA) illustrates the trends for coastal areas worldwide and the North Atlantic Ocean (MEA, 2005). This decline is a clear indication of unsustainable fisheries management because it undermines the integrity of the food chain ultimately leading to ecological collapse (Pauly et al., 1998).

Mean depth of catch is a measure of how far out fishing fleets must go to find economically valuable species concentrated enough to profitably meet demand.[3] As shown in Figure 4, since the early 1970s, industrial fishing fleets have also shifted to fishing further

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[3] Mean depth refers not to the linear depth where fishing effort takes place, but the mean ocean depth surrounding fishing vessels. Thus, the catch can still be drawn from shallower ocean levels consistent with the fishing down the food web phenomenon but take place in deep sea areas further from productive coastal fisheries.

offshore and in deeper water to meet global demand (MEA 2005). This is a strong signal that coastal fish stocks have been unsustainably managed at least since that time.

Two additional indicators lend support for using the mid 1970s as a reference point for an ESYT. The first is an estimate of maximum sustained yield for global fisheries published by Briceno et al. (1990). Globally, their estimates ranged from 62 and 96 million tonnes annually. Given that FAO data likely contain errors reported by Watson and Pauly (2001) leading to overestimated catches and that MSY calculations are not ecologically based (i.e. they don't incorporate trophic level considerations) the low end of this spectrum is probably the most valid. According to FAO catch data, the low end of this spectrum was attained during the early 1970s. Yet another important indicator is the steep rise in marine fisheries deemed overexploited, depleted, or recovering. As can be seen in Figure 5, the number of these imperiled fish stocks was level during the early seventies and then rose steeply thereafter.

Taken together, trends in the relative rate of catch increase, trophic levels, mean depth and degree of stock exploitation coupled with initial MSY estimates by Briceno et al. (1990) strongly suggest that the mid 1970s was an important transition point for marine fisheries. After the mid 1970s, global fisheries exhibit several unmistakable signs of overexploitation and unsustainability on a global level. Thus, we begin the debate over an appropriate ESYT to incorporate into the fishprint framework with our mid 1970s reference point.

Model 2

Model 2 is identical to Model 1 but adds one additional factor creating an imbalance between the fishprint and biocapacity at the global level. In particular, we deduct an area equivalent to 20% of all EEZs from biological capacity as a "reserve" for other species. This amplifies the ability of our new fishprint model to satisfy condition 1 from above.

The general approach of deducting portions of the Earth's biological capacity essential for the well being of other species in the footprint framework is discussed at length in Venetoulis and Talberth (2006). The motivation for doing this can be understood with a forestry example. Imagine a forest area of 100 hectares. Ecologists studying forests have concluded that 20 hectares should be kept untouched as a reserve for species and natural processes critical to the long term health of the entire 100 hectares. If the footprint generated by our consumption of forest products extends to the full 100 hectares, we can conclude that, at minimum, 20% of that footprint is unsustainable. And since we cannot use that 20% of biological capacity sustainably, we must deduct it from biological capacity since biological capacity is, by definition, the area we can use year after year without degrading overall ecosystem health.

This is exactly what we have done in Model 2. While the method is sound, the precise threshold is certainly debatable. Admittedly, the 20% figure is largely arbitrary and set at this level to make a point about fishprint methods, not to suggest this is all that is needed to sustain the health of our global fisheries in the long run. However, multiple studies on the effects of marine protected areas (MPA) suggest that this threshold may not be too far off the mark.

Over the past two decades, there has been a proliferation of research on the impacts of marine protected areas on fishery yields. These studies strongly suggest that large "no-take" MPAs with fully functional food webs are a critical tool for rebuilding and maintaining the overall health of fish stocks, minimizing the risk from overexploitation of unprotected areas, and protecting biological diversity (Lauck et al., 1998; Pauly et al., 1998). In fact, several studies have found that MPAs boost overall yields. For example, Sladek-Nowlis (2000) modeled the effects of reserves on catches of the Caribbean white grunt and found that at moderate fishing intensities, catches peaked at reserves covering 30% of the management area. Holland and Braze

(1996) simulated the effects of reserves on red snapper catches in the Gulf of Mexico and concluded that for a range of heavy exploitation rates optimal reserve areas that maximized the catch ranged from 15 to 29% of the fishing area. Table 3 provides a list of MPA related studies compiled by the National Academies of Sciences (NAS 2000).

The last two columns of Table 3 show low and high ranges for recommended MPA size expressed as a percentage of fishing area addressed by each study. If the study did not provide such a range or if the recommended MPA size was not based on actual analysis we simply included an “n/a” in those columns. Assuming that these studies are reasonable comparable, we can look to the median as a possible starting point for a recommended reserve size to introduce into the fishprint framework. As shown in Table 3, the median “low” end of the range was 20% of fishing area size, while the median “high” end was 33%. To be conservative we adopt the former and deduct 20% of global marine fisheries biocapacity from EEZs (a crude proxy for fishing area) as a necessary set aside for protecting the resiliency and sustainability of global fisheries. This reduces global marine biocapacity from 33.94 billion global hectares (gha) to 29.21 gha. Hereafter, we refer to this adjusted biocapacity as BC_{MPA}.

Model 3

In the standard footprint framework, ecological overshoot begins when footprints exceed biocapacity. The standard explanation of how footprints can exceed the Earth’s biocapacity is that we are “drawing down natural capital stocks” – i.e. living off the “principle” represented by the stock of a particular natural resource rather than the “interest” represented by renewable resource flows regenerated on an annual basis by that stock (Rees and Wackernagel, 1994). Again, drawing from our previous forestry example, we can maintain a sustained yield of timber from 100 hectares of forest as long as the ecological integrity of the entire 100 is kept intact by setting aside 20% as no cut reserves. If we exceed that threshold, say by cutting 90 hectares, it stands to reason that our ability to appropriate timber from that forest in the future will be eroded either by a reduction in yields or a reduction in area available for harvest. So in the next year, we may only be able to harvest 70 hectares, the year after that 60, and so on as long as we are managing the forest unsustainably by intruding into the proportion of the remaining forest stand that should be reserved. Thus, to be internally and logically consistent, EFA must show that biocapacity remains constant until overshoot, declines during periods of overshoot, and recovers when overshoot ceases. Of course, this is just a restatement of condition 2 from above. Models 1 and 2 do not reflect this condition. In both models, biocapacity is constant over time. In Model 3, we introduce a modification that satisfies condition 2.

We accomplish this by deducting the marine fishing area unsustainably used each year from biocapacity. We define the area unsustainably used area as the area needed to generate the amount of catch over and above the ESYT adjusted to conform with FAO's periodic assessments that identify the percentage of all assessed stocks known to be overexploited. That percentage has risen from 10% in the 1970s to 24% today. Without this adjustment, overshoot would be evenly distributed across all stocks rather than concentrated in the subset of stocks actually overfished. Thus, we modify the biocapacity equation to be conditional on the degree of overshoot and the percentage of stocks listed as overexploited so that:

[9] $$\text{If } \frac{TPP_{G_y}}{ESYT_G} > 1, \text{ then } BC_{G_y} = BC_{MPA} - \{[(\frac{TPP_{G_y}}{ESYT_G} - 1) \times BC_{MPA}] \times FAO_y\}$$

$$\text{If } \frac{TPP_{G_y}}{ESYT_G} \leq 1, \text{ then } BC_{G_y} = BC_{MPA}$$

In other words, if the global catch in PPR (TPP_G) in year y exceeds the ecological sustained yield threshold ($ESYT_G$) then the MPA adjusted biocapacity is further reduced by the percentage of overshoot discounted by the percentage of stocks FAO lists as overexploited in a given year (*FAO*). If the global catch is less than or equal to the ESYT, then biocapacity reverts to 100% of the MPA adjusted level.

