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TOPICAL REVIEW

Pollution and economic development: an empirical research review

Saleem H Ali[1,3] **and Jose A Puppim de Oliveira**[2]

[1] University of Delaware (USA) and Professorial Research Fellow, University of Queensland, Australia
[2] Fundação Getulio Vargas (FGV), São Paulo and Brazilian School of Public and Business Administration (FGV/EBAPE), Rio de Janeiro, Brazil
[3] Author to whom any correspondence should be addressed.

E-mail: saleem@alum.mit.edu **and** jose.puppim@fgv.br

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Abstract

Pollution and the economy seem to have been inextricably linked throughout human history. Yet the relationship between environmental harm and economic development is complex and its understanding has been fragmented by disciplinary biases. Economists and environmental scientists have diverged on the urgency of abatement mechanisms and the marginal returns on investment on control technologies and social adaptations. The Environmental Kuznets Curve hypothesis has dominated this discourse, but is only one part of a broader pollution-economy nexus. As we consider a societal shift towards a circular economy, there is a need to consider a more integrated framework for analyzing the empirical evidence that connects pollution and economic development, and its implications for human well-being and the achievement of the sustainable development goals. This paper develops the main connections between pollution and economic development by reviewing the existing empirical evidence in the literature.

1. Introduction

The relationship between pollution and economic development has been widely debated across various disciplines in the natural and social sciences. The prevalence of the Environmental Kuznets Curve (EKC) has blurred the more complex relations between economic development and environmental outcomes, despite the limitations of the EKC to consider ecological carrying capacity concerns. Moreover, the empirical isolation of many studies in highly specific disciplinary contexts has hitherto prevented us from considering an integrated framework for analysis. As we consider ways of moving towards a circular economy in which pollution itself could be harnessed as a material asset for usage in products to diminish waste, a more integrated framework is needed. This is particularly true in developing countries where pollution rates are rising most dramatically and where governments and firms are often being confronted with conflicting narratives about the impact of environmental regulations on economic growth and broader human development. The relationships between pollution and economic development are complex with several possible feedback loops that are predicated on drivers and consequences of economic growth, ecosystem resilience and the ultimate reliance of financial capital on nature. The aim to achieve the sustainable development goals (SDGs) is an opportunity to revise and organize the debates between pollution and economic development.

Historically, the modern ecological movement, which started in industrialized countries in the 1960s blamed economic development as the main driver of pollution. Studies, such as the Report of the Club of Rome (Meadows *et al* 1972), suggested that if the economy continued with the same pattern we would deplete natural resources and reach unpredictable, and perhaps unacceptable, levels of pollution, advising zero growth as an alternative to environmental and human catastrophe. Zero or negative economic growth emerged as the ardent environmentalist's solution for ecological problems, particularly in more industrialized countries at the time, as economic growth and a clean environment appeared to be antagonistic and interchangeable. The environment-economy antagonism permeated the debates during the UN Conference on Human Development in

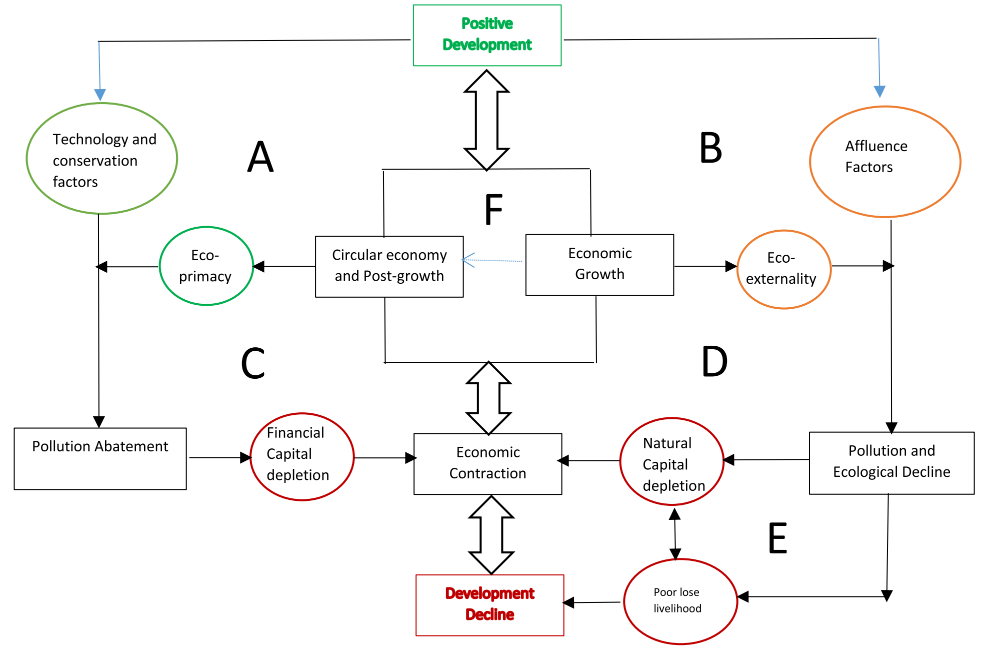

Figure 1. Schematic representation of feedbacks between pollution, economic growth and development which will be covered in this review with possible causal pathways which are further explicated in narrative.

Stockholm in 1972. However, some dissenting voices, such as the prime-minister of India Indira Gandhi, argued that poverty, or lack of economic development, can also be problematic to environmental pollution (e.g. lack of sanitation) (Gandhi 1972). Indeed, later on, we found that the relation between the environment, the economy and human well-being was much more complex. Nevertheless, the zero growth movement has been influential since then and has a diversified range of contemporary streams, such as the more European degrowth movement and the more American steady-state economy (Daly 1991, Demaria *et al* 2013).

Figure 1 attempts to distill some of these connections and this literature review will focus on five of the fundamental connections noted in this diagram in pathways, A, B, C, D and E with clarification on some of the other feedback loops and connections also noted. This figure is meant to reflect the various debates and controversies in the field as represented by possible causal pathways and is not meant to be an exhaustive or deterministic diagram of all possible causal mechanisms. Some of the most common intervening variables that can lead us towards one or another pathway are presented and will be further explicated in the accompanying text.

