12-2019

The Treadmill of Information: Development of the Information Society and Carbon Dioxide Emissions

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ABSTRACT The world is facing a crisis of global warming due to the release of CO_2 and other greenhouse gasses by human activities. Many scholars and stakeholders argue that information and communication technology (ICT) development will mitigate CO_2 emissions. Advocacy of technological solutions to CO_2 mitigation is consistent with ecological modernization theory's assertion that reflexive societies will modernize sustainably. In contrast, we define the "treadmill of information" as the unique contribution of ICT development to environmental degradation. We examine the impact of ICT development on total CO_2 emissions and source-sector emissions from electricity, buildings, manufacturing, and transportation using a multilevel growth model for panel data from 113 countries split into the world, developed country, and less-developed-country samples. We find that the level of fixed telephone development is a strong predictor of higher CO_2 emissions in less-developed countries, while internet use predicts higher CO_2 emissions in developed countries. The effect of mobile telephone development is not significant. Thus, it appears that ICTs are not having an ameliorative effect on global warming as expected by ecological modernization theorists, and instead reinforce the treadmill of production's negative effect. KEYWORDS information and communication technology, development, carbon dioxide emissions, climate change, treadmill of information

INTRODUCTION

Few forces are as consequential for the future as (1) the development of information and communication technologies (ICTs) and (2) anthropogenic climate change due to carbon dioxide (CO_2) and other greenhouse gas emissions. ICT development is an aspirational goal for many nations eager to overcome the global digital divide and become an "information society" (Castells 2000; Crenshaw and Robinson 2006; International Telecommunications Union 2016). Climate change is one of the greatest threats facing the security and well-being of the planet (Intergovernmental Panel on Climate Change 2014; Dunlap and Brulle 2015)—so much so that 195 nations came together in Paris in December 2015 to commit to CO_2 emissions reductions to limit anthropogenic warming to less than 2 °C (United Nations Framework Convention on Climate Change 2015). ICT development and limiting the effects of climate change are central international development issues, and they appear on both the UN's list of Millennium Development Goals and its more recent list of Sustainable Development Goals.[1] As nations develop policies to achieve these two goals, it is essential to ask if they are mutually supporting. Fixed telephones, mobile telephones, and the internet have become global technologies that enhance economic development, which raises two interrelated questions: has this significant level of global ICT development had any impact

Sociology of Development, Vol. 5, Number 4, pps. 381–409. electronic ISSN 2374-538X. DOI: https://doi.org/10.1525/sod.2019.5.4.381.

on CO_2 emissions, and, if so, is the effect positive or negative? Answering these questions will inform a core debate in environmental sociology: the sustainability of societal development.

Our paper is in six sections. First, we discuss theoretical perspectives on ICT development. Second, we explore the various treadmills of environmental degradation and the utility of the treadmill metaphor for the sociology of development and conceptualize a new *treadmill of information* in contrast to the ecological modernization perspective on ICT development. Third, we examine the empirical literature on human drivers of CO_2 emissions as it relates to the effects of ICT development on CO_2 emissions, and then present four hypotheses. Fourth, we develop a hierarchical linear growth model to test the hypotheses with panel data from 113 nations. Fifth, we present the results of our analysis and discuss their implications. We conclude with a discussion of difficulties in assessing the environmental effects of ICTs, and the need to investigate the treadmill of information further.

DEVELOPMENT OF THE INFORMATION SOCIETY

ICTs are extensions of human sensory capacity and cognition (McLuhan 1964). New ways of extending the human capacity to communicate, retain, and process information mark developmental epochs of human civilization. Because of this broad scope, it is necessary to define ICTs narrowly. Our focus is the 21-year period from 1990 to 2010. This period has many monikers: post-industrial society, the information age, the new economy, the network society, and the digital society—all referring to the transformative capacity of new ICT developments (Bell [1973] 1999; Tapscott 1996; Castells 2000). "All new communication means belong to one product constellation that is the driver of the new economy: [fixed] main telephone lines, mobile phones, personal computers, and the internet, they are significantly correlated with each other" (de Mooij 2003:122).

The idea of development is bound up with ICTs, as noted early on by Max Weber (1978:224): "[T]here are certain extremely important conditions in the fields of communication and transportation. The precision of [bureaucratic] functioning requires the services of the railway, the telegraph, and the telephone, and becomes increasingly dependent on them." Early electronic ICTs were integral to the modernization period of development in the late nineteenth and early twentieth centuries. The three primary technologies associated with the information age—fixed telephones, mobile telephones, and the internet—were all developed or refined in the late 1960s and early 1970s and implemented throughout the world over subsequent decades (Figure 1). Of these technologies, the fixed telephone looks anachronistic next to the more recent inventions of mobile telephony and the internet; however, during the same incubation period that produced the internet and mobile telephony, mainline telephones incorporated the development of touch-tone dialing, digital electronic switching, and common channel switching (AT&T 2012). Early switching was manual and then electromechanical. Digital electronic switching introduced the use of computers in call switching and advanced a century-old technology for the new, more global and information-intensive economy of the late twentieth century. Digital switching was also essential for the widespread adoption of mobile telephony and the internet.

As scholars began to account for the impact of these new "extremely important conditions" they argued that these new technologies were not only replacements for old ICTs but

