ENTROPIC DISORDER: NEW FRONTIERS IN ENVIRONMENTAL SOCIOLOGY

LAURA A. McKINNEY
Tulane University

ABSTRACT: *Environmental sociologists have identified various facets of anthropogenic ecological degradation such as deforestation, greenhouse gas emissions, natural resource depletion, and water and land pollution. Virtually all of these outcomes are encompassed by one important dimension—the introduction of "entropy" or disorder via processes of production, consumption, and waste creation that are critical to understanding current cleavages in sustainability profiles of nations. This article synthesizes thermodynamic laws with global political-economic interpretations on the environment. A cross-national structural equation model demonstrates the theoretical and empirical importance of entropy as it relates to natural resources and environmental degradation. Conclusions and implications for research in environmental sociology, particularly, and sociology, generally, are discussed.*
Keywords: entropy, environment, thermodynamics, global sustainability, structural equation modeling

There is little doubt that humans are consuming Earth's natural resources at an unprecedented rate, and the consensus among the scientific community is that, unchecked, this will lead to ecological calamities such as global warming, habitat encroachment, biodiversity loss, and air, land, and water pollution (Hansen, Nazarenko, Ruedy, Sato, Willis, DelGenio, Koch, Lacis, Lo, Menon, Novakov, Perlwitz, Russell, Schmidt, and Tausnev 2005; Intergovernmental Panel on Climate Change 2007; United Nations Environment Programme 2007). Alterations to the organic composition of the environment occurring since the industrial revolution are unrivaled by those accumulated in any prior epoch in history (Ewing, Moore, Goldfinger, Oursler, Reed, and Wackernagel 2010; UNEP 2007). In addition to burgeoning population growth, many attribute this to the staggering rate of fossil fuel extraction and combustion that supplies energy to machines for production and transportation purposes (Ewing et al. 2010; IPCC 2007). Monitoring and managing the magnitude of resource depletion is essential to sustainability, or the provision

Address correspondence to: Laura A. McKinney, 220 Newcomb Hall, New Orleans, LA 70118; *e-mail*: laura.mckinney@gmail.com.

***Sociological Perspectives*, Vol. 55, Issue 2, pp. 295–317, ISSN 0731-1214, electronic ISSN 1533-8673.**
© 2012 by Pacific Sociological Association. All rights reserved. Please direct all requests for permission to photocopy or reproduce article content through the University of California Press's Rights and Permissions website, at http://www.ucpressjournals.com/reprintinfo.asp. **DOI: 10.1525/sop.2012.55.2.295.**

of inputs critical to survival of the planet's species. This article explores these dynamics in an entropic framework that encompasses virtually all forms of environmental degradation and weds strands of theorization from the social, natural, and physical sciences.

"Entropy" is a foundational concept in the physical sciences that is treated as a fundamental law of nature, as explained by the second law of thermodynamics (Georgescu-Roegen 1971; Prigogine 1967). In the physical world, degradation of order into chaos is an irreversible and continuous process that is captured by the term "entropy" and is intrinsically linked to issues of environmental sustainability[1] (Daly and Cobb 1989). While the first law of thermodynamics states that no energy may be created or destroyed (which could be taken to suggest limitless energy usage), it is the second law of thermodynamics that captures what is lost—the "orderliness" or quality of energy that is irreversibly impacted when applied in production. Essentially, entropy refers to the capacity for rearrangement; as an entity tends toward high entropy, it is less able to be rearranged and thus less useful (Prigogine 1967). Pristine natural resources exist in states of low-entropy with maximum capacity for rearrangement so that "work" may be done, but processes of extraction and production reconfigure raw materials, create pollution, and generate entropy or disorder. Low-entropy natural resources range from air, land, water, coal, oil, wood, plant, and animal biota and serve multiple purposes related to the current sustainability of all life forms. Economic advance is accelerating the deterioration of the physical world due to its dependence on natural resource inputs and the pollution it creates (Georgescu-Roegen 1971). Thus, entropic dynamics are inextricably linked to economic processes and the social relations in which they are embedded. This article seeks to delineate those dynamics in a theoretical framework that lends itself to empirical examination.

Sociological research has advanced a number of perspectives ranging from metabolic rift (Foster 1999; 2009), treadmill of production (Schnaiberg and Gould 1994), world-systems theory (Wallerstein 1974), and unequal ecological exchange (Jorgenson and Clark 2009) in empirical examinations of diverse forms of environmental degradation, including greenhouse gas emissions, deforestation, ecological footprints, and biodiversity loss (Bunker 1984; 1985; Jorgenson 2006; McKinney, Kick, and Fulkerson 2010; York, Rosa, and Dietz 2003a; 2003b). These and myriad other forms of environmental degradation commonly treated by sociologists are symptomatic of general ecological disorder indicative of increased entropy. Despite their overarching importance and treatment in other disciplines (e.g., economics, see Georgescu-Roegen 1971; anthropology, see Hornborg 2001; human ecology, see Rees 2004; ecological economics, see Daly and Cobb 1989), most theories in environmental sociology have yet to fully embrace the entropic dynamics that anchor nearly all ecological outcomes of interest. What is missing, and what this article offers, is a theoretical and empirical approach to environmental degradation that accounts for the underlying element of deterioration of the physical world—the generation of entropy.

This article synthesizes the concept of entropy with prior theorizations in environmental sociology by introducing laws derived from the physical and natural sciences. The theoretical and empirical importance of entropy is demonstrated in a cross-national structural equation model of entropic disorder in the world-system. For purposes of comparison, it is presented alongside an identical model of a popular outcome of interest in environmental sociology, the ecological footprint of nations. Important differences in the analyses are discussed and related to issues of theoretical articulation and model specification. It is concluded that entropy is an essential aspect of environmental degradation commonly overlooked by sociologists, which is consequential for theoretical and empirical advance in the field.

The Ecological Footprint and Entropy

The ecological footprint has enjoyed an appreciable amount of treatment in the economic (e.g., Chambers and Guo 2009), sociological (e.g., Jorgenson and Clark 2009; York et al. 2003a), ecological (e.g., Dietz and Neumayer 2007), and development (e.g., Torras 2003) literatures. Indeed, it has become one of the most widely utilized operationalizations of environmental degradation in the sociology of the environment literature (see, e.g., Jorgenson and Clark 2009; York et al. 2003a). The ecological footprint quantifies nations' production and consumption demands and related waste generation in terms of biologically productive land requirements to support those activities and absorb waste. Yet strict reliance on the ecological footprint is problematic—the concern is its failure to account for nations' regenerative capacities. Indeed, production, consumption, and waste degrade the environment, but rates beyond the ecological limits of a nation endanger global sustainability, particularly for supplier nations and the people in them. Put simply, footprints that exceed national carrying capacity indicate that a nation is creating entropy or disorder abroad. Thus, what is needed is an analysis of footprints *beyond* natural resource limitations, precisely what this research provides.

It is essential that any estimate of entropic creation account for domestic production (GDP), international exchanges (imports and exports), as well as ecological regeneration capabilities (or biocapacity). Using estimates of the ecological footprint alone does not incorporate these important dynamics. Yet Global Footprint Network (2009) data provide a comparison of demand on (i.e., the ecological footprint), and supply of (i.e., biocapacity), the relative natural resources of countries (Wackernagel and Rees 1996).[2] The "ecological footprint" quantifies the amount of land and water area (i.e., low-entropy natural resources) necessary to support production and consumption and absorb the resultant waste of a given human population, which is one half of the equation. The other half, available (low-entropy) natural resources—referred to as "biocapacity"—with maximum capacity for rearrangement, are also provided by the Global Footprint Network (2009).[3] By subtracting the amount of natural resources necessary to support consumption and absorb waste of a nation (the ecological footprint) from the stocks of domestically available natural resources (biocapacity), the residual represents consumption supported abroad or biocapacity undisturbed by domestic consumption. This value approximates the entropic conditions of countries by gauging the overshoot or undershoot of domestic consumption with carrying capacity, resulting in a classification of nations as "entropic debtors" (i.e., consumption exceeds biocapacity) or "entropic creditors" (i.e., consumption below biocapacity), regarding global ecological stewardship.