The extreme nodes of the vertical development axis of the diagram is meant to reflect an established and accepted spectrum of development goals. Economic growth is clearly the dominant pathway towards reaching the positive goals of development but alternative approaches are also considered in terms of ecological constraints that could take us via a circular economy or post-growth model of development which will be discussed towards the end of this review as a possible opportunity for 'win–win' outcomes. This diagram is meant to show a range of possible paths and impact categories as a heuristic exercise rather than a deterministic model.

The term 'eco-primacy' reflects the assumption which proponents of that pathway make regarding environmental issues requiring priority because of long-term reliance of economic systems on the environment (Daly 2014). The role of technology in providing a positive development outcome along this pathway is an essential part of the literature that also connects economics with engineering and operations research (National Academy of Engineering 1991). In contrast 'eco-externality' refers to the dominant approach in neoclassical economics wherein environmental impact is perceived as exogenous to economic performance of firms and consumers and presents a more short-term approach to considering pollution (Oats 2006, Stavins 2012). Increased consumption, or 'affluence factors', is indicative of what comes forth as a natural outcome of development processes in most cases up to a certain point (Myers and Kent 2004). However, it is important to recognize that there is huge variation between countries regarding how this affluence effect leads to pollution. Japan, Germany and the United States are the most compelling examples of divergence in pollution impact and resource use intensity despite comparable economic development indicators (Schreurs 2003). The economic contraction is contending with the trade-offs between financial and natural capital depletion, which is investigated in further detail from the perspective of interdependence of livelihood generation on both forms of capital in the contemporary context of market economies. Let us now consider each of these key areas of interactions between the economy and the environment in terms of evidence-based research that can inform policy formulation.

This paper attempts to distill some of these environment-economy connections (labeled in figure 1) and provide new analysis from the recurring discussions on the links between environmental protection and economic development, and their implications for human well-being. It will focus on six of the fundamental connections (A, B, C, D, E and F) that have permeated the environment-development debate as follows:

(A) Economic development outcomes leading to pollution abatement (EKC hypothesis).

(B) Economic development increasing pollution.

(C) Pollution abatement's negative impact on economic growth.

(D) Pollution's negative impact on economic growth.

(E) Pollution's negative impact on development (even with economic growth—inequality effect).

(F) Circular Economy as a way forward?

Each of the following sections examine those connections between the environment and economic development based on the literature.

1.1. Can economic development outcomes lead to pollution abatement? The EKC hypothesis

Are some negative effects of economic development worth enduring as a necessary sacrifice to reap greater rewards of growth, that would self-correct the deleterious impacts of development? This was the prognosis of the work of economist Simon Kuznets, whose name is now immortalized in the famous 'Kuznets curve.' The original curve shows the result of his hypothesis that economic inequality would increase with economic growth but eventually decline (Kuznets 1955). The same logic was also employed by subsequent economists to environmental harm, suggesting that ecological damage was a price to pay for initial development, after which a self-correcting mechanism would somehow kick in to improve environmental performance (Grossman and Krueger 1995, Stern *et al* 1996, Smulders and Gradus 1996). Such an approach is known as the EKC hypothesis.

This hypothesis has been debated for at least 25 years in various forms (Stern 2017). Much of the controversies have revolved around the scale of the analysis, the kind of pollutant chosen and the relative determinism of the pollution reduction with income. The curve also does not account for the pollution haven phenomenon that is associated with growing pockets of unequal pollution impacts. Shafik (1994) while working at the World Bank found that for many pollutants the relationship between income and pollution is not shaped like an upside down U (which might suggest that the solution to pollution is more growth) but rather more like a cedilla—'rising with income, then falling as the low-hanging fruit of pollution abatement is plucked, then rising again as the underlying thermodynamic-physical reality asserts itself' (Zencey 2012).

However, the empirical evidence has only marginally supported the reduction of inequality and environmental harm with economic development (Stern 2004). The literature now suggests that the EKC is by no means deterministic in terms of a development path, and that there can be variations in its trajectory, based on the pollutant as well as frequent changes in its inflexion, based on what form of development path is chosen. The temporal variation in pollution loading needs to be considered over much longer time horizons and also with greater granularity of measurements to gain an accurate understanding of the relationship between economic growth variables and pollution. For example, Wagner (2007) showed how EKC estimates related to greenhouse gas emissions could be deconstructed if one considered how the nonlinear transformation of integrated regressors were generated as well as cross-sectional dependence in the data used (World Bank Group 2012).

Kahn (2006) provides an important study of how the EKC explains some kinds of pollution such as air and noise while not other forms of environmental harm such as land degradation, deforestation and soil erosion, particularly in urban ecosystems. Grossman and Krueger (1995) used the Global Environmental Monitoring System database on air and water quality and conducted an analysis which supported the EKC hypothesis. They concluded that the inflection point of the Kuznets curve for most of the 14 major pollutants they studied occurred when a country's annual per capita income reached around \$8000. However, their analysis also revealed some 'baffling' results—in their own words—for example, coliform bacteria's correlation to per capita income rises with income and then falls but then rises again after \$10 000 per capita.

In a study of countries in the Mediterranean basin Gurluk (2009) conducted an EKC fit analysis for 15 countries in the basin and only for France did a quadratic relationship similar to an EKC emerge when biological oxygen demand (BOD) was used as a pollution variable. The inflection point was found to be at per capita income reaching \$22 161. All the remaining countries follow either a logarithmic increasing or an inverse-logarithmic increasing function between BOD and per capita income.

Such results point towards a weakness of using econometric techniques in such analysis as well where highly specific variation may be found with certain pollutants and where more qualitative research methods are needed to ascertain any definitive relationship between variables. In another study Hettige *et al*

(2000) measured the effect of income growth on three determinants of pollution: the share of industry in national output, the share of polluting sectors in industrial output, and 'end-of-pipe' (EOP) pollution intensities per unit of output in the polluting sectors. They found that the industry share of national output follows a Kuznets-type trajectory, but the other two determinants do not and in combination their results implied the rejection of the EKC hypothesis for industrial water pollution. The sectoral composition follows a clean technology dividend for low-income developing countries, but exhibits little or no trend beyond the middle-income range. However, EOP pollution intensity declines continuously with increased income.

