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The effort factor: Evaluating the increasing marginal impact of resource extraction over time

Debra J. Davidson [a,*], Jeffrey Andrews [a], Daniel Pauly [b]

[a] Department of Resource Economics and Environmental Sociology, University of Alberta, Canada
[b] Fisheries Centre, University of British Columbia, Canada

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ABSTRACT

Concern for the increasing impact of human activities on Earth's ecosystems has generated a growing effort to monitor those impacts and measure the success, if any, of mitigation measures. This contribution argues that ecological impact assessments that tend to rely primarily on the volume of natural resources produced and subsequently consumed overlook the degree to which ecological impact can vary significantly independently of production volumes, due to the varying impact that results from production effort. Production effort, in turn, is directly linked to the quality of raw materials, which inevitably tends to decrease over time. As a result, unless technological improvements were able to compensate for the resource quality decline indefinitely, we face a future of increasing marginal ecological impact over time. This is demonstrated here based on three resource extraction systems, coal mining in the UK, grain production in China, and global marine fisheries.

1. Introduction

Contemporary discussions of society's precarious relationship with the ecosphere often start and end with the spotlight on consumption. Such predilections have led to numerous calls for consumer responsibility, with each new "10 Things You Can Do" list including more creative steps individuals can apply to reduce their personal consumption. Even more prevalent are encouraging prescriptions for, and in some case observations of, increased efficiency in resource use, with ecological modernizationists and industrial ecologists offering optimistic accounts of our collective potential for "dematerialization" of our consumptive economies, the implication being that reductions in material consumption represent a key route to ecological improvement. Other lines of inquiry are more nuanced in their treatment of consumption in socio-ecological relations, but the assertion that consumption is the driving force behind changes in ecological well being has now come to frame many debates, with political implications. For example, projections of future impact on the basis of historical consumption (emission) rates have become central to scenario analyses by, for example, the Intergovernmental Panel on Climate Change (IPCC) (e.g. Moore et al., 2012; Galli et al., 2012).

Consumption unquestionably drives ecological impact, but it is by no means the only factor, nor is it the most direct indicator of ecological impact. Importantly, even if demand for ecosystem services leveled off, perhaps a result of population stabilization, redistribution of affluence, or strict sanctions, increases in ecological impact could still result. As first introduced in a recent article in *Science* (identifying citation), ecological impact is a function of effort, not reward. In other words, the relative inputs required to "produce" material commodities through the extraction and processing of natural resources has a more direct causal relationship with ecological impact than does the volume of resulting commodities that are subsequently consumed. More importantly, this effort will tend to increase over time, as reserves of natural resources become degraded due to historical production. This counters two dominant, inter-related paradigms guiding environmental sciences and policy: consumption levels directly affect ecological impact; and secondly, continued improvements in efficiency technologies will enable reduced material consumption without compromising the use values derived from consumption (i.e. we can drive longer using less fuel). We offer a conceptual exploration of the role of production effort in ecological impact, followed by three supplementary examples in the coal, grain and fisheries sectors, illustrating a consistent historical trend toward increasing marginal ecological impact in each case. We conclude

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* Corresponding author at: 515 General Services Building, University of Alberta Edmonton, AB T6G2H1, Canada. Tel.: +1 780 492 4598; fax: +1 780 492 0268.
E-mail addresses: debra.davidson@ualberta.ca (D.J. Davidson), abjeffre@ualberta.ca (J. Andrews), dpauly@fisheries.ubc.edu (D. Pauly).

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with discussion of the implications of these findings for contemporary efforts to ameliorate society's global ecological impact.

2. Theory

Why would ecological impact increase even if consumption were constant? Consider a hypothetical coalfield. When coal is first exploited, the richest, most accessible features of those deposits are exploited first. Over time, deposits further from the surface and of lower density become the sites of exploitation. When this becomes economically unfeasible, more geographically remote deposits are exploited. Finally, as even these become exhausted, investments are made in technologies to squeeze commodities out of lower quality reserves. In each case, the resulting increase in effort required to extract, process and transport those resources for consumption require more raw material and chemical inputs, and create more waste. While for much of our industrial history, global trends of this sort have been masked as depleted mines were replaced with discoveries of richer deposits elsewhere, today declines in the quality of many resource pools can be observed globally.