Admittedly, this is a quick fix to problems with EFA's fishprint component. To be rigorous, the model needs to account for (1) a declining *ESTY* over time as biocapacity is reduced; (2) time lags, and (3) more accurate data on the spatial extent of overfishing. Obviously, with reduced biocapacity, the *ESYT* should also decline because if it does not, the model assumes that it is ecologically sustainable to catch the same weight of fish from a reduced area. The model should also recognize that there is a significant time lag between overexploitation of a fishery and ecological collapse as well as a significant time lag between reduced catch and ecological recovery. In Model 3, effects are instantaneous. Biocapacity is reduced the same year overshoot occurs, and biocapacity increases the same year the catch is reduced. Lastly, the FAO adjustment factor is a convenient proxy for a more precise estimate of the spatial area subject to overshoot in a given year by incorporating species specific data. Just because 10% or 24% of stocks are listed as overexploited in a given year does not mean that overshoot should be assigned to an equivalent proportion of ocean area. Clearly, these are fruitful areas for further refinements. In the meantime, we offer Model 3 as a highly stylized approach for modifying EFA to reflect declining biocapacity in the face of overshoot.

Model 4

Model 4 constrains the size of the fishprint to be equal to or less than raw (i.e. unadjusted for MPAs and overshoot) marine fisheries biocapacity, or 33.94 billion gha in order to be more consistent with standard EFA. In standard EFA, humanity's global footprint can never exceed the surface of the Earth. The reason for this is the assumption that each hectare of the Earth's surface only provides one function at a time, so that if we appropriate that hectare for one of these functions, it cannot be counted again. Venetoulis and Talberth (2006) relaxed this assumption and recognized that each hectare can perform multiple functions such as carbon sequestration *and* food provision so if we fully appropriate both functions, our footprint is two hectares per hectare of land and not one. In this way, they calculated humanity's global footprint in 2001 to be significantly greater than the Earth's 51 billion hectares.

Still, a fishprint larger than the ocean area has its drawbacks in terms of intuitive appeal. For this reason, we adjust the fishprint size in Model 4 to match raw biocapacity during the year of maximum catch, and scale all other years back proportionally from this level. According to the *Sea Around Us* data, PPR reached its maximum value in 1999. Thus, we add an additional scaling factor to the left hand side of equation [7] to set the fishprint equal to raw biocapacity in 1999 and proportionally less in all other years so that:

[10] $$FP_{G4_y} = 33.94 \times \frac{FP_{G_y}}{FP_{G_{1999}}}$$

In equation [10], FP_{G4} is the Model 4 fishprint. Again, it is equal to raw biocapacity (33.94 billion gha) in 1999, and reduced in other years by multiplying this figure by the ratio of a particular year's fishprint as calculated in Models 1-3 to the 1999 fishprint.

4.4 Sustainability thresholds in the country level fishprint model

Models 1 – 4 introduce sustainability thresholds into the global fishprint and biocapacity calculations. To incorporate such thresholds into country specific fishprint and biocapacity calculations, we take a rather simplistic approach. For biocapacity, we multiply each country's population in a given year by the global per capita biocapacity calculated by each model for each year. For the fishprint, we assume that global overfishing in each year under each model is equally distributed so that each country's fishprint is reduced or enlarged by a corresponding percentage in that year. For example, under Model 3, global catch exceeded the ESYT by 79.70%. Accordingly, we scale each country's fishprint as calculated by equation [5] up by a factor of 1.7970. In this way, the sum of country level fishprints equals the global fishprint calculated by each model. In Model 4, we multiply country level fishprints calculated in Model 3 by an additional scaling factor to insure that the sum of the country-level fishprints match the constrained global fishprint from Model 4. In 2003, that scaling factor is .56, which is the ratio of the Model 4 global fishprint in 2003 to the global fishprint from Model 3.

5.0 Results

We applied all four models to time series data provided by the *Sea Around Us* project. The data are current through June 30th, 2006. For each model we produced global fishprint accounts detailing both total and per capita primary productivity required, marine fisheries biocapacity, fishprint, and ecological balance. For each model, we also produced a set of country level accounts for the same time period. Global results are illustrated by Figures 6 and 7. Table 4 reports country level figures for 2003. In this section we provide highlights of both global and country level accounts and present the results of a cross sectional multivariate regression model to explain differences in country level fishprints.

5.1 Global results for 1950-2003

Figure 6A reports global results for Models 1 and 2. Under both models, the fishprint rises steadily from a value of 12.49 billion global hectares (gha) in 1950 to 60.95 gha in 1999, then drops back to 60.79 in 2003. Biocapacity remains fixed at 33.83 billion gha under Model 1 and 29.21 under Model 2. Recall that Model 2 incorporates a 4.62 billion gha deduction as the suggested extent for marine protected areas off limits to commercial fishing. Importantly, both models show substantial ecological overshoot, indicating that our use of marine fisheries is well beyond the threshold of ecological sustainability. In Model 1, overshoot began intermittently in 1974, peaked at 80.16% in 1999, and stood at 79.70% in 2003. In Model 2, overshoot begins in 1970, peaks at 108.62% in 1999, and then falls slightly to 108.10% in 2003.

Figure 6B reports global results for Models 3 and 4. In Model 3, the innovation was to reflect declining biocapacity in years when the ecological sustained yield threshold of 26.19 billion tonnes of primary productivity was breached. Biocapacity loss is a function of the magnitude of that overshoot as well as stock status as reported by FAO. While the fishprint remains the same as in Model 2, biocapacity declines from 29.21 billion gha in 1950 to 22.66 in 1999, and then rises to 23.62 gha in 2003. Overshoot is first indicated in 1970 and rises steadily to 169% in 1999, falling back to 157% in 2003. Of course, this is a substantial increase in overshoot over Models 1 and 2, but may be more in line with ecological realities. For example, in their study of the live reef fish food trade in Southeast Asia, Warren-Rhodes et al. (2004) estimated overshoot to be up to 159% for Hong Kong's consumption of groupers.

In Model 4 we introduced a constrained fishprint that equaled raw biocapacity when global PPR reached a maximum in 1999. The fishprint rises from 6.94 billion gha in 1950 to 33.83 in 1999, then back down to 33.74 in 2003. Overshoot in Model 4 begins in 1988, peaks at 49% in 1999, and backs down to 43% in 2003. One additional feature of note in Model 4 is the fact that biocapacity begins its decline (1974) prior to overshoot (1988), an apparent inconsistency with condition 2 from Section 4.3. While the Model 4 equations could have been written differently to bar this result, we have presented it this way to illustrate another important modification to fishprint analysis that bears consideration – making marine biocapacity loss a function of other factors besides overfishing. Indeed, Caddy et al. (1998) found that eutrophication from land based runoff to be an important factor making fisheries in parts of the Meditteranean, Black Sea, and U.S. Gulf Coast "shadows of their former selves."

Figure 7 illustrates per capita trends. In Models 1 and 2, the fishprint rises from 5.25 gha per capita in 1950, to 10.81 in 1999, then down to 10.28 in 2003. In Model 1, increasing world population causes biocapacity per capita to fall steadily from 14.21 gha in 1950 to just 5.72 in 2003. In Model 2, biocapacity falls steadily from 12.27 gha in 1950 to 4.94 in 2003. In Models 3 and 4, biocapacity falls more steeply to a low of 3.93 gha in 2002, rising slightly to 3.99 in 2003. In Model 4, the constrained fishprint rises from 2.91 gha in 1950 to 6.00 in 1999, then back to 5.70 in 2003. For each model, per capita overshoot is identical to the overshoot percentages reported above for global totals.