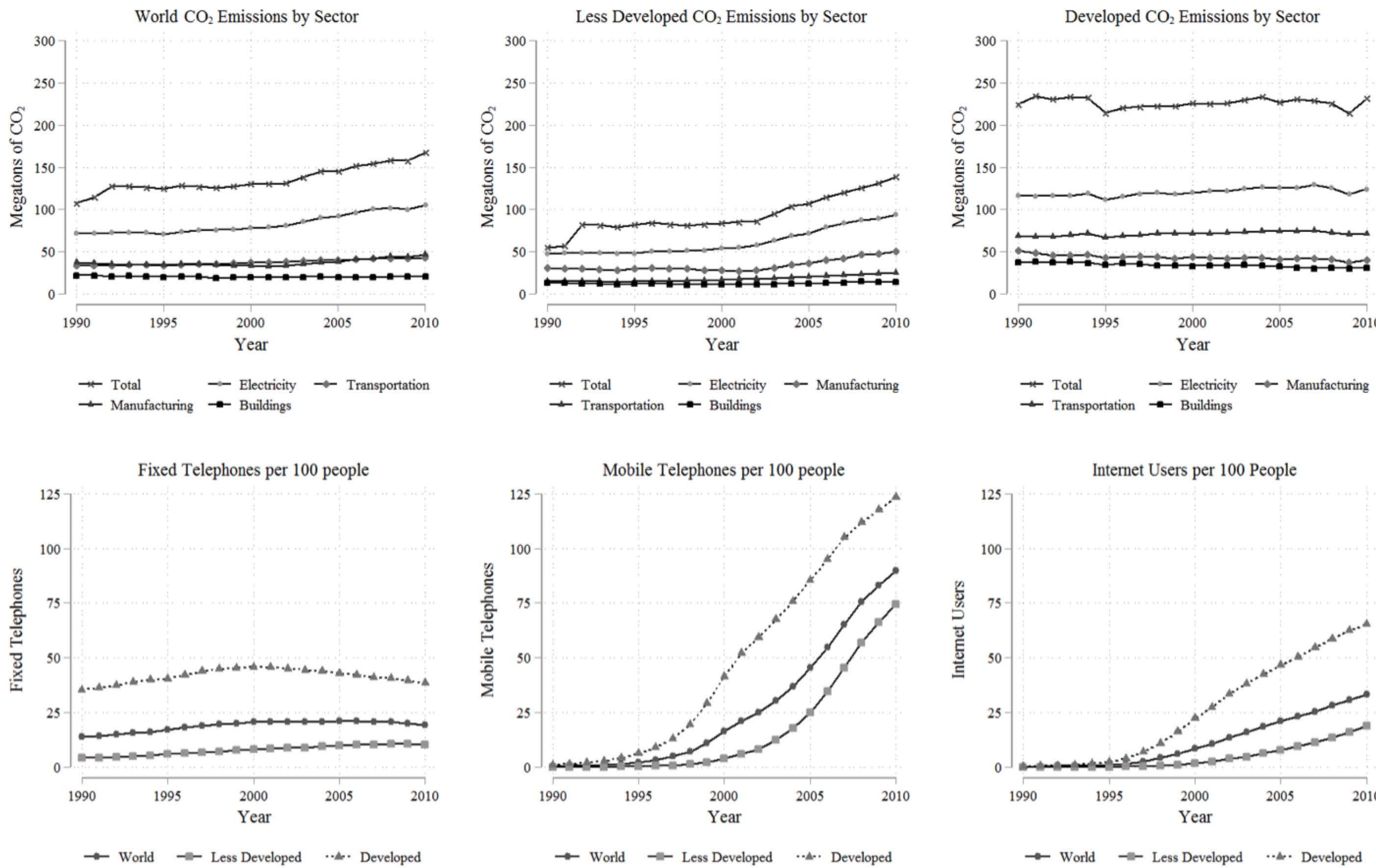

FIGURE 1. Change in CO_2 Emissions by Source Sector and Information and Communication Technology Development Indicators

would produce a qualitatively different form of societal development (Weber 1978:224; Bell [1973] 1999; Tapscott 1996; Castells 2000). Castells (2004:9) noted three distinctive features of these technologies that set them apart from other drivers of societal development:

- their self-expanding processing and communicating capacity in terms of volume, complexity, and speed [emergent properties];
- their ability to recombine on the basis of digitization and recurrent communication [hypertext]; [and]
- their distributing flexibility through interactive digitized networking [time-space distanciation].

As ICT development became more important to transnational corporations and international governmental bodies, two paradigms of ICT development policy emerged (Unwin 2013). The ICTD (ICT and development) perspective is a modernist top-down development paradigm. ICTD sees ICT development as a technical challenge, with the primary purpose being economic development. This top-down perspective accounts for the direct investment of billions of dollars in foreign investment in ICT development projects in the developing world since the 1990s (Cho, Lee, and Kim 2007). ICT4D (ICT for development) is more critical and promotes bottom-up development that is responsive to local needs and context. Driven by indigenous policy, ICT4D meets day-to-day needs in developing counties rather than opening markets for the telecom industry. While ICTD takes its direction from engineering, ICT4D is more closely connected to a social science perspective (Schech 2002; Kleine and Unwin 2009; Unwin 2013).

TREADMILLS OF ENVIRONMENTAL DEGRADATION

The treadmill metaphor has become the defining frame of environmental degradation in environmental sociology. Schnaiberg's *The Environment: From Surplus to Scarcity* (1980) introduces the treadmill metaphor to explain the coalition of industry, labor, and government that propels an economic growth agenda. Treadmill of production theory (ToP) asserts that technological development accelerates production (and profit) by increasing efficiency but displacing workers. This pushes labor to demand more growth, to create new job opportunities. Governments also push pro-growth policies, to increase the tax base and support higher welfare expenditures, such as unemployment benefits. Industry extracts as much profit as possible by degrading wages and benefits, pushing for lower taxes and looser regulations, and employing production technologies that have the least economic cost but often higher environmental costs (Gould, Pellow, and Schnaiberg 2004, 2008).

The ICTD perspective is an example of the growth agenda of ToP (Gould, Pellow, and Schnaiberg 2008), as ICT infrastructure is deemed essential for economic development. Development of ICT infrastructure—microwave towers, undersea cables, data centers, broadband internet, and computing power—is never-ending, and it would be easy to consider the impact of ICT development as another component of the treadmill of production, but we must consider the qualitative difference of ICT development processes in comparison to economic processes. Further interrogation of the treadmill of production is warranted (Gould, Pellow, and Schnaiberg 2004; Wright 2004).

While ToP became the dominant critical perspective in environmental sociology, it faced four forms of critique. First, ecological modernization theory (EMT) offers the starkest critique of ToP. Proponents of EMT conceptualize capitalism as an adaptive system that will reflexively adopt more sustainable modes of production and development because they are more efficient than previous iterations of capitalism (Spaargaren and Mol 1992; Mol 2002). In response, York (2004) argues that the treadmill of production continually diversifies. While there are cases of organizations and countries developing sustainably, the aggregate global effect of development is unsustainable. Second, ToP is at its core a Marxist critique of the capitalist system (Foster 2005), and Marxist critics argue that "treadmill of production" is just a veiled way of saying "capitalism" (Wright 2004). These critics suggest that "treadmill of accumulation" is more reflective of the political economy of environmental degradation (Foster 2005). Third, ToP is a supply-side economics perspective and does not account for an inverse treadmill of consumption where consumers pursue self-fulfillment through the purchase of goods, driving ever more consumption and thus stimulating increased production (Bell 2011). However, ToP considers the role of consumer behavior, often viewed as a complementary pull to the push of production, as clearly subordinate to the primacy of production (Schnaiberg 1980; Pellow, Gould, and Shnaiberg 2008).

Fourth, perhaps the most significant critique of ToP is treadmill of destruction theory (Hooks and Smith 2004, 2005; Clark, Jorgenson, and Kentor 2010; Clark and Jorgenson 2012). This theory posits that the institution of the military and the processes of militarization offer a unique logic for the causes of environmental degradation, separate from the processes of capitalism outlined by ToP (Hooks and Smith 2005). Military organizations often treat war zones harshly, as in the use of Agent Orange in Vietnam, the burning of oil fields in Iraq, or the use of nuclear weapons in Japan (Hooks and Smith 2004). The greater the proportion of their GDP that countries spend on the military, the higher their CO_2 emissions (Clark, Jorgenson, and Kentor 2010; Clark and Jorgenson 2012). Hooks and Smith (2004, 2005) make a strong case for militarization having a distinct effect on the environment, even though the aims of the military often closely align with capital and government interests, as Mills noted in *The Power Elite* (1956).

These four critiques provide alternate pathways for theoretical development of treadmill perspectives. EMT rejects the inevitable environmental degradation of the capitalist social order; the treadmills of accumulation and consumption view the focus on production as a misattribution, in one case pointing to capitalist accumulation and in the other to consumption. In the case of the treadmill of destruction, militarization is seen as having a distinct yet parallel (to production) effect on environmental degradation. The treadmill of destruction critique thus offers a model for conceptualizing the impact of ICT development on environmental degradation. Should the impact of ICT development be subsumed under the broader frame of the treadmill of production, or should it be considered an independent structural component of ecological degradation, like the treadmill of destruction?

Akin to Mills's (1956) care in not conflating the disparate domains of "the power elite," Hooks and Smith (2005:21) opened theoretical space for conceptualizing "multiple treadmills" of environmental degradation. Industry's drive for technological efficiency, a key issue for treadmill of production scholars, is not sufficient to explain the development of ICTs.

Just as Hooks and Smith (2005) believe that militarism is under-theorized by ToP, we believe that informationalism—"the shift toward a technological paradigm based on information technologies" (Castells 2000:99)—is under-theorized. While ToP proponents might be inclined to view ICT development as just another iteration of technological innovation, others view it as facilitating the emergence of a fundamental new aspect of society (McLuhan 1964; Bell [1973] 1999; Tapscott 1996; Castells 2000; Romm 2002). Similar to the treadmill of destruction's relationship to ToP, we think the processes of informationalism should be considered complementary to but analytically distinct from the treadmill of production—capable of having an autonomous impact (whether positive or negative) on environmental degradation.