An analogous story is offered by recent analyses noting the increases in energy investments required to access and process depleted conventional fuels and non-conventional energy sources (Energy Return on Investment, or EROI) (e.g. Murphy and Hall, 2010; Brown and Cohen, 2009; Brown and Ulgiati, 2001), although these accounts tend to focus less empirical attention on the ecological implications of declining energy return on investment, and do not apply their framework to other resource sectors. The growing number of projections (in some cases observations) that the reserves of many non-renewable resources are reaching a maximum threshold of production, most notably oil (Murphy and Hall, 2010; Fantazzini et al., 2011; Prior et al., 2011; IEA, 2010; Campbell, 2002, 1997), renders this finding particularly disconcerting. Popularized forms of these conversations about "Peak Everything" are often misconstrued, however; in most cases we are not running out, we are simply running out of the easy stuff (Fantazzini et al., 2011). We could continue to extract oil, coal, natural gas, and several minerals for many decades, but the escalating ecological and social implications of doing so, more so than forecasts of peak dates, demand attention.

Odum (1971 [2007], 1997) was perhaps the first to highlight this energy input/output relation, initially in 1973, and later with his articulation of the term *emergy*, defined as "the availability of energy (exergy) of one kind that is used up in transformations directly and indirectly to make a product or service" (Brown and Ulgiati, 2001: 62). This statement, rooted in basic principles of metabolism, warrants further elaboration. As noted by Magdoff (2011), the extraction, processing and consumption of natural resources are central pathways in the metabolism of social systems. The metabolic processes performed by any cell or organism require effort. The effort required to support metabolic pathways are not general, however, but specific: some simple compounds, such as sugar, can be quickly metabolized by the human body, while proteins take more work, for example. The amount of effort required can also be affected by the 'fitness' of the laborer: certain illnesses can compromise the efficiency of metabolic processes within an organism; lack of fishing skill would likely translate into longer time requirements to catch a fish than it would otherwise. Effort is also affected by the original condition of the materials being processed: it takes a human body more work, through additional consumption, to extract needed nutrients from foods with low nutrient density (with negative consequences in the form of obesity and/or health complications).

And – the focus of the present paper – it takes more effort to convert lower quality natural resources into something of social use value. 'Quality' in this sense refers to those biophysical characteristics of a natural resource desired for human use that determine the ease with which use value can be derived from it. This includes, for example, the density of a mineral or energy source within the substrate in which it is contained, or the amount of impurities that would need to be removed. The sulfur content of fossil fuels, which must be removed before consumption, for example, can vary tremendously. Quality can also refer to accessibility, such as the depth of an oil reserve, or other conditions restricting access, such as extensive ice cover. The 'Effort' required for society to access natural resources and agricultural products for consumption consists of human labor, the tools and technologies that are extensions of that labor, and the material inputs, including land, water, energy and chemicals, that are employed in extraction, processing, transport and consumption.

Odum's work, and that of more recent energy return on Investment analysts, have been focused specifically on energy flows, however, rather than socio-ecological relations as such, and thus the broader implications of their contributions for global ecosystems have not been taken up to any great extent. One complementary line of inquiry, however, dates further back than Odum's work, with Karl Marx and his employment of the concept of Metabolic Rift. Contemporary environmental sociologists have built upon his foundations for application to current environmental crises. Marx's work was based upon observations made during the Second Agricultural Revolution in the 19th Century, when rapid soil depletion caused by intensive agriculture came to light, inducing the inception of a fertilizer industry. Laid out in detail by Foster (1999), the general rudiments of Marx's theory are as follows: (1) Humans are only able to survive by virtue of their metabolic relation with the natural world. (2) The means by which metabolic relations manifest is labor (technology), which is conditioned by both natural limits and social relations, (3) particular forms of social relations can cause ruptures in this metabolic relationship. (4) The social relations dictated by capitalism have induced just such a rupture. Marx referred specifically to the large-scale agricultural processes associated with capitalism: intensive production robs the soil of nutrients, while depopulation of the countryside prevents the nutrient replenishment embodied in the organic waste produced by humans, who now live in cities. Given capitalism's growth imperative, it depends upon ever-larger inputs of energy and material resources over time to reproduce itself. This has, through the course of history, culminated periodically in significant restructuring as capital confronts the limits of nature, the introduction of synthetic fertilizers being just one example. In each mode of restructuring, however, the Metabolic Rift is not repaired, but merely transformed (Moore, 2000, 2001, 2003).