5.2 Country level results for 2003

Table 4 provides a snapshot of Model 3 fishprint accounts for 149 nations for which *Sea Around Us* data is presently available. Table four ranks countries from "worst" to "best" in terms of ecological balances. Japan, Indonesia, China, Norway, the Philippines, Taiwan, Thailand, the United States, Iceland and Russia top out the list with an average ecological balance of minus 2.1 billion gha. For the group as a whole, overshoot is 188%. In footprint speak, if every other nation on Earth placed similar demands on the world's marine fisheries, we would 2.88 Earths to sustain this demand in perpetuity.

To be fair, much of this excess production is distributed to nations who do not fish so intensively. As such, the overshoot figures overstate the case against these countries' fisheries practices. Nonetheless, the degree of overshoot for these and other nations near the top of the list in Table 4 is an ominous signal consistent with what we know about the state of fisheries exploited by these nations. For example, we previously noted that LPR accounts for 2004 indicate that Russia, Norway and the United States all fish within their biological capacities despite well know episodes of overfishing and stock depletion for Atlantic cod, Atlantic salmon and capelin. Likewise, in the 2004 LPR, Indonesia was reported to have no overshoot with a per capita marine fisheries biocapacity of .28 gha and a fishprint of .25. Our results suggest that Indonesia has a 301% overshoot, more in line with known fisheries concerns such as the collapse of wild-caught grouper populations due in part to destructive blast fishing practices (Pet-Soede and Erdamm, 1998).

5.3 Regression analysis

To help explain country-level fishprint differences, we conducted multivariate cross sectional analysis on the 2003 fishprint figures. Due to the wide range in absolute fishprint values, we used the natural log of each country's 2003 fishprint as the dependent variable (*lnfp*). In our model, we tested the effects of EEZ size (*lneez*), fisheries export value (*lnfex*), mean trophic level (*tl*), primary productivity required by the catch per EEZ hectare (*ppreez*), and dummy variables for eight reporting regions: Africa (*afr*), Caribbean (*car*), Latin America (*lat*), Far East (*fare*), Near East (*neas*), North America (*na*) and Oceania (*oce*). Europe was the omitted regional dummy.

EEZ size is a supply size variable approximating actual biocapacity available to each nation (as opposed to figures used in the accounts which simply distribute biocapacity evenly amongst nations on a per capita basis). Greater biocapacity, of course, implies greater catches if we assume that most fisheries are nearing or exceeding full exploitation. Thus, we expect a positive correlation here. We also expect a positive correlation between fisheries export value and the fishprint since nations with more developed export markets for fish are more likely to be fishing more intensively. As a general measure of intensity, we included primary productivity required by the catch (regardless of where that catch was obtained) divided by EEZ area. Again, we expect a positive correlation. We did not, however, have any *a priori* expectations about the sign of trophic level. On the one hand, with an equal tonneage of catch, the fishprint will be greater with an increase in the mean trophic level of that catch. On the other hand, nations fishing down food webs often experience an increase in landings for a while before inevitable stock depletion sets in (Pauly at al., 1998). Nor did we have any *a priori* expectations about the sign or significance of coefficients for the dummy variables, except for the fact that nations with the highest profiles in terms of fishery collapses are clustered in the Far East and Europe.

Table 5 reports the results. Model A includes all variables, while in Model B, we omitted all regional dummies. In Model C, we excluded fisheries export value (*lnfex*) since it was missing from a number of countries. All three models had significant explanatory power with adjusted r-squared values of .6647 (Model A), .6012 (Model B), and .5142 (Model C). All three values are quite high for cross sectional data. As expected, *lneez, lnfex*, and *ppreez* were significant and positive. Of these, the size of the EEZ (*lneez*) had the greatest influence. In particular, for a 1% increase in EEZ area size, Model A predicts a .62% increase in its fishprint. Not surprisingly, Model A suggests that fishprints of Far Eastern countries were more likely to be greater. In particular, Model A predicts a 1.26% increase in the fishprint for countries located in the Far East as compared with the European baseline.

In terms of trophic level, all three models imply a negative correlation, though the effect is only significant in Model C. Model C suggests that for every one unit decrease in mean trophic level, a country's fishprint can be expected to rise by 1.11%. In other words, the models imply that fishing down food webs increases a country's fishprint – a somewhat counterintuitive finding but one consistent with Pauly et al. (1998; 2005).

6.0 Concluding Thoughts and Future Refinements

In this paper we proposed a series of modifications to global and country-level marine ecological fishprint accounts so they more accurately reflect the alarming state of the world's fisheries. The modifications addressed several deficiencies in ecological footprint analysis (EFA) in general and the fishprint component of EFA in particular noted in the literature. In the context of four separate models, we modified marine fisheries biocapacity to include the entire ocean but made a deduction for the suggested extent of marine protected areas. We changed the basis of reporting from tonnes to tonnes of primary productivity, introduced an ecological sustained yield threshold (ESYT) for the global catch, and incorporated a biocapacity degradation factor to account for natural capital depletion in years when global marine landings exceed the ESYT.

The new fishprint accounts at the global level indicate substantial marine fisheries overshoot beginning as early as the late 1960s. In our models, the degree of overshoot in 2003 ranges from 80 to 157%. Our results contrast sharply with published accounts provided by Loh (2002) and Loh and Wackernagel (2004) indicating that humanity's use of the marine and inland fisheries biome is within ecological limits. At the country level, regression analysis suggests that EEZ size, fisheries export value, and fishing intensity are positively correlated with the fishprint while mean trophic level of the catch is inversely related. We also found that the new accounts are more in line with the ecological realities of overfishing by countries such as the United States, Russia, Indonesia and Norway.

Despite these results, there are many additional refinements needed to make fishprint accounts more relevant in scientific, policy, and educational settings. One such advance is to use real time satellite derived data as a basis for calculating both fishprints and biocapacity in terms of appropriated and available primary productivity. Improvements in satellite mapping have made continuous monitoring of primary productivity possible, and work is underway to incorporate these data into the general EFA framework (Venetoulis and Talberth, 2006; Running et al. 2004). Right now, there is a several year time lag in the reporting of fishprint accounts, and satellite derived data should certainly help close that gap.

By mapping out export and import flows, new data being assembled by the *Sea Around Us* project will allow us to express fishprints in terms of consumption (catch by fleet minus exports plus imports). Right now, the accounts measure fishprint in terms of catch by a country's fleet, regardless of where that catch takes place and whose dinner plate that catch ends up on. An additional expansion in scope would be to calculate fishprints separately for capture and cultured fisheries to make fishprint accounts more relevant to the debate over appropriate regulation of the fast growing aquaculture industry.

In this paper, we used the mid 1970s catch level as a first cut at an ecological sustained yield threshold (ESYT). A fruitful area for future refinements would be to incorporate extensive work that has already been completed estimating ESYT on a fishery by fishery basis so that country level fishprint accounts more accurately signal when overshoot is occurring. Taken together, these refinements to the marine ecological fishprint will enhance its reputation as a rigorous sustainability analysis tool relevant in a growing number of scientific, policy, and educational applications.