Despite possibilities due to the widespread data availability, it is rare for any analysis to examine footprint *and* biocapacity data together to derive national accounts of entropic disorder. The natural resource base of nations, or their natural capital (Flora and Flora 2008), is fundamental to investigating patterns of production, exchange, consumption, and waste creation that contribute to environmental degradation around the world. Oftentimes, the connections among resources, wealth, power, and exchanges in the global system result in ecological damage far removed from the source of demand as more powerful nations exploit ecosystems abroad to support domestic consumption and maintain their relatively ordered environments. To be sure, the intersection of natural resource endowments, power/dependency relations, and economic globalization determines the bulk of global inequalities, especially those related to the sustainability profiles of nations (Gallagher 2009; Stiglitz 2007). This article examines these processes through an ecological accounting of nations' entropic generation based on available natural resources, domestic production, and imports and exports profiles that, when taken together, provide a holistic assessment of the generation of disorder abroad by nations in the world-system. Prior theorizations ripe for incorporating entropic dynamics are discussed below.

THEORIES OF GLOBAL POLITICAL-ECONOMYAND ENTROPY

Global political-economic theories offer themes that are especially auspicious for integrating entropic processes at the nation-state level of aggregation, which also correspond with the available data discussed above. Theories of global political economy broadly include metabolic rift (Foster 1999; Moore 2000; 2011), treadmill of production (Schnaiberg and Gould 1994), world-systems/dependency theory (Frank 1978; Wallerstein 1974), and unequal ecological exchange (Hornborg 2001; Jorgenson and Clark 2009). Although not without their particular emphases and nuanced discrepancies, these theoretical approaches identify the ever-expanding system of capital predicated on the exploitation and depletion of natural resource as in direct contradiction to sustainability. In particular, the inherent expansionary tendency of the system of capital to accumulate greater profits in the hands of few at the expense of so many poses an insurmountable hurdle to achieving global sustainability goals. Not only is the proclivity to capital accumulation and constant financial growth economically untenable, but it is often derived from the squandering of natural resources that generates disorder and compromises the prospects of environmental sustainability.[4] The interdependencies and intricate linkages among the three pillars of sustainability (environmental, economic, and social) indicate that damage in one dimension imperils the others; that is, there are social, economic, and environmental consequences that result from entropic disorder. Thus, the cleavages in power, wealth, and access to natural resources among nations diminish the possibility for sustainability inasmuch as global inequality is reproduced and the disadvantaged positions of some nations relative to others is maintained under a system based on a productive mode of capital accumulation.

Global political-economy interpretations view the economic stagnation and lack of development in peripheral areas as manifestations of the current world order that maintain the advantaged positions of core countries relative to poorer, peripheral ones. Dependency and world-systems theory are among the dominant cross-national theoretical strands to explain cross-national linkages and exchanges (Beckfield 2008; Bollen 1983; Chase-Dunn 1975; Chase-Dunn, Kawano, and Brewer 2000; Clark 2010; Snyder and Kick 1979), including environmental outcomes such as deforestation, biodiversity loss, air and water pollution, and global climate change, generally (Bunker 1984; Jorgenson and Kick 2003).[5] Thus, they serve as a valuable theoretical point of departure for the present endeavor that synthesizes the entropic dynamics of nation-states with political-economic interpretations of the world-system. Specifically, the relatively unfavorable economic, environmental, and social conditions observed in the lower strata of the world-system are indicative of entropic disorder, the effects of which ripple through and negatively impact wealth, production, and the health and well-being of communities and the people in them.

Rooted in the classical theorizations of Marx ([1867]1977) and theories of imperialism such as Luxembourg (1912), modern dependency and world-systems theory largely spring from the work of Singer (1950), Baran (1957), Frank (1978), Amin (1974), Cardoso and Faletto (1979), Wallerstein (1974), and Chase-Dunn (1989). What varying interpretations within the perspective share is the premise that the world political-economic order and global division of labor therein dictate nation-to-nation resource flows and national capital accumulation. This approach interprets current states of development and dependency as outcomes of historical and current globalized linkages and exchanges. Specifically, "core" or wealthy nations appropriate surplus value from non-core settings through the purchase, exchange, and use of cheap, raw (low-entropy) materials and labor (Bunker and Ciccantell 2005). Multinationals and local elites assist in the remittance of profits to core nations garnered from the exchange of low-entropy natural resources abroad, with the consequence of returning little to no capital to the host nation or its constituents, which is prohibitive for their future domestic growth and development (Kentor and Boswell 2003). McMichael (2004) elaborates on the "globalization project," an international initiative executed by organizations such as the International Monetary Fund, the World Bank, and World Trade Organization that seeks to modify developing countries' political structure largely to support the global flow of capital and goods to developed nations, which exacerbates dependency and incites economic stagnation in developing nations. Non-core nations engage in extraction, mining, agricultural, industrial, and manufacturing processes—under the auspice of pursuing their "comparative advantages" (Smith 1776) to spur development and modernization—that are especially damaging to their environments and create entropy, or disorder, as these materials are exported to core settings. At every point of production, entropic disorder is generated with compound effects that manifest in the form of weakened economies and impaired social progress. Characteristically, peripheral nations orient toward agricultural, extraction, and mining activities while semiperipheral nations favor both these and industrial and manufacturing sectors as elements of integration into international trade and pathways to prosperity.

Numerous channels reinforce and reproduce unequal exchanges in favor of core nations. These include currency differentials, international aid, structural adjustment loans, debt regimes, threats of domestic subsidies, trade barriers, tariffs, and technology transfers, all of which benefit core nations at the expense of others (McMichael 2004). Classical dependency treatments enumerate the limitations to development posed by dominance in the agricultural sector, narrowness of exports, limited trading partners, and the presence of multinational corporations with foreign state protection. Taken as a whole, the historical patterns of colonialism are echoed in the modern era of dependency as wealthy nations continue to exploit linkages and exchanges that serve to maintain semiperipheral and peripheral nations' dependent status.

Importantly, a handful of theorists have linked the system of capital accumulation and global political economy to entropic dynamics (Biel 2006; Burkett and Foster 2006; Frank 2005; Hornborg 2001). Frank (2005) notes the dissipation of entropy (disorder) is integral to these dependency dynamics, although, unfortunately, he did not fully develop this line of argumentation. Hornborg (2001) assumes an anthropological approach in striving to *defamiliarize* concepts such as technology and economy from the cultural framework in which they operate to evaluate more objectively the extent to which ecologically unequal exchanges in the world-system represent a zero-sum game where gains in one area necessitate losses in others. His epistemological analysis asserts that economic discourse eschews thermodynamic laws while advancing a tautology between utility and price that serves to justify highly unequal market exchanges that reward the dissipation of entropy, resulting in an inverse relationship between prices and actual utility in physical (thermodynamic) terms. For example, raw materials ("crude" oil) are less valuable market commodities than finished goods (refined oil), although in the physical sense the latter is more entropic than the former; therein lies the cognitive dissonance of modern society that is unable to reconcile economic theories with physical principles. For Hornborg, the system of exchanges that financially rewards the dissipation of entropy is predicated on machine fetishism and culturally engineered visions of prices, markets, and development as a cornucopia. Similarly, Biel (2006) views international political economy and relationships therein as dissipative systems that transfer contradictions inherent to capitalism from the economy to the physical environment and social realms, with the adverse outcomes concentrated in non-core areas. Finally, Burkett and Foster (2006) refute the stance that Marxist theory is devoid of thermodynamic processes by offering a compelling report of the chronology of written exchanges between Marx, Engels, and those physicists at the forefront of advancing what later came to be known as the first and second laws of thermodynamics. In essence, they assert that, despite omissions of physical nomenclature, Marx fully embraced and accounted for entropic dynamics in the theory of capital; any misnomers regarding concepts such as entropy in his work simply reflect the lack of scientific consensus on terminology among members of the emerging field of physics.