Contrast these analyses to another formula far more frequently used to capture those broader relationships between societies and ecological impact, IPAT, which states that Impact is a function of the product of Population, Affluence, and Technology. IPAT was introduced by Ehrlich and Holdren (1971) and largely accepted today, with solid empirical support indicating that growing population and affluence in particular have been drawing down earth's biocapacity (Rosa and Dietz, 2012; Liddle, 2011; Liddle and Lung, 2010; York et al., 2003; Schulze, 2002; Fischer-Kowalski and Amann, 2001; Dietz and Rosa, 1997). A more recent line of IPAT-related research that employs an adapted, stochastic model (STIRPAT, standing for Stochastic Impacts by Regression on Population, Affluence and Technology) has offered compelling evidence of the stability of the effect of population size over time (Jorgenson and Clark, 2010, 2012); and the asymmetric, or path-dependent effects of economic development: in essence while CO2 emissions increase with economic growth, they do not tend to decrease at the same rate when those economies shrink (York, 2012).

While empirical analysis often prioritizes population and affluence, both of which are readily operationalized with a number of available data sources, other efforts follow on Commoner's early attempts to draw more attention to the T-technology term. This literature takes a more optimistic tone, supporting arguments that improvements in technological efficiency can counter the downward pressures on the ecosphere exerted by population and affluence, a premise that has had a strong influence on climate policy of late, as noted by Steinberger and Krausmann (2011). The premise centers on potential increases in efficiency (T), basically defined as intensity of ecological impact per unit of economic production, and/or declining intensity of material use per GDP (dematerialization) (Chertow, 2001; Waggoner and Ausubel 2002). Other studies have challenged this optimistic prognosis, however, however, with evidence of continued increases in impact despite various forms of technological efficiency (e.g. Steinberger and Krausmann, 2011; Schandl and West 2012). Of course this should come as no surprise. As Jevons argued 150 years ago Jevons (1865), efficiency gains in the use of any resource tend to be followed by *increases*, rather than decreases in consumption. York (2006) offers a succinct contemporary example, extending Jevons' Paradox to resource substitution as well, noting the increase of paper consumption following the move towards "paperless offices".

In sum, there is no question that ecological impact is directly linked to consumption, which all three of these variables measure in one way or another: P-population and A-affluence are direct measures of volume of consumption, the former reflecting change in the total number of consumers and the latter reflecting per capita levels of consumption. T-technology is a bit more indirect, a measure of *how* we do our consuming ("paper or plastic?"). This line of research has made extremely important contributions to knowledge, and we do not dispute the validity of its findings. But the underlying assumption that society's relationship to (impact on) ecosystems can be evaluated (and managed) most directly as a function of consumption—the premise of political debates even more so than academic ones—only holds if we assume that nature is treated as a flat, a historical actor in this relationship, i.e. that one unit of consumption, say of a joule of natural gas, a pound of beef, or a cubic meter of pine, will have the same degree of impact wherever and whenever the production/consumption takes place. Other lines of inquiry discussed offer important insights that draw attention to the more complex processes associated with socio-ecological relations. Yet in sum, we believe one simple, historical process has been largely overlooked: regardless of number of consumers, type of economic system, or initial resource wealth, history is traced by declining resource quality, which translates into increased extraction effort, and—unless labor can keep pace with this effort trend indefinitely, which is an impossibility theorem—increased marginal impact on social and ecological systems.