We propose a parallel *treadmill of information*, which acts both as an "extremely important condition" for economic development *and* as a source of emergent properties from the self-expanding processes, hypertext, time-space distanciation, and informationalism processes intrinsic to ICT development (Weber 1978:224; Castells 2000, 2004). Four social forces define the treadmill of information:

- the accelerating increase in digital information production and storage;
- the accelerating increase in network linkages between humans, machines, and the natural environment;
- the accelerating use of matter and energy for the production and consumption of information, and for the maintenance of network linkages; and
- the indirect and systemic effects on the resource use of other sectors of the economy, such as manufacturing and transportation.

While the treadmill of information as defined here could be conceptualized as a component of the treadmill of production, we argue that, like militarization, the development of ICTs can have a unique, independent effect on environmental degradation (Hooks and Smith 2004; York 2004).

Castells's (2000) framework moves ICTs beyond a support infrastructure for capitalism and contextualizes their potential for fundamental societal transformation. While it is beyond the scope of this investigation to assess whether ICT development has had a fundamental effect on society, a robust theoretical consensus and a preponderance of evidence suggest that it has induced some form of fundamental change (Weber 1978; Bell [1973] 1999; Tapscott 1996; Castells 2000, 2004; Schech 2002, Kleine and Unwin 2009; Unwin 2013). The core theoretical question for us is: Do ICT development and the treadmill of information operate as forces of sustainable development, as EMT posits, or do they exacerbate environmental degradation?

EMT views reflexive modernization as the central force in the sustainability of human societies. While often a catch-all for optimistic green perspectives, EMT is concerned with social transformations that transcend the ecology–economy divide (Mol 2002, 2008; Mol, Spaargaren, and Sonnenfeld 2009). EMT is squarely in the field of what Buttel (2003) calls the "sociology of environmental reform." EMT puts forward the idea "of overcoming the environmental crisis without leaving the path of modernization" (Spaargaren and Mol 1992:334). In this vein, ICTs have been identified as a cornerstone of socio-environmental transformation, providing a pathway for structural change in behavior, politics, and resource use (Mol 2008).

There are three potential ecological benefits of ICT development. First, ICTs create efficiencies in other technological sectors. While ICTs' direct demand on the electrical system is apparent, their indirect effects on the management of electrical grids, creating climate control systems, reducing demand for transportation, and the dematerialization of manufactured goods are all hypothesized to reduce CO_2 emissions (Romm 2002; International Telecommunications Union 2010). Second, ICTs aid in the surveillance of environmental conditions and our ability to analyze data (Spaargaren and Mol 1992; Mol 2008). As an example, the endeavors of the IPCC—perhaps the most extensive international network of scientists ever assembled—would be impossible without the ubiquity of networked computers for both computational resources and the organization of scientists. Third, ICTs provide an enhanced organizational platform for environmental social movements, such as the climate justice movement, to mobilize across the planet (Mol 2008). Ecological modernization theorists believe that these features are a path to sustainable development (Mol 2002, 2008): the EMT "project is the development, inauguration, and diffusion of new technologies that are more intelligent than older ones and that benefit the environment" (Sparrgan and Mol 1992:335).

ICT DEVELOPMENT AND CO_2 EMISSIONS

As the world wrestles with the threat of climate change, understanding the role of human drivers of CO_2 emissions becomes critical (Rosa and Dietz 2012; Rosa et al. 2015; Dietz 2017). While the direct impacts of fossil fuel combustion, deforestation, and concrete construction are well known, the effects of other technological drivers of CO_2 emissions, such as ICTs, are less well understood (Rosa et al. 2010; Rosa and Dietz 2012). ICT development accounts for about two percent of global emissions (Gartner 2007; Malmodin and Bergmark 2015). However, ICTs are often put forward as a pathway to CO_2 mitigation strategies, as an essential component of climate system monitoring, and as a facilitator of ecological modernization (Mol 2008). It is an open question whether ICT development will eventually fulfill the promise of being a technofix and perhaps even a positive force for human well-being in general (Dietz 2015; Givens 2017).

The IPAT identity (impacts = population × affluence × technology) conceptualized technology as any efficiency not accounted for by population dynamics and wealth concentration (York, Rosa, and Dietz 2003a). Sociologists using the STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) methodology have extended our understanding of "technology" to include the stochastic effects of structural and cultural variables on environmental impacts (York, Rosa, and Dietz 2003b, 2003c). However, the technological dimensions of environmental impacts are still an under-studied dimension:

> Technological change . . . is omitted [from this volume] not because it lacks importance, but because of the difficulty of harnessing the complex and proximate effects of technological change. . . . [This] pinpoints one of the most serious gaps in human dimensions research and the one, perhaps, most desperately in need of concerted attention. (Rosa et al. 2010:5)

To this end, McGee, Clement, and Besek (2015) reinterpret urbanization as terrestrial technology and use spatial regression techniques to find that impervious surface area is positively related to CO_2 emissions. New conceptualizations and operationalizations of technology such as this are vital for filling this gap. The structural human ecology research program promoted by STIRAT scholars has deepened our understanding of the roles that population, economic development, unequal exchange, militarization, urbanization, trade, and global environmental governance play in environmental degradation generally and CO_2 emissions specifically (Rosa and Dietz 2012; Rosa et al. 2015; Dietz 2017; Thombs 2018), but the role of technology deserves more attention.

Kyoto Controversy

Determining the influence of ICT development on energy production was at the center of a minor controversy at the Kyoto protocol testimony (Koomey 2000). An exaggerated estimate of the increasing energy demands of an information-driven economy concluded that ICTs would soon become the largest single energy consumer (Mills 1999; Huber and Mills 1999). This questionable finding was used to support continued dependence on coal to meet the world's rapidly growing energy demands. This exaggerated claim about the internet's energy demands is not surprising, as the supporting "research" was linked to the American conservative think-tank community (Jacques, Dunlap, and Freeman 2008). Romm (2002) countered that the impact of the internet's growth in the United States accounted for only a minor increase in electricity production and suggested that the growth of the internet was correlated with recent reductions in the energy intensity of economic growth. This early research into the relationship between the internet and CO_2 emissions examined the reduction in energy intensity in the United States during the 1990s. In search of an explanation for this trend, the Center for Energy and Climate Studies concluded that the "internet economy" could lead to a "new energy economy" that would transform emissions drivers (Romm 2002:134–35). Manufacturers were presumably reducing their supply chains and investing in capital rather than labor to produce efficiencies and increase productive capacity, reducing the need for retail stores and warehouses, and thus for transportation to and from these locations (Romm 2002).

Hilty (2008) and MacLean and St. Arnaud (2008) explicitly model ICT impacts as a series of nested effects, beginning with direct impacts, leading to enabling impacts, and through to systemic impacts. This model is modified slightly in the International Telecommunications Union's (2010) three-tier model of direct, indirect, and systemic effects. Direct impacts are the real production-consumption costs of ICTs across their product life cycle. Indirect or second-order impacts involve the application of ICTs in contexts such as telecommuting or e-commerce. Second-order effects differ across institutional and technological fields that map to CO_2 emission source sectors. Systemic or third-order impacts are broad changes in behavior and social structure. The transition from an industrial to a post-industrial economy is one potential manifestation of a systemic impact. The model is nested to indicate that each order of impact is dependent on the level before it. To model the effects of ICT development on CO_2 emissions' direct, indirect, and systemic impacts, each needs to be accounted for, in addition to the effect of ICT development over time and between nations. The three-tier model of impacts assumes that most of the negative consequences occur at the direct level, with the secondary and systemic effects viewed as beneficial (Mol 2008; Ospina and Heeks 2010). In contrast, the treadmill of information idea considers that in addition to the negative direct effects of ICT development, its indirect and systemic effects could be environmentally degrading.