These represent significant theoretical contributions to the wedding of thermodynamics and political economy, yet they have not reached the level of prominence one might expect for such enterprising endeavors. The resistance to incorporating physical and social sciences could conceivably spring from the increased specialization and fragmentation across academic disciplines that narrow the focus of scientific inquiry so dramatically that it is difficult to conceptualize connections to bridge islands of knowledge together. Speculations aside, one frailty of this body of research is the lack of rigorous empirical conceptualization, measurement, and analysis—precisely what this research offers.[6]

A number of empirical examinations demonstrate the unequal environmental outcomes for dependent versus core nations involved in an exchange of goods or services. Diverse environmental damages emanating from production are shown to be concentrated in non-core settings, including deforestation (Burns, Kick, and Davis 2003), biodiversity loss (McKinney et al. 2010), methane emissions (Jorgenson 2006), and waste (Frey 1998; Pellow 2007). As disorder is created in disadvantaged locales, the evidence of environmental decline becomes ever concentrated in those areas. Ecological deterioration arises from unsustainable consumption, the rates of which are consistently higher in core nations. The divergence between the physical location of environmental degradation and the consumption it supports is referred to as the "Netherlands fallacy," which indicts core nations' relatively intact environments and exorbitant levels of mass consumption as predicated on natural resource exchanges with other nations—thus alleging that core nations export much of their environmental degradation. Notably, some measures of environmental degradation more accurately reflect the locus of offensive activities (i.e., consumption) in core nations prompting ecological decline, such as carbon dioxide emissions (York et al. 2003b) and the ecological footprint that approximates consumption and waste (Jorgenson and Clark 2009; York et al. 2003a). In the core, entropic disordering takes the form of landfills, smog, land transformation, water pollution, and chemical and industrial contamination, generally. Outside the core, entropic disordering from natural resource extraction, mining, deforestation, soil degradation, and habitat encroachment mars landscapes, as well as more severe industrial air, water, and land pollution—indicative of the relatively lax environmental regulations. Building on prior efforts, this research conceptualizes environmental degradation in an entropic perspective, utilizing an outcome variable that controls for stocks of natural resources as well as rates of consumption, production, and waste generation.

HYPOTHESES AND THEORETICAL PREDICTIONS

The theories covered are suggestive of a number of testable hypotheses. Complementing the global political-economy literature with physical laws reviewed above, the relative scope of power and wealth of developed nations facilitates higher rates of domestic consumption with attendant rates of entropic disorder abroad. World-systems and dependency theory posit that the global political-economic regime and division of labor therein dictate the highest levels of modernization characterize the wealthy, core nations, while suppressing modernization, respectively, in semiperipheral and peripheral nations. Further, these disadvantaged nations execute the bulk of natural resource depletion to support core consumption while disordering their domestic environments. Thus, while core nations' consumption far outweighs that of semiperipheral and peripheral nations, it is argued that the environments of the core are relatively preserved while dependent countries engage in exports in their attempts to modernize and spur economic growth. The hypothesis based on the literature reviewed above is that positions of power in the system, which themselves co-vary with geographical indicators (e.g., arable land), are positively associated with the modernization levels of nations and that modernization generates entropic disorder (Hypothesis 1).

Concomitantly, it is theorized by world-system proponents that foreign investment facilitates the appropriation of a host nation's storehouse of raw materials to support core consumption and capital accumulation. Thus, foreign direct investment is specified as impacting entropic disorder in the world-system (Hypothesis 2) and the modernization of nations (Hypothesis 3), both in an expectedly positive manner.[7] Integrating world-systems theory and entropic processes, foreign direct investment is hypothesized to affect the entropic states of nations in two ways: (1) as a mediator variable from world-system position that facilitates the appropriation of resources, thus directly exacerbating disorder in the global system (Hypothesis 2), and (2) as a moderate facilitator of economic growth (modernization) that also increases entropic disorder in the global system (Hypothesis 3).

Related ecological and energetic approaches in the natural sciences warrant the inclusion of pertinent indicators, such as forest change (deforestation), arable land, and the use of renewable energy sources. Deforestation is specified as indirectly affecting entropic disorder, mediated by modernization. Based on prior research (Bunker 1984; 1985; Burns et al. 2003), deforestation is predicted to be inversely related to the level of modernization (Hypothesis 4). Arable land is also expected to negatively impact modernization, highlighting the tension between urban expansion and land conversion versus land conservation (Hypothesis 4). Additionally, arable land is theorized to attenuate the rate of entropic disorder, as these areas lend themselves to cultivation and, thus, provide invaluable regenerative functions for ecosystems (Hypothesis 5). Finally, the percent of energy in a nation derived from renewable sources is included as an indicator to test the ability of those energetic sources to mitigate entropic disorder in the system (Hypothesis 6). Concomitantly, the model tests the effects of arable land on use of renewable energy sources (Hypothesis 5), as those inputs are often predicated on the availability of low-entropy natural resources. To sum, the following hypotheses are tested:

Hypothesis 1: World-system position increases modernization, which accelerates entropic disorder.

Hypothesis 2: World-system position conditions foreign direct investment that directly generates entropic disorder.

Hypothesis 3: Foreign direct investment facilitates modernization that, in turn, accelerates entropic disorder.

Hypothesis 4: Arable land and deforestation are negatively associated with modernization.

Hypothesis 5: Arable land directly abates the rate of entropic disorder, and indirectly abates it through its positive association with renewable energy usage.

Hypothesis 6: Renewable energy usage directly attenuates entropic disorder.

DATA AND METHODOLOGY

Sample

All nations for which data are available for the outcome variable are included in the analysis, resulting in a sample size of 125. The rate of entropic disorder—or consumption beyond domestically available natural resources—is calculated by subtracting the ecological footprint (a nation's demand on nature) from the available biocapacity (low-entropy natural resources), resulting in a ranking of nations with "entropic debtors" and "entropic creditors" on either ends of the continuum (Ewing et al. 2010). Appendix A lists the countries included in the analysis arrayed on those scores.[8]

Dependent Variable

Having established the crucial influence of natural resource endowments and global political-economic dynamics on development trajectories, sustainability profiles, and the creation of disorder in the world-system, an analysis that controls for these variables is warranted. This research examines the entropic conditions of nations by subtracting the ecological footprint from domestically available biocapacity in 2006 (Global Footprint Network 2009),[9] resulting in an estimate of national consumption below or beyond that which can be sustainably supported. Transforming the footprint to account for natural resource endowments makes the analysis more encompassing of ecological metabolic constraints and entropic processes that inform how those phenomena result in divergent sustainability outcomes for nations, a topic that has heretofore received no empirical treatment in the environmental sociology literature. An analysis such as this brings us one step closer to concluding which nations are in the worst violation of domestic carrying capacity that generates disorder in the system.

The outcome measure of rate of entropic disorder in the global system is a most conservative appraisal of overshoot, as it does not account for the biocapacity necessary to sustain any species other than humankind. Thus, the omission of land area and resource inputs to support other forms of biodiversity results in a cautious estimate of the consumption of nature. The dependent variable is log transformed to meet the assumptions of the estimation technique (Bollen 1989; Garson 2009). To ease interpretation, the logged values were then multiplied by –1, so that "entropic debtor" nations had higher scores than "entropic creditor" countries. Thus, the outcome approximates a nation's contribution to disorder in the global system. Following convention, logarithmic transformation is undertaken for all skewed or kurtotic variables in the analysis (see York et al. 2003a). The outcome is specified in a structural equation model (SEM) as directly and indirectly resulting from global power/dependency dynamics, ecological factors, and domestic developmental and economic attributes. The latter themselves are interconnected and tested, based on extant theoretical formulations.

Independent Variables

Power/Dependency and Global Political Economy. A measure of world-system position developed by Kick, McKinney, McDonald, and Jorgenson (2011) for the period 1995–1999 is employed. This measure replicates and updates the findings of Snyder and Kick (1979) to measure world-system positions for the modern period. The measure is based on a multiple-network analysis of transnational economic, political, cultural, and military linkages among 160 countries. Specifically, the network analysis is comprised of ties between nations across four relational dimensions—trading partners, co-membership in international nongovernmental organizations (INGOs), internation embassy sponsorship, and arms transfers. The multiple network analysis of these ties produces clusters of nations that are structurally situated in similar positions across the system. Thus, countries are grouped not because they are closely tied with one another but instead because their patterns of relationships to all other countries are very similar. Arraying the density of ties between country blocks in a matrix facilitates rank ordering of each cluster or block of countries based on the hierarchy of overall power in the system. Doing so results in ten structurally similar clusters of nations in the world-system that are then converted to a numeric rank ordering (1–10), such that a value of 10 represents nations with the greatest scope of power and influence while a value of 1 equates to the most disadvantaged, dependent, and peripheral nations in the world-system.