3. Methods

While Odum has been accused of determinism, by ascribing too much causal weight to the historical role of energy availability (Rosa and Machlis, 1983), our conceptualization of Effort is wholly probabilistic, describing an interactive process between societies and ecosystems, captured in the following simple conceptual equation:

$$\mathrm{EFFORT} = \mathrm{fn}(\mathrm{Q}, \mathrm{L})$$

where Q refers to natural resource "Quality," capturing numerous features of natural resources including its density, accessibility, and so on; and L refers to "Labor," capturing the human and technological resources available to extract and process that resource in a given time and place. As with all interactive processes, certain historical trends can become masked by variations within, and interactions across, multiple drivers. In this instance, while the Q for a given regional resource supply (e.g. an oil reservoir) can be seen to follow a reasonably consistent downward historical trajectory, L most certainly cannot. To the contrary, L is influenced by political, economic, and cultural dimensions, which vary widely over time and region. Escalating tot the global level, this relationship becomes even more muddled, by regional differences in both Q and L, and varying extractive histories. Bearing these challenges in mind, we substantiate this argument by conducting a comparative assessment of three distinct resource sectors, which, despite the strong and variable influence of both scale, L and Q in each case, exhibit analogous trends in increasing Effort and hence ecological impact over time. We do so by identifying for each case changes in volumes of production over time, and one indicator expressing level of Effort over time for each. Ecological impacts are inevitably correlated with social impacts as well, which are equally warranting of attention, however in this initial treatment we focus solely on three simple, measurable indicators of Effort known to impose ecological impact in three distinct resource sectors. We begin with coal production, which exhibits a trend toward more ecologically destructive extraction practices. Then we turn our attention to agriculture, focusing on China's apparent diminishing returns in grain production despite increased intensity of inputs like groundwater and fertilizer, and finally, to global fisheries, where declining population levels have induced increased fishing effort, with associated ecological impact.

4. Findings

4.1.1. Coal

Although civilizations have been using coal for five millennia, unlike oil, we still have substantial global reserves. Its production is currently growing at a faster rate than any other fossil fuel, with deleterious implications for our global carbon budget. Deposits that have been extensively exploited are on the wane, however, encouraging a shift in extraction method from underground mining to surface mining (Palmer et al., 2010), including mountain-top removal, because these are more efficient means of extracting lower density deposits. While both forms of mining have serious ecological effects, surface mining involves significantly more disruption, in the form of redistribution of overburden, and exposure of toxin-producing compounds to water run-off, among other things (e.g. Palmer et al., 2010). Thus, a global shift to increased reliance on coal-based electricity not only elevates greenhouse gas intensity, but also increases the ecological footprint per ton of coal. Surface mining now accounts for over 40% of global coal production, but in some regions the proportion is much higher (WCA, 2012).

In Great Britain, where coal has been extensively mined for three centuries, annual production has been declining, but its ecological impact may not be, since the proportion of production derived from surface mining has been increasing steadily (except for the year coal workers went on strike!) (UKDECC, 2012, Fig. 1A).

In Australia, the world's largest coal exporter, 80% of the 540 million tonnes of coal mined in 2009 was surface-mined (ABARE, 2011: 21). In the United States coal production in 2011 stood at 1.1 billion tonnes, a figure that has more than doubled since the mid 20th Century. In 1953, surface mining accounted for around 25% (139 million tonnes) of the total U.S. coal production. As of 2010, however, surface mining accounted for 69% (747 million tonnes), showing a dramatic increase in proportion of total production and