The causal pathway by which economic development can lead to environmental conservation is presented through the EKC in terms of consumer pressure on government to engage in more stringent regulations once a certain income level is achieved, which can then also lead to win–win outcomes of a 'green economy' or 'ecological modernization' (Hajer 1996). Yet environmental activism is by no means correlated with greater income in and of itself, although in specific cases, it may have greater policy impact in higher income countries (Mertig and Dunlap 2001). Moreover, the idea that higher income groups of countries are more environmentally conscious is also contested, as the poor may be more environmentally friendly than the rich (Martinez-Alier 2003). Furthermore, another important determinant of the EKC can be the influence of trade whereby pollution intensity in some sectors is simply exported to other parts of the world. Although this may be true for a few sectors like mining of rare earths, which shifted largely to China due to environmental regulations, the most comprehensive evaluation of the embedded pollution of imports suggests that within the US, there has been a gradual shift to greener imports (Levinson 2010).

In their comparative analysis of countries at various stages of economic development Suri and Chapman (1998) found that while both industrializing and industrialized countries have added to their energy requirements (as a corollary for environmental impact) by exporting manufactured goods, the growth has been substantially higher in the former. Concomitantly, industrialized countries have been able to reduce their energy requirements by importing manufactured goods. They conclude that 'exports of manufactured goods by industrialized countries has thus been an important factor in generating the upward sloping portion of the EKC and imports by industrialized countries have contributed to the downward slope'.

Despite the contentions surrounding its empirical observation (Ekins 1997) and the need for a more nuanced approach to pollution policy, the EKC provides a good initial framing mechanism for further unpacking the pollution-development dynamic. The upward and downward slopes of the curve are thus an important heuristic mechanism for investigating the other four loci of analysis in this paper.

1.2. How economic development can lead to increasing pollution

The environmental pollution impact of economic development stems from two key pathways that have been widely studied in the literature: (a) The resource base needed to develop infrastructure to deliver key economic development outcomes such as access to transport, electricity, water and food; (b) the increased consumption of pollution-intensive resources that comes from access to more disposable income (Brannlund and Ghalwash 2007). These consumed goods may be more pollution-intensive in their production and life cycle. This can arguably further exacerbate income inequality and differential community impacts on the poor (Boyce 1994).

Within development discourse there is a recognition that some environmental pollution will be an inevitable outcome of achieving other urgent development aspirations (Constantini and Monni 2008), most recently enshrined in the United Nations' 17 SDGs up to the year 2030. However, the linkages and feedback loops that exist between deterioration of the environment and other development outcomes deserves to be considered as a complex system. LeBlanc (2015) has developed a detailed network map for the SDGs and intriguingly enough Goal 12 (Ensuring Sustainable Production and Consumption) has the most network connections (14) to the other goals. This would be fairly intuitive in terms of the broad economic nexus of the goal but the linkages to the other environmentally-linked goals deserves attention. This goal is most directly linked to pollution externality concerns and the network analysis highlights how reaching the broadest range of development outcomes can have an impact on the environmental sustainability of production and consumption systems.

Infrastructure remains a major direct determinant of environmental impact from economic development in absolute terms. Roads and other transport infrastructure is the most widely studied impact category in this arena as it is considered a conduit for other forms of pollution-intensive infrastructure development as well. Much of the research on these impacts has focused on forest cover, land degradation and biodiversity decline as key indicators of overall environmental quality decline. The studies have often been conducted by biologists who are considering the impact of roads that dissect habitats in high biodiversity forests and the resulting impacts on species loss (Caro *et al* 2015). However, there is also a recognition that infrastructure could also provide access for conservation research data that could help protect vulnerable populations, and that some positive social development impacts are inextricably linked to infrastructure of structures like better access to human and animal hospitals; breeding centers for endangered species and water treatment plants for higher density settlements. Thus there has been a focus on the literature to use optimization techniques in determining the least impactful mechanism for infrastructure development (Laurance *et al* 2015). Such techniques offer an amicable way forward for managing the environmental impacts of development and for ongoing monitoring to allay conservation concerns.

Complex modeling techniques have not only been used for optimization analysis but also to do forecasting and thereby consider development pathways. In 2008, The Organization for Economic Cooperation and Development (OECD) harmonized the most widely accepted global economic and environmental change models of long-term development-environment linkages in their *OECD Environmental Outlook* 2030[4]. The results clearly showed that economic growth which was likely to occur up to 2030 primarily in developing countries would have serious environmental implications. The overall share of environmental impact of development would increase in developing countries, particularly with reference to sulfur dioxide pollution from fossil fuel energy generation and impairment of waterways. As an example, the model captured data from 6000 major rivers worldwide and the analysis showed that India, China and Africa would account for almost half of all the water-induced soil degradation, and around one-third of all anthropogenic nitrogen loading into river-ways by 2030 (OECD 2008). Thus forecasting models project that further economic growth in developing countries is likely to substantially worsen pollution levels in a 'business as usual (BAU)' scenario and thus pollution control mechanisms would be needed to mitigate these impacts.

However, there is also a new strand of research called Shared Socioeconomic Pathways, which has been developed by research communities working in modeling and scenarios for energy and climate over a century time scale (O'Neill *et al* 2014, 2017). It examines the set of challenges humanity will face to adapt to the impacts of and mitigate climate change under different social, economic and environmental conditions in the long-term (Wagner 2007).

Moving from macro-models to specific examples, Malaysia provides an important case study of a country which has shown a rapid increase in development indicators over the past 50 years but has also fared well on environmental performance indices such as the Yale Environmental Performance Index. However, even in this case of a 'win–win' outcome trajectory, research shows that overall pollution loading, particularly in waterways, has been directly correlated with economic development. Muyibi *et al* (2008) considered several economic variables and conducted a regression against water quality indicators in Malaysia. Their results showed that despite employing a range of technologies and government interventions there were strong correlations between development and pollution loading in waterways. GDP per capita variable accounted for 81% of variances in rivers' pollution episode with an alpha level of 0.005; population accounted for 74% of total polluted rivers with R^2 of 74.2 and p-value less than 0.005 and industrial production accounted for 78% of the yearly variances in levels of river pollution (p less than 0.005).