Modernization. Affluence is a conventional measure of modernization and a central predictor of environmental impact for many relevant theorizations. National affluence (or economic output and prosperity) is operationalized using the standard measure, gross domestic product per capita (GDP/C) for the year 2005. GDP/C is a continuous variable converted into current international dollars using Purchasing Power Parity (PPP) rates, log transformed to address skewness, and taken from World Bank (2009). Percent urban also is a key indicator of modernity and is used in a variety of cross-national quantitative studies, including the sociology of environment literature.[10] Data measuring the percent of urban areas in each country are taken from the World Bank (2009) for the year 2005. Affluence and urbanization are indicators of the latent variable modernization in the model, which reflects the literature on the modernization process (Durkheim 1893 [1997]; Rostow 1960; Smelser 1964) and is empirically validated by the SEM analysis.

Ecological Variables. The inclusion of arable land area for 2000 (World Resource Institute [WRI] 2009) is warranted as an ecological control based on its obvious, positive impacts on biocapacity. This value also reflects, to some extent, the historical legacy of colonialism and imperialism that seeks to expand national boundaries, resulting in a greater resource base for the conquerors. Moreover, abundant arable land corresponds to the viability of renewable energy sources such as wind, solar, and hydropower. Thus, arable land is specified as directly affecting modernization, percent renewable energy sources, and the outcome. Additionally, the percent change in forest area from 1990–2000—derived from estimates of total forest extent in 1990 and 2000[11] (WRI 2009)—is included as an exogenous variable. Change in total forest area is anticipated to be negatively associated with modernization, based on prior research (e.g., Burns et al. 2003) that shows deforestation is increasingly concentrated in nations outside the core, which tends to evidence trends of reforestation.

Foreign Direct Investment (FDI). To gauge the impact of economic influence by external actors (e.g., multinational corporations), foreign direct investment flows are included as an indicator of global market integration. FDI is specified as a mediator from world-system position to modernization and to the outcome.[12] To circumvent the anomalies that might stem from the use of one year of data, the average annual value of foreign direct investment flows for 2002–04, taken from the World Bank (2009), is used in the model.

Renewable Energy. The percent of energy in a nation derived from renewable energy sources (e.g., wind, solar, hydro) in 2005 from the Environmental Sustainability Index (Esty, Levy, Srebotnjak, and de Sherbinin 2005) is specified as a mediator from arable land to entropic disorder. This variable is included to determine the degree to which alternative energies may palliate entropic disorder and preserve an otherwise rapidly dwindling resource base that is a chief concern for sustainability.

ANALYSIS AND RESULTS

A more in-depth discussion of the entropic disorder scale for nations presented in Appendix A is appropriate given its fundamental importance to the present effort and lack of prior empirical treatment. Inspection of the rank order of countries' rates of consumption beyond or below domestically available biocapacity renders a number of noteworthy trends. First, the clustering of Middle Eastern countries (United Arab Emirates, Kuwait, Qatar, and Israel) in the top four positions of overshoot (i.e., entropic debtors) is likely indicative of the deleterious combination of voluminous carbon dioxide emissions,[13] scant biologically productive resources in desert nations—especially forestland—to mitigate those emissions, and the impact of affluence on consumption profiles.[14] Second, the World Bank (2009) classifies the twenty-five countries in worst violation of their biocapacity (i.e., entropic debtors) as "high-income economies," further suggestive of the adverse effects of affluence on the environment. The relationship between income classification and entropic profiles (high to low and debtors to creditors, respectively) emerges as a general trend. Exceptionally, a handful of high-income economies (Canada, Finland, New Zealand, Estonia, and Norway) cluster at the entropic creditors' end of the continuum. Reasonably, this pattern is demonstrative of those nations' abundant repositories of biocapacity.[15]

Structural equation modeling (SEM) is the chosen estimation technique due to its favorable treatment of measurement error, latent variables, and direct and indirect effects.[16] In addition, SEM provides goodness-of-fit statistics for the model as a whole, enabling the researcher to judge the fit of the model to the data and make adjustments (e.g., model building and model trimming) based on these estimations. The ability to test the fit of the model to the data provided is a feature that sets SEM quite apart from more traditional estimation methods, such as OLS regression. The superiority of SEM for this particular application also is its ability to derive unbiased coefficient estimators, even in the face of severe multicollinearity—or correlated independent variables—that is "the bane of cross-national

TABLE 1

Descriptive Statistics and Bivariate Correlation Matrix

		M	*SD*	*X1*	*X2*	*X3*	*X4*	*X5*	*X6*	*X7*	*X8*	*X9*
X1	Entropic disorder (ln)[a]	–2.223	0.371	1								
X2	Ecological footprint (ln)	1.076	0.552	.459*	1							
X3	World-system position (ln)	1.367	0.670	.314*	.558*	1						
X4	Arable land (ln)	7.755	1.883	–.274*	–.121	.284*	1					
X5	Deforestation 1990–2000 (ln)[a]	–3.400	0.488	–.302*	–.322*	–.337*	.089	1				
X6	GDPC (ln)	8.726	1.313	.469*	.873*	.678*	–.069	–.450*	1			
X7	% Urban	57.312	21.376	.333*	.673*	.483*	–.082	–.372*	.766*	1		
X8	Average FDI 2002–04 (ln)	7.779	1.262	.267*	.361*	.464*	.316*	–.186	.442*	.336*	1	
X9	% Renewable energy (ln)	1.8757	1.377	–.382*	–.166	–.009	.232*	.095	–.131	–.202	–.042	1

Note. FDI = Foreign Direct Investment; GDPC = Gross Domestic Product Per Capita.
a. Both Entropic Disorder and Deforestation variables underwent log transformation to meet the assumptions of SEM; the logged values were then multiplied by –1 to ease interpretation of results.
*p < .01, two-tailed test.

research" (Firebaugh 1983:263). Examination of the correlation matrix in Table 1 indicates this is a significant consideration, further warranting the use of the method chosen.

For purposes of comparison, I first offer a model of the ecological footprint of nations for the year 2006. Recall that the footprint is a favored dependent variable in a variety of empirical studies in environmental sociology (e.g., Jorgenson and Clark 2009; York et al. 2003a). The model renders a low RMSEA (.047) value and high IFI (.992), CFI (.992), and TLI (.977) values, all of which indicate a well-fitted model. However, employing this outcome masks the influence of biophysical, energetic, and economic conditions. Specifically, it finds no effect of FDI (–.02), arable land (–.04), or renewable energy sources (–.05) on the footprints of nations, although these are found to be significant predictors in the entropic disorder model presented below. Thus, the conclusion reached by the ecological footprints model is purely a story of the impact of modernization (.88) and offers no avenues to ameliorate degradation, demonstrating the utility of analyzing stocks of natural resources in tandem with levels of consumption as presented below.

Figure 2 presents the SEM predicting the rate of global entropic generation among nations (*N* = 125). The model fit statistics are well within the acceptable ranges, with a low RMSEA (.049) value and high IFI, CFI, and TLI values (.989, .988, and .967,

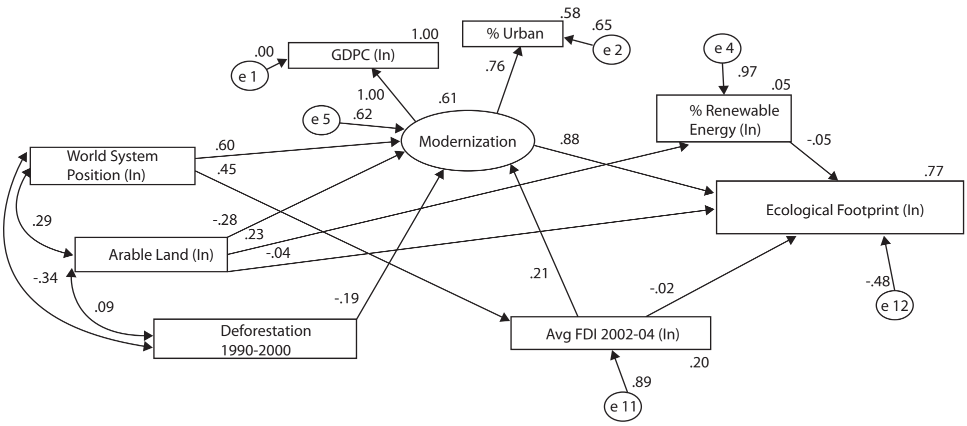

FIGURE 1

Cross-National Structural Equation Model of the Ecological Footprint, $N = 125$ Countries
Note: The pathways from FDI, renewable, and arable land to the outcome are nonsignificant; all other relationships are significant at the $p < .05$ level. Model Fit: $\chi^2 = 16.631$, $df = 13$ (not significant), ratio = 1.279, RMSEA = .047, IFI = .992, CFI = .992, TLI = .977.

respectively), permitting interpretation of coefficients (see Byrne 2009; Garson 2009). Further, all relationships in the model are statistically significant at the $p < .05$ level or better. Error terms and covariances among exogenous variables are appropriately specified in the model to meet assumptions of the estimation technique. The final model was derived after a series of model estimations, using the model building and model trimming techniques discussed in-depth by Byrne (2009). The model presented in Figure 2 represents the best-fitted model, based on fit statistics and the statistical significance of relationships among the variables.