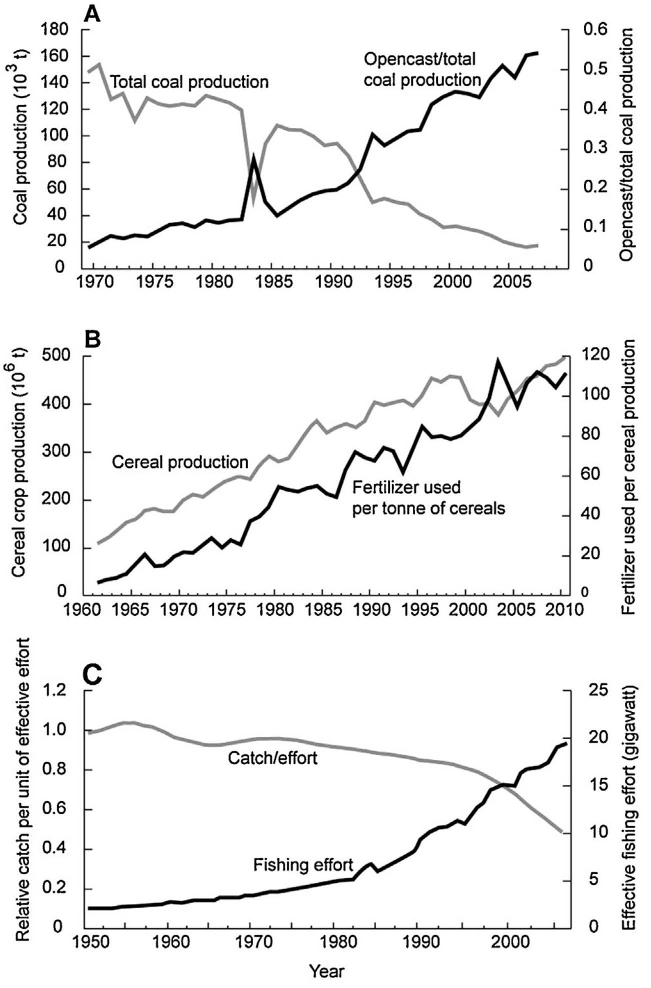

Fig. 1. Graphs showing changes in marginal extraction effort and volume of production over time in three resource sectors, showing similar increases in the Effort Factor over time.

absolute volume alike (EIA, 2012). The efficiency of surface-mining techniques did improve over time, such that a greater volume of coal can be extracted per unit of land today than was the case when surface mining was first adopted. But this is largely due to the increased depth that mining extractions technologies have been able to achieve. For example, historical data from the Mining Museum in Durham reports that the maximum depths of the original open pit mines in the UK, which originally began in World War II, were only around 10 m and typically had an overburden to coal ratio of around 5–1. By 1948 the maximum depth had jumped to 30 m. Today the average mine has a depth of around 80 m and a typical overburden ratio of 18–1, in some mines exceeding 40–1 (Durham Mining Museum, 2009). Despite this, today's surface mines (not including the land disturbed by overburden) still consume roughly twice as much land per ton of coal than does long wall mining, an underground mining technique (Sourcewatch, 2013).

In China, surface mining currently accounts for just 9% of total coal production (Ji, 2012), but still an enormous volume in raw tonnage. Considering that industrial-scale coal exploitation in China is still young (Chinese production increased 566% since 1981, compared to a 33% increase in the same period in the US), China's future, and that of other coal-producing regions, will likely include a growing proportion of surface mining.

Coal is certainly not the only resource associated with growing reliance on surface mining, nor is extraction method the only change associated with an increased ecological footprint. As Prior et al. (2011) show, the ratios of cyanide and water inputs per volume of mineral production also increase exponentially as the quality of the ore declines.

4.1.2. Agriculture

Agriculture exhibits an analogous trend, with production pressures motivating the conversion of forestlands, and marginal agrarian lands with lower yield potential (Lambin and Meyfroidt, 2011) imposing direct costs to terrestrial ecosystems. Agriculture has other impacts on ecosystems as well, including water withdrawals and chemical inputs, which in turn in turn increase energy requirements (for pumping groundwater and manufacturing fertilizers), and pollutant emissions. Heavy volumes of both water and chemical inputs were keys to production of high-yield Green Revolution hybrids, but in some cases the resulting ecosystem degradation eventually had a negative impact on yield growth (Pingali, 2012).