In an intriguing converse study of the impact of economic contraction and reduced industrial activity on pollution, Davis (2012) found that over a 20 year data period in California (1980–2000), economic recessions were correlated with reduced pollution. The study concluded that '33% and 48% of the variability in air pollution levels was estimated by the overall R2 values. The relationship between the employment measures and air pollution was statistically significant, suggesting that air quality improves during economic downturns' (Davis 2012, p 1956).

One may argue that poverty itself can generate environmental impacts and hence pollution abatement costs should be seen in the context of how they might increase poverty and thereby lead to a negative spiral of de-development. This mainly well-recognized causal pathway is that larger family size is often correlated with poverty. However, the actual environmental impact of this relationship between population and poverty is contested. A notable study to consider these impacts by Heath and Binswanger (1998) conducted in Colombia concluded that the population and poverty impacts can easily be modulated by specific policy interventions and are not in themselves deterministic. Furthermore, the demographic dividend offered by higher population in terms of labor availability for development and tax income still needs to be considered.

Baland *et al* (2006) find that the net environmental impact of poverty itself in the context of rural Nepal is negative but is quantitatively negligible: an increase of 10% in income leads to a net fall of 0.2% in firewood collected. They find the impact of forest degradation (via increased collection times) on local living standards is also miniscule and support similar findings from the Himalayan region and suggest that demographic factors rather than economic growth itself will determine ecological impacts.

More recently, the idea of 'Green Growth' has emerged as a policy alternative that could reconcile economic development and pollution. With a mix of smart management and advanced environmental technology, we could avoid many of the deleterious

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[4] The OECD used the ENV-Linkages computable general equilibrium model, alongside the Integrated Model to Assess Global Environment (IMAGE) and the Timer Image Energy Regional (TIMER) model—developed by the Netherlands Environmental Assessment Agency (MNP)—with some additional input from the Global Trade Analysis Project (GTAP) agricultural-economy model developed at the Agricultural Economics Institute of the Netherlands.

effects of economic growth and use the environmental improvements to prop up economic growth. Indeed, some proponents of green growth suggested that rapid economic growth could help us to tunnel through the EKC and move us quickly to a rich and clean society. However, green growth policies have brought mixed results. For example, green growth policies in South Korea, which was the strongest proponent of the green growth alternative, were questioned as they were based on nuclear energy, construction of dams and land reclamation leading to irreversible impacts on the natural environment (Bluemling and Yun 2016).

Similar analyses are needed more widely across a broader range of pollutants to consider the causal mechanisms that exist in this upward and downward sloping component of the EKC in terms of development leading to increased pollution through material usage and pollution in the long-term.

1.3. Pollution abatement's negative impact on economic growth

Pollution, particularly downstream from the polluter, can be a classic externality problem wherein the curtailment of the pollution to protect those downstream or payment for pollution charges has an immediate cost on the polluter. When the polluted resource is somehow shared as a resource the incentives for cooperation on pollution control increase. Unlike a 'tragedy of the commons,' where a focus on quantity of extraction leads to depletion, in a model where resource quality is the locus of interest, greater cooperation is possible (Ostrom 1990). Thus, in principle, there is more likely cooperation over lakes that require sharing of borders, than with rivers that are often asymmetric in terms of their benefits for the upstream riparian versus the downstream riparian suffering the impact of pollution. In order to thus grapple with pollution, the downstream riparian has to invest considerable cost which has to either come from public funds or from private industrial margins. There is an opportunity cost for any such investment; government could utilize those funds for other higher-growth generation activities, and businesses could potentially invest in expansion and further enterprise. Although some growth may be generated by the pollution abatement technology sector itself in terms of 'green growth,' the proximate short-term negative impact of pollution abatement on economic development cannot be ignored. Many studies that show the negative economic impact of pollution abatement costs consider the analysis at the level of a firm, a sector or a locality and are heavily waited towards private costs rather than public benefits. Operations research tools are now being applied to find a workable balance between the abatement cost's short-term impact and its long-term technological and societal dividend (Fare *et al* 2016).

Since 1973, the United States government has had a formal system of tracking Pollution Abatement Costs and Expenditures through the census bureau, largely to keep track of industry competitiveness. A detailed government study of pollution abatement expenditures on plant-level productivity due to these costs found wide variation between sectors in terms of the impacts being felt (Shadbegian and Gray 2003). Using a Cobb–Douglas production function to study 68 pulp and paper mills, 55 oil refineries and 27 steel mills, it was found that a $1 increase in pollution abatement costs leads to an estimated productivity decline of $3.11, $1.80 and $5.98 in the paper, oil and steel industries respectively. However, the study noted that that these figures indicate proximate impacts and long-term viability of the sector through pollution abatement in terms of increased worker productivity was not estimated. Researchers within the United States have largely avoided focusing on pollution costs at the industry level because of these concerns. This is why focused studies that only lay out pollution abatement costs as a constrained locus of analysis in the short-term are very few. Such studies are largely industry consulting reports for internal usage since broader environmental economics research tends to focus on development outcomes for a larger number of stakeholders in society.

For example, within China (Liu 2012), there has been some ongoing research on pollution abatement costs in the context of energy competitiveness. However, here too researchers are trying to consider the cost models in terms of different technological options. Indeed, the marginal return on investment in pollution control based on particular technologies, can be the most constructive short-term way of analyzing abatement costs for corporate decision-making and public policy. For specific pollutants where high morbidity and mortality in health and ecosystem function are feared, performance based regulations can encourage development of newer more cost-effective technologies. This has been the approach taken on mercury pollution in China. For example, Alcora *et al* (2015) found that 193 tons of mercury was removed in 2010 in China's coal-fired power sector, with annualized mercury emission control costs of 2.7 billion Chinese Yuan (Aprox $ 450 million). Under a projected 2030 Emission Control (EC) scenario with stringent mercury limits compared to BAU scenario, the increase of selective catalytic reduction systems technology was then considered alongside halogen injection (HI), that could contribute to 39 tons of mercury removal at a cost of 3.8 billion CNY. Policy makers would thus need to consider economic tradeoffs based on incentives for new technological development within this time period or consider subsidies for reduction.