There have been some studies of energy consumption that included ICT variables. Mazur's (2013) study of the energy and electricity consumption of industrialized nations finds that the internet correlates with increased energy consumption, but phones do not. Longo and York (2015) find that development of internet and cellphones have a marginal effect on electricity production, per capita electricity consumption, and the number of cars, while fixed telephones have a more robust positive impact. While research on the human drivers of climate change does not focus on ICTs as an explanatory variable, the sociological community has examined the ICT industry. Pellow and Park (2002) examine the dimensions of environmental justice in Silicon Valley and conclude that the ICT industry uses the image of a clean industry as cover for toxic production and labor abuses. Similarly, *Challenging the Chip* (Smith, Sonnenfeld, and Pellow 2006) paints a picture of an industry that is troubled by many cases of environmental abuse.

From a political-economy perspective, it makes sense to view the development of ICTs through a pessimistic lens (Rudel, Roberts, and Carmin 2011). Developed countries (DCs) continually seek to increase their status through capital accumulation. There are two forces at play here. First, DCs can use ICT development to advance the efficient use of available resources. These increased efficiencies in DCs are often relative; absolute resource use almost always increases, reflecting the Jevons paradox (Jevons [1865] 2001; Clark and York 2005; York 2006, 2010; York and McGee 2016). Thus, increasing eco-efficiency does not necessarily reduce CO_2 emissions (Clark and York 2005; Clement 2011; York 2010, 2016). Second, DCs are able to exploit natural resources in other countries, increasing the resource usage of less developed countries (LDCs) while providing little benefit to them (Rice 2007; Jorgenson, Austin, and Dick 2009; Huang 2018).

Examinations of the impact of ICT development on CO_2 emissions forecast future emissions and focus on individual countries, for example the United States and South Korea (Berkhout and Hertin 2001; Romm 2002; Cho, Lee, and Kim 2007; International Telecommunications Union 2015). Based on the principle that ICT development will have an inverse relation to CO_2 emissions, the interaction of ICT development on different CO_2 source-sectors—electricity production, buildings, manufacturing, and transportation—also assumes an inverse relation (Erdmann and Hilty 2010). Research on the role of global ICT development in CO_2 emissions is limited, but we can use what we know about the relationship between economic development and CO_2 emissions. York (2012) finds an asymmetrical relationship between GDP per capita and CO_2 emissions: emissions increases during expansionary periods are greater than the decreases during comparable economic contractions. And while in some DCs we see a mild decoupling of economic development from CO_2 emissions, we see a constant or intensified coupling in LDCs (Jorgenson and Clark 2012).

Similarly, we expect to see differing ecological effects of ICT development at high and low levels of economic development (Mazur 2013; Jorgenson and Clark 2012). Our study offers a global historical perspective on the impact of ICT development on CO_2 emissions and takes into consideration the potential for different impacts in DCs and LDCs (Jorgenson, Austin, and Dick 2009; Mazur 2013). We test four hypotheses:

Hypothesis 1: The development of information and communication technologies will increase CO_2 emissions either in total or within source-sectors.

Hypothesis 2: The development of fixed telephones will increase CO_2 emissions either in total or within source-sectors in less developed countries.

Hypothesis 3: The development of mobile telephones will increase CO_2 emissions either in total or within source-sectors in developed countries.

Hypothesis 4: The development of the internet will increase CO_2 emissions either in total or within source-sectors in developed countries.

METHODS

A multilevel model for growth is used to model the impact of ICT development on CO_2 emissions over time (Raudenbush and Bryk 2002; Singer and Willett 2003). The multilevel model for growth consists of two components: the level-1 model for change within countries over time and the level-2 model for time-invariant country differences (Singer and Willet 2003:45). In the following analyses, the level-1 unit of analysis is country-years, or to put it another way, the observation for each year for each country. The level-1 model examines changes within countries over time, and models are specified with variables that explain the change in CO_2 emissions over time within a given country. The level-2 unit of analysis is the country. The level-2 model examines questions about (1) time-invariant differences in the average level of CO_2 emissions between countries and (2) differences in CO_2 emissions trajectories over time between countries. A multilevel model is used rather than more commonly used fixed effects models because of its ability to control for both change over time and differences between countries (Raudenbush and Bryk 2002; Singer and Willett 2003; Jorgenson, Rice, and Clark 2010; Longo and York 2015).

We use repeated national-level panel data on 113 countries from the International Telecommunications Union via the World Bank (2013). We use three samples in our analyses from the years 1990 to 2010. The first sample consists of 1926 country-years (level 1) nested within 113 countries (level 2); this "world sample" includes as many countries as possible given the available data. The second sample is the subset of the DCs in the first sample; it consists of 731 country-years nested within 41 countries. This sample was selected to analyze the divergent pattern of ICT development in DCs both across time and between countries (Mazur 2013). The third sample is the subset of the LDCs in the world sample, with 1,195 country-years nested within 72 countries. This sample was selected to analyze the differences between and changes within LDCs. DCs are those countries in the top third of GDP per capita, and LDCs are those countries in the bottom two-thirds. Table 1 lists all the countries and their frequency of observations.

TABLE 1. Countries in Each Sample and Frequency of Observations (f)

Developed countries		Less developed countries			
Country	**f**	**Country**	**f**	**Country**	**f**
Australia	18	Albania	15	Mongolia	13
Austria	21	Angola	16	Morocco	17
Belgium	16	Argentina	20	Mozambique	16
Chile	20	Armenia	17	Namibia	16
Croatia	16	Azerbaijan	15	Nepal	21
Cyprus	20	Bangladesh	15	Nicaragua	17
Czech Republic	18	Belarus	14	Nigeria	16
Denmark	21	Bolivia	17	Pakistan	16
Estonia	16	Bosnia and Herzegovina	15	Panama	18
Finland	21	Botswana	18	Peru	17
France	21	Brazil	20	Philippines	18
Gabon	16	Cambodia	14	Republic of Congo	15
Germany	20	Cameroon	15	Senegal	17
Greece	16	China	19	South Africa	21
Hong Kong S.A.R.	11	Colombia	18	Sri Lanka	18
Hungary	16	Costa Rica	20	Sudan	15
Iceland	14	Cuba	17	Syria	10
Ireland	16	Dem. Rep. of the Congo	16	Tajikistan	11
Italy	21	Dominican Republic	17	Thailand	21
Japan	21	Ecuador	20	Togo	20
Luxembourg	16	Egypt	19	Tunisia	18
Malta	17	El Salvador	16	Turkey	19
Mexico	21	Eritrea	12	Ukraine	18
Netherlands	21	Ethiopia	17	Tanzania	16
New Zealand	20	Georgia	15	Uruguay	18
Norway	21	Ghana	17	Uzbekistan	16
Oman	13	Guatemala	10	Venezuela	20
Poland	16	Honduras	17	Vietnam	15
Portugal	16	India	20	Yemen	12
Saudi Arabia	17	Indonesia	18	Zambia	18
Singapore	21	Iran	15	Zimbabwe	14
Slovakia	16	Ivory Coast	17		
Slovenia	16	Jordan	17		

(*continued*)

TABLE 1. Countries in Each Sample and Frequency of Observations (*f*) (*continued*)

Developed countries		Less developed countries			
Country	**f**	**Country**	**f**	**Country**	**f**
South Korea	21	Kazakhstan	16		
Spain	16	Kenya	17		
Sweden	21	Kyrgyzstan	13		
Switzerland	21	Latvia	15		
Trinidad and Tobago	17	Lebanon	16		
United Arab Emirates	10	Macedonia	16		
United Kingdom	21	Malaysia	20		
United States of America	14	Moldova	17		

Dependent Variables

We use total CO_2 emissions as our primary dependent variable. We also include measures of CO_2 emissions by economic sector to capture the differential effects of ICT development across key source-sectors. Other analyses use a similar rationale to show the effects of ICT development across dependent variables, such as electricity production, electricity consumption per capita, and number of cars (Longo and York 2015). Source-sectors include electricity production, residential buildings, manufacturing, and transportation.[2] Emissions from electricity production include the total emissions from public utilities, electricity generated for producer use, and petroleum refineries. Emissions from buildings include all residential, commercial, and public service fuel combustion for heat production. Emissions from manufacturing include all fuels burned by industry and construction. Emissions from transportation include all domestic aviation, domestic navigation, road, rail, and pipeline transport; international maritime and aviation are not included. Source-sectors were developed by the Intergovernmental Panel on Climate Change (1996) and are available through the World Bank's (2013) development indicators.