Considering the tremendous regional variation in production conditions and histories, the Effort Factor in agriculture is most readily captured by looking at a single region of intensive production. China is the world's largest producer of cereals, producing 433 million tonnes in 2010—20% of the world's total (FAO, 2012a,b). China's grain production has steadily increased since 1960. The most direct form of ecological impact from agriculture is the conversion of land for crops and pasture. The total amount of land under agricultural production in China reached over 130 million hectares in 2006 (dropping somewhat during the 2008 recession) (FAO, 2012a,b). China aggressively adopted Green Revolution technologies, which promised improved efficiencies in land use by enabling higher yields. Higher yields were indeed observed, at least for a while, but since 1980 efficiency gains have largely petered out, describing a declining return on technological investments in productivity. Fig. 1B contrasts the total increase in grain production over time (black line) with the ratio of total land under cultivation to total production (gray line), indicating that yield returns resulting from technology investments may diminish over time (FAO, 2012a,b, Fig. 1B).

While efficiency gains resulting from improved technologies leveled off 30 years ago, these inputs continue to increase. China expanded its irrigated landbase from roughly 45,000–65,000 Ha since 1960, with most of that increase occurring in the last ten (FAO, 2012a,b). This has translated into a ten-fold increase in groundwater extraction, since 70% of irrigated cropland depends on groundwater, raising concerns about the sustainability of this supply, not to mention the increasing greenhouse gas emissions associated with pumping groundwater to the surface (Wang et al., 2012). Another significant input is fertilizer. Fertilizer use in China expanded from 330 to 26,000 tonnes between 1961 and 2009 (FAO, 2012a,b). The relationship between increases in fertilizer use and grain production suggests a trend of continuously increasing marginal fertilizer input for every tonne of grain produced (Fig. 1B).

4.1.3. Fishing

Global marine fisheries catches have strongly increased since the 1950s, in response to increasing demand in both the developed and the developing worlds, with two key ecological consequences. First, as with other resources, the cream of the crop—in this case the large, long-lived fish at high trophic levels—are harvested first, with the result that the size and mean trophic levels of fisheries catches have been declining (Pauly et al., 1998). Similar to mining, researchers have catalogued the progressive collapse of regional fisheries, and ultimately the failure of those fisheries exploited subsequently to compensate for declining catches in areas accessed previously (Pauly et al., 2005). Second, as populations of desired species decline near the coast (in shallow waters), more fishing effort further offshore and in deeper waters is required to maintain catches (Morato et al., 2006), resulting in more “collateral impacts”: increases in by-catch, or non-target species of fish that are thrown overboard, and more damage from habitat-impacting fishing gear (Chuenpagdee et al., 2003). The consumption of more fuel and other operational costs, of course, also rise (Tyedmers et al., 2005).

Following a peak and stagnation period in the early 1990s, the reported catch of marine fisheries started to decline, from 86.4 million tonnes in 1996 to 74.4 million tonnes in 2010 (FAO, 2012b). Fishing effort continues to increase, however. Increased fishing effort manifests itself in the increasing deployment of trawlers relative to other vessel types, currently making up one-third of the global fleet. But trawlers also have a deleterious effect on marine ecosystems, with significant effects on community structure observed (Sánchez-Jerez and Esplá, 1996; Chuenpagdee et al., 2003), and they generate 50% of global by-catch, a huge waste of perfectly edible fish. This translates into decreasing levels of catch per effort (Fig. 1C), implying both declining resource abundance and profitability of the vessels exploiting these resources (Watson et al., 2012).

5. Discussion and conclusions

We have offered a brief look at the trend toward increasing ecological impact as a function of production effort in three sectors, but would anticipate similar trends in others. This research supports other recent critiques of environmental remedies that focus on controlling consumption. Alcott (2010), for example, argues for direct taxation on impact, since all three of the factors on the right side of the IPAT equation are interconnected, and thus efforts to control either one may have rebound effects in others (See also Steinberger and Krausmann, 2011). Thus, even if we could imagine a political structure that accommodated full-cost pricing of ecological impact, if the positive relationship between ecological impact and production effort is borne out, it would translate into a continuously escalating cost of production that would need to be absorbed by capital, states, and citizens.