The concern about focused research on pollution abatement costs also stems from the context that the impacts of environmental pollution is realized at different time scales from economic benefits. Therefore, we tend to use a discounting factor (often manifest even as high discount interest rate) for future benefits of pollution abatement and conversely a high economic cost for the short-term investment needed to curtail the pollution. Thus pollution abatement gets presented as a 'luxury' for those who are already entitled with economic security and the immediacy of income generation can trump the long-term concern about environmental resilience of the full economic system.

This perception of grassroots priorities is often reflected in developing country respondents to surveys on prioritization of government expenditure. Consider, for example a survey conducted by Globescan of 10 000 Africans from 10 countries across the continent in 2007[5]. The fundamental question asked was: What should be our government's top priority? The results reflect the salience of livelihoods to residents of the world's most impoverished continent. Finding jobs may well be the most significant issue for Africans, whereas protecting the environment is of least priority in terms of expenditure. This seeming paradox between the observable impact of pollution on health and well-being versus a lack of public prioritization has also been documented by Greenstone and Jack (2015). They suggest some possible causal mechanisms that deserve further research in what they term as a new field of 'envirodevonomics'. Such a research agenda would specially help in considering livelihood and jobs linkages to environmental harm.

It can also be argued that making a linear argument for any industry simply on the basis of jobs can be problematic, if the jobs being created are harmful to society—for example, the huge employment created by the highly pollution-intensive arms trade (Yang *et al* 2015). Instead, what is needed is a consideration of opportunity costs of particular forms of employment with a view of livelihoods that considers various potential paths to development that may involve a short-term slow-down in job creation in pollution-intensive sectors to deliver a more long-term and sustainable job creation in other sectors (Elliott and Lindley 2017).

There is thus a need to consider abatement costs in proximate terms versus long-term benefits of the abatement cost as an investment towards a sustainable economy. There is also evidence to suggest that pollution abatement costs tend to provide increasing returns to scale, which in turn can also explain some observations of why inflection points in the EKC framework can be found. Managi (2006) studied how pollution abatement through choice of pesticide and dispensing technologies due to regulations led to increasing return on investments. Investment in abatement technologies for most common air pollutants for which major abatement costs are incurred such as sulfur or nitrogen oxides reduction also shows an increase in marginal return on investment per unit of pollution abated (Pappin *et al* 2015).

Moser *et al* (2013) suggest that we consider pollution abatement in terms of a competitive market economy where a continuum of identical firms using identical technologies produce a homogenous income creation, which impacts aggregate macroeconomic indicators such as GDP. In this economy, two types of capital are accumulated. First, there is conventional capital, also called brown capital, which is more pollution-intensive. Secondly, a less-polluting green capital is presented. Furthermore, the government sets environmental performance standards which entrepreneurs (who are often the job creators in a development process) are obligated to meet. The necessary abatement effort and costs depend on the stringency of these environmental regulations. Consequently, firms adopting cleaner technologies have to spend less on EOP abatement. This benefit, however, comes at a cost because the required resources for green research and development could be invested otherwise profitably in conventional research and development.

However, their analysis shows, that increasing environmental regulation indeed has a positive impact on the accumulation of green capital and on the increase of green R&D investments. This can especially be seen when the shares of capital levels and R&D investments under varying stringency of environmental standards are considered. Although both capital levels decline, increasing abatement costs even accelerate the decrease of brown capital levels so that in total production turns out to be greener the higher environmental quality standards are. The same applies for R&D investments. They conclude that environmental regulation standards can cause a shift to greener production but only at the cost of reduced economic growth. Therefore, the introduction of additional environmental instruments, such as taxes or subsidies, could be considered if this causal pathway for pollution abatement is taken into account. Indeed, there are studies showing that a pollution tax can potentially have a 'double dividend' by reducing pollution while spurring economic growth (Fisher and van Marrewijk 1998). This was unfolded in the concept of co-benefits as the idea of having alternatives for achieving economic, environmental and human development goals at the same time, even though there is a long way to bring it to mainstream practice due to technical and political economy factors (Puppim de Oliveira 2013). Moreover, environmental regulations have different effects on different environmental problems and may not be possible in a different governance context. For example, Mie Prefecture in Japan was successful to tackle air pollution with environmental regulations in 1960s, but it has had problems with reducing the emissions of greenhouse gases (Puppim de Oliveira 2011).

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[5] Survey conducted under the auspices of the Commission for Africa: http://commissionforafrica.info/.

An empirical example of how 'green capital' can be considered in terms of the cost of pollution control regulations was researched by Cai *et al* (2011). They studied pollution mitigation policies in China's power generation sector from 2006 to 2009 and noted that this caused a total of 44 thousand net jobs losses. However, as the share of renewable energy that has an indirect employment impacts increased. The renewable energy policies from 2006 to 2010 actually resulted in 472 thousand net job gains. Their research suggests that to ensure the co-existence of green economy and green jobs in China's power generation sector, policy makers should further promote solar PV, biomass and wind technologies. They concluded therefore that in 2010, for every 1% increase in the share of solar PV generation there could be a 0.68% increase in total employment in China, larger than any other power generation technology.