Independent Variables: Time-Varying and Time-Invariant Covariates

In a panel fixed effects model, time-invariant components are typically not included, as their effects are controlled with a first-difference model, which eliminates the impact of time-invariant predictors (Jorgenson, Rice, and Clark 2010:194). Here we use a multilevel model for growth, disaggregating the effects of our independent variables over time, within countries, and between countries. This requires three steps. First, all outcomes and predictors are natural logged to produce a difference-of-logs model with the coefficient interpretable as the rate of change over time for within-country differences and the time-invariant effects of between-country differences (Crenshaw and Robinson 2006). Logging all the variables creates an analytical framework similar to ecological elasticity models, with the addition of a multilevel model framework (York, Rosa, and Dietz 2003a). Also, nearly all the predictors require natural log transformation to deal with skewness. Second, all independent variables are group-mean centered to produce a set of level-1 time-varying covariates that are orthogonal to any between-country effects at level 2. Third, each time-varying covariate is aggregated to level 2, grand-mean centered, and included as a level-2 time-invariant covariate contextual to its level-1 counterpart (Curran and Bauer 2011). Coefficients at level 1 are interpreted as the percentage increase in CO_2 emissions on average each year due to a change in the respective independent variable within countries. Coefficients at level 2 are the percentage increase in CO_2 emissions for each one percent the independent variable exceeds the grand mean between countries.

There are three ICTs that are the primary focus of this research: fixed telephones, mobile telephones, and the internet. The first two are extensions of each other and are frequently even measured together, as they freely interact, and each uses the capabilities of the other's infrastructure (James 2012). They are examined separately here to test for potential impacts on CO_2 emissions from their separate development.

Fixed telephones refers to main-line telephones that connect a subscriber to a public switched telephone network with a port on a telephone exchange, measured as the number of main-line telephone subscriptions per 100 people. Similarly, *mobile telephones* refers to subscriptions to a public mobile telephone service using cellular technology with access to the public switched telephone service, measured as telephone subscriptions per 100 people. The internet, arguably one of the most significant technological developments in the twentieth century, is especially representative of the new possibilities of ICTs. Unlike fixed and mobile telephones, we measure this in users (rather than subscriptions) per 100 people. *Internet users* are defined as people who have access to the worldwide network.

We also include a set of standard control variables. Population, GDP per capita and its quadratic, trade as a percentage of GDP, the percentage of energy use from fossil fuels, the percentage of the population living in urban areas, and the percentage of GDP made up by the service economy are included as both level-1 group-mean-centered time-varying covariates and level-2 grand-mean-centered time-invariant covariates. The year is included to calculate the rate of change from year to year at level 1. A dummy for LDC status is included at level 2 for the world sample; the exponent of the coefficient is reported (York, Rosa, and Dietz 2003b). The intercept is termed the initial status and is interpreted as the average log CO_2 emissions in 1990 for a nation with group-mean values for each of the covariates.[3] We report only the fully saturated model for each dependent variable and each sample.[4]

RESULTS AND DISCUSSION

Focusing first on the effects of our control variables, we find that our multilevel model for growth provides outcomes consistent with those found by STIRPAT models in the literature on human drivers of climate change (Rosa et al. 2015). The effects of population and GDP per capita across our two levels of analysis are robustly significant for all three samples—world, LDCs, and DCs—as well as across the four CO_2 source-sectors, with few exceptions. Consistency in these predictors is a good indicator that our multilevel growth model is a reliable estimator of CO_2 emissions.

We can determine several things about the overall structure of total CO_2 emissions during this period based on the random effects. Results for the world sample are found in Table 2.

TABLE 2. Total CO_2 and Source-Sector CO_2 Emissions for the World Sample: A Panel Multilevel Model for Growth with AR(1) Error Correction, Random Intercepts, and Random Slopes for Rate of Change; Coefficients (Coeff.) and Standard Errors (SE)

Independent variables[a]	**Total**		**Electricity**		**Buildings**		**Manufacture**		**Transport**	
	Coeff.	**SE**	**Coeff.**	**SE**	**Coeff.**	**SE**	**Coeff.**	**SE**	**Coeff.**	**SE**
Level 1[b]										
Rate of change	−0.01	0.00	0.00	0.00	−0.00	0.00	−0.03***	0.00	−0.00	0.00
Population	1.02***	0.15	0.79***	0.17	0.49**	0.16	1.06***	0.16	0.54***	0.12
GDP per capita	0.46***	0.05	0.32***	0.05	0.09	0.06	0.42***	0.05	0.39***	0.04
GDP per capita squared	−0.18*	0.08	−0.20**	0.08	0.08	0.08	−0.03	0.08	−0.06	0.06
% trade	−0.04*	0.02	−0.04	0.02	0.00	0.02	0.01	0.02	−0.01	0.01
% fossil energy	0.63***	0.04	0.48***	0.04	0.21***	0.04	0.21***	0.04	0.25***	0.03
% urban	0.87***	0.22	0.28	0.24	0.28	0.23	0.52*	0.24	0.42*	0.17
% service	−0.17***	0.04	−0.10*	0.04	−0.06	0.04	−0.06	0.04	−0.07*	0.03
Fixed telephones	0.02	0.02	0.02	0.02	0.02	0.02	0.04*	0.02	0.03*	0.01
Mobile telephones	0.00	0.01	−0.00	0.01	−0.01	0.01	0.02*	0.01	0.01	0.01
Internet users	−0.01	0.01	−0.01	0.01	0.02	0.01	0.00	0.01	0.01	0.01
Level 2 (mean)[c]										
Less developed country	0.70	0.18	0.39***	0.27	0.55*	0.26	0.78	0.22	0.99	0.13
Population	1.04***	0.04	0.88***	0.05	0.78***	0.05	0.85***	0.04	0.79***	0.03
GDP per capita	0.29**	0.09	−0.03	0.13	0.14	0.13	0.26*	0.11	0.43***	0.07

TABLE 2. Total CO_2 and Source-Sector CO_2 Emissions for the World Sample: A Panel Multilevel Model for Growth with AR(1) Error Correction, Random Intercepts, and Random Slopes for Rate of Change; Coefficients (Coeff.) and Standard Errors (SE) (*continued*)

Independent variables[a]	Total		Electricity		Buildings		Manufacture		Transport	
	Coeff.	**SE**	**Coeff.**	**SE**	**Coeff.**	**SE**	**Coeff.**	**SE**	**Coeff.**	**SE**
% trade	0.13	0.11	0.18	0.17	0.02	0.16	−0.01	0.13	−0.12	0.08
% fossil	0.75***	0.10	0.76***	0.15	0.04	0.15	0.40**	0.12	0.24**	0.08
% urban	0.13	0.14	0.26	0.20	0.22	0.20	0.01	0.16	0.04	0.10
% service	−1.18***	0.25	−0.75*	0.36	−0.16	0.35	−1.09***	0.29	−0.53**	0.18
Fixed telephones	0.26**	0.08	0.30*	0.12	0.39***	0.12	0.26**	0.10	0.19**	0.06
Mobile telephones	−0.16	0.12	−0.11	0.17	−0.32	0.17	−0.19	0.14	−0.01	0.09
Internet users	0.30*	0.15	0.19	0.22	0.08	0.21	0.28	0.18	0.02	0.11
Initial status at mean	10.70***	0.13	3.15***	0.18	2.06***	0.18	2.58***	0.15	2.35***	0.10
Random effects (SD)										
Level 1:										
Within country	0.19***	0.03	0.14***	0.01	0.15***	0.01	0.14***	0.01	0.34***	0.02
ρ	0.88***	0.16	0.77***	0.07	0.74***	0.06	0.77***	0.07	0.98***	0.06
Level 2:										
In rate of change	0.01***	0.00	0.02***	0.00	0.02***	0.00	0.02***	0.00	0.00***	0.00
In initial status	0.40***	0.03	0.62***	0.04	0.60***	0.04	0.50***	0.04	0.00	0.00