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Table 1
Summary of Global Footprint Calculations
(All units expressed in global hectares per capita)

Biome	Biocapacity	Footprint	Ecological Balance
Living Planet Report 2000			
Crop land	0.69	0.69	0.00
Pasture land	0.31	0.31	0.00
Forest land	1.03	0.28	0.75
Marine and inland fisheries	0.03	0.04	-0.01
Built space	0.12	0.12	0.00
Energy land	0.00	1.41	-1.41
Total:	2.18	2.85	-0.67
Living Planet Report 2002			
Crop land	0.53	0.53	0.00
Pasture land	0.27	0.12	0.15
Forest land	0.86	0.27	0.59
Marine and inland fisheries	0.14	0.14	0.00
Built space	0.10	0.10	0.00
Energy land	0.00	1.12	-1.12
Total:	1.90	2.28	-0.38
Living Planet Report 2004			
Crop land	0.53	0.49	0.04
Pasture land	0.27	0.18	0.09
Forest land	0.81	0.14	0.67
Marine and inland fisheries	0.13	0.13	0.00
Built space	0.07	0.07	0.00
Energy land	0.00	1.20	-1.20
Total:	1.81	2.21	-0.40
Venetoulis and Talberth (2006)			
Crop land	0.46	0.52	-0.06
Pasture land	1.20	0.47	0.73
Forest land	1.78	0.46	1.32
Marine and inland fisheries	0.87	1.05	-0.18
Built space	0.02	0.05	-0.03
Energy land	8.23	19.36	-11.13
Open oceans	2.34	0.00	2.34
Less productive lands	0.78	0.00	0.78
Total:	15.68	21.91	-6.23

Table 2
Global Marine Fisheries Biocapacity

Region	Area (billion ha)	Equivalence Factor	Biocapacity (billion ha)
Exclusive economic zones (EEZ)	13.88	1.67	23.18
Open oceans	22.41	0.48	10.76
Total:	36.29	0.94	33.94