There is also an overarching international dimension of pollution abatement's impact on global economic activity which needs to be considered in the context of trade. In the landmark anthology on this topic, the role of environmental regulation on economic activity edited by Boyle (1994), Benedict Kingsbury identifies a tripartite division of trade measures which need to be considered in terms of overall regulatory impacts on the economic activity: those intended to have a direct effect on a perceived environmental problem (e.g. trade measures relating to transboundary environmental issues, or to protection of the domestic environment); those taken in direct support of a different measure directed at the environmental problem (e.g. the ban on trade in ozone-depleting substances under the Montreal Convention); and trade measures (sanctions or incentives) intended to change environmental behavior which is essentially unrelated to the trade measure (Boyle 1994). Each of these approaches can have highly divergent impacts on the economy at a local level as well as on long-term international economic stability. However, international governance mechanisms which recognize the danger of a 'race to the bottom' in terms of pollution havens emerging at national and sub-national levels deserve attention (Porter 1999). The relevance of this 'unpacking' of trade policy can assist governments in considering the kind of pollution abatement pathway that should be deliberated within each regional context.

1.4. Pollution's negative impact on economic growth

The primacy of natural capital as a limiting means from which we derive other forms of capital is a fundamental premise in both economic and ecological sciences. Technological progress and innovation can often augment the availability of natural capital but a decline in basic environmental systems that support natural capital still remains a looming concern (Kolstad 2010). Yet, neoclassical economics has generally thought of pollution as a 'social cost' rather than an 'economic cost.' Harkening back to the work of Nobel laureates Ronald Coase (1960) and Robert Solow (1971), pollution was presented as an externality. There was historically also a distinct differentiation in the study of natural resource depletion (resource economics) which was embarked upon by pioneering resource economists such as Hotelling (1931) and concerns about the pollution outcomes of economic activity (environmental economics) by scholars such as Krutilla (1967) and Kneese (1971). Later economists, like 2018 Nobel laureate William Nordhaus, extended some of the concerns about pollution's impact on society and the economy as whole in the context of planetary pollutants such as ozone and greenhouse gases (Nordhaus 1994), but largely kept issues of resource depletion and pollution separate.

This reductionist approach came under sharp criticism from ecological economists who saw environmental decline both in terms of absolute depletion of resource stocks, as well as relative depletion due to pollution impairing use of the resource (Norgaard 1989, Krishnan *et al* 1995). Ultimately, if natural capital is depleted through overharvesting of stocks or through unviability of harvests due to pollution impact on the resource (for example heavy metal contamination of fish), there will inevitably be a negative impact on economic growth.

However, there is also another important dimension of how pollution can stifle the full potential of economic growth which was first noted and modeled by Fisher and van Marrewijk (1998). In their model of extended generations of human development where clean air was a pure public good that could be used as a private input for production, they noted that firms that profit from pollution crowd out investment in innovation and slow economic growth.

There is growing evidence of the negative impact of pollution on economic growth and that we need to pay far more attention to indicators of environmental harm such as the ecological carrying capacity to prevent irreversible harm to particular ecosystems that also sustain livelihoods. In addition to direct impacts on environmental systems that can impact natural capital which in turn influences growth, there is also a major loss in productivity caused by the health impacts of pollution. Respiratory distress can lead to lost work days and have a major impact on the economic output of a locality. A rigorous study of air pollution in Jakarta, Indonesia is a widely cited example in recent years in which the annual cost of air pollution, which is estimated to result on average around 3000 deaths, at around $180 million, which is 1% of the city's GDP (Resosodarmu and Napitupulu 2004). The study also considered the benefits of pollution abatement in this context by forecasting at the time of publication up to 2015 using a range of policy and growth scenarios.

At the national level, China (Lu *et al* 2016) is perhaps the archetypal example of the ultimate impact of pollution on economic indicators, and for the past ten years or so, the government has measured the economic impact of pollution on its economy. One Chinese government study in 2006, cited by the New China Agency, suggested that the country's western provinces will suffer an annual loss equivalent to 15 billion euros, or 13% of the region's gross domestic product, because of environmental damage[6]. The Indian government conducted a similar study of damage caused by pollution in in the country in 1999 and estimated the cost at $14 billion annually: amounting to close to 4.5%–6% of GDP (Managi and Ranjan Jena 2008). Such estimates rely on a mixture of lost production due to closure of sites due to pollution; health impacting workers resulting in lost labor hours as well as healthcare costs. Despite clear evidence emerging of the long-term impacts of pollution on conventional measures of macroeconomic performance such as growth, often the more consequential impact which needs to be considered by development practitioners.

The direct loss of livelihoods from natural resources can also be an additional metric of pollution impacts on economic growth. For example, research on acid rain's impact on fisheries in the Adirondack region by Caputo *et al* (2017) and Beier *et al* (2017) suggest that the economic value of the fishing resource itself declines measurably with reduced pH. For small regional economies, this can have substantive localized impact on economic growth but is challenging to isolate and measure.

Another means of estimating the connection between pollution and economic growth is to consider productivity impacts in particular sectors. For example, a study by Aragona and Rud (2016) in Ghana used a consumer–producer household framework to estimate the agricultural production function and found that farmers located near pollution-intensive mines experienced a relative reduction in total factor productivity of almost 40% between 1997 and 2005.

Concerns of pollution's impact on productivity are not confined only to the outdoor environment. There is also clear evidence from research in experimental economics that there can be productivity losses of between 6% and 9% due to indoor air pollution in common office spaces coupled with noise pollution (Wyon 2004).

A corollary for economic growth which has also been used by researchers interested in studying the impact of pollution is the labor supply availability. In a recent study of the impact of pollution in Mexico City on the hours worked by residents near an oil refinery Hanna and Oliva (2015) found that a 20% drop in sulfur dioxide results in 1.3 h increase in hours worked the following week. This implies an $126 per worker gain from reduced absenteeism over the course of the year for those who lived in close proximity to the refinery. Aggregating such analysis can generate some estimates for direct growth impacts, though accounting for intervening exogenous variables makes that next leap of estimating more challenging.

Thus studies looking at the negative impact of pollution on economic development tend to focus on aggregated impacts in the whole economy in larger scale at the medium and long-term, instead of analyzing impacts of pollution abatement private costs on specific firms in the short-term (such as in item C).

1.5. Pollution's negative impact on human development in spite of economic growth

As noted by the World Bank in its Approach paper on pollution, approximately nine million people die annually from pollution, mostly young children (1.7 million) and older people (4.9 million). 94%, or 8.4 million, of the 9 million deaths caused each year by pollution occur in lower-middle-income countries (Landrigan and Fuller 2016). The paper further notes that 'healthy life years lost due to pollution in developing countries amount to 15 times that of developed countries' (WHO 2014a, 2014b).