(*continued*)

TABLE 2. Total CO_2 and Source-Sector CO_2 Emissions for the World Sample: A Panel Multilevel Model for Growth with AR(1) Error Correction, Random Intercepts, and Random Slopes for Rate of Change; Coefficients (Coeff.) and Standard Errors (SE) (*continued*)

Independent variables[a]	**Total**		**Electricity**		**Buildings**		**Manufacture**		**Transport**	
	Coeff.	**SE**	**Coeff.**	**SE**	**Coeff.**	**SE**	**Coeff.**	**SE**	**Coeff.**	**SE**
Model statistics										
df	21		21		21		21		21	
Deviance	−3,201		−2,996		−2,701		−2,996		−4,616	
Countries	113		113		113		113		113	
Observations	1,926		1,926		1,926		1,926		1,926	

[a] All variables are natural log transformed.
[b] Level-1 time-varying variables are group-mean centered.
[c] Level-2 time-invariant variables are grand-mean centered.
Model uses maximum likelihood estimation and unstructured covariance.
$*p < 0.05$, $**p < 0.01$, $***p < 0.001$

The variance between countries' rate of change is small, with the greatest variation found in DCs (0.02). However, the standard deviation in initial status is wider for the world (0.40) and LDC (0.37) samples than for the DC sample (0.30). The world and LDC samples illustrate that the variation from year to year is smaller in the developed sample than in the rest of the world. Examining the rate of change in total CO_2 emissions, we find no significant effect when holding all else constant. The initial status of emissions in 1990 for a country with average time-varying covariates is predicted to be 44,356 metric tons of CO_2. Initial status has a standard deviation of 0.40 percent, while the slope for each country has a standard deviation of 0.01 percent. Within-country growth from year to year has a standard deviation of 0.19 percent.

The growth in both internet users and mobile phones over the period of investigation is dramatic, yet does not influence total CO_2 emissions. Year-to-year changes in total CO_2 emissions are affected very little by the rapid growth of ICTs. This pattern holds for the world, DC, and LDC samples. However, at level 2 (between-country differences) we do find some notable results. In the world sample, for every one percent above the average global development of fixed telephones, a country's total CO_2 emissions increase 0.26 percent ($p < .01$), all else constant. We expect such an effect because of the close connection between fixed telephone development and the development of electrical infrastructure (Looney 1998; Mazur 2013; Longo and York 2015). In contrast, the development of mobile telephones does not affect CO_2 emissions, even between countries. Countries with above-average numbers of internet users have 0.30 percent higher CO_2 emissions ($p < .05$), all else constant.

Since the development status dummy indicates that LDCs have about 0.70 percent higher total CO_2 emissions on average, we should find a larger effect in the LDC sample. Results for the LDC sample are found in Table 3. As expected, for LDCs we find that for every one percent above the average fixed telephone development, total CO_2 emissions are 0.32 percent higher ($p < .001$), all else constant. Since fixed telephones were built across the developing world over this period, it is interesting that we do not see growth in emissions over time. What this indicates is that for this period the average between-country differences are more important for the effect of ICT development on total CO_2 emissions than year-to-year growth.

Results for the DC sample are found in Table 4. For DCs, we find that fixed telephone development does not have a significant impact on CO_2 emissions. We expect this, as most DCs had ceased developing telephone lines by 2000 and often had declining fixed telephone use. Countries that have fewer fixed telephones are replacing their infrastructure with mobile telephones, and they are using old infrastructure to develop broadband internet. DCs that are using the internet one percent more than the average have 0.58 percent higher total CO_2 emissions ($p < .001$), all else constant. This finding indicates that it is unlikely that the transition to a new ICT infrastructure will fundamentally change the impact of ICT development on CO_2 emissions in DCs. For as much as dematerialization is lauded, there is little difference between placing an order over the phone and placing an order over the internet (Berkhout and Hertin 2004). Considered in global context, examinations of individual countries such as South Korea (International Telecommunications Union 2015) and the United States (Romm 2002) ignore the unequal ecological exchange between

TABLE 3. Total CO_2 and Source-Sector CO_2 Emissions for the Less-Developed Countries Sample: A Panel Multilevel Model for Growth with AR(1) Error Correction, Random Intercepts, and Random Slopes for Rate of Change; Coefficients (Coeff.) and Standard Errors (SE)

Independent variables[a]	Total		Electricity		Buildings		Manufacture		Transport	
	Coeff.	SE	Coeff.	SE	Coeff.	SE	Coeff.	SE	Coeff.	SE
Level 1[b]										
Rate of change	−0.00	0.01	0.00	0.01	0.00	0.01	−0.02***	0.01	−0.00	0.01
Population	0.99***	0.20	0.81**	0.28	0.31	0.27	0.78***	0.23	0.49*	0.19
GDP per capita	0.47***	0.06	0.29***	0.07	0.12	0.07	0.33***	0.06	0.36***	0.05
GDP per capita squared	−0.21*	0.09	−0.22*	0.09	0.09	0.10	−0.10	0.09	−0.07	0.07
% trade	−0.05*	0.03	−0.05	0.03	0.03	0.03	−0.02	0.03	−0.00	0.02
% fossil energy	0.61***	0.04	0.43***	0.04	0.20***	0.05	0.20***	0.04	0.26***	0.03
% urban	0.91***	0.22	0.41	0.30	0.07	0.29	0.72**	0.26	0.67**	0.21
% service	−0.17***	0.05	−0.08	0.05	−0.09	0.06	−0.04	0.05	−0.08*	0.03
Fixed telephones	0.02	0.02	0.02	0.02	0.01	0.02	0.05**	0.02	0.03*	0.01
Mobile telephones	−0.00	0.01	−0.00	0.01	−0.02	0.01	0.03*	0.01	0.01	0.01
Internet users	−0.02	0.02	−0.01	0.02	0.02	0.02	−0.01	0.02	0.01	0.01
Level 2 (mean)[c]										
Population	1.17***	0.05	0.94***	0.08	0.71***	0.06	0.99***	0.06	0.80***	0.04
GDP per capita	0.32**	0.10	0.03	0.17	−0.08	0.14	0.24	0.13	0.40***	0.08
% trade	0.45**	0.15	0.62*	0.25	0.05	0.21	0.45*	0.19	0.11	0.11
% fossil	0.62***	0.12	0.54**	0.19	0.23	0.16	0.21	0.15	0.19*	0.09
% urban	0.49**	0.19	0.56	0.31	0.63*	0.26	0.46	0.24	0.10	0.14
% service	−0.47	0.28	−0.18	0.46	−0.36	0.39	−0.31	0.36	−0.34	0.21
Fixed telephones	0.32***	0.08	0.43**	0.14	0.36**	0.12	0.39***	0.11	0.25***	0.06

TABLE 3. Total CO_2 and Source-Sector CO_2 Emissions for the Less-Developed Countries Sample: A Panel Multilevel Model for Growth with AR(1) Error Correction, Random Intercepts, and Random Slopes for Rate of Change; Coefficients (Coeff.) and Standard Errors (SE) (*continued*)