Figure 1
Relative Rate of Catch Increase for Global Marine Fish Landings

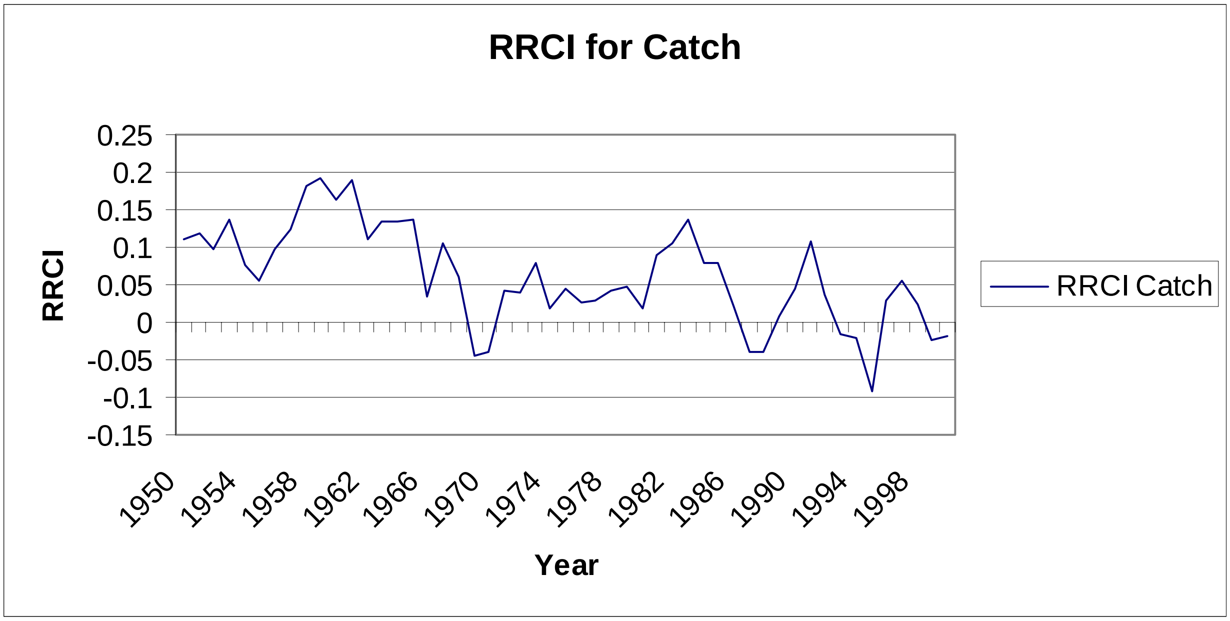


Figure 2
Relative Rate of Catch (PPR) Increase for Global Marine Fish Landings

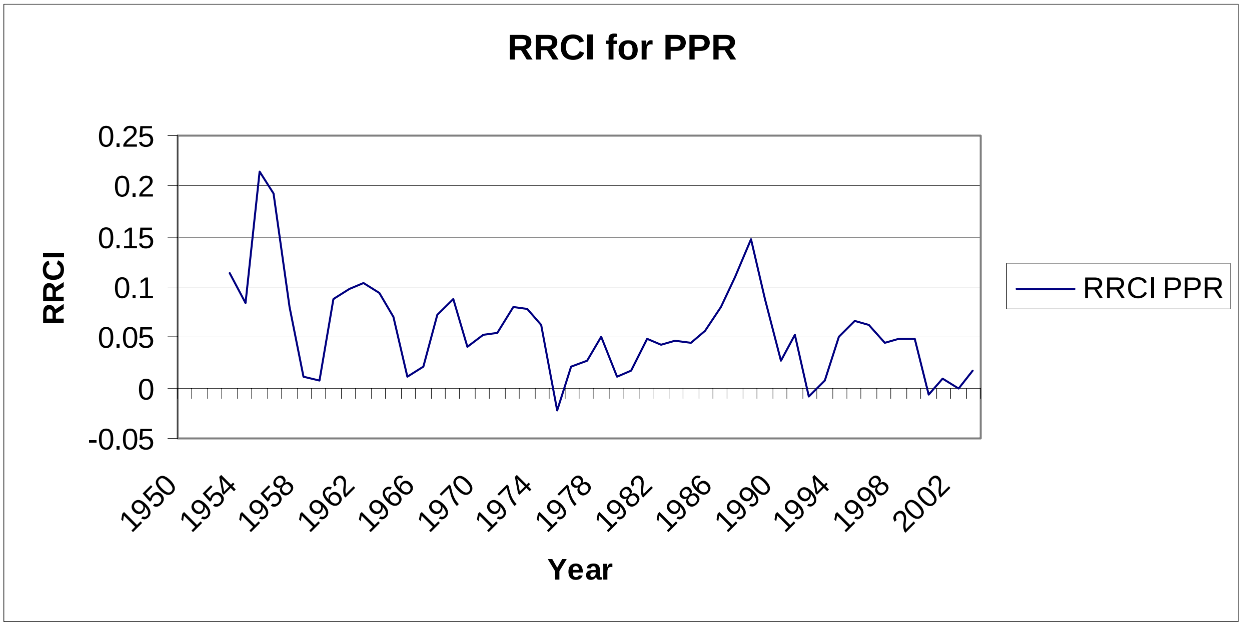


Figure 3
Decline in Mean Trophic Level of Fisheries Catch Since 1950

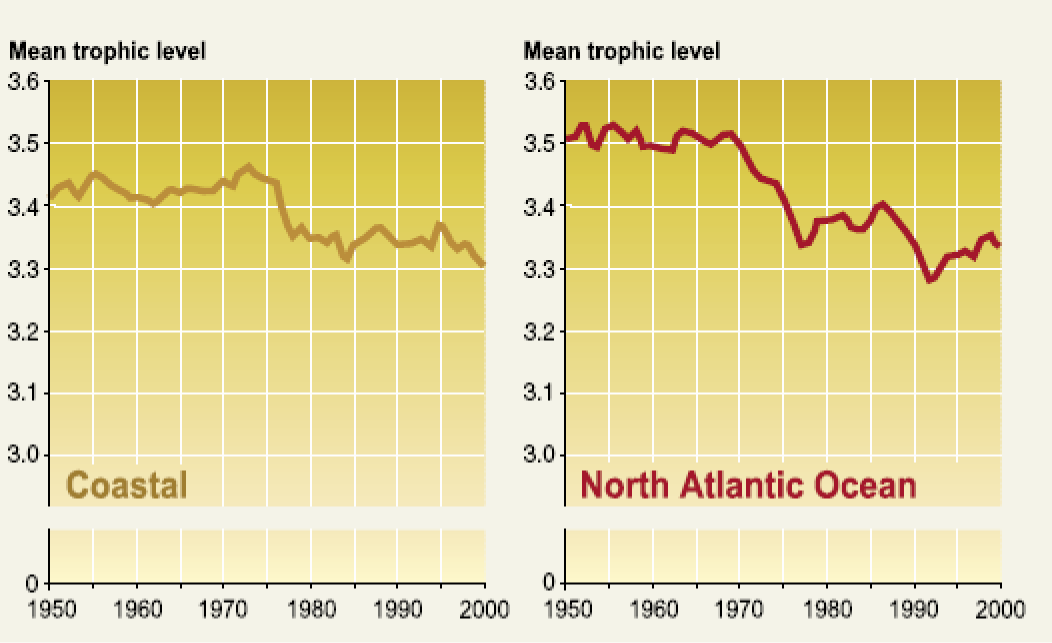
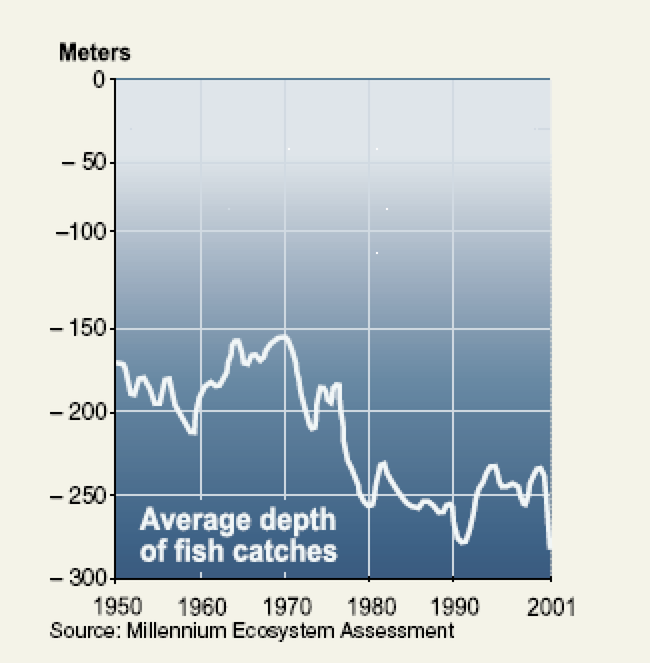


Figure 4
Trend in Mean Depth of Catch Since 1950



Source: Millennium Ecosystem Assessment

Figure 5
Global Trends in the State of World Marine Fish Stocks Since 1974

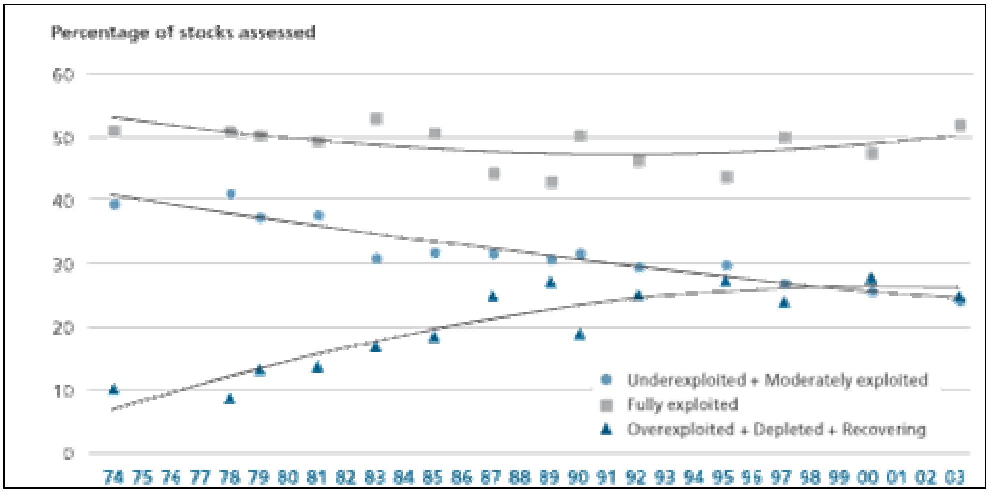
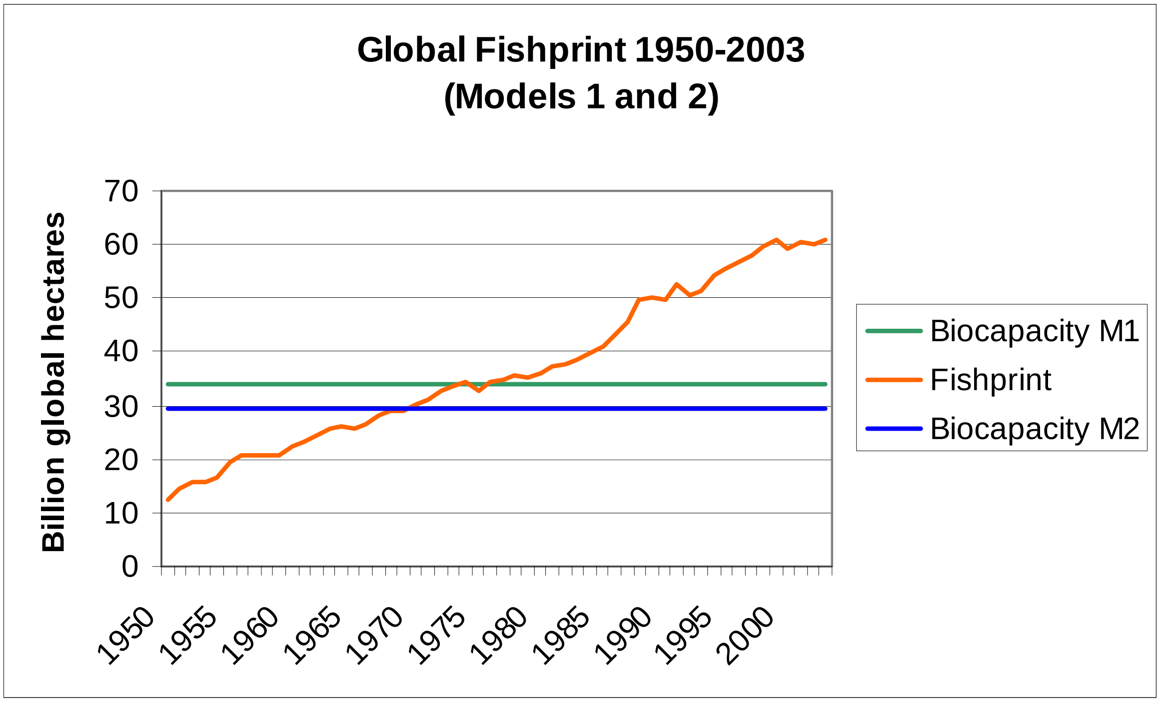


Table 3
Meta Analysis of MPA Related Studies Compiled by NAS (2000)