World-system position is shown to have a positive effect on modernization (.60) and FDI (.45). FDI is also positively related to modernization (.22), and both subsequently contribute to entropic disorder (.18 and .34, respectively). Thus, world-system position indirectly affects entropic disorder in the following ways: (1) its heightening effect on the modernization level of nations and (2) its positive association with FDI that also increases modernization, both of which, in turn, directly exacerbate entropic disorder. The results for the ecological variables included in the analysis consist of the direct effects of arable land on modernization (–.28), renewable energy (.23), and entropic disorder (–.23), as well as negative relationship of forest change on modernization (–.18). The effects of arable land are wholly interpretable, based on the logic reviewed above. Deforestation is negatively associated with modernization, indicating that rates of deforestation are greater in less developed countries and supporting the notion that a dwindling resource base negatively affects development trajectories. Hence, ecological factors influence entropic disorder in direct and indirect ways. The model supports the mitigating effect of renewable energy sources on entropic disorder (–.28), thus providing optimism for alternative energy sources to impart some respite for overshoot. However, it is unfortunate that in earlier estimations, the effect of modernization on renewable energy was tested with results that approached the threshold for

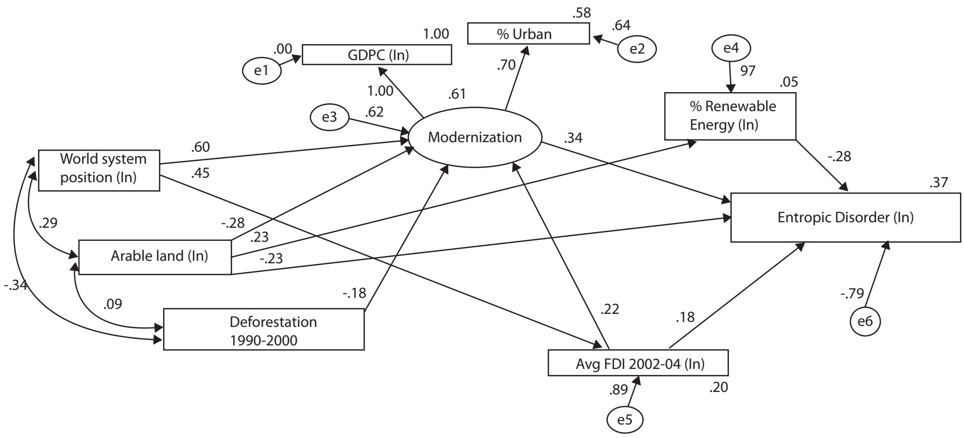

FIGURE 2

Cross-National Structural Equation Model of Entropic Disorder, N = 125 Countries

Note: All relationships statistically significant at the $p < .05$ level or better. Model Fit: χ^2 = 16.850, df = 13 (not significant), ratio = 1.296, RMSEA = .049, IFI = .989, CFI = .988, TLI = .967.

statistical significance, although in the *negative* direction. This contradicts the aspiration that modernization and technological advance facilitate the development and emergence of efficient, more sustainable sources of energy.

A comparison of Figures 1 and 2 is instructive. The former finds no effect of FDI on ecological footprints, yet it is confirmed that it significantly accelerates entropic disordering in the latter. Additionally, the ecological footprints model finds no effect of arable land, which is shown to attenuate entropic disorder. Finally, the effect of renewable energy sources does not reach significance in the ecological footprints model but is found to directly moderate entropic disorder. Overall, the entropic disorder model (Figure 2) highlights avenues for preserving low-entropy resources that are not supported by the footprint model (Figure 1). As we face current ecological crises, it becomes ever more important for scientists to discern the ways in which our social relations expedite decline as well as those processes that mitigate disorder. The accumulation of knowledge in this research area benefits from uncovering the specific dynamics that condition global entropic disorder, which unquestionably impacts prospects for sustainability.[17]

DISCUSSION

Forces of globalization that lead to vast increases in interconnectedness across nations are among the mechanisms that further global environmental inequality and undermine sustainability. While footprint data are useful for assisting in comparisons of consumption and waste generation cross-nationally, they are limited in application, due to the omission of crucial facets of the current world order such as the connection between a nation's supply of natural resources and its development trajectories (Sachs and Warner 1995; 2001). Consequently, this research incorporates both the ecological footprint and biocapacity of nations to more accurately reflect cross-national consumption that accelerates the degradation of some nations while essentially preserving the culture of consumerism and relatively intact environments of others.

The models presented provide a wealth of information related to global political-economic theories in environmental sociology, physical laws of entropic processes, and the introduction of disorder into the world-system. It is confirmed that the inclusion of entropic dynamics in environmental sociology theorizations is an important dimension that cannot be overlooked. Ecological factors emphasized by natural science models prove to be significant predictors as well, warranting their inclusion in any examination of entropic outcomes. Additionally, renewable energy use mitigates entropic disorder, although it is disheartening that modernization does not appear to facilitate the use of renewable energy, as this could improve the prospects of global sustainability, generally. Thus, these specifications are especially useful in exposing the frailties of approaches that argue societal modernization alleviates pressures on the environment. To sum, the incorporation of physical and natural science tenets benefits theoretical and empirical advance in environmental sociology.

These findings are uncovered when the global system is empirically modeled to reflect the interwoven nature of social, physical, and natural systems. Thus, the paramount significance of synthesizing strands of theorization from the social, physical, and natural sciences is demonstrated. Marx ([1867]1977) had good reason to be concerned with the physical and natural undergirding of ecological degradation as it relates to capital accumulation (see, e.g., Burkett and Foster 2006), and in the contemporary period, it is just as profitable an endeavor as we aspire to strengthen our scientific understanding of the world. At least implicitly, we should be cautious of approaches to scientific discovery that reduce highly interdependent dynamics—such as those linking our social, physical, and natural worlds—into disparate fragments examined in isolation of the systems they constitute. Moving forward, the creation of improved measures of entropic dynamics, such as accounting for the biocapacity to support all species and incorporating estimates of terrestrial energy sources, is a fruitful undertaking. Entropy is an especially promising area for progress in environmental sociology, as it encompasses nearly all environmental outcomes of interest and, in doing so, allows researchers to hone comprehensive assessments of current and future prospects for sustainability.

Not only is the incorporation of entropic dynamics crucial to progress in environmental sociology, but other branches in the discipline can benefit as well from such analyses. Harkening back to our earlier discussion of sustainability, the concept is comprised of environmental, economic, and social dimensions. The emphasis on the environment is a new one and notable because economic advance and social progress hinge on quality inputs gained from it. To illustrate, economic production depends on soil, air, water, and energy inputs to run operations. Basic needs—such as food, shelter, and clothing—are met through the manipulation of natural resources gained from the environment. As entropy measures the amount of unavailable energy in our world, it reflects the growing scarcity of resources available to civilizations as they aspire to progress in economic and social terms. While the creation of entropy in the environment is inevitable, it is possible to more sustainably manage and minimize its generation, which is beneficial for the well-being of present and future generations.

CONCLUSIONS AND IMPLICATIONS

Humanity depends on nature to supply the crucial inputs to run the economies of the world and provide invaluable ecological services, but in order to be sustainable, we must learn to live within our ecological budget—that is, reckoning our use of natural resources and generation of waste with nature's regenerative and metabolic capacities. In order to be sustainable, it is essential that we are cognizant of how much we have and how much we use and that we strive to reconcile the two in an effort to enrich our ability to persist into the future. The present effort responds to this need by comparing nations' footprints in tandem with biocapacity, providing a more comprehensive assessment of ecological burdens. Patterns of consumption, production, and waste generation that transcend natural limits put us in global ecological overshoot, undermining the basis on which humanity (and all life) depends. Assessments of ecological deficit or surplus are informative for managing ecological assets and instructive for individual and collective action to support sustainable living. Analogous to financial overspending, it is also possible to exceed our ecological budget, but ultimately, violations can only be fleeting. In the long term, continued overuse and expanding ecological deficits will bankrupt nature with one very tangible consequence—life on Earth will not be sustained.