Independent variables[a]	**Total**		**Electricity**		**Buildings**		**Manufacture**		**Transport**	
	Coeff.	**SE**	**Coeff.**	**SE**	**Coeff.**	**SE**	**Coeff.**	**SE**	**Coeff.**	**SE**
Mobile telephones	−0.23	0.12	−0.20	0.20	−0.16	0.17	−0.22	0.15	0.02	0.09
Internet users	0.03	0.18	−0.25	0.30	−0.22	0.25	−0.21	0.23	−0.16	0.14
Initial status at mean	10.31***	0.12	2.16***	0.17	1.14***	0.15	2.22***	0.14	2.32***	0.09
Random effects (SD)										
Level 1:										
Within country	0.21***	0.02	0.15***	0.01	0.17***	0.02	0.15***	0.01	0.33***	0.03
ρ	0.88***	0.11	0.76***	0.08	0.75***	0.10	0.75***	0.07	0.97***	0.08
Level 2:										
In rate of change	0.00***	0.00	0.02***	0.00	0.02***	0.00	0.02***	0.00	0.00	0.01
In initial status	0.37***	0.04	0.62***	0.06	0.52***	0.05	0.48***	0.04	0.00	0.18
Model statistics										
df	20		20		20		20		20	
Deviance	−1,831		−1,644		−1,394		−1,683		−2,557	
Countries	72		72		72		72		72	
Observations	1,195		1,195		1,195		1,195		1,195	

[a]All variables are natural log transformed.
[b]Level-1 time-varying variables are group-mean centered.
[c]Level-2 time-invariant variables are grand-mean centered.
Model uses maximum likelihood estimation and unstructured covariance.
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

TABLE 4. Total CO_2 and Source-Sector CO_2 Emissions for the Developed Countries Sample: A Panel Multilevel Model for Growth with AR(1) Error Correction, Random Intercepts, and Random Slopes for Rate of Change; Coefficients (Coeff.) and Standard Errors (SE)

Independent variables[a]	Total		Electricity		Buildings		Manufacture		Transport	
	Coeff.	SE	Coeff.	SE	Coeff.	SE	Coeff.	SE	Coeff.	SE
Level 1[b]										
Rate of change	−0.00	0.01	0.01	0.01	−0.01	0.00	−0.03***	0.01	−0.00	0.00
Population	0.96***	0.21	0.75***	0.19	0.47**	0.17	1.34***	0.23	0.76***	0.13
GDP per capita	0.29**	0.10	0.35***	0.10	0.06	0.09	0.56***	0.11	0.54***	0.06
GDP per capita squared	−0.28	0.21	0.04	0.20	0.12	0.20	0.45*	0.23	0.05	0.13
Trade % GDP	0.01	0.05	0.00	0.04	−0.09*	0.04	0.14**	0.05	−0.07**	0.03
Fossil energy %	0.99***	0.13	1.44***	0.12	0.34**	0.12	0.51***	0.13	0.15*	0.07
Urban %	−0.76	0.57	−0.31	0.51	0.46	0.45	1.05	0.65	−0.19	0.36
Service % GDP	−0.17*	0.08	−0.13	0.08	0.05	0.08	−0.11	0.08	0.05	0.04
Fixed telephones	−0.03	0.06	0.02	0.05	0.07	0.05	0.08	0.06	0.04	0.03
Mobile telephones	0.00	0.02	0.01	0.02	0.01	0.02	−0.01	0.02	0.01	0.01
Internet users	0.01	0.02	−0.02	0.02	0.00	0.01	0.02	0.02	0.01	0.01
Level 2 (mean)[c]										
Population	1.07***	0.05	0.92***	0.09	0.88***	0.10	0.83***	0.06	0.78***	0.05
GDP per capita	0.31*	0.12	−0.13	0.19	0.37	0.22	0.38**	0.13	0.53***	0.11
Trade % GDP	0.18	0.14	−0.12	0.23	0.06	0.26	−0.19	0.15	−0.34**	0.13
Fossil energy %	0.50**	0.19	1.10***	0.30	−0.36	0.34	0.51*	0.20	0.40*	0.17
Urban %	−0.22	0.17	0.17	0.27	−0.30	0.30	−0.32	0.18	0.15	0.15
Service % GDP	−0.91	0.52	−1.15	0.80	0.97	0.90	−1.25*	0.55	−0.25	0.45
Fixed telephones	−0.19	0.20	−0.05	0.31	0.14	0.35	−0.41	0.21	−0.18	0.17

TABLE 4. Total CO_2 and Source-Sector CO_2 Emissions for the Developed Countries Sample: A Panel Multilevel Model for Growth with AR(1) Error Correction, Random Intercepts, and Random Slopes for Rate of Change; Coefficients (Coeff.) and Standard Errors (SE) (*continued*)

Independent variables[a]	Total		Electricity		Buildings		Manufacture		Transport	
	Coeff.	SE	Coeff.	SE	Coeff.	SE	Coeff.	SE	Coeff.	SE
Mobile telephones	−0.11	0.22	0.07	0.34	−0.69	0.39	−0.41	0.24	−0.26	0.19
Internet users	0.58**	0.22	0.66	0.35	0.39	0.39	0.99***	0.24	0.48*	0.19
Initial status at mean	11.00***	0.18	3.15***	0.28	2.18***	0.31	2.86***	0.20	2.35***	0.16
Random effects (SD)										
Level 1:										
Within country	0.15***	0.05	0.13***	0.02	0.11***	0.01	0.37***	0.04	0.30***	0.04
ρ	0.86***	0.30	0.82***	0.15	0.75***	0.10	0.98***	0.11	0.99***	0.15
Level 2:										
In rate of change	0.02***	0.00	0.02***	0.00	0.01***	0.00	0.01***	0.00	0.01***	0.00
In initial status	0.30***	0.06	0.51***	0.06	0.58***	0.07	0.00	0.00	0.00*	0.00
Model statistics										
df	20		20		20		20		20	
Deviance	−1,489		−1,502		−1,492		−1,439		−2,278	
Countries	41		41		41		41		41	
Observations	731		731		731		731		731	

[a]All variables are natural log transformed.
[b]Level-1 time-varying variables are group-mean centered.
[c]Level-2 time-invariant variables are grand-mean centered.
Model uses maximum likelihood estimation and unstructured covariance.
$*p < 0.05$, $**p < 0.01$, $***p < 0.001$

DCs with decelerating emission profiles and LDCs with accelerating emission profiles (Rice 2007; Jorgenson et al. 2009; Jorgenson and Clark 2012).

Source-Sector Emissions

We now turn to emissions across the four key sectors, beginning with electricity. Emissions from electricity production make up the largest segment of total CO_2 emissions. Because of this, electricity production follows a trajectory similar to total CO_2 emissions. For all three samples, we find that ICT development has no significant effect on CO_2 emissions from electricity over time. At level 2, above-average development of fixed telephones significantly increases CO_2 emissions for the world and LDC samples. The effect is higher than for total CO_2 emissions, indicating that total emissions driven by fixed telephone development are linked to electricity production. We do not see a comparable increase in electricity emissions for DCs. The development of the internet did not spread electricity in DCs as it did in LDCs, largely because in DCs the electrical grid was already well developed (Looney 1998). Mobile telephones did not affect emissions from electricity.

Emissions from buildings are not significantly impacted by year-to-year changes in ICT development. Again, the differences in the effect of ICT development are mostly between countries. For the world and LDC samples, fixed telephone development increases CO_2 emissions from buildings 0.39 percent and 0.36 percent, respectively ($p < .001$), for countries with one percent higher development than the average, all else constant. For DCs, we find no significant effect of ICT development indicators on CO_2 emissions from buildings.

Emissions from manufacturing in the world sample are influenced by the growth of both fixed telephone infrastructure and mobile telephone infrastructure year to year. Each one-percent increase in fixed telephone development increases CO_2 emissions from manufacturing by 0.04 percent ($p < .05$), while mobile telephone development increases emissions by 0.02 percent ($p < .05$) each year on average, all else constant. These effects also hold for LDCs but not for DCs. Countries in the world and the LDC sample with one percent higher-than-average fixed telephone development have 0.26 percent ($p < .01$) and 0.39 percent ($p < .001$) higher emissions from manufacturing, respectively, all else constant. As fixed telephones develop in LDCs, they open opportunities for increased manufacturing, often sponsored by direct foreign investment from DCs, in a way that mobile infrastructure does not. The globalized market requires effective communication for the operation of manufacturing facilities that may be producing components in a globalized supply chain. For DCs, the development of the internet fills this same role. DCs with one percent more internet users have 0.99 percent greater CO_2 emissions from manufacturing ($p < .001$), all else constant. The internet connects manufacturers with each other and provides a platform for small manufacturers to reach wider audiences than previously.