When efficiency efforts do not succeed, declining reserves to production ratios are presumed to induce substitution. Discussions have been especially enthusiastic of late for the application of renewable energy resources, and to a lesser extent nuclear power, as less carbon-intensive substitutes for fossil fuel. While all options for climate mitigation ought to be thoroughly considered, and we do not dispute the potential benefits of energy alternatives, all material requirements impose ecological costs. Therefore substituting one form of fuel/mineral/protein for another when one becomes depleted, in those instances in which alternative resources capable of comparable performance are available, simply substitutes one portfolio of social and ecological impacts for another. Replacing coal with nuclear power reduces CO_2 emissions but raises the specter of accidents involving widespread radiation; replacing fish with soy increases pressure on agrarian lands, further motivating the use of chemical inputs to boost production. Grains on the other hand simply have no substitute. Technological innovations directed toward efficiency, moreover, as with all investments in science and technology, suffer from declining returns: big discoveries tend not to be followed by bigger discoveries, they are followed by smaller, and more expensive ones (Strumski et al., 2010). A brief case in point, Imperial Oil has brought water consumption at its Cold Lake oilsands in-situ operations down from 3.5 barrels of water per barrel of oil in 1985 to about 0.5 barrels today (CAPP, 2012). But that 0.5 threshold was achieved over twelve years ago, basically within the first few years, and further improvements have not been realized despite continued investments in efficiency technologies.

More broadly, social path dependencies and biophysical realities often preclude transformative shifts, even when theoretically possible with current technology (Huesemann and Huesemann, 2011). Our dependence on oil, for example, has proven remarkably resilient in the face of declining reserve/production ratios. As a result, technological investments are far more likely to be directed toward accessing and processing those resources upon which we are already dependent, rather than changes in sources, efficiencies, or lifestyles. Efficiency technologies, rather than extraction technologies, have been virtually the sole technology focus in the IPAT literature, and the industrial ecology and ecological modernization literatures. While the former are presumed to offer ecological benefit, however, the latter tend to do the reverse. Indeed, the forces driving technological advances in accessing and processing lower quality raw materials may well be far out-pacing the forces driving investments in efficiency/impact reduction technologies. The technologies now in use to extract and process bitumen took decades to develop; we are now capable of drilling well over a mile below the surface to extract oil and natural gas, and send a horizontal drill just as far to extract oil and gas from solid shale deposits. But the adoption of ever-more complex technologies required to access and process lower quality resources has in many instances introduced new levels of social and ecological catastrophe risk, as were realized when the 10 km-deep Horizon oil well operated by British Petroleum failed in April 2010. Even comparatively low-tech extraction and harvesting tools, such as purse seine nets, have their costs, as discussed.

Risks aside, confidence in the prospects of technology keeping up with the ecological impacts of increased demand, increased production effort, *and* declining returns on investment requires a hearty dose of faith indeed. The “Effort Factor” poses an unpalatable but critical trend that warrants careful consideration in future ecological impact analyses and scenario planning. While for much of the Industrial Revolution the regular discovery of new “frontiers” of resource richness offered a sense of security, this reality becomes far more vivid in an age of resource scarcity. The current paper is offered not as conclusive, but rather as an invitation for future confirmation, refutation, and elaboration. Doing so is not without its challenges, however. One significant challenge is the location of historical measurements of trends that can be considered valid proxies for ecological impact that have been collected consistently for any length of time. The other challenge is the integration of the complex social dimensions defining the Labor term into measurable Effort indicators, which likewise have been collected in a consistent manner over time. Confronting such challenges is fully warranted, however, to elicit further the historical and projected future relationships between resource quality and labor, how they manifest in historical trajectories of both ecological and social impact, and perhaps most importantly, how individuals, organizations and societies respond.

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