This article confirms the inextricable linkages among the social, physical, and natural scientific disciplines. As such, there are implications for existing theories in sociology, generally, and environmental sociology, particularly. Regarding the latter, it is essential that ecological outcomes be conceptualized in the context of entropic disorder. This allows researchers to collapse myriad forms of environmental degradation under the umbrella of entropy. Incorporating the entropic framework into current theorizations in environmental sociology is not only possible, as shown in this article, but doing so provides a more complete picture of the dynamics prompting environmental decline as well as ways to mitigate it. Theories of global political economy prove to be a powerful framework ripe for the incorporation of entropic processes. This analysis confirms that the synthesis of global political-economic treatments and physical laws not only is a worthwhile theoretical endeavor but also generates empirical conclusions that contrast the ones reached otherwise. These features point to the potential for applications of entropic dynamics in environmental sociology to advance the accumulation of knowledge in the area.

Having established the primal importance of natural capital, economic production, and entropic disorder to sustainability, these dynamics should be incorporated into current theorizations in the sociological discipline as a whole. The state of relative order or disorder of an environment unquestionably conditions economic and social progress, which are linked in webs of cause, effect, and feedback. Future research should integrate entropic dynamics to analyze their role in the development trajectories of groups, communities, regions, and societies as they condition the lives of individuals. The axiom of systems to tend toward high entropy justifies the inclusion of these important processes in order to fully understand the nexus of interaction linking social, physical, and natural systems. This article treats only one facet of this interplay, but the implications for other lines of sociological inquiry abound and should be explored.

A few specific calls for future sociological research are offered. Most broadly, the quest for low-entropy resources could be applied to the history of civilizations, explaining at least in part why certain areas were attractive candidates for human settlements and how these endowments (or the lack thereof) affect historical and present-day configurations of wealth, power, and conquest. Examining the influence of entropic disorder can also be undertaken at the regional level as a possible dimension of stagnation or underdevelopment in some spaces relative to others. Finally, and most assuredly, assessments of environmental degradation should incorporate entropic disorder into theorizations and empirical treatments to gain clarity on the negative consequences of overshooting ecological limits. In general, social and economic well-being depends on inputs from ecosystems, and inquiries into related antecedents, conditions, and outcomes should, at minimum, consider the role of entropy. The efforts of Biel (2006) and Hornborg (2001) to link entropic dynamics to gender and social inequality, respectively, are exemplary initiatives suggestive of particular applications to be further explored in this vein.

In conclusion, the contemporary global system depletes natural resources at an unsustainable pace, processing them in unsustainable ways and returning the perilous by-products to the earth; if these patterns remain unchecked, they will lead to calamity of the commons (Diamond 2005). Knowing how much we have and how much we use is fundamental to securing human well-being. While entropic exchanges in some fashion characterize the succession of world empires, it is in their most modern industrial and global form that they pose the newest and gravest threat to the sustainability of all life forms. It is possible in the short term for core countries to escape their entropic destiny by laying claim to low-entropy natural resources abroad to support consumption and absorb waste, but in the end, there is but one planet that we all must depend on for sustenance and survival. The greater entropic disorder we introduce into the environment, the more we will be haunted at a later time, when we realize the limits to our presently unsustainable generation of entropic disorder.

Acknowledgments: I would like to thank Ed Kick, Brett Clark, Sarah Bowen, Jason Moore, Michael Schulman, the editors, and four anonymous reviewers for helpful discussions and comments. Of course, any remaining errors are entirely my own.

APPENDIX

Rank of Nations' Entropic Conditions (Negative Numbers Indicate Overshoot of Biocapacity)

United Arab Emirates	–8.9	Japan	–3.5	Albania	–1.6
Kuwait	–7.4	Korea, South	–3.4	Libya	–1.6
Qatar	–5.8	Portugal	–3.2	Croatia	–1.5
Israel	–5.1	Czech Republic	–2.7	Mexico	–1.5
Belgium	–4.6	Saudi Arabia	–2.2	Slovenia	–1.5
United States	–4.6	Slovak Republic	–2.2	Azerbaijan	–1.3
Singapore	–4.5	Germany	–2.1	Turkey	–1.3
United Kingdom	–4.5	Poland	–2.1	Cuba	–1.2
Greece	–4.4	Denmark	–2	Fiji	–1.2
Spain	–4.3	Austria	–1.9	Algeria	–1.1
Switzerland	–4.3	France	–1.8	Egypt	–1.1
Ireland	–3.9	Bosnia & Herzegovina	–1.7	Iraq	–1.1
Italy	–3.9	Iran, I.R. of	–1.7	Oman	–1
Netherlands	–3.6	Jordan	–1.7	South Africa	–1
		Lebanon	–1.7	Armenia	–0.9

(Continued)

APPENDIX

Rank of Nations' Entropic Conditions (Negative Numbers Indicate Overshoot of Biocapacity) (Continued)

China, P.R.	–0.9	Benin	–0.2	Guinea	1.4
Costa Rica	–0.9	Honduras	–0.2	Liberia	1.4
Belarus	–0.8	Burkina Faso	–0.1	Solomon Islands	1.5
Dominican Republic	–0.8	Djibouti	-0.1	Chad	1.6
Korea, North	—0.8	Kazakhstan	–0.1	Zambia	1.7
Tunisia	–0.8	Tanzania	–0.1	Norway	1.9
Uzbekistan	-0.8	Cambodia	0	Russia	1.9
Nigeria	–0.7	Gambia, The	0.1	Colombia	2
Syrian Arab Republic	–0.7	Somalia	0.1	Congo, DR	2
Bulgaria	–0.6	Kyrgyz Republic	0.2	Madagascar	2
Guatemala	–0.6	Niger	0.2	Papua New Guinea	2
Hungary	–0.6	Panama	0.2	Guinea-Bissau	2.3
Moldova	–0.6	Senegal	0.2	Peru	2.3
Thailand	–0.6	Sierra Leone	0.2	Angola	2.5
Ghana	–0.5	Botswana	0.4	Estonia	2.6
Sri Lanka	–0.5	Ecuador	0.4	Latvia	2.6
Ukraine	–0.5	Lao P.D.R.	0.4	Mauritania	3.2
India	–0.4	Lithuania	0.4	Argentina	4.1
Morocco	–0.4	Venezuela, Rep. Bol.	0.4	New Zealand	4.4
Romania	–0.4	Mali	0.6	Namibia	5.7
Tajikistan	–0.4	Myanmar	0.6	Brazil	6.1
Turkmenistan	–0.4	Sudan	0.6	Central African Rep.	7
Vietnam	–0.4	Côte d'Ivoire	0.8	Paraguay	7.4
Haiti	–0.3	Cameroon	0.9	Finland	7.5
Pakistan	–0.3	Eritrea	0.9	Canada	11.3
Yemen, Rep.of	–0.3	Chile	1	Congo, Rep. of	12.2
Zimbabwe	–0.3	Nicaragua	1	Bolivia	16.9

NOTES

1. The United Nations (1987) makes useful distinctions between environmental, economic, and social sustainability. Of course, in treatment of environmental sustainability, implications for economic and social sustainability also are drawn.
2. The Global Footprint Network (2009) provides data for both the ecological footprint and biocapacity. The footprint quantifies land requirements (i.e., cropland, grazing land, forest land, and fishing grounds) to house infrastructure, absorb waste, and produce that which is consumed by the population (in the form of food, fiber, and timber). Biocapacity quantifies the amount of biologically productive resources (i.e., cropland, grazing land, forest land, and fishing grounds) available in a nation. Thus, the latter provides a benchmark of carrying capacity to which the ecological footprint may be compared to determine "overshoot" of those vital resources.
3. Fortunately, the ecological footprint data and biocapacity data exist in the same metric, using identical controls for environmental differences at the nation-state level of aggregation. See Ewing et al. (2010) for elaboration.
4. Some ecological economists (e.g., Neumayer 2010) propose a form of "weak sustainability" that assumes various forms of capital are substitutable. Thus, technological advance and capital accumulation are compensatory mechanisms that alleviate the

need to preserve natural capital stocks. However, the dependence of current technologies (e.g., machines) on natural resource inputs (e.g., oil) to operate necessarily dissipates entropy; that is, these "solutions" cannot overcome physical laws that govern the availability of quality energy. Moreover, the Jevons (1865) paradox, which is the tendency for efficiency gains to increase (rather than decrease) consumption of natural resources, refutes pleas for gains in efficiency to curb overconsumption.