Source	Year	Objective	Description	% of Fishing Area Needed for Reserves	
				Low	High
Ballantine	1997	Ethics	Key principle at stake is that we should not fish everywhere	n/a	n/a
Lauck et al.	1998	Risk minimization	In the face of uncertainty in fishing mortality, reserves covering between 30 and 70 percent of fishing ground should be needed to maintain populations above 60% of their underexploited size (argued to be an economic optimum) over a 40 year time horizon.	30	70
Roughgarden	1998	Risk minimization	Maintain exploited populations at 75% of their unexploited size in order to avoid recruitment over fishing.	n/a	n/a
Guenette et al.	2000	Risk minimization	Due to temporal closures to trawls and gill nets, reserves covering 20% of the area would have been adequate to prevent the 1992 collapse of the migratory northern cod.	n/a	20
Mangle	2000	Risk minimization	If a stock was initially heavily fished (i.e., starts at 35% of its un-fished size) reserves of 20-30% of the management are guaranteed persistence above this level for 20 and 100 years.	20	30
Goodyear	1993	Risk minimization	Maintaining fish populations above 20% of their unexploited size would avoid recruitment over fishing.	n/a	n/a
Mace and Sissenwine	1993	Risk minimization	Of spawning potential ratio would be a conservative management target. Safe minimum population levels ranged as high as 70% for some species.	n/a	n/a
Mace	1994	Risk minimization	Above unexploited size if the relationship between population size and recruitment is unknown.	n/a	n/a
Sumaila	1998	Risk minimization	Provide significant protection for stocks without greatly reducing current economic benefits. (Yet the largest reserve, covering 70% of the management area, offered the greatest future security for stocks, but had the highest cost in terms of current yields.)	30	50
Man et al.	1998	Risk minimization and by catch avoidance	When by catch is included as a taking- reserves from 4, 6, and 16% of the area played a key role for species over a 20 year time period	4	16
Foran and Fijita	1999	Risk minimization and yield maximization	The maximum long-term catch was from a reserve area of 25% and a moderately heavy level of fishing outside (the reserve area).	n/a	25
Guenette and Pitcher	1999	Risk minimization and yield maximization	Reserves maintain the highest yields. Larger reserves (>30%) provided more robust biomass of spawning fish and reduced the number of years with poor recruitment compared to a no reserve regime.	n/a	30
Pezzey et al.	2000	Yield maximization	Reserve levels depending on the fishing intensity outside the reserves, which represent a gradient from moderate to intensive exploitation.	21	40
Sladek Nowlis and Roberts	1997, 1999	Yield maximization	Depending on fishing intensity. At more moderate fishing intensities, reserves covering 40% of the management area would offer major benefits to yields. In the most intensively exploited areas of the Caribbean reserves covering 75-80% would be needed to maximize catch.	40	80
Sladek-Nowlis	2000	Yield maximization	At moderate fishing intensities (20% of fishery recruited individuals removed per year) catches peaked with reserves covering 30%.	n/a	30
Sladek-Nowlis andYoklavich	1998	Yield maximization	Optimum reserve areas, those producing the greatest long term catches, ranged from roughly 20-27% of the management area as fishing intensity grew.	20	27
Holland and Brazee	1996	Yield maximization	For a range of heavy exploitation rates, optimal reserve areas increased from 15 to 29%.	15	29
Hannesson	1998	Yield maximization	Will produce an increase in spawning stocks of 40-130%. Catches were greater than open access over a range of 10-80%. In order to produce rates and spawning stock levels equivalent to those of an optimally controlled fishery the reserve would have to be 70-80% of the management area.	50	80
Polacheck	1990	Yield maximization	Reserve areas of between 10-40% of the fishing grounds increased catches.	10	40
DeMartini	1993	Yield maximization	Reserves ranging from 20-50% of the management area would offer significant levels of insurance against over fishing, although at increasing the cost to present catches.	20	50
Hastings and Botsford	1999	Yield maximization	Maintaining reproductive output at 35% of the unexploited level might require less than 35% of the area in reserves.	n/a	35
Bostford et al.	1999	Yield maximization	The catch maximizing fraction of the management area needs to be within this range for the most probable level of vulnerability (for the sea urchin). A reserve of 17% of the coasts would equated to and increase catch of 18%.	8	33
Attwood and Bennett	1995	Yield maximization	Depending on the species.	25	65
Quinn et al.	1993	Yield maximization	Population sizes and sustained catches were greatest with 50% of the coast protected for all except the lightest level of fishing examined (for the CA red sea urchin)	n/a	50
Daan	1993	Yield maximization	Protecting 25% could reduce mortality by 10-14%; reserves of 10% would let to reduction of mortality of only 5% at the lowest transfer rate of cod from reserves to fishing grounds.	10	25
Turpie et al.	In press	Biodiversity Representation	A 10% reserve would represent 97.5 species, yet not include 15 endemic species. A reserve size of 36% would represent all species in the core regions of their range.	10	36
Bustamante et al.	1999	Biodiversity Representation	In order to protect all of the areas of high biological importance in the Galapagos Marine Reserve.	n/a	36
Halfpenny and Roberts	In review	Biodiversity Representation	Most but not all biogeographic regions and habitats	n/a	10
Trexler and Travis	2000	Biodiversity Representation	A 10% reserve decreased directional selection by 60%, while a 20% reserve would eliminate the selective effects of fishing from the population entirely.	10	20
Roberts	In review	Increase connectivity among reserves	Target size increased steeply as the proportion of the management area protected grows, and was four times greater at 30% of the area in reserves compared to 5%.	5	30
Allison et al.	In review		If the aim is to protect a certain proportion of habitats in an undisturbed state, we must protect a larger fraction of the area.	n/a	n/a
			Mean	**19.29**	**38.28**
			Median	**20**	**33**
			Mode	**10**	**30**

Figure 6
Global Fishprint and Biocapacity Models 1 – 4

(A)



(B)