Emissions from transportation are affected by increases in internet users and fixed telephones. For the world and LDC samples, we find that a one-percent increase in fixed telephones leads to a 0.03 percent rise in emissions ($p < .05$), all else constant. Increased manufacturing requires increased transport of goods. For each percent a country is above the average level of fixed telephones, CO_2 emissions from transportation increase by

0.19 percent for the world ($p < .01$) and 0.25 percent for LDCs ($p < .001$), all else constant. Mobile telephone and internet development do not have an effect over time or between countries for the world or LDC samples. For DCs, countries with one percent more than average internet users have 0.48 percent greater CO_2 emissions ($p < .05$), all else constant. Internet use has the only significant effect on CO_2 emissions in the DC sample. Rather than demobilizing society, the internet seems to increase the demand for transportation. Increased demand for goods increases emissions from transportation and reveals a fallacy in the logic of the telecommuter (Rotem-Mindali and Weltevreden 2013).

CONCLUSION

Overall, the preponderance of our results supports the treadmill-of-information view represented in Hypothesis 1 (ICT development will increase CO_2 emissions). The development of the internet in DCs and the development of fixed telephones in LDCs both increase CO_2 emissions, substantially. We also find that the evidence strongly supports Hypothesis 2; fixed telephones had not only between-group effects but also growth effects for the world and LDCs. In contrast, we find no support for Hypothesis 3; mobile telephone development seems to have no significant effect on CO_2 emissions. Lastly, the evidence strongly supports Hypothesis 4; an increase in internet users increases CO_2 emissions in total and from manufacturing and transportation for DCs. One possible conclusion is that wired communication infrastructure—fixed telephones and the internet—requires more energy to maintain and thus stimulates increased use of energy.

It is important to note that the issue at hand is not merely whether ICTs contribute directly to CO_2 emissions—they do—but also the consequences of their application in the structural context of our fossil-fuel-dependent economy. The internet and fixed telephones increase demand for manufacturing and transportation services that generate CO_2 emissions. Across the developing world, fixed telephones and electrical grids provide the opportunity for LDCs to gain the benefits of economic development that DCs have received at the expense of ever-increasing CO_2 emissions. The efficiency gains of technology—in this case ICTs—have been at the heart of evaluating technological impacts on the environment (Spaargaren and Mol 1992; York et al. 2003b). While population and affluence have been relatively well defined in the STIRPAT literature, technology has not (York et al. 2003a, 2003b; Rosa et al. 2015). The effects of technology are complex and are the least well-developed dimensions of structural human ecology (Rosa et al. 2010; Rosa and Dietz 2012; Dietz and Jorgenson 2013; Rosa et al. 2015; McGee et al. 2015). It is difficult to model the environmental impact of even one field of technological development. We have illustrated some of the depth of this complexity by including source-sector-dependent variables along with total CO_2 emissions.

There are many areas of research left to explore concerning ICT development and environmental impacts, including a more robust theoretical model of the treadmill of information; the relationship of ICTs to the adoption of renewable energy sources; the dynamics of technological leapfrogging for ICT development; and the incorporation of other measurable factors, such as broadband speed, international data transfers, submarine cables, microwave transmitter towers, and communications satellites. Unfortunately, providing historical analyses such as we have presented here is problematic, since data for many countries, and for variables such as broadband speed, servers, and data-use volume, are spotty and recent. Further operationalizing the treadmill of information and contextualizing it within other crucial sustainable development frameworks such as unequal ecological exchange, environmental decoupling, and human well-being are needed to enhance our understanding of the ecological viability of the information society (Rice 2007; Jorgenson and Clark 2009, 2012; Dietz 2015; Givens 2017; Huang 2018).

ICT development is integral to the modernization of societies (Weber 1978; Castells 2000; International Telecommunications Union 2016). However, it is unclear whether ICTs play much of a role, if any, in decoupling economic development from environmental degradation in the form of CO_2 emissions, despite optimistic projections along these lines by proponents of ecological modernization theory (Mol 2008). While there are marginal efficiencies gained in specific source-sectors from specific ICTs, overall, ICT development seems to support our model of the treadmill of information. Based on our results we conclude that it is not enough to develop ICTs and expect that they will transform how societal development impacts the environment. ICTs contribute to growing energy demands both directly and indirectly, by providing access to new markets and generating new modes of consumption and production. Amazon, Google, Apple, and Facebook are the most highly valued corporations in history—a designation once held by ExxonMobil, Royal Dutch Shell, Chevron, and PetroChina—and the ubiquity of ICTs magnifies their ability to facilitate wealth accumulation and externalize environmental harms. Our screens are portals to every store in the world, a map to every place in the world, and a node in the network of every connected device in the world.

Castells (2000) outlines the transformative capacity of ICTs: the entire logic that operates society will be transformed from a linear logic (based on books) to a decentralized network logic based on the networked logic of the internet. The treadmill of production is a metaphor capturing the relationship between modern societies' quest for growth and the resulting impacts on the environment (Rudel et al. 2011). It is linear, accelerating, and concerned with growth above all else. Accumulation is the core logic, and that accumulation is still present in our contemporary networked information society. However, we cannot dismiss the distinct contribution of the treadmill of information. ICTs affect the environment, but they also affect culture and social structure. The battle for a safer future climate, for example, is not merely a push to mitigate the effect of technological development, but also a battleground of ideology and power played out over trillions of network nodes, through billions of screens, and into billions of human minds. Opposition to limiting CO_2 emissions from the forces of anti-reflexivity, enhanced by social media reliant on ICTs, is as much a feature of the treadmill of information as is the lithium-ion battery, and perhaps more dangerous (McCright and Dunlap 2010).

Adding more users to the internet does not reduce the pressure for carbon intensity; instead, it provides even more opportunities to exert such pressure, through the network. Networks grow. They make new linkages. Power may be decentralized, but that power remains in the network. Theoretically, the wisdom of networks has been mobilized to solve problems that were unsolvable before (Castells 2000). Yet, the acceleration of this networked informational society on our "post-exuberant" planet has led to greater wealth concentration, more dependency, and greater risk to our planet than at any time in history (Catton and Dunlap 1980). Rather than ameliorating the negative impacts of the treadmill of production, it seems that ICTs may well be exacerbating them. This captures our thesis: like the treadmill of destruction, the treadmill of information highlights a source of environmental degradation distinct from yet complementary to the treadmill of production. ■

A version of this paper was presented at the Annual Meeting of the American Sociological Association, Chicago, 2015.

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NOTES

1. Specifically, Millennium Development Goals 7 (Ensure Environmental Sustainability) and 8 (Global Partnership for Development), and Sustainable Development Goals 13 (Climate Action) and 9 (Industry, Innovation, and Infrastructure) (United Nations General Assembly 2000, 2015).

2. We did not include the "other" source-sector in our analyses because it contains a collection of miscellaneous emissions sources and does not represent a cohesive segment of the economy.

3. Since we group-mean center our level-1 variables and center time on the initial year 1990, the interpretations of the intercept and random effects components are not strictly the initial status for each time-varying covariate but instead represent the value for a country in 1990 with the group mean.

4. We do find some sensitivity to the inclusion of specific control variables. Models without fossil energy, service, trade, and urbanization show a more significant effect of ICT development variables. Leaving out one or more of the ICT development indicators also affects the significance of some outcomes. As Longo and York (2015) note, these indicators are not reliably stable, and further investigation is needed to account for the sensitivity issues.