5. Moore (2011) synthesizes environmental conditions and power and capital accumulation under the all-encompassing concept of "ecology" to transcend what he views is a false binary of nature and society.
6. For exceptions, see Lawrence's (2009) empirical analysis of energy and monetary flows (i.e., carbon dioxide emissions and GDP, respectively) as evidence of unequal ecological exchanges from 1975–2005 and Hornborg's (2006) estimates of land and labor inputs for three commodities of British trade for 1850. However, neither of these appraisals accounts for reserves of low-entropy natural resources, warranting an analysis of this sort.
7. Although there is disagreement on the impact of foreign direct investment (see Dixon and Boswell 1996; Firebaugh 1996; Firebaugh and Beck 1994), the discrepancies tend to center on the use of FDI stocks versus FDI flows. The present study employs a measure of FDI inflows; thus, I take for granted the notion that, at least initially, any amount of domestic investment (e.g., FDI) will boost national measures of economic productivity (e.g., GDP).
8. These values are offered so that the reader may compare the entropic conditions of countries. To ease interpretation of the analysis, after undergoing log transformations, these values were then multiplied by –1 such that larger values on the outcome variable indicate the generation of entropic disorder abroad.
9. Per capita values are used for measures of the ecological footprint and biocapacity in the analyses.
10. While this statement is generally true, some assessments of developing nations point to the dynamics of "overurbanization" (Kentor 1981). Thus, the periphery houses countries that are more rural, in general.
11. Percent change in total forest area was calculated by dividing the forest area in 1990 by the change in forest area from 1990–2000: (T2 – T1) / T1.
12. The use of FDI stocks versus FDI flows is debated in the sociological literature (see, e.g., Firebaugh and Beck 1994). Given the primary nature of this analysis, an average score of FDI flows for three years is used, thus qualifying conclusions drawn here to the literature on FDI flows. However, important empirical questions regarding the effect of FDI stocks on entropic disorder should be undertaken in future analyses.
13. In 2006, Qatar, Kuwait, and United Arab Emirates ranked as the top three emitters, respectively, of carbon dioxide measured in metric tons per capita (World Bank 2009).
14. The World Bank (2009) classifies United Arab Emirates, Kuwait, Qatar, and Israel as "high income economies."
15. Canada, Finland, and New Zealand are among the top five nations regarding available domestic biocapacity; Estonia and Norway rank in the top fifteen nations regarding the same.
16. These relationships are specified in accordance with theoretically derived, causal hypotheses. Specifically, the model is time-ordered such that exogenous variables (circa 2000) precede mitigating variables (circa 2005), and all independent variables predate the outcome, taken for the year 2006. This specification facilitates, to some degree, inferring causality from a cross-sectional design. Future analyses should examine these

dynamics using longitudinal data, depending on availability, to assess the agents of change in entropic disorder.

17. Figure 1 indicates that the model explains 77 percent of variation in ecological footprints, compared to 37 percent of variation explained in the outcome for Figure 2, entropic disorder. These squared-multiple correlation values indicate there is room for scientific research to uncover more explanatory factors related to entropic disorder.

REFERENCES

Amin, Samir. 1974. *Accumulation on a World Scale*. New York: Monthly Review Press.

Baran, Paul A. 1957. *The Political Economy of Growth*. New York: Monthly Review Press.

Beckfield, Jason. 2008. "The Dual World Polity: Fragmentation and Integration in Intergovernmental Organizations." *Social Problems* 55(3):419–42.

Biel, Robert. 2006. "The Interplay between Social and Environmental Degradation in the Development of the International Political Economy." *Journal of World-Systems Research* 12(1):109–47.

Bollen, Kenneth. 1983. "World-System Position, Dependency and Democracy: The Cross-National Evidence." *American Sociological Review* 48(4):468–79.

———. 1989. *Structural Equations with Latent Variables*. New York: John Wiley.

Bunker, Stephen G. 1984. "Modes of Extraction, Unequal Exchange, and the Progressive Underdevelopment of an Extreme Periphery: The Brazilian Amazon." *American Journal of Sociology* 89(5):1017–64.

———.1985. *Underdeveloping the Amazon: Extraction, Unequal Exchange and the Failure of the Modern State*. Urbana, IL: University of Illinois Press

——— and Paul S. Ciccantell. 2005. *Globalization and the Race for Resources*. Baltimore, MD: The Johns Hopkins University Press.

Burkett, Paul and John Bellamy Foster. 2006. "Metabolism, Energy, and Entropy in Marx's Critique of Political Economy: Beyond the Podolinsky Myth." *Theory and Society* 35(1):109–56.

Burns, Thomas J., Edward L. Kick, and Byron Davis. 2003. "Theorizing and Rethinking Linkages between the Natural Environment and the Modern World-System: Deforestation in the Late 20th Century." *Journal of World-Systems Research* 9(2):357–90.

Byrne, Barbara N. 2009. *Structural Equation Modeling with AMOS*. New York: Psychology Press/Routledge Academic.

Cardoso, Fernando H. and Enzo Faletto. 1979. *Dependency and Development in Latin America*, Marjory Mattingly Urquidi, trans. Berkeley: University of California Press.

Chambers, Dustin and Jang-Ting Guo. 2009. "Natural Resources and Economic Growth: Some Theory and Evidence." *Annals of Economics and Finance* 10(2):367–89.

Chase-Dunn, Christopher. 1975. "The Effects of International Economic Dependence on Development and Inequality: A Cross-National Study." *American Sociological Review* 40(6):720–38.

———. 1989. *Global Formation: Structures of the Global Economy*. Cambridge, MA: Basil Blackwell.

———, Yukio Kawano, and Benjamin D. Brewer. 2000. "Trade Globalization since 1795: Waves of Integration in the World-System." *American Sociological Review* 65(1):77–95.

Clark, Rob. 2010. "World-System Mobility and Economic Growth, 1980-2000." *Social Forces* 88(3):1123–51.

Daly, Herman and John Cobb, Jr. 1989. *For the Common Good: Redirecting the Economy toward Community, the Environment, and a Sustainable Future*. Boston: Beacon Press.