One of the most widely studied pollutant is arsenic, which also occurs naturally in parts of Eastern India and Bangladesh and often contaminates the water supply. However, the same inference about pollution linkages to development could be drawn of anthropogenic pollutants as the causal pathways of impact on human capital is identical, whether the pollutant is coming from natural or man-made sources. In one study of Murshidabad region of India Samadder (2011) studied a population of 1.07 million with 0.32 million exposed to arsenic above the 0.05 mg l^{-1}, which the WHO considers permissible in drinking water. The Human Development Index of all six spatial blocks analyzed in this study was severely impact by the arsenic pollution and reduced by as much as 25%, largely due to reduction in life expectancy. Another way to analyze the data could be to consider the environmental justice concerns (Schlosberg 2002), which would suggest that property values would be lower in areas of arsenic and hence pollution would more greatly impact the poor through market mechanisms. Evidence for such differentiated exposure to pollution by the poor has been documented most comprehensively by Walker (2012).

Mercury is another notable pollutant which has been widely studied and has recently resulted in an international treaty on its control (The Minamata Convention on Mercury, which entered into force in

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[6] Study cited by Brice Pedroletti, 'En Chine, le déficit de politique écologique menace les performances économiques.' *Le Monde,* 2 July 2005. This point is expanded in Ali, Saleem H 'In China globalization can be green.' *The International Herald Tribune* (30 May 2006).

August 2017). In the most widely cited study Trasande *et al* (2005) found that the costs to the U.S. economy of anthropogenic (or human produced) mercury emissions due to decreased IQ's ranges from $2.2 billion to $43.8 billion annually (costs are in 2000 dollars). Given the vast range in cost estimates, there can be even greater concern for local variation in terms of policy-making. Thus, for example, this study was used by the state government of Minnesota to develop mercury policy and concluded that American mercury emissions cost Minnesota an estimated $6.7–$263.2 million annually and American power plant emissions cost Minnesota an estimated $1.7–$108.3 million annually. The total cost of anthropogenic mercury emissions, including emissions worldwide, is roughly $36.6–29.5 million annually. Minnesota's use of coal (which attributes to mercury emissions) to generate power is higher than the national average. In 2004, coal was the source of 65% of Minnesota's energy across the total electric power industry.

In addition to health impacts, pollution can hamper development by reducing the viability of land for agriculture, water usage for fishing and trees for forestry. The connection of the poor to global value chains is often considered a way to help quell poverty. Yet, the ecological resilience of the environment to pollution in which the poor are often situated can test this presumption (Bolwig *et al* 2008).

The concept of ecosystem services as a common-good that is provided to all social strata of society may help to address some of these concerns about environmental injustice as well as providing an accounting mechanism for us to reconcile economic development and environmental conservation (Adams *et al* 2004). Quantifying the financial value that comes from conserving nature has been a major area for research and led to the concept of 'ecosystem services'—those benefits provided by nature that have direct economic benefit but do not have a market (Daily ed. 2012). This also led to further investment by the international banking community in recent years including The World Bank in programs which can allow for accounting of these ecosystem services[7]. The next question to ask, however, is if the accounting can be carried out, how might we use financial transaction to help the poor conserve nature. The concept of 'payment for ecosystems services' (PES) has emerged as a result and is now being widely used as a policy tool to mitigate the ultimate development harms of environmental decline (Kumar and Muradian 2009).

Research on the efficacy of PES deserves greater attention The findings of Bulte *et al* (2008) support the analysis of Pagiola *et al* (2005) who suggested that the pre-condition for PES programs to have beneficial effects on poverty reduction is that the poor should: (i) be in the 'right place'; (ii) want to participate (e.g. it should 'fit' into the farm practice); and (iii) be able to participate (e.g. they should be able to make the necessary investments, have sufficiently secure tenure, etc). However, they also conclude that tying PES and poverty reduction may result in lower efficiency in meeting either objective—and in fact it may be better to focus programs on one or the other objective separately. Nonetheless, since PES programs can have indirect effects on the poor-through changes in food prices, wages and land access—poverty and the poor do need to be taken into consideration in designing PES programs, even if poverty reduction is not an objective of the program. However, there is a rising concerns of some authors about the 'commoditization' of the ecosystem services in a market, which can lead to over-exploitation and evictions of the traditional ecosystem users to make the services available to those who can afford paying for the ecological services (Lohmann 2016). Thus 'green growth' could be achieved, but the benefits would not be distributed evenly for all.

1.6. Circular economy a way forward?

As we consider win–win opportunities in balancing economic and environmental issues, the nascent concept of a 'circular economy' posits a definitive paradigm shift in the way industrial processes relate to the modern economy (World Economic Forum 2014, Ghisellini *et al* 2016). The conventional economic model has been focused on linear material flows from mines to markets. However, a circular economy approach that has emerged in recent years suggests the need to reconfigure the economic systems around materials recycling and hence circularity. As with any such major shift in human endeavor, a strong philosophical underpinning can help to draw theoretical insights which in turn allow for transferability of concepts across cases. In this article, the aim is to suggest that a form of dialectical analysis has particular potential in addressing many of the concerns raised by critics of a circular economy. Circularity in modern discourse often implies stasis and thus the circular economy paradigm encounters the same criticism from many neoclassical economists which was faced by Herman Daly (1991) three decades ago with his concept of a 'Steady-State Economy.' There were two key avenues of critique with regard to such an approach: (a) 'steady-state' implied an atrophy of incentives for innovation and hence would diminish the potential for technological advancement of humanity; (b) the development needs of the indigent on the planet meant we had a moral imperative for economic growth that would be precluded by a steady-state economy. It is important to note, however, that proponents of circular economy are willing to embrace growth, so long as material flows are better cycled within the growth paradigm—they are thus focused on stability at the microeconomic level rather

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[7] Refer to the World Bank's Wealth Accounting and Valuation of Ecosystem Services portal: www.wavespartnership.org.

than having a steady-state at the macro-economic level (George *et al* 2015).