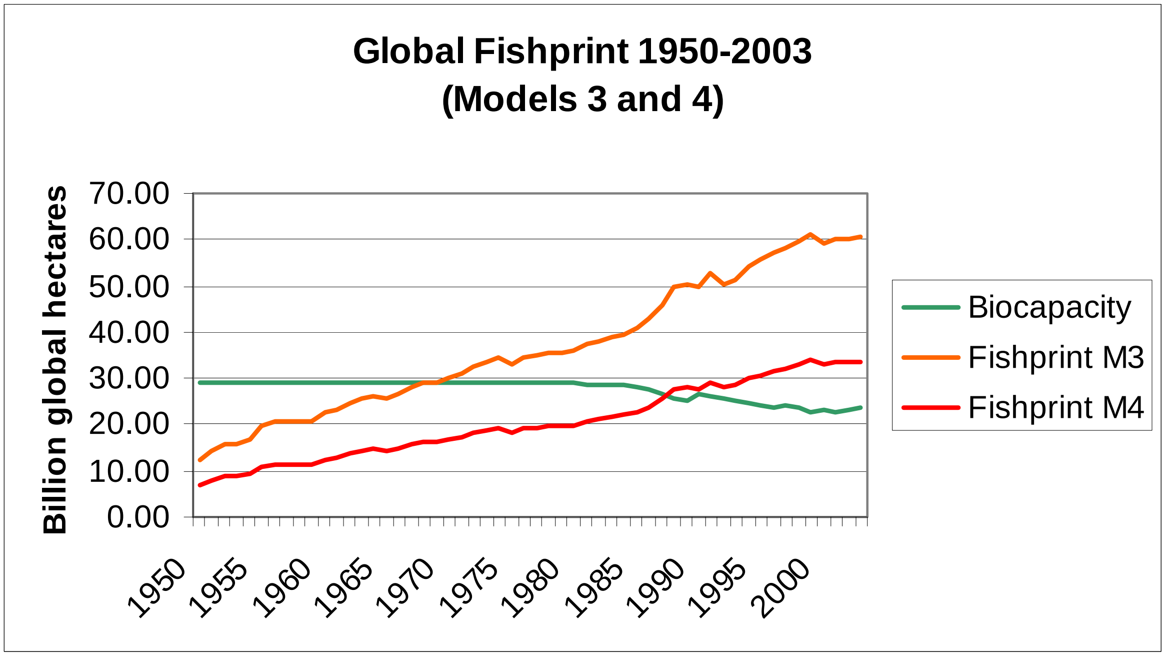
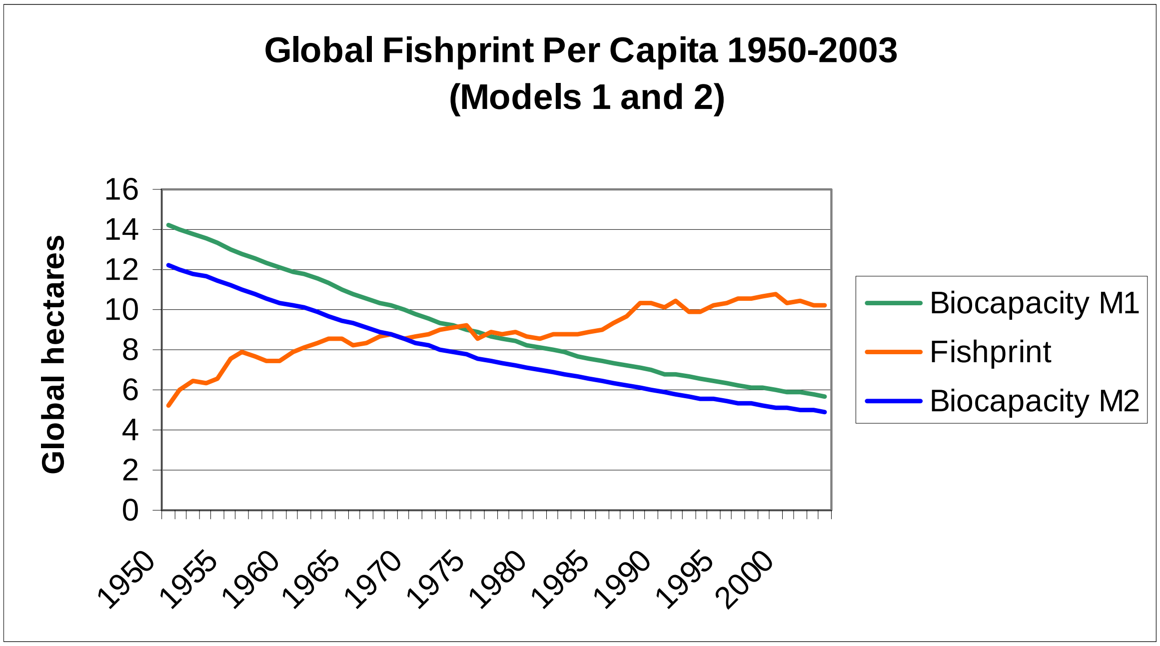


Figure 7
Global Fishprint and Biocapacity Per Capita Models 1 – 4

(A)



(B)

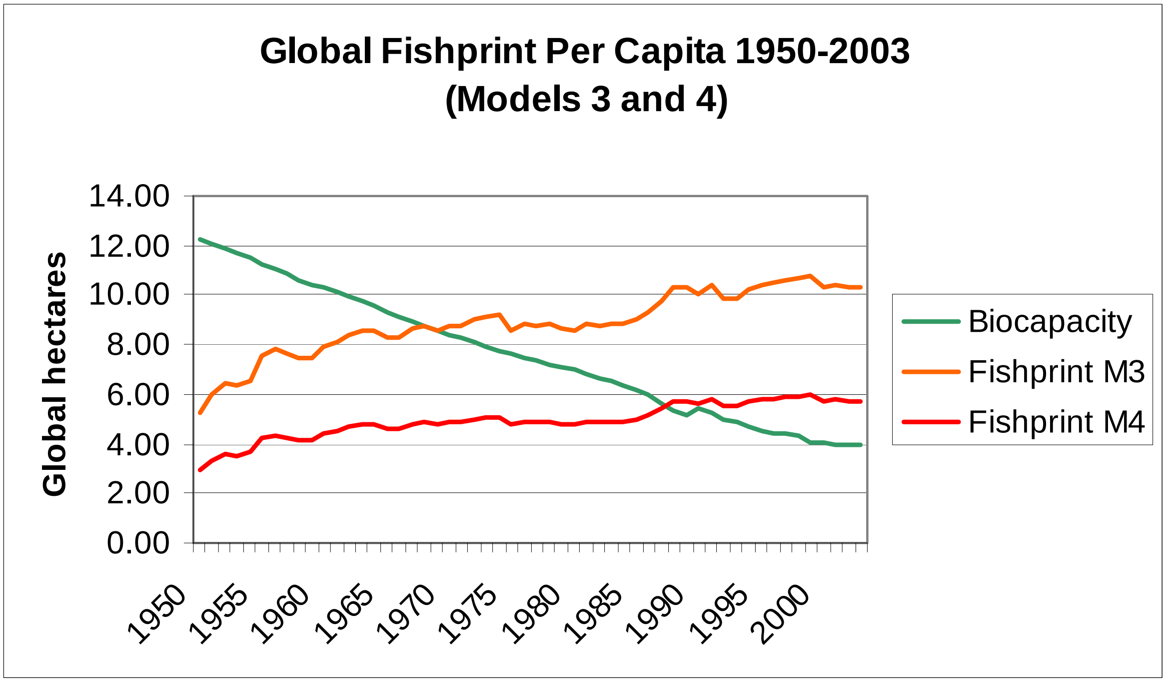


Table 4
2003 Country Level Fishprint and Biocapacity Accounts

Country	Primary Productivity Required (million tonnes)	Biological Capacity (million gha)	Fishprint (million gha)	Ecological Balance (million gha)
Japan	3093.41	635.02	3996.13	-3361.11
Indonesia	3327.70	1071.41	4298.79	-3227.39
China	6589.23	6445.12	8512.09	-2066.97
Norway	1570.63	22.38	2028.97	-2006.59
Philippines	1843.12	384.65	2380.98	-1996.33
Taiwan	1612.12	114.15	2082.57	-1968.41
Thailand	1757.70	317.09	2270.63	-1953.54
United States	2367.80	1425.91	3058.77	-1632.85
Iceland	1079.28	1.42	1394.23	-1392.81
Russia	1627.74	721.44	2102.75	-1381.31
Korea (South)	1174.87	234.73	1517.73	-1282.99
Chile	1039.39	76.81	1342.71	-1265.90
New Zealand	889.18	18.99	1148.66	-1129.67
Spain	985.63	199.09	1273.26	-1074.17
Malaysia	890.28	111.75	1150.08	-1038.33
Namibia	678.62	8.92	876.65	-867.74
Myanmar	852.31	241.19	1101.03	-859.84
Peru	650.81	130.13	840.73	-710.61
Argentina	672.46	186.95	868.69	-681.74
Viet Nam	809.74	394.85	1046.04	-651.19
Ecuador	549.55	64.23	709.92	-645.69
France	725.99	296.49	937.85	-641.36
Mexico	787.39	500.54	1017.17	-516.63
Denmark	400.41	26.60	517.26	-490.66
Papua New Guinea	361.87	24.54	467.47	-442.93
Maldives	322.84	1.55	417.05	-415.49
South Africa	479.86	218.39	619.90	-401.50
Venezuela	404.56	122.84	522.62	-399.78
Canada	385.91	154.67	498.53	-343.85
Sri Lanka	316.01	95.27	408.23	-312.96
Seychelles	187.30	0.40	241.96	-241.56
Ghana	233.82	98.41	302.05	-203.64
Iran	427.75	355.92	552.57	-196.66
Panama	141.82	14.46	183.21	-168.75
Portugal	160.61	50.03	207.48	-157.44
Lithuania	128.25	18.40	165.68	-147.28
Morocco	230.23	151.75	297.41	-145.66
Senegal	148.55	48.18	191.90	-143.72
Netherlands	168.28	79.44	217.39	-137.95
Oman	118.28	20.34	152.80	-132.46
Sweden	132.96	44.05	171.76	-127.71
United Arab Emirates	100.28	13.24	129.55	-116.31
Ireland	103.12	19.16	133.21	-114.06
Marshall Islands	84.94	0.28	109.73	-109.45
Australia	156.90	96.44	202.68	-106.24
Vanuatu	72.90	1.04	94.17	-93.12
Solomon Islands	71.27	2.32	92.06	-89.74
Micronesia	68.99	0.54	89.12	-88.58
Angola	112.53	67.46	145.37	-77.92
Uruguay	72.51	16.60	93.67	-77.07
United Kingdom	281.05	298.03	363.07	-65.04
Yemen	114.84	95.32	148.36	-53.04
Fiji	42.11	4.12	54.39	-50.28
Mauritania	41.40	13.70	53.48	-39.78
Kiribati	25.17	0.49	32.52	-32.03
Guyana	26.01	3.77	33.60	-29.83
Costa Rica	36.14	20.51	46.68	-26.18
Korea (North)	105.11	111.85	135.78	-23.93
Madagascar	81.44	81.97	105.20	-23.23
Latvia	23.29	12.00	30.09	-18.09
Estonia	17.53	6.87	22.64	-15.78
Qatar	13.99	2.98	18.07	-15.08
Samoa	11.36	0.88	14.67	-13.79
Sierra Leone	27.35	22.88	35.33	-12.45
Saint Vincent & the Grenadines	9.43	0.59	12.18	-11.59
El Salvador	33.03	31.92	42.66	-10.75
Gabon	13.28	6.56	17.15	-10.59
Comoros	10.72	3.75	13.84	-10.10
Guinea	39.69	41.26	51.27	-10.01
Tunisia	44.57	47.69	57.58	-9.89
Trinidad and Tobago	12.67	6.48	16.37	-9.89
Suriname	8.36	2.14	10.80	-8.66
Mauritius	10.68	5.84	13.80	-7.96