Diamond, Jared. 2005. *Collapse: How Societies Choose to Fail or Succeed*. New York: Penguin.
Dietz, Simon and Eric Neumayer. 2007. "Weak and Strong Sustainability in the SEEA: Concepts and Measurement." *Ecological Economics* 61(4):617–26.
Dixon, William J. and Terry Boswell. 1996. "Dependency, Disarticulation, and Denominator Effects: Another Look at Foreign Capital Penetration." *The American Journal of Sociology* 102(2):543–62.
Durkheim, Emile. [1893] 1997. *The Division of Labor in Society*. Glencoe, IL: Free Press.
Esty, Daniel C., Marc Levy, Tanja Srebotnjak, and Alexander de Sherbinin. 2005. *2005 Environmental Sustainability Index: Benchmarking National Environmental Stewardship*. New Haven, CT: Yale Center for Environmental Law & Policy. Retrieved May 27, 2009, from http://www.yale.edu/esi/.
Ewing, Brad, David Moore, Steven Goldfinger, Anna Oursler, Anders Reed, and Mathis Wackernagel. 2010. *The Ecological Footprint Atlas 2010*. Oakland, CA: Global Footprint Network.
Firebaugh, Glenn. 1983. "Scale Economy or Scale Entropy? Country Size and Rate of Economic Growth, 1950-77." *American Sociological Review* 48(2):257–69.
——— and Frank D. Beck. 1994. "Does Economic Growth Benefit the Masses? Growth, Dependence, and Welfare in the Third World." *American Sociological Review* 59(5):631–53.
———. 1996. "Does Foreign Capital Harm Poor Nations? New Estimates Based on Dixon and Boswell's Measures of Capital Penetration." *American Journal of Sociology* 102(2):563–75.
Flora, Cornelia Butler and Jan L. Flora. 2008. *Rural Communities: Legacy and Change*, 3rd edition. Boulder, CO: Westview Press.
Foster, John Bellamy. 1999. "Marx's Theory of Metabolic Rift: Classical Foundations for Environmental Sociology." *The American Journal of Sociology* 105(2):366–405.
———. 2009. *The Ecological Revolution*. New York: Monthly Review Press.
Frank, Andre Gunder. 1978. *Dependent Accumulation and Underdevelopment*. New York: Monthly Review Press.
———. 2005. "Urban Location and Dissipation of Entropy (A Programmatic Statement)." Retrieved from http://rrojasdatabank.info/agfrank/research.html#dissipation.
Frey, R. Scott. 1998. "The Hazardous Waste Stream in the World-System." Pp. 84–103 in *Space and Transport in the Modern World-System*, edited by P. Ciccantell and S. Bunker. Westport, CT: Greenwood.
Gallagher, Kevin P. 2009. "Economic Globalization and the Environment." *Annual Review of Environmental Resources* 34:279–304.
Garson, G. David. 2009. "Structural Equation Modeling." *Statnotes: Topics in Multivariate Analysis*. Retrieved from http://faculty.chass.ncsu.edu/garson/pa765/statnote.htm.
Georgescu-Roegen, Nicholas. 1971. *The Entropy Law and the Economic Process*. Cambridge, MA: Harvard University Press.
Global Footprint Network. 2009. "Ecological Footprint and Biocapacity, 2006." Based on *National Footprint Accounts 2009*. Retrieved from http://www.footprintnetwork.org/en/index.php/GFN/page/ecological_footprint_atlas_2008.
Hansen, James, Larissa Nazarenko, Reto Ruedy, Makiko Sato, Josh Willis, Anthony DelGenio, Dorothy Koch, Andrew Lacis, Ken Lo, Surabi Menon, Tica Novakov, Judith Perlwitz, Gary Russell, Gavin A. Schmidt, and Nicholas Tausnev. 2005. "Earth Energy Imbalance: Confirmation and Implications." *Science* 308(5727):1431–35.
Hornborg, Alf. 2001. *The Power of the Machine*. Walnut Creek, CA: Altamira Press.
———. 2006. "Footprints in the Cotton Fields: The Industrial Revolution as Time-Space Appropriation and Environmental Load Displacement." *Ecological Economics* 59(1): 74–81.

Intergovernmental Panel on Climate Change (IPCC). 2007. "Climate Change 2007: Synthesis Report," edited by R. K. Pachauri and A. Reisinger. Geneva, Switzerland: IPCC. Retrieved from http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf.

Jevons, William Stanley. 1865. *The Coal Question*. London: Macmillan and Co.

Jorgenson, Andrew K. 2006. "Global Warming and the Neglected Greenhouse Gas: A Cross-National Study of Methane Emissions Intensity, 1995." *Social Forces* 84(3):1779–98.

——— and Brett Clark. 2009. "The Economy, Military, and Ecologically Unequal Relationships in Comparative Perspective: A Panel Study of the Ecological Footprints of Nations, 1975-2000." *Social Problems* 56(4):621–46.

——— and Edward L. Kick. 2003. *Globalization and the Environment*, 2nd edition. Chicago: Haymarket.

Kentor, Jeffrey. 1981. "Structural Determinants of Peripheral Urbanization: The Effects of International Dependence." *American Sociological Review* 46(2):201–11.

——— and Terry Boswell. 2003. "Foreign Capital Dependence and Development: A New Direction." *American Sociological Review* 68(2):301–13.

Kick, Edward L., Laura A. McKinney, Steve McDonald, and Andrew Jorgenson. 2011. "A Multiple-Network Analysis of the World System of Nations, 1995-1999." Pp. 311–27 in *Sage Handbook of Social Network Analysis*, edited by J. Scott and P. Carrington. Thousand Oaks, CA: Sage Publications.

Lawrence, Kirk S. 2009. "The Thermodynamics of Unequal Exchange: Energy Use, CO2 Emissions, and GDP in the World-System, 1975-2005." *International Journal of Comparative Sociology* 50(3–4):335–59.

Luxembourg, Rosa. 1912. *The Accumulation of Capital: An Anti-Critique*. New York: Monthly Review Press.

Marx, Karl. [1867] 1977. *Capital Vol. 1*. New York: Vintage.

McKinney, Laura A., Edward L. Kick, and Gregory M. Fulkerson. 2010. "World System, Anthropogenic, and Ecological Threats to Bird and Mammal Species: A Structural Equation Analysis of Biodiversity Loss." *Organization and Environment* 23(1):3–31.

McMichael, Phillip. 2004. *Development and Social Change: A Global Perspective*, 3rd edition. Thousand Oaks, CA: Pine Forge Press.

Moore, Jason W. 2000. "Environmental Crises and the Metabolic Rift in World-Historical Perspective." *Organization and Environment* 13(2):123–57.

———. 2011. "Transcending the Metabolic Rift: A Theory of Crises in the Capitalist World-Ecology." *Journal of Peasant Studies* 38(1):1–46.

Neumayer, Eric. 2010. *Weak Versus Strong Sustainability: Exploring the Limits of Two Opposing Paradigms*, 2nd edition. Northampton, MA: Edward Elgar Publishing.

Pellow, David Naguib. 2007. *Resisting Global Toxics: Transnational Movements for Environmental Justice*. Cambridge, MA: MIT Press.

Prigogine, Ilya. 1967. *Introduction to Thermodynamics of Irreversible Processes*. New York: Interscience Publishers.

Rees, William E. 2004. "The Eco-Footprint of Agriculture: A Far-from-(Thermodynamic)-Equilibrium Interpretation." Pp. 87–110 in *NABC Report 16 Agricultural Biotechnology: Finding Common International Goals*, edited by A. Eaglesham, A. Wildeman, and R. W. F. Hardy. Ithaca, NY: National Agricultural Biotechnology Council.

Rostow, Walt Whitman. 1960. *The Stages of Economic Growths: A Non Communist Manifesto*. Cambridge, UK: Cambridge University Press.

Sachs, Jeffrey D. and Andrew M. Warner. 1995. "Natural Resource Abundance and Economic Growth," National Bureau of Economic Research Working Paper No. 5398. Cambridge, MA: National Bureau of Economic Research.

——— and Andrew M. Warner. 2001. "The Curse of Natural Resources." *European Economic Review* 45(4–6):827–38.

Schnaiberg, Allan and Kenneth A. Gould. 1994. *Environment and Society: The Enduring Conflict*. New York: St. Martin's Press.

Singer, Hans W. 1950. "The Distribution of Gains between Investing and Borrowing Countries." *American Economic Review* 40(2):473–85.

Smelser, Neil. 1964. *Toward a Theory of Modernization*. New York: Basic Books.

Smith, Adam. 1776. *An Inquiry into the Wealth of Nations*. Oxford, UK: Claredon.

Snyder, David and Edward Kick. 1979. "Structural Position in the World-System and Economic Growth, 1955-1970: A Multiple-Network Analysis of Transnational Interactions." *American Journal of Sociology* 84(5):1096–26.

Stiglitz, Joseph. 2007. *Making Globalization Work*. New York: Norton.

Torras, Mariano. 2003. "An Ecological Footprint Approach to External Debt Relief." *World Development* 31(12):2161–71.

United Nations. 1987. "Report of the World Commission on Environment and Development, 96th Plenary Meeting, 42nd Session." Retrieved from http://www.un.org/documents/ga/res/42/ares42-187.htm.

United Nations Environment Programme (UNEP). 2007. "Ecosystem Management." United Nations, Division of Environmental Policy Implementation. Retrieved from http://www.unep.org/pdf/brochures/EcosystemManagement.pdf.

Wackernagel, Mathis and William Rees. 1996. *Our Ecological Footprint*. Gabriola Island, British Columbia, Canada: New Society Press.

Wallerstein, Immanuel. 1974. *The Modern World System*. New York: Academic Press.

World Bank. 2009. *World Development Indicators*. Data for various years retrieved from http://www.worldbank.org/.

World Resource Institute. 2009. Data for various years retrieved from http://www.earthtrends.wri.org/.

York, Richard, Eugene Rosa, and Thomas Dietz. 2003a. "Footprints on the Earth: The Environmental Consequences of Modernity." *American Sociological Review* 68(2):279–300.

———, Eugene Rosa, and Thomas Dietz.2003b. "A Rift in Modernity? Assessing the Anthropogenic Sources of Global Climate Change with the STIRPAT Model." *International Journal of Sociology and Social Policy* 23(10):31–51.