A neglected aspect of the circular economy discourse has been an evaluation of how such a paradigm would impact basic human development challenges. There seems to be is a presumption that 'win–win' outcomes would emerge from efficient systems in a circular economy that could provide development dividends in the world's poorer nations (Ghisellini *et al* 2016). Yet some of the dominant premises of a circular economy necessitate reduced consumption and increased durability of material products which has the potential for a major impact on human development in areas that depend on livelihoods from those processes. The simple idea of increasing efficiency by a circular economy will lead to the solution for the increasing ecological footsteps does not hold true, as the Jevon's Paradox may boost aggregate consumption of more efficient system in the long-term in a market economy (Jevons 1865, Dale *et al* 2016). Overall reduction in consumption may be necessary.

As a locus of analysis, consumption of myriad products and services and the fundamental primary resources on which they depend provides an essential link between economic development and environmental impact (Ali 2010). In this regard, there have been calls in the literature to have a better environmental accounting system to track elemental inputs and outputs so as to gauge the tradeoffs between positive economic impact of a project and is negative environmental effects (Almeida *et al* 2017). Further enhancements to the classic input-output modeling developed by Nobel laureate Wassily Leontief (1986) have been enhanced by some of his protégés within ecological engineering most notably Duchin and Glenn-Marie (1995).

A major concern in implementing a circular economy model would be the ultimate provision of employment in an economy structured around conventional jobs. Optimists in this regard would argue that a transition to a service sector and its concomitant wealth creation would counterbalance the reduced throughput of manufacturing employment and livelihoods for industrial economies. The transition of livelihoods following automation of major labor-intensive industries during the past century is often alluded to in this vein. Core to such a transition in employment has been the role of entrepreneurs that fuel new opportunities for employment and livelihood growth (McMillan and Woodruff 2002). However, the opportunities to benefit from a more circular economy through increasing the value and efficiency of waste material can displace jobs from those less powerful. For example, increasing the value to recyclables can lead to the emergence of recycling companies to the detriment of waste pickers (Do Carmo and Puppim de Oliveira 2010). Moreover, there are limits to the absorption of employment by the service sector, even in advanced economies, as researched by scholars such as Ebner (2010). The potential for high population developing countries in reaching a saturation of entrepreneurial activity deserves further study in the green technology sector, similar to how it has been studied in the case of the IT sector in India. However, such analysis will require a much broader global effort to harness data across supply chains of material usage. In a neoclassical paradigm of green growth, the long-term economic development through increasing efficiency in a more circular economy may lead to more green jobs in the short and medium term, but overall less jobs in the long-term with the continuous push to efficiency through competition mechanisms (Dale *et al* 2016).

2. Conclusion: opportunities for win–win policy options

Harkening back to the 1992 World Development Report which was themed for the first time on issues of 'Development and the Environment' there was a clear recognition that economic growth and the environment were inextricably linked and that neither are functionally exogenous to each other (World Bank 1992). That salient observation still holds true, though it has since been unpacked through research. The literature presented in this paper has highlighted the mechanisms by which the interactions between financial and natural capital, as manifest often in terms of economic growth and ecological resilience, respectively occur.

Population growth, particularly in the context of developing countries, remains a lingering imponderable for a more coherent vision for balancing environmental tradeoffs with economic growth. Even with short-term economic growth, a downward spiral can occur by the negative feedback loops *between* natural capital decline, and rush to overexploitation due to desperation—the fabled 'tragedy of the commons' outcome that we were warned of by Hardin (1968). Such a presumption of population impacts on irreversible environmental decline further led Hardin to post the extreme view of 'Life Boat Ethics' whereby we would sacrifice other development goals in favor of extreme resource conservation, for what was deemed by many neo-Malthusians as an existential environmental crisis (Hardin 1974). However, such an approach is no longer plausible in terms of global ethical norms and a realization that some level of irreversible global environmental decline may well be acceptable to meet some human development objectives. The key focus of environmentalists is now to ascertain which 'planetary boundaries' are the most salient for conservation (Steffen *et al* 2015).

Population growth can suggest greater innovation potential and an able workforce—often termed 'the demographic dividend'—but also a major drain on resource endowments. The IPAT equation (Ecological impact = Population × Affluence × Technology) needs to be revisited here to consider how best to operationalize a circular economy within a development context. The various permutations of this equation have been admirably studied before (particularly, Chertow 2001) and are beyond the scope of this article. Suffice it to say that for our purposes here, the technological variable needs to be better connected to the concept of 'planned obsolescence', which is an important feature of consumer product-driven development (Guiltinan 2009). One effort to incorporate the IPAT analysis within a circular economy has been posited for the development of Shaanxi province in China (Ying and Wen-ping 2015). However, the technological variable in their analysis is not adequately unpacked to consider the development and innovation dividends of obsolescence (Kurz 2015). Product design, modularity and finding more ecologically sustainable energy sources would likely be needed to ensure that a 'spiral of development' that was envisaged by social ecologist Murray Bookchin (1995) as a dialectical process can occur as the circular economy is established. Other win–win opportunities are also offered by proponents of green technology economic multipliers and ways of 'technological leapfrogging' which would reduce resource intensity and pollution while growing the economy, albeit more slowly (Pollin 2015).

Ultimately, the costs of pollution to society and economic growth occur over longer time horizons than the internalization of abatement costs at the level of industry. However, the kind of governance established can influence the outcomes and response from economic actors (Puppim de Oliveira and Jabbour 2017). Moreover, pollution's impact on economic growth is measured more indirectly as well through loss of productivity and health costs rather than through a direct causal relationship. Thus the pollution-development nexus must continue to be an area of intense research activity from a broad range of disciplines. Ultimately, the value of pollution control will need to be constantly evaluated as new technologies emerge across the multiple pathways and connections between pollution and development presented in this review paper.

ORCID iDs

Saleem H Ali https://orcid.org/0000-0002-2943-9557
Jose A Puppim de Oliveira https://orcid.org/0000-0001-5000-6265

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