Table 4 (Continued)

Country	Primary Productivity Required (million tonnes)	Biological Capacity (million gha)	Fishprint (million gha)	Ecological Balance (million gha)
Greece	46.97	52.98	60.67	-7.70
Cape Verde	7.49	2.27	9.68	-7.41
Tonga	4.68	0.54	6.05	-5.51
Grenada	4.09	0.44	5.28	-4.84
Gambia	8.43	7.04	10.88	-3.84
Tuvalu	2.33	0.06	3.01	-2.95
Finland	22.00	25.82	28.42	-2.60
Saint Lucia	2.38	0.80	3.07	-2.27
Sao Tome and Principe	2.27	0.90	2.94	-2.04
Barbados	2.31	1.33	2.99	-1.65
Dominica	1.53	0.34	1.98	-1.63
Malta	2.58	1.94	3.34	-1.39
Antigua and Barbuda	1.00	0.34	1.29	-0.95
Palau	0.65	0.10	0.84	-0.74
Saint Kitts and Nevis	0.35	0.19	0.45	-0.26
Nauru	0.09	0.06	0.12	-0.05
Brunei Darussalam	1.25	1.75	1.62	0.13
Belize	0.58	1.15	0.75	0.40
Equatorial Guinea	0.67	2.41	0.86	1.55
Djibouti	0.42	2.26	0.55	1.71
Cyprus	0.98	3.94	1.26	2.68
East Timor	0.32	3.85	0.41	3.44
Guinea-Bissau	1.11	6.12	1.43	4.69
Jamaica	5.17	12.96	6.68	6.28
Congo, R. of	8.90	18.19	11.50	6.69
Kuwait	1.93	9.83	2.49	7.34
Eritrea	8.35	19.03	10.78	8.25
Liberia	5.56	15.50	7.18	8.32
Slovenia	0.30	9.90	0.39	9.51
Togo	9.88	23.22	12.77	10.46
Benin	16.08	32.15	20.77	11.37
Libyan Arab Jamahiriya	11.63	26.97	15.03	11.94
Albania	1.65	15.68	2.14	13.55
Croatia	7.00	23.21	9.04	14.17
Guatemala	33.83	58.28	43.70	14.58
Lebanon	1.94	17.73	2.51	15.22
Nicaragua	8.10	25.97	10.47	15.51
Singapore	1.31	20.71	1.69	19.02
Dominican Republic	14.83	42.42	19.16	23.26
Cambodia	33.12	67.03	42.79	24.24
Jordan	0.12	25.19	0.16	25.03
Georgia	0.39	26.13	0.51	25.62
Honduras	3.44	32.79	4.45	28.34
Israel	1.88	30.78	2.43	28.35
Cuba	19.32	56.04	24.96	31.08
Somalia	9.03	45.67	11.67	34.00
Saudi Arabia	54.02	104.87	69.78	35.09
Colombia	137.22	213.46	177.27	36.19
Belgium	13.28	53.39	17.16	36.24
Bulgaria	1.31	39.16	1.69	37.47
Haiti	2.44	41.24	3.16	38.09
Serbia Montenegro	0.36	52.01	0.46	51.55
Mozambique	30.52	92.98	39.43	53.55
Côte d Ivoire	17.50	81.53	22.61	58.92
Cameroon	10.72	75.82	13.84	61.98
Syrian Arab Republic	2.73	82.83	3.52	79.31
Italy	154.50	286.77	199.59	87.18
Romania	0.38	111.65	0.49	111.16
Ukraine	102.73	244.92	132.71	112.21
Algeria	29.85	153.80	38.56	115.24
Iraq	1.60	117.61	2.06	115.55
Turkey + Territories	159.42	337.28	205.95	131.33
Tanzania	34.92	179.36	45.11	134.25
Poland	39.29	192.38	50.75	141.63
Bahamas	3.14	153.99	4.06	149.94
Kenya	4.71	156.06	6.09	149.97
Germany	198.74	408.97	256.74	152.23
Sudan	2.71	158.63	3.50	155.13
Congo (ex - Zaire)	1.80	258.36	2.32	256.04
Egypt	58.84	344.50	76.00	268.50
Pakistan	339.47	722.97	438.53	284.44
Brazil + Territories	403.60	860.55	521.38	339.18
Bahrain	4.84	353.35	6.26	347.09
Bangladesh	223.30	700.02	288.46	411.56
Nigeria	130.85	583.13	169.03	414.10
India	1952.66	5112.16	2522.49	2589.67

Table 5
Cross Sectional Regression Analysis on Log of Country-Level Fishprint

Indepenent Variable	Model A Ln(fp)	Model B Ln(fp)	Model C Ln(fp)
lneez	0.62	0.54	0.85
	(7.71)***	(7.14)***	(11.69)***
lnfex	0.28	0.36	-
	(4.92)***	(6.92)***	
tl	-0.11.	-0.32	-1.11
	(-0.23)	(-0.69)	(-2.16)**
ppreez	0.07	0.08	0.13
	(3.94)***	(4.56)***	(6.72)***
afr	-0.33	-	-
	(-0.85)		
car	-1.26	-	-
	(-2.33)**		
lat	-0.22	-	-
	(-0.52)		
fare	1.26	-	-
	(2.92)***		
neas	0.33	-	-
	(0.71)		
na	-0.38	-	-
	(-0.36)		
oce	-1.04	-	-
	(-1.78)*		
constant	5.76	5.91	11.29
	(3.09)***	(3.15)***	(5.88)***
R-squared	.7283	.6668	.5240
Adjusted r-squared	.7042	.6567	.5142
Observations	136	136	149
F-stat	30.21***	65.55***	